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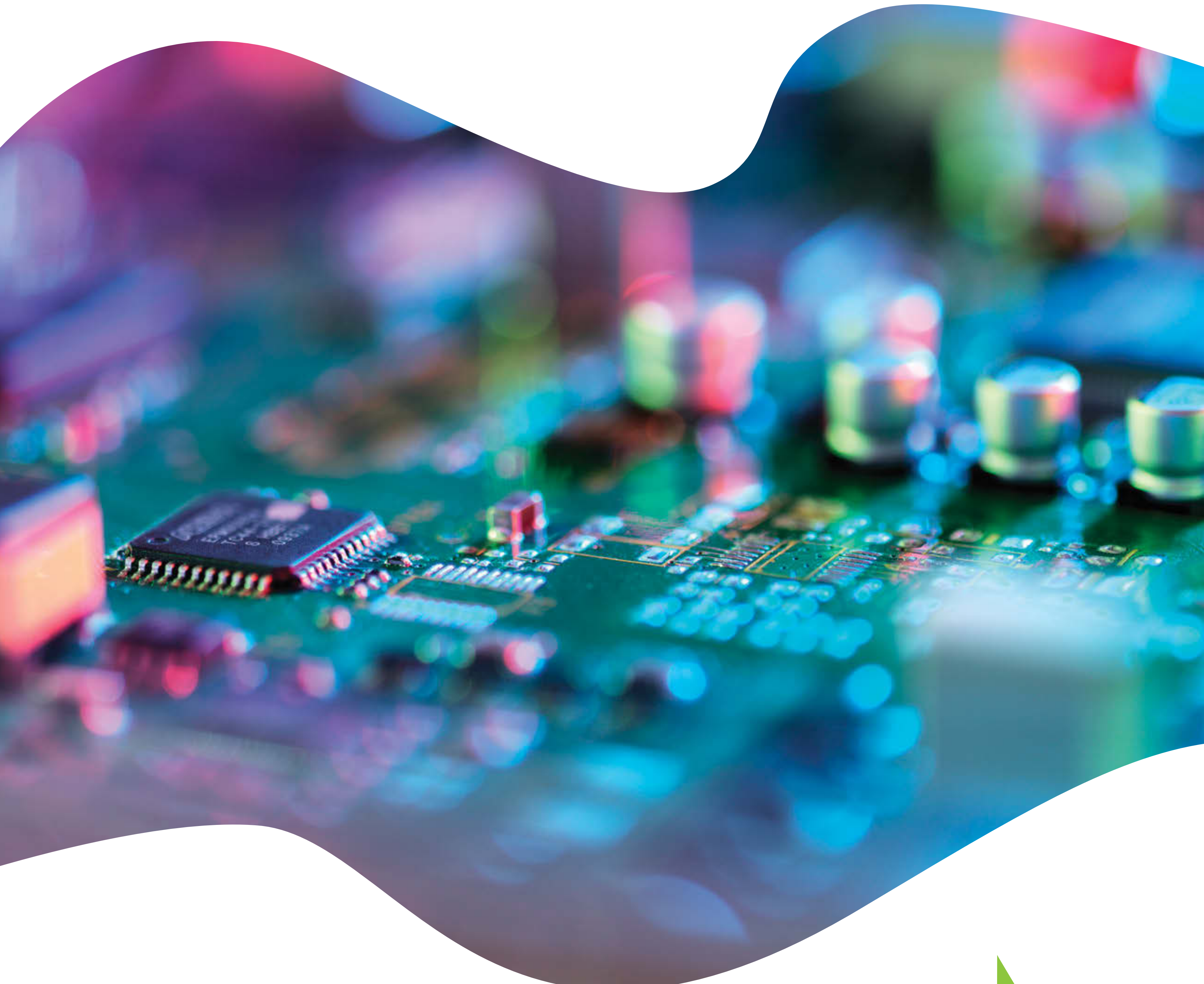
UNITS 3 & 4



QCE 2019 SYLLABUS

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UNITS 3 & 4

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We wish to acknowledge the publication *Multiple representations in physics education*, which provided the insight and inspiration for Module 1.1 Successful learning in physics. The editor David Treagust has graciously reviewed this module. We thank David, Reinders Duit and Hans E. Fischer who collected and reviewed many articles to inform this important aspect of science education.

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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We are grateful to the following people for their time and expertise in contributing to the *Pearson Physics 12 Queensland* project.

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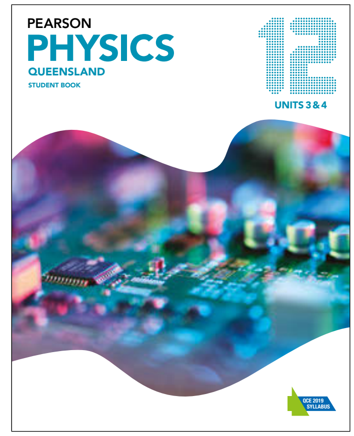

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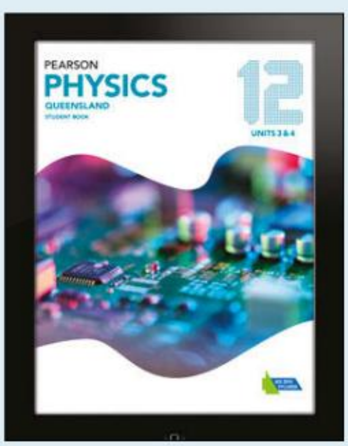
Contents

ONLINE CHAPTER

Chapter 1 Physics skills and assessment toolkit

Go to your eBook to access this chapter.
Page numbering begins at 'e1' for this eBook chapter.
Unit 3 starts on page 1, followed by Chapter 2.



Unit 3 Gravity and electromagnetism

Topic 1: Gravity and motion

Topic 2: Electromagnetism

Unit 4 Revolutions in modern physics

Topic 1: Special relativity

Topic 2: Quantum theory

Topic 3: The Standard Model

How to use this book

PEARSON PHYSICS 12 QUEENSLAND STUDENT BOOK

Pearson Physics 12 Queensland Student Book has been written to the new QCAA Physics General Senior Science Syllabus. The book is an easy-to-use resource that covers Units 3 & 4 and comprehensively addresses skills and assessment requirements.

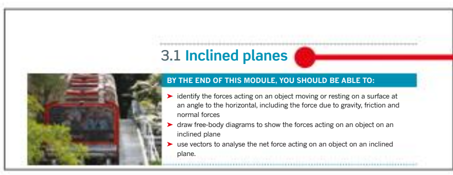
Explore how to use this book below.

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.

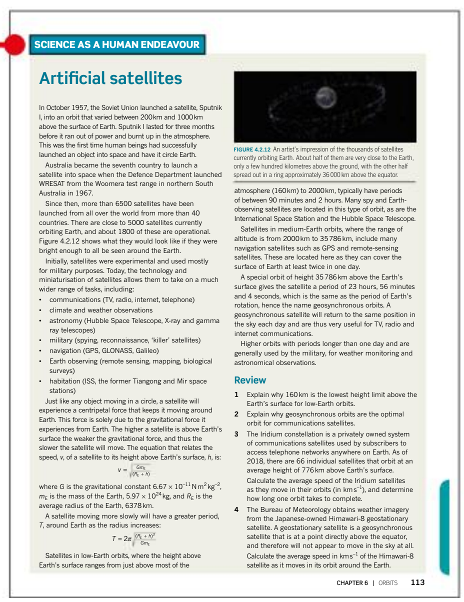


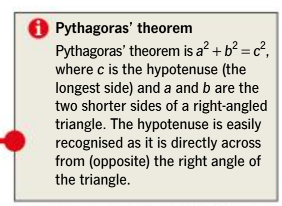
Module

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

This 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.



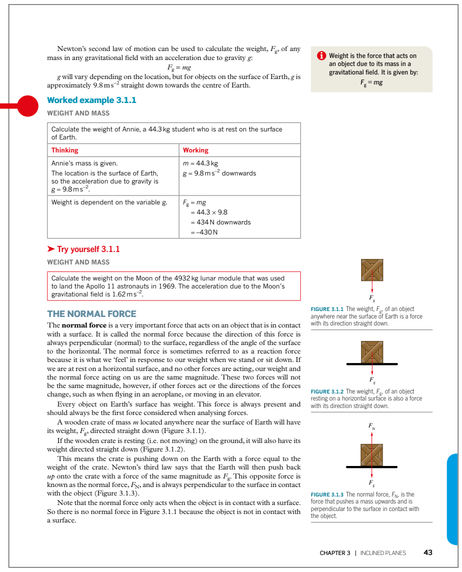


Highlight box

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

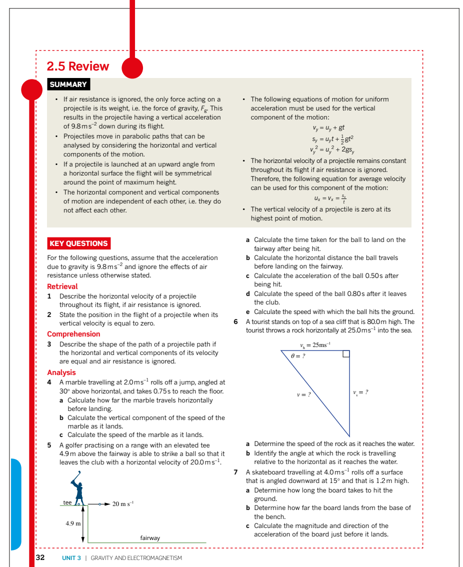
Worked examples

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 12 Queensland Teacher Support*.



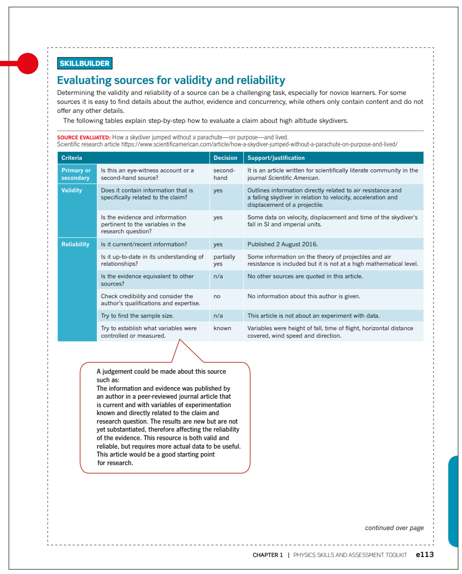
Module summary

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



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.

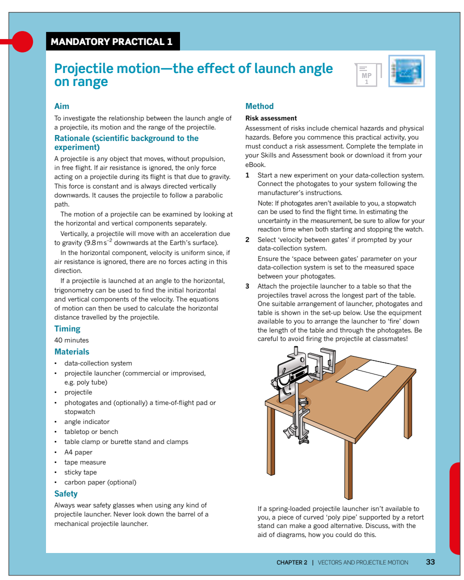


Module review

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.

Mandatory practicals

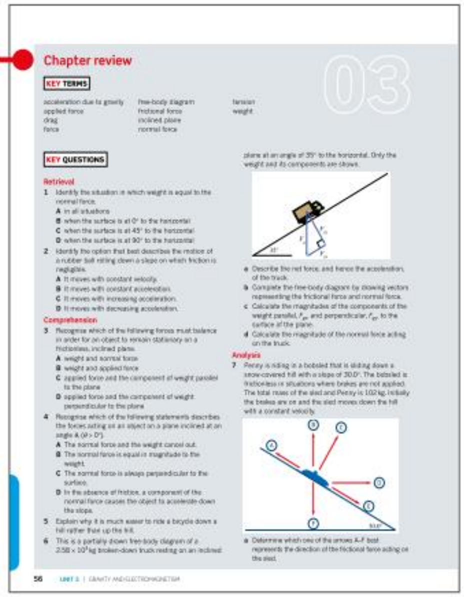
The student book includes all mandatory practicals. Practicals fully address the syllabus requirements. Each practical has been trialled and tested to ensure it can be safely performed and yields effective, safe results.



How to use this book

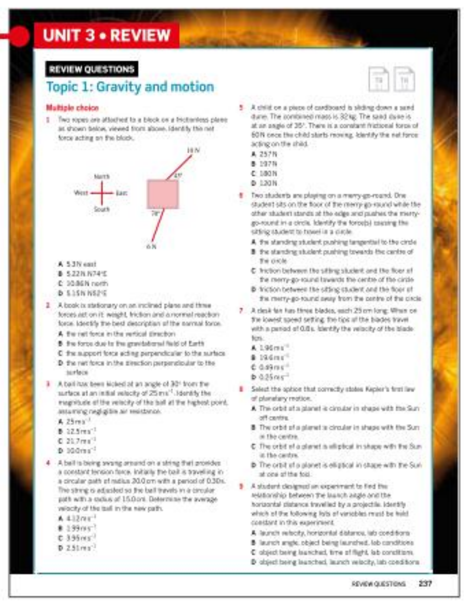
Chapter review

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.



Unit review

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



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 *Pearson Physics 12 Queensland 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 ➤

Every mandatory practical is supported by a complimentary **SPARKlab** alternative practical.

The ***Pearson Physics Skills and Assessment*** book icons indicate the best time to engage with an activity for practice, application and revision. The type of activity is indicated as follows:

Worksheet (WS) — WS 3.1.1

Topic Review (TR) — TR 3.1

Mandatory Practical (MP) — MP 1

Practical Activity (PA) — PA 3.2.1

Sample Assessment Task (SAT) — SAT IA2

The **Reader+** icon indicates when to engage with an asset via your Reader+ eBook. Assets may include videos and interactive activities.

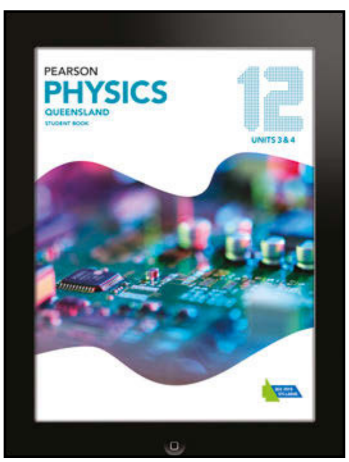
Pearson Physics 12 Queensland

Student Book

Pearson Physics 12 Queensland Student Book has been developed by experienced Queensland teachers to address all the requirements of the new QCAA Physics General Senior 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.

Skills and Assessment book

Pearson Physics 12 Skills and Assessment book gives students the edge in preparing for all forms of assessment. Specifically prepared to provide opportunities to consolidate, develop and apply subject matter and science inquiry skills, this resource features a toolkit, key knowledge summaries, worksheets, practical activities and guidance, assessment practice and topic review sets.



Reader+ the next generation eBook

Reader+ is our next generation eBook. Students can read, take notes, save bookmarks and more in the one seamless experience. Integrated multimedia (audio/video) and interactive activities enhance and extend the learning experience.

Teacher support

Pearson Physics 12 Queensland Teacher Support provides:

- complete answers, fully worked solutions or suggested answers to all the questions in the *Student Book* and *Skills and Assessment* book
- expected results, common mistakes, suggested answers and full safety notes and risk assessments for all practical activities
- teaching and learning assessment programs.

Pearson

Access your digital resources at **pearsonplaces.com.au**
Browse and buy at **pearson.com.au**

Understanding the course

Begin your study of the Physics Units 3 & 4 course by clearly establishing what you are required to do and where you can go to for help. Your teacher will teach and guide you through the course. Your Pearson Queensland Physics Units 3 & 4 resources are a one-stop shop for support in every aspect of the course. This support is delivered via two resources:

- *Pearson Physics 12 Queensland Student Book*
- *Pearson Physics 12 Queensland Skills and Assessment* book.

The syllabus details all the requirements of the QCAA Physics General Senior Science course. This syllabus document is long and challenging to interpret. The Pearson resources comprehensively unpack and address all aspects of the syllabus, presenting all the subject matter, practical experiences and application opportunities (questions and activities) in a user-friendly way. Refer to the following tables for a summary of where to look for different types of syllabus support, and where to look for summative assessment support.

Guide to syllabus support in Pearson resources

Where do I go for help with ... ?	*Pearson Physics 12 Queensland Student Book*	*Pearson Physics 12 Queensland Skills and Assessment* book
ensuring coverage of the syllabus	The student book is organised by units, and the **unit opener** outlines the unit objectives addressed. The student book is further organised into chapters. Each **chapter opener** addresses specific subject matter and mandatory practicals, quoted from the syllabus. **Module openers** within each chapter restate subject-matter learning outcomes in student-friendly language.	The Skills and Assessment book is organised by units, and the **unit opener** outlines the unit objectives addressed. The Skills and Assessment book is further organised into topics. Each **topic** addresses all of the subject matter and mandatory practicals, and is quoted from the syllabus.
subject matter and applications	All subject matter is thoroughly covered. **SkillBuilders** and **worked examples** scaffold and model applications. Further opportunities to practise are provided through mirrored **try yourself** problems.	The subject matter is summarised for each topic in **key knowledge** summaries that provide handy notes for revision and study. Extensive opportunities to apply learning from the student book are provided through **worksheets**, **practical activities**, **topic review sets** and **sample assessment tasks**.
calculations using algorithms	**Chapter 1 Physics skills and assessment toolkit** (eBook) is a reference tool for refreshing your skills with calculations and other key physics skills. Many **worked examples** in chapters model the use of calculations using algorithms.	Opportunities to apply and practice performing calculations and using algorithms are integrated throughout **worksheets, practical activities** and **question sets**.
mandatory practicals	All **mandatory practicals** are included and have been structured to reflect the structure and assessment objectives of the student experiment to provide consistency and experience.	All **mandatory practicals** are included and have been structured to reflect the structure and assessment objectives of the student experiment to provide consistency and experience. These are more scaffolded in the Skills and Assessment book, but provide the same learning outcomes. **Additional practicals** are also included to provide further practice and opportunities for drawing out your student experiment.
general skills in science	**Chapter 1** (eBook online) is a reference tool covering a wide range of basic skills and understandings, such as use of significant figures, units of measurement, tables and graphs, errors and uncertainties.	
definitions of key terms	The detailed **glossary** explains all key terms that are in bold throughout the student book. Where the term is defined in the QCAA syllabus, you will find this term and definition is reproduced in the glossary.	

practice questions and answers	At the beginning of your student book (pages xii to xiii) you will find a **Marzano and Kendall taxonomy guide**, which unpacks each of the cognitive verbs and helps you interpret the requirements of the question. This helps ensure that the answer you provide meets the syllabus expectations and maximises the mark you will receive. A large number and variety of questions are available to check for understanding and provide practice. Questions are provided in each: • **module review** • **chapter review** • **unit review**. Questions are organised by complexity of thinking and are presented in instruction form, as per the data test and external assessment. You will also find questions in each **mandatory practical**, and the **Science as a human endeavour** feature.	**Worksheets** and **practical activities** provide contextualised opportunities to practice and answer questions.
practice exams	**Chapter 1 Physics skills & assessment toolkit (eBook) Part D** End of **unit review** questions are presented in a style similar to that you will experience in the exam.	End of **topic review** questions are presented in a style similar to that you will experience in the exam.

Guide to summative assessment support in Pearson resources

Where do I go for help with assessments?	***Pearson Physics 12 Queensland Student Book***	***Pearson Physics 12 Queensland Skills and Assessment* book**
data test	Chapter 1 PART A (eBook online) provides examples and steps for performing calculations, analysing and presenting data.	**Sample assessment task IA1**
student experiment	Chapter 1 PART B (eBook online) unpacks the requirements and provides a detailed guide for completing this assessment.	**Sample assessment task IA2**
research investigation	Chapter 1 PART C (eBook online) unpacks the requirements and provides a detailed guide for completing this assessment.	**Sample assessment task IA3**
external examination	Chapter 1 PART D (eBook online) provides helpful tips and guidance in preparing for and showcasing your knowledge in an examination. **Unit review—exam-style questions**	**Topic review**

Understanding assessment instructions

The QCAA Physics 2019 General Senior 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 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 3, Topic 1 showing the underlining of terms

Subject matter

Vectors

- use vector analysis to resolve a vector into two perpendicular components
- solve vector problems by resolving vectors into components, adding or subtracting the components and recombining them to determine the resultant vector.

Projectile motion

- recall that the horizontal and vertical components of a velocity vector are independent of each other
- apply vector analysis to determine horizontal and vertical components of projectile motion
- solve problems involving projectile motion.
- Mandatory practical: Conduct an experiment to determine the horizontal distance travelled by an object projected at various angles from the horizontal.

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 12 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 levels of 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 sketch 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 12 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 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
	sketch	execute a drawing or painting in simple form, giving essential features but not necessarily with detail or accuracy
	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

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

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 3 and 4.

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 the following areas:

- Successful learning in physics
  - Representations in physics
  - Developing strategies for learning
  - Reducing barriers to learning
- Development and application of scientific skills
  - Mathematical and statistical processes used in Physics
  - SI units
  - Visual representations
  - Graphical representations
  - Measurement—errors and uncertainty
- Responding to the assessment tasks
  - Data test (IA1)
    - Understanding, analysing and interpreting data and statistics
  - Student experiment (IA2)
    - 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 (IA3)
    - Understanding and analysing claims
    - Developing research questions
    - Strategies to evaluate resources
    - Note-taking
    - Writing a scientific report
  - Examination (EA)
    - Understanding the features and conditions of each of the two papers
    - Strategies to apply through the course, to enhance learning
    - Strategies for revising and consolidating learning
    - Techniques and hints when sitting the exam

The chapter is organised in four parts:

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

An outline of these parts is provided below.

Please note: The examples provided in this chapter assist in modelling how students may arrive at a testable hypothesis or research question. All summative assessment tasks will need to be officially endorsed prior to undertaking and should be checked to ensure they address the QCAA ISMG criteria. Experiments must also be carefully reviewed in consultation with your science teacher or school laboratory technician.

QCAA Physics General Senior 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.

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 are 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 to learn, revise or practice skills in the areas in which you need help.

Module	Look here for	eBook page
1.2 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 as multipliers of powers of ten of the base units • converting between various units of the same type using SI and some non-SI units	e19
1.3 Uncertainties in measurement	• explanations of the terms uncertainty, error, accuracy, precision • differentiation 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 analog and digital instruments • converting between absolute, fractional and percentage uncertainties • performing propagation of uncertainties including addition, subtraction, multiplication, division and powers of measurements and their uncertainties	e25
1.4 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	e41

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Part B: Student experiment (IA2)

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 a practical already completed in class.

Part B supports you through all aspects of the student experiment. The syllabus objectives and instrument-specific marking guide (ISMG IA2) for the assessment are explained.

Engage with Part B for examples of how to modify, extend, refine or redirect the class 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 uncertainty in data, reliability and 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 practice skills in the areas with which you need help.

Module	Look here for	eBook page
1.5 Research and planning	• identifying and explaining the difference between controlled, measured, independent and dependent variables • developing a research question or hypothesis • evaluating the research question and hypothesis • 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	e61
1.6 Conducting an experiment	• 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	e81
1.7 Results	• analysing raw data to produce processed data • interpreting data to draw valid conclusions • identifying errors • analysing precision	e87
1.8 Communicating and writing a scientific report	• sections of a report • scientific writing style • writing a scientific report • acknowledging sources • addressing the ISMG	e92

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Part C: Research investigation (IA3)

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 syllabus objectives and instrument-specific marking guide (ISMG IA3) 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 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 practice skills in the areas in which you need help.

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Part D: Examination (EA)

The focus of Part D is on the summative External Assessment (EA). The examination requires students to complete two papers. Each paper covers the whole physics course; Unit 3 and Unit 4. The examination constitutes 50% of the total assessment for the course.

Part D supports you through all aspects of the examination process. Refer to this section early in the year, not just in the weeks prior to the examination. Effective exam preparation needs ongoing consolidation of learning and revision of course material at regular intervals. Effective preparation begins with a sound understanding of the course and its requirements. Also important is that you know where you can go to for support and what sort of support is available to you through the course.

The examination assessment requires that you use particular skills and strategies that are not necessarily used in the student experiment and research investigation. The data test and examination are similar in the strategies you should apply to complete them. There is possibly more anxiety felt by students regarding the examination, as it accounts for 50% of the total mark in physics.

Part D guides you through all aspects of preparation for the examination. Refer to it to get tips on strategies to help you consolidate your learning and for revision hints and suggestions. Before completing practice exams, read through the list of strategies to use during reading (perusal) and writing time. Apply these as you answer each practice paper. Sitting the exam is more than having subject matter understanding and skills. It is also about exam technique, as this can boost your performance. Refer to Part D as needed, through the year.

Refer to the following outline of Part D: Examination, to learn about strategies and techniques to enhance your learning, revision and examination performance.

Module	Look here for	eBook page
1.13 Examination preparation	• an overview of the two papers: duration, content, response items, equipment • strategies for consolidating learning • strategies for revising and practising • strategies for sitting the exam	e128

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1.1 Successful learning in physics

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

- appreciate effective strategies for high-impact learning
- develop your understanding of the role of representations
- develop connections and provide strategies for learning
- appreciate how knowledge of the three representations can enhance your learning
- develop a deeper understanding of concepts and applications in physics
- identify barriers to your learning
- identify some strategies to use to reduce barriers to learning.

Your experience and understanding of science would have developed during the junior years of science lessons and from your observations in the world. Your understanding forms through scientific experimentation, conducting investigations and through learning from your textbooks and teachers.

Science is an evolving body of knowledge that can be captured and explained using different tools, such as physical and mathematical models, diagrams, explanations and equations. These tools, which can be referred to as representations, help build meaning and deepen understanding of the science you are studying.

In order to help you improve your learning, it is useful to be able to identify the role of the different representations and the level at which they are used. These representations can be simplified into three categories. Table 1.1.1 lists these three categories and provides examples.

TABLE 1.1.1 Representation levels

Representation level	Examples of representation
macroscopic	observable phenomena, e.g. refraction of light through a prism, lunar eclipse
sub-micro	images and illustrations used to show the properties or characteristics of phenomena at an atomic level, e.g. structure of the atom, nuclear fission and fusion and quantum physics
symbolic	figures, numbers or symbols used primarily in mathematical equations, e.g. Snell's law to describe light passing through an optical medium and formulas to show Newton's laws of motion

HIGH-IMPACT LEARNING STRATEGIES

Recent research into best practices for teaching and learning, to optimise student learning, has highlighted some interesting findings. Many of the results relate to teachers and their classroom strategies. There are, however, some important learning strategies that you can apply which will make learning more effective and assist you in working through the challenges of learning. The high-impact learning strategies discussed in the chart below are proven ways to improve learning outcomes. The strategies are not exclusive to the learning of physics, and can be applied to all learning in all subjects and situations. At the core of all learning is the idea that you, the learner, gain increasing regulation and control of your own learning, propelling you along the path of life-long learning.

The high-impact student learning chart shown in Table 1.1.2 identifies three key characteristics— attitudes, behaviours and metacognition—and their associated strategies that positively influence learning outcomes. Research has shown that the listed strategies are among the most highly effective, and through applying these, students directly influence their learning and achievement.

TABLE 1.1.2 Facets of high-impact student learning

	Attitudes	Behaviours	Metacognition
Characteristics	Attitude relates to your frame of mind, the approach to your learning and the responses to challenges to produce your desired level of learning.	Behaviour relates to the actions you take and habits you develop and implement as learning strategies.	Metacognition relates to thinking about how you think, and the gaining of awareness of how you learn. Metacognition is very complex thinking and involves you reflecting on how you best learn.
Strategies	**Effort.** Increasing the level of effort can improve your abilities in and mastery of the subject. Effort can be directed at subject matter and skill competence. **Motivation.** This is the desire to learn for learning's sake rather than learning specifically. If motivation is sometimes waning, try breaking down tasks into smaller chunks and reward yourself when each task is finished. **Concentration, persistence and engagement.** Learning is enhanced with concentration and sustained application. Create a study area that minimises distractions. The quality of study time has a greater impact on achievement than length of time studying. **Perception.** Perceive difficult tasks as challenges to be tackled and overcome. See mistakes as an opportunity to improve.	**Practice.** Practice, practice and more practice. Few people have such natural ability that they are experts. Most people devote hours repeating and retrying tasks to achieve expert levels in a field. **Verbalising.** Learning is improved by speaking or verbalising material, as a variation to the more common reading and writing. Try talking through the steps to complete a task. Check assessment tasks by reading them out loud. **Seeking assistance from classmates and/or teachers.** Regularly work with a partner or in a group to discuss learning issues and subject matter. Learning is enhanced when you explain material to others. **Summaries of subject matter.** Creating concept maps of key subject matter is an effective way of summarising material, as well as other graphic organisers. **Study skills.** Note-taking, underlining and highlighting are three effective examples of study skills. Use these strategies throughout the year to identify key ideas and enhance understanding. **Memorisation and using mnemonics.** Some material simply needs to be memorised, such as formulas and key glossary definitions. Using mnemonics may help, as well as making charts to summarise key information.	**Feedback.** This is a powerful tool for improvement. Carefully read feedback comments on your work. If you need more clarification, discuss the feedback with the teacher. Understanding and internalising comments on your work helps you to learn from your mistakes. It also helps you look more critically at your own work, so you develop self-evaluation skills. **Reciprocal teaching.** Students become the teachers. This is a very effective way of improving understanding by placing you, the learner, in an active role rather than being the passive recipient of knowledge. Create a study group of classmates. Rotate between students, as each takes a turn at teaching (revising) a concept or skill to the others. **Evaluation and reflection.** Try assessing your own work against set criteria, such as the syllabus ISMGs. Doing so requires an understanding of task objectives and evaluation of whether the criteria are met. This fosters growth as an independent learner who can guide their own learning. Spend some time reflecting on what you did well, what you need to focus on for improvement, and think about what actions you can take to make those improvements.

BARRIERS TO LEARNING

In education, factors that prevent a person from learning something effectively are referred as 'barriers to learning'. There are many different barriers to learning, ranging from language barriers to learning difficulties. Everyone is capable of learning, but finding the techniques and strategies that help to break down these barriers can be a challenge. Each learner has his or her own preferences regarding the way he or she learns, so the barriers differ from one person to the next. Within the more abstract disciplines in science, such as physics, there are additional barriers that come with the subject matter, resulting in further challenges to learning.

To learn physics effectively, you need to identify your personal barriers to learning, and then work towards overcoming them. Common barriers to learning in physics are explained for effective learning and building of connections and meaning.

Scientific literacy

The term 'scientific literacy' refers to the ability to make sense of and understand the scientific world in order to make informed decisions. This means having knowledge and understanding of scientific concepts and processes in order to make decisions. Literacy also applies to learning and being able to correctly apply new scientific terms in order to both understand and communicate scientific information. This includes being able to use different representations to deepen your understanding. In other words, being scientifically literate means to operate competently as a scientist.

MULTIPLE REPRESENTATIONS IN PHYSICS

Physicists often talk about phenomena and objects that we cannot see. Hence physics requires the use of imagination and the ability to visualise. To assist this visualisation, teachers and scientists often produce representations of complex concepts, such as magnetic fields and the structure of matter. Visual aids usually take the form of symbols, diagrams or animations used to represent a concept (Figure 1.1.1). Developing a good understanding of science disciplines requires students to be able to effectively interpret these representations.

FUNCTIONS OF MULTIPLE REPRESENTATIONS

The function, or purpose, of using multiple representations in science (here we discuss physics) can be split into three:

1. Complementary—multiple representations can be used together to express different processes or information.
2. Aid understanding—if a student has interpreted a concept incorrectly using a specific representation, using multiple representations provides the opportunity to rectify any misconceptions.
3. Construct deeper learning—multiple representations have been shown to support the construction of deep learning through students' use of integrating and applying information from more than one type of representation.

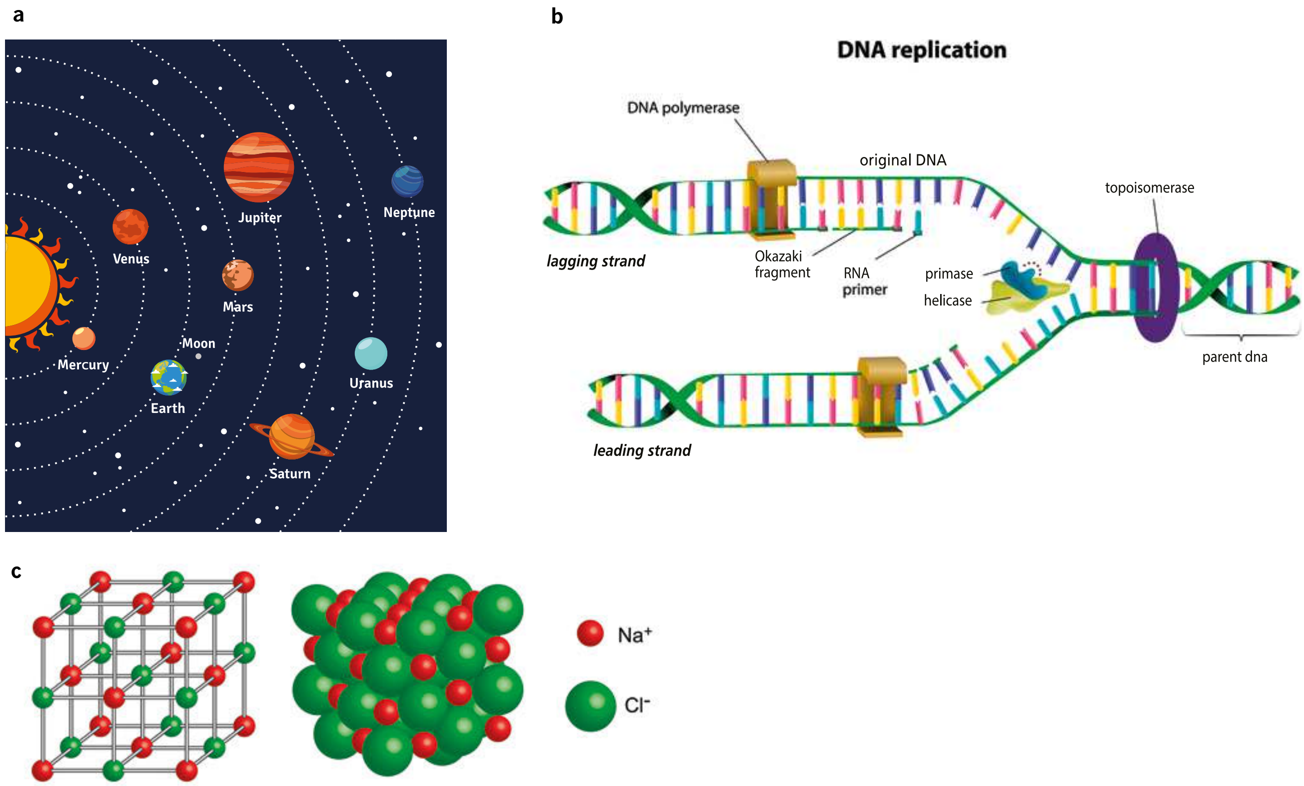


FIGURE 1.1.1 (a) A representation of our solar system (used in physics); (b) a representation of DNA replication (used in biology), and (c) a representation used to show the formation of an ionic lattice (used in chemistry)

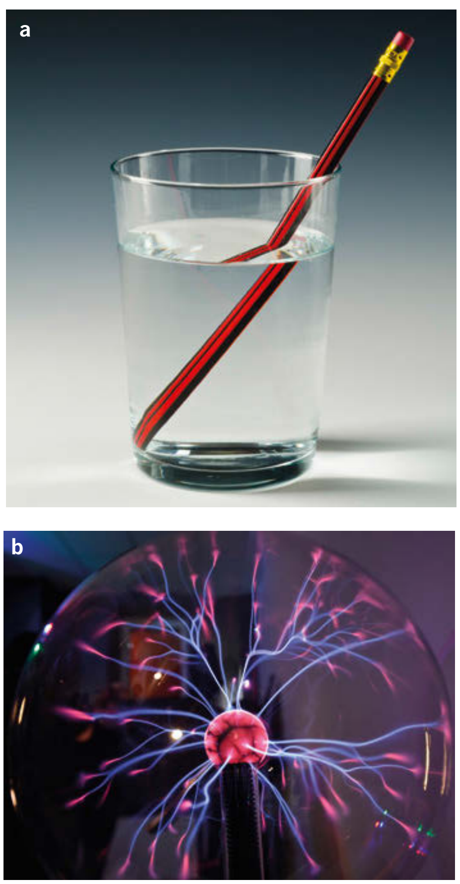


FIGURE 1.1.2 Two examples of macroscopic representations: (a) light refraction in water and (b) a Tesla coil

The use of representations in physics is essential for effective learning. Understanding physics requires students to engage with a multiple forms of representations. Studies have shown that the key to learning successfully in physics comes down to an awareness and understanding of the representation used to explain and model physics concepts. Scientists have looked at these representations in great detail and, although there are variations in the exact terminology used, all the scientific studies agree that there are three levels of representation used in physics:

- the macroscopic level
- the sub-micro level
- the symbolic level.

The macroscopic level

You are probably familiar with the term 'micro' as meaning something very small. 'Macro' is the opposite and, as such, refers to anything that is considered large. In physics, we refer to anything we can observe with our senses, or which can be observed in an experiment, as macro, such as the refraction of a laser beam or the spark created in a Van de Graaff generator or Tesla coil (Figure 1.1.2). It also focuses on phenomena that can be measured, such as temperature, current or time.

Macroscopic phenomena can be observed first hand and are usually the first way in which a concept or idea is experienced, introduced or learnt. Additional and more complex representations are often needed to help explain what is happening at an atomic level. This is where sub-micro and symbolic representations are used.

Sub-micro level

Sub-micro refers to phenomena that are too small to see, even with a microscope (*micro* meaning 'small', and *sub* meaning 'under/beneath'). This level is used to represent extremely small entities such atoms, nuclei and quarks. Physics at the atomic level or lower can be organised using two levels:

- level 2 sub-micro—qualitative representations such as diagrams, illustrations or animations
- level 3 symbolic—quantities representations such as nuclear equations and calculations.

For the sub-micro type of representation, models are usually introduced as an aid to understanding (Figure 1.1.3).

Rather than focusing on observations and measurements as in the macroscopic level, sub-micro representations consider properties and characteristics of atoms or nuclei to aid understanding of their behaviour.

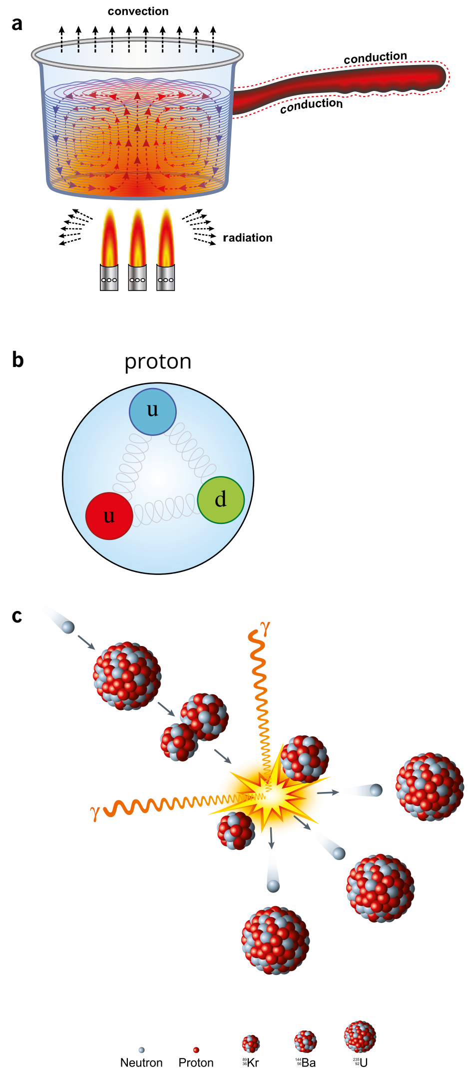


FIGURE 1.1.3 These models are used to explain the physical phenomena of (a) conduction, convection and radiation, (b) the structure of protons showing three quarks and gluons and (c) nuclear fission.

Symbolic level

As might be expected the symbolic representation level involves the use of a variety of different symbols. These include everything from mathematical formulas and the use of subscripts, to vector notation and scientific notation (Figure 1.1.4).

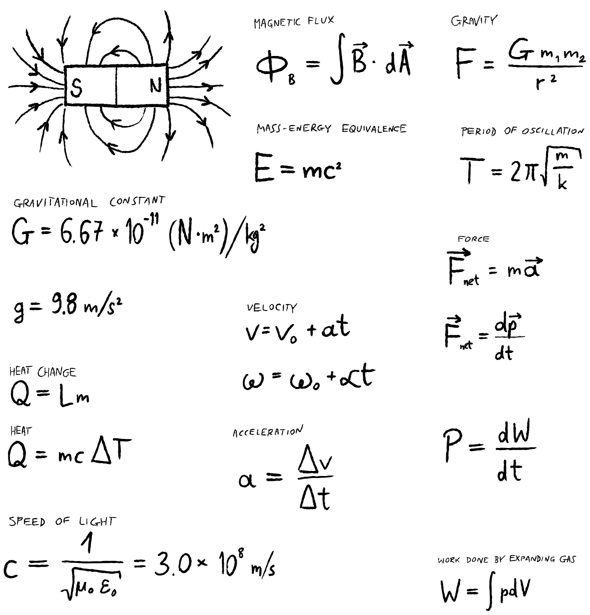


FIGURE 1.1.4 This illustration shows examples of symbolic representations in the form of formulas.

While the sub-micro level focuses on the properties or characteristics of submicroscopic phenomena, the symbolic level representations, such as the formulas in Figure 1.1.4, focus on ways to easily illustrate these properties or characteristics without having to write long passages of text.

Physics-specific representation levels

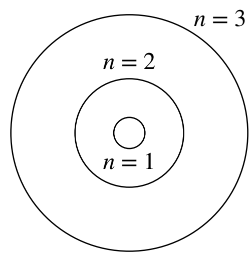
Within these three broad levels of representations, there are some very specific representations that are used more commonly in physics than in chemistry or biology, because physics involves more mathematical problems. These representations are also covered in this physics book (Table 1.1.3 and Figure 1.1.5):

1 verbal
2 mathematical
3 graphical
4 pictorial.

TABLE 1.1.3 Examples of the physics-specific representations

Representation level	Examples of representation
verbal	written sentences expressing an idea or concept, e.g. naming processes, stating laws and theories
mathematical	equations and associated symbols, e.g. quantitative relationships and equations
graphical	graphs of mathematical functions or of the relationships between the different quantities use to describe a physical symbol, e.g. *x–y* scatterplots
pictorial	images or diagrams of a physical system, e.g. force diagrams

a



b $r_n = \frac{n^2h^2}{mke^2}$

Radius of electron orbitals in hydrogen, in terms of fundamental physical constants and quantum number *n*.

c In the Bohr model of the atom, the electron follows fixed, concentric, circular orbits about the nucleus. The orbital distances scale quadratically in the quantum number *n*.

d

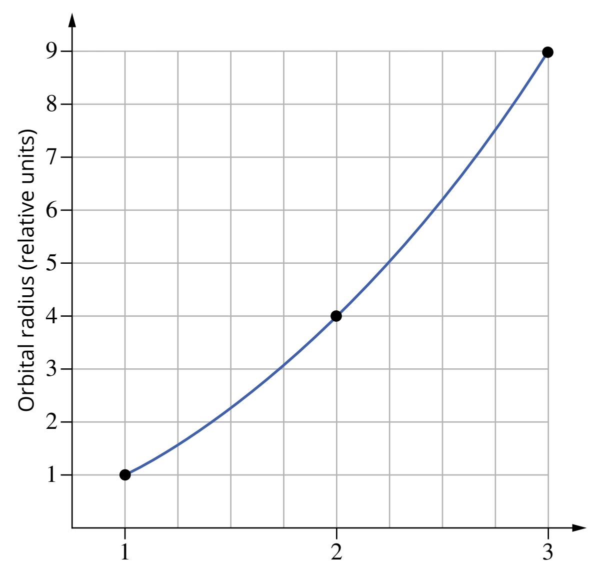


FIGURE 1.1.5 Representations of the Bohr model of the atom can be (a) pictorial, (b) mathematical, (c) verbal and (d) graphical.

Studies that have looked into the common types of representations used in physics (verbal, graphical, mathematical and pectoral) have indicated that some topics lend themselves to certain types of representations more than others. For example, sometimes verbal representations are easier to understand than graphical representations in topics such as gravity. However, there are some topics for which graphical or mathematical representations help explain a topic more clearly than verbal representations, such as in understanding Newton's laws. Therefore the context in which a representation is used is very important. This highlights the importance of using multiple types of representations when learning (Figure 1.1.5).

Verbal explanations

In physics, verbal explanations make up a substantial number of the macroscopic representations used. They can be divided into written or spoken representations, and usually take the form of observable phenomena, statements or questions (Figure 1.1.6).

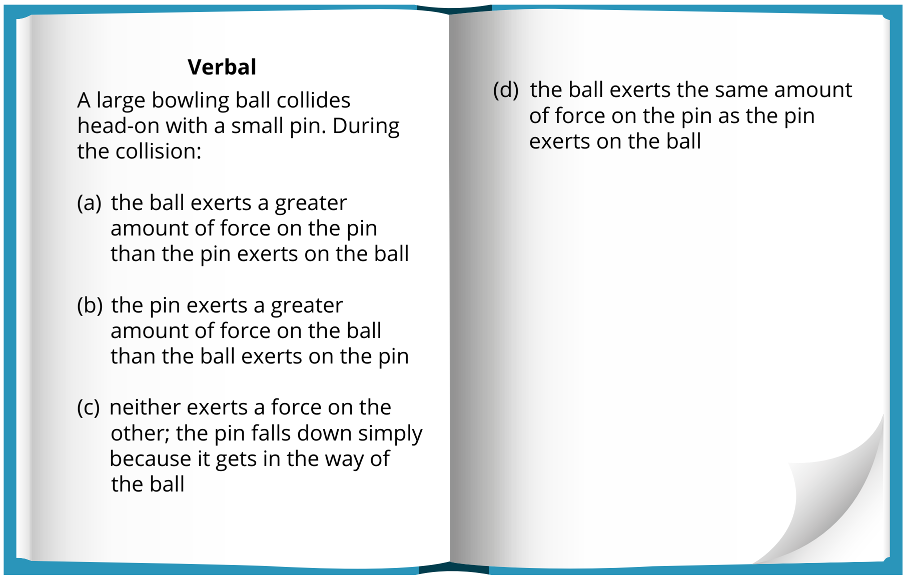


FIGURE 1.1.6 Examples of verbal representations of a scenario in which a ball collides with a bowling pin. This type of representation is commonly used alongside an image or illustration.

Mathematical

Mathematical formulas are extremely widespread and relied upon extensively in physics (Figure 1.1.7). Mathematical representations involve the use of calculations and formulas and sometimes do not require the same level of conceptual reasoning as verbal, graphical or pictorial representations.

a $F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$ **b** $\Delta E = \Delta mc^2$

FIGURE 1.1.7 Formulas such as for (a) Coulombs' law and (b) Einstein's mass–energy equivalence relationship are used in physics.

Graphical

Mathematical equations are often represented graphically, and the interpretation of these graphs is a vital skill for learners. Figure 1.1.8 shows a bar chart representation of a large bowling ball that collides head-on with a small bowling pin. The direction of the force exerted by the ball on the pin is positive. Let us denote the force exerted by the ball on the pin as $F_{\text{ball}\rightarrow\text{pin}}$ and the force exerted by the pin on the ball as $F_{\text{pin}\rightarrow\text{ball}}$. Which of the following alternatives best describes the magnitude of the average forces, $|F|$, exerted on the ball and the pin during the collision?

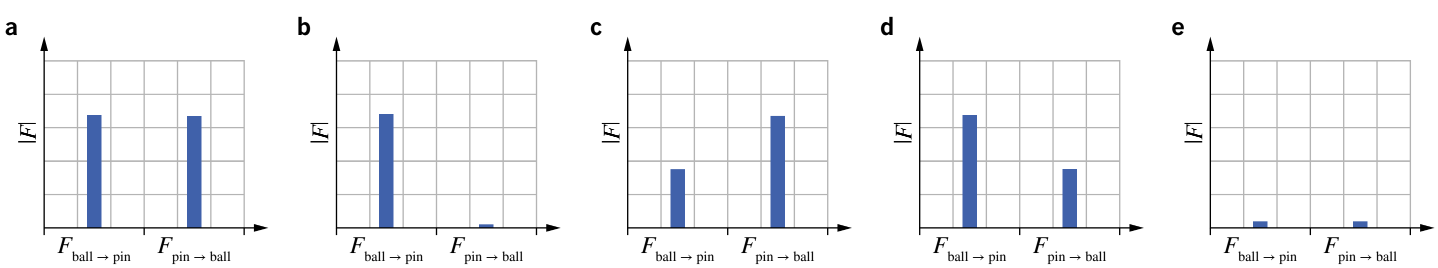


FIGURE 1.1.8 Options for answers to a question are presented as graphical representations (bar charts).

Pictorial

Pictorial representations can be split into two main categories:

1 static—pictures, photos and drawings
2 dynamic—videos, animations and interactives.

Dynamic representations can be superior to static representations when it comes to aiding learning. This is because animations and videos are able to present information in a way that is easily accessible to learners. This is especially the case in topics that rely heavily on the use of sub-micro representations (which often require the learner to imagine processes of phenomena). However, static pictorial representations are still very beneficial to learning, especially when accompanied by a verbal representation (usually in the form of an explanation). Dynamic representations can fall into both the macro or sub-micro level of representation (Figure1.1.9).

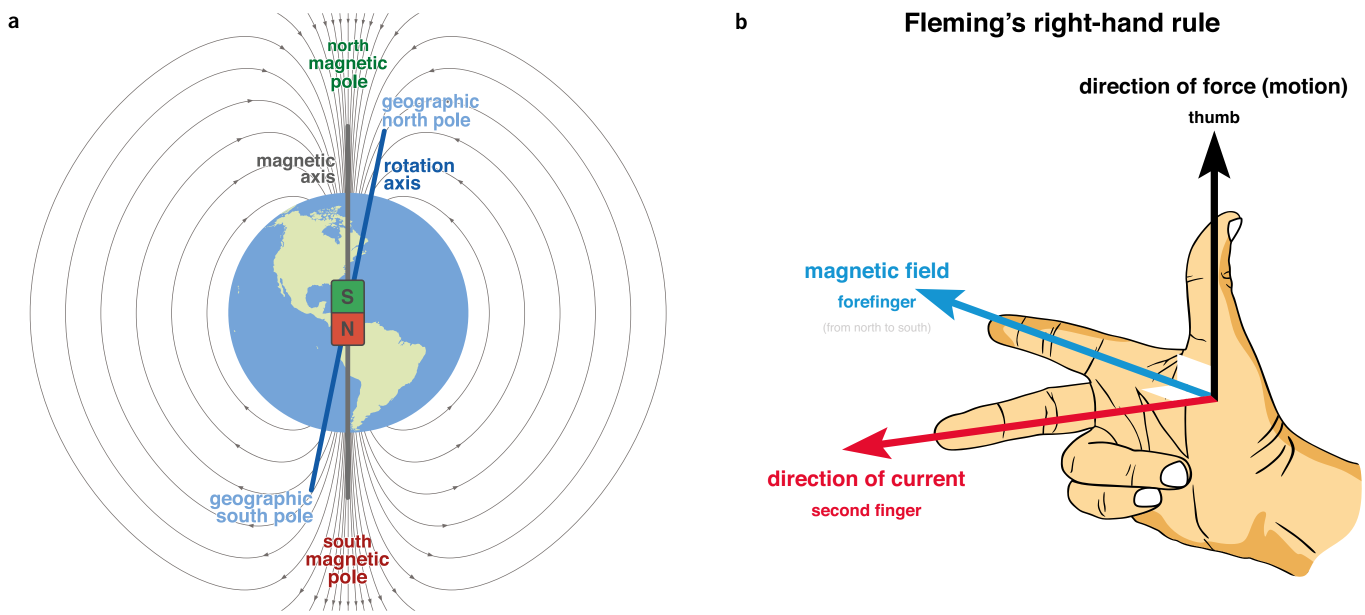


FIGURE 1.1.9 These static pictorial representations are used for (a) Earth's magnetic field and (b) Fleming's right-hand rule.

This textbook will primarily feature static pictorial representations, but you can access dynamic pictorial representations such as interactives and animations via your Reader+ eBook.

Using representations to ensure effective learning

This section has emphasised the importance of representations, but it also has identified those barriers that can be created for some learners. It is important to be proactive in trying to overcome these barriers. Being equipped with some strategies that you can apply will help you to help yourself if you require assistance.

Here are some potential strategies to use:

- Use concept maps. Begin with a process or concept in the middle, and then branch out into the three ways in which it can be represented (macroscopic, sub-micro and symbolic). Try to find multiple examples of each representation (Figure 1.1.10).

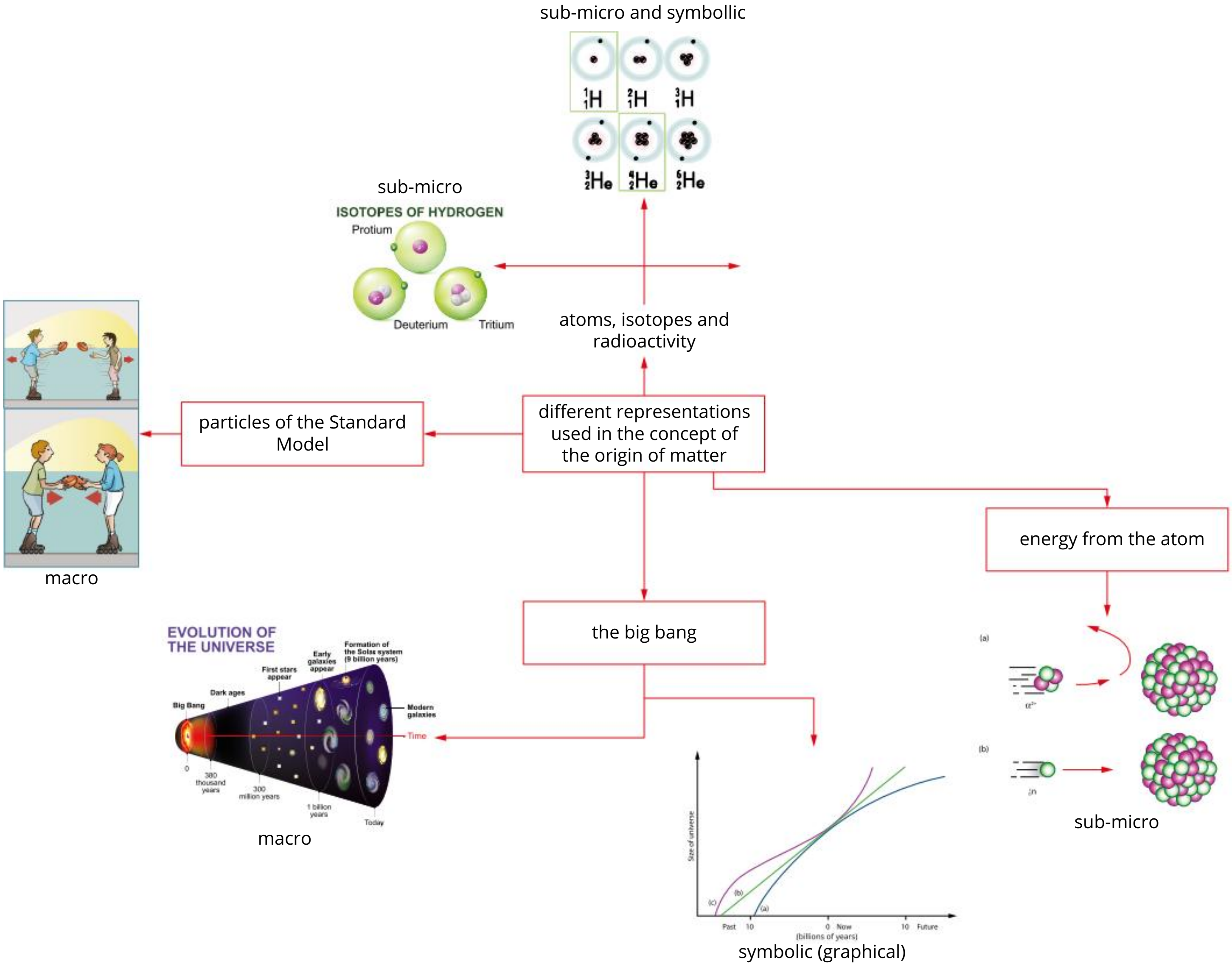


FIGURE 1.1.10 This concept map includes multiple representations of the structure and origin of matter.

- Use tables to identify gaps in your knowledge. Identify parts of your physics course that you have found difficult and try to identify the types of representations that have been used to help explain it. If one is missing, try to create your own. If there is a representation that you do not understand, reflect on what the barrier might be, such as terminology or a diagram you do not understand. Create your own representation for it. Approach your teacher for assistance if necessary.

In addition to these strategies, this student book contains other examples of the different representation levels that you can use. Table 1.1.4 outlines the application and purpose of these features. The list is not exhaustive, and you may find additional examples of features that address the different levels of representations.

TABLE 1.1.4 Features of the representation levels found in the Pearson Physics Queensland series

Representation level	Pearson Physics series feature	Resource	Application/purpose
literacy	glossary	student book	definitions of key scientific terms
	preliminary material, Marzano and Kendall's cognitive verbs list and explanation	student book	explaining the meaning of an instruction and enabling understanding of the type of response required
	literacy review worksheets	Skills and Assessment book	building language and meaning of discourse terminology
macro	mandatory practicals	student book	requires use of observation skills to record results
	additional practicals	Skills and Assessment book	requires use of observation skills to record results
sub-micro	diagrams	student book and Skills and Assessment book	illustrations help to visualise complex processes or concepts used in physics
	interactives	Reader+	animations aid with visualising more complex processes or concepts used in physics
	video clips	Reader+	helps illustrate complex processes or concepts used in physics
	module, chapter and unit reviews	student book	practise applying learnt terminology in answering questions
symbolic	nuclear equations	student book	a simpler, and often shorter representation of a nuclear reaction
	field diagrams	student book and Skills and Assessment book	a more efficient way of illustrating the shape and direction of electric, magnetic and gravitational fields
	mandatory practicals	student book	requires use of observation skills to record results
	additional practicals	Skills and Assessment book	requires use of observation skills to record results

Teachers and textbooks use physics representations to assist students in their learning. Having an understanding of the use of these representations allows you as a learner to proactively identify how you learn best. By identifying the types of representations that cause difficulty in your learning, you can be proactive in overcoming the learning barrier. Use the strategies mentioned to ensure effective learning throughout your physics course.

1.1 Review

SUMMARY

- Scientific concepts can be expressed by different representations.
- Scientific representations can usually be placed into three levels of representations or categories: macroscopic, sub-micro and symbolic.
- The macroscopic level deals with observable events in physics.
- The sub-micro level deals with events that are too small to be seen by the naked eye, e.g. friction, which occurs at the atomic scale.
- The symbolic level often expresses events at the atomic scale; these symbols are used in mathematical calculations.
- Effective learning in physics involves understanding the representations used in the subject, identifying your own personal barriers to learning and working to overcome them.

KEY QUESTIONS

Retrieval

1 List the different representations used physics.

Comprehension

2 Demonstrate your understanding of each type of representation by providing an example of each.

Analysis

3 Reflect on your learning in physics.

a Identify any barriers that block your learning.

b Explain how you might overcome this barrier to your learning.

PART A WORKING SCIENTIFICALLY

Part A will consider the basic mathematical skills and applications that will be required for the data test, a range of mandatory and suggested experiments as well as the student experiment.

The data test (IA1)

The data test assessment (IA1) is completed at the end of Unit 3 and relates only to material in that part of the physics course. The data test is completed in conditions similar to those of the examination at the end of Unit 4, although the focus of the data test is wholly on understanding, analysing and interpreting data and drawing evidence-based conclusions.

The table below outlines some important information about the data test such as the types of response items, the test conditions and the equipment that can be used.

	Data test
types of items	• short answers: sentence or short paragraphs • longer paragraphs (50–250 words per item) • other types of item responses involving calculations, interpretations
syllabus coverage	Unit 3 (Gravity and electromagnetism)
assessment objectives	• apply understanding • analyse evidence • interpret evidence and draw conclusions
conditions	• perusal (reading) time: 10 minutes • writing time: 60 minutes
equipment	• QCAA-approved graphics calculator permitted • seen formula and data booklet provided • unseen stimulus material
marks	• constitutes 10% of total assessment

Studying for the data test cannot be rushed just before the test. It is not a memory-style test for which you can cram at the last minute. The skills and thinking required to effectively complete the data test are best acquired over an extended period of time, with practice and more practice. Part A outlines many of the skills that will enhance your performance when working with data. Refer to Part A on a need-to-know basis, to develop your skills.

1.2 Units and prefixes

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

- appreciate that physics uses the International System (SI) of units
- 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 1.2.1) use and understand these units, as they are internationally accepted in everyday life.

FIGURE 1.2.1 Only three countries are still yet to officially adopt the metric system: Myanmar (in Asia), Liberia (in Africa) and the USA.

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 1.2.1 on the next page. Note that the standard definition of the kilogram changed in 2019. A piece of platinum–iridium alloy was used as the standard definition for the kilogram, but now the kilogram is defined using constants from nature, in line with all other SI base units.

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

TABLE 1.2.1 The seven fundamental SI units used in physics, 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 $\frac{1}{299792453}$ of a second	1983
mass	kilogram	kg	taking the fixed numerical value of the Planck constant h to be $6.62607015 \times 10^{-34}$ when expressed in the unit J s, which is equal to $kg\,m^2\,s^{-1}$	2019
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

FIGURE 1.2.2 One 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.

All the units in Table 1.2.1 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 the quantity of a substance. The candela is a measure of light intensity. It is discussed in Chapter 11 and shown in Figure 1.2.2. In 2017, plans were 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.

DERIVED UNITS

Every other unit that is used in physics is a mathematical combination (such as division, multiplication, squaring) involving at least one of the seven fundamental units, and are called derived units. Table 1.2.2 lists some of the most common derived units encountered in high school physics.

TABLE 1.2.2 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	$1\ Bq = 1\ decay\,s^{-1}$

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.

A derived unit is a unit that is a mathematical combination involving at least one of the seven fundamental units.

NON-SI UNITS USED IN PHYSICS

Two non-SI units are used extensively in physics, 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.

$$1\ \text{kWh} = 3.60 \times 10^6\ \text{J}$$

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

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

SI PREFIXES

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 1.2.3 lists the 20 SI prefixes used in physics.

TABLE 1.2.3 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 1.2.3).
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 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	The μg is commonly used as the unit for medicine dosage.
nano	n	10^{-9}	billionth	0.000 000 001	The wavelength of the 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.

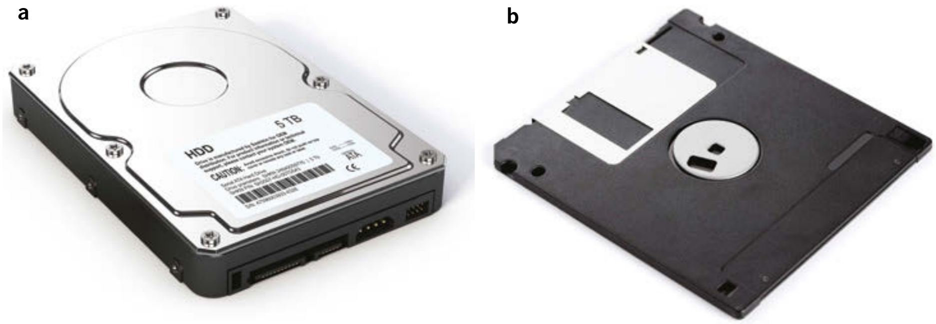


FIGURE 1.2.3 A 1.0 terabyte hard drive (a) in 2016 compared to a 1.44 megabyte floppy disc (b) in the 1990s. The hard disc drive holds more than 690 000 times the information that can be stored on the floppy disc.

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 the kilogram has 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 measurements with a prefix can be substituted into a formula, they must be converted into SI units without the prefix, in scientific notation. Figure 1.2.3 shows examples of storage devices that compare storage sizes in bytes using SI prefixes.

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

Worked example 1.2.1

UNIT CONVERSIONS

The average strength of Earth's magnetic field in Queensland is 50 000 nT. Determine this value in Tesla.

Thinking	Working
Write 50 000 nT as a power of ten.	50 000 nT = $50\,000 \times 10^{-9}$ T
Use scientific notation to write the answer.	$50\,000 \times 10^{-9}$ T $= 5 \times 10\,000 \times 10^{-9}$ T $= 5 \times 10^{4} \times 10^{-9}$ T $= 5 \times 10^{-5}$ T

➤ Try yourself 1.2.1

UNIT CONVERSIONS

The barn (b) is a non-SI unit used to measure the cross-sectional area of nuclear reactions. It is equal to 100 fm^2. Calculate the size of a barn in m^2.

1.2 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 some mathematical combination of the fundamental units.
- The SI prefixes are symbols that go before a unit and indicate multiplication of the unit by a power of 10.
- Units with a prefix need to be converted into scientific notation before they can be used in a physics formula.

KEY QUESTIONS

Retrieval

1 Name a derived unit that is a combination of two fundamental units.

2 Name the fundamental units.

Comprehension

3 Lucy thinks that an ampere second and an ampere per second are the same unit. Explain to her why they are, in fact, two different units.

4 Explain the difference between fundamental units and derived units.

5 Show that the unit weber can be written in fundamental units as:

$$1\ \text{Wb} = 1\left(\frac{\text{kg}\,\text{m}^2}{\text{A}\,\text{s}^2}\right)$$

Analysis

6 Calculate the number of metres in the 656 nm wavelength of red light emitted from hydrogen.

7 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.

1.3 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

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 discrepancy (or measurement discrepancy 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 $\mathrm{m\,s^{-1}}$. An accurate measurement is 300 000 000 $\mathrm{m\,s^{-1}}$, which has only a 0.07% error:

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

An inaccurate measurement is 780 000 000 $\mathrm{m\,s^{-1}}$, which has a 160% percentage error:

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

Devices that measure smaller and smaller units 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 firing arrows at an archery target (Figure 1.3.1). Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot.

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

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

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

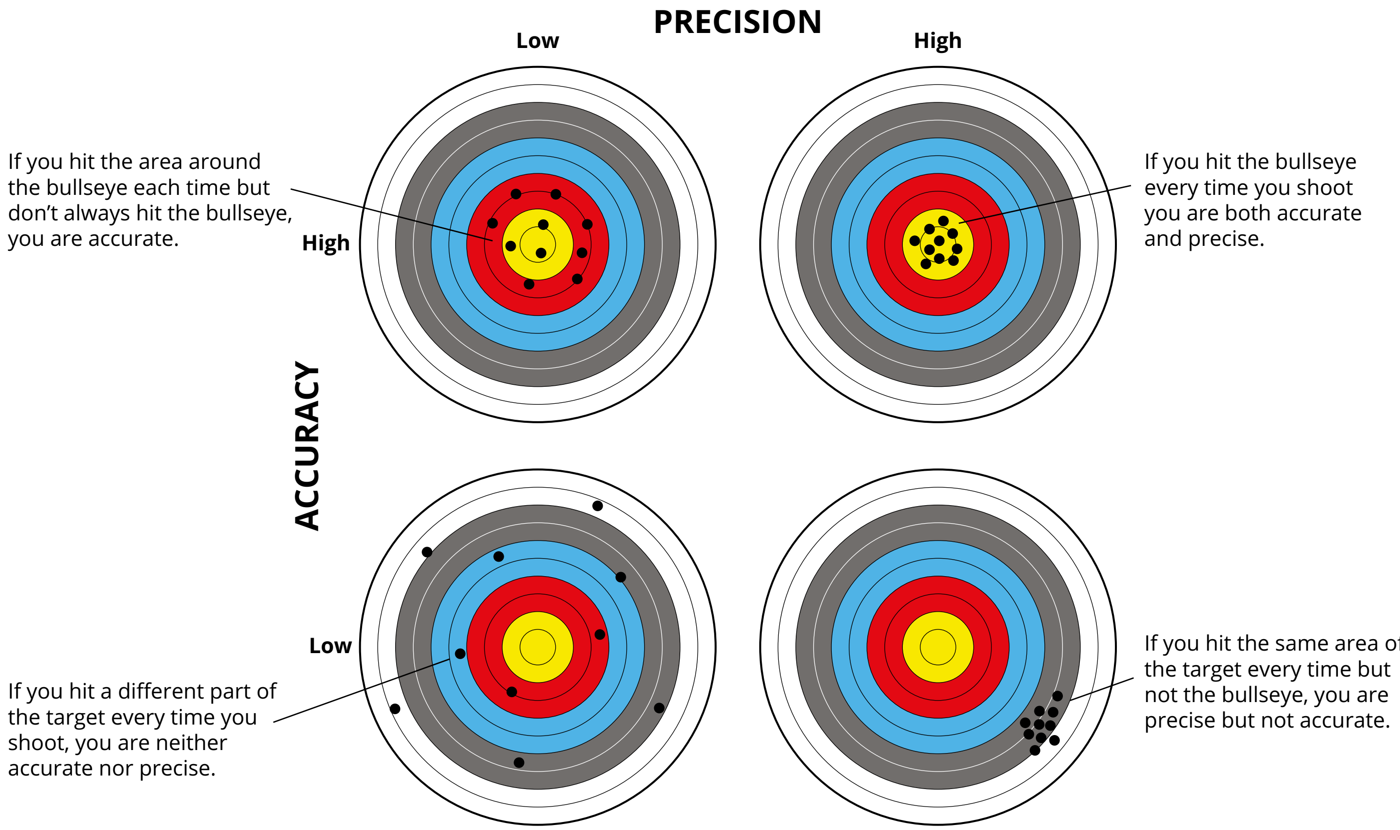


FIGURE 1.3.1 Using a dartboard with darts illustrates the difference between accuracy and precision. Measurements should be both precise and as accurate as possible.

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, you should note that:

- All digits (including the 0s) 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.

Therefore, to avoid confusion, always write measurements in scientific notation, as every digit in the coefficient is treated as significant. Table 1.3.1 shows some examples of measurements written in scientific notation and the number of significant figures.

TABLE 1.3.1 Some examples of determining the number of significant figures in measurements written in scientific notation

Measurement	Number of significant figures
$\mathbf{9.6021} \times 10^{-5}$ T	5
$\mathbf{4.7} \times 10^{23}$ Hz	2
$\mathbf{2.300} \times 10^{2}$ Wb	4
$\mathbf{2} \times 10^{24}$ V m^{-1}	1

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 that are 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 a placeholder are not significant.
  For example:
  23 000 000 J has 2 significant figures because all of 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 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 placeholders.
- 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 2 are significant, as they are located between non-zero digits, and the final three zeros must have been measured or 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 1.3.1

SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 7.03×10^{14} Bq
b 1.00 C
c 0.000 800 8 A
d 1260 W

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 1.3.1

SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 65 000 J

b 0.000 000 331 Pa

c 8.30×10^{-17} $C\,s^{-1}$

d 22.066 $m\,s^{-3}$

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 1.3.2

ADDITION AND SUBTRACTION WITH SIGNIFICANT FIGURES

Determine the answer to these calculations to the correct number of significant figures.	
a 743 L + 3.7 L + 9.40 L – 0.05 L	
Thinking	**Working**
Perform the calculation keeping all decimal places.	743 L + 3.7 L + 9.40 L – 0.05 L = 756.05 L
Determine the measurement with the least number of decimal places.	743 L 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 756.05 L must therefore be rounded down to 756 to have no decimal places.
Write the final answer.	756 L
b 7800 N + 412 N + 74.8 N – 0.2 N	
Thinking	**Working**
Perform the calculation keeping all decimal places.	7800 N + 412 N + 74.8 N – 0.2 N = 8286.6 N
Determine the measurement with the least number of decimal places or with the largest number of placeholders.	7800 N has 2 placeholders (i.e. to the hundreds placeholder) and this is the largest 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 8286.6 N must therefore be rounded up to the nearest hundred.
Write the final answer.	8300 N

➤ Try yourself 1.3.2

ADDITION AND SUBTRACTION WITH SIGNIFICANT FIGURES

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

a 0.02882 C – 0.0005521 C + 0.0093 C

b 924673 W – 367228 W

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 1.3.3

MULTIPLICATION AND DIVISION WITH SIGNIFICANT FIGURES

Determine the answer to these calculations to the correct number of significant figures.	
a 7.02 m × 61.33 m^2 × 2.4 m^2	
Thinking	**Working**
Perform the calculation keeping all decimal places.	7.02 m × 61.33 m^2 × 2.4 m^2 = 1033.287 84 m^5
Determine the measurement with the least number of significant figures.	2.4 m^2 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 1033.287 84 m^5 must therefore be rounded up to 1.0 × 10^3 m^5 to have 2 significant figures.
Write the final answer.	1.0 × 10^3 m^5
b 5600.0 N ÷ 802.6 s	
Thinking	**Working**
Perform the calculation keeping all decimal places.	5600.0 N ÷ 802.6 s = 6.977 323 7 N s^{-1}
Determine the measurement with the least number of significant figures.	802.6 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 6.977 323 7 N s^{-1} must therefore be rounded down to have 4 significant figures.
Write the final answer.	6.977 N s^{-1}

➤ Try yourself 1.3.3

MULTIPLICATION AND DIVISION WITH SIGNIFICANT FIGURES

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

a Use the formula $V = \frac{4\pi r^3}{3}$ to calculate the volume (in m^3), of a sphere of radius 23.1 cm.

b Use the formula $\lambda = \frac{h}{p}$ with $h = 6.626 \times 10^{-34}$ J s and $p = 8.1 \times 10^{-23}$ 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, it is impossible to know a measurement exactly. This is a law of physics!

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

- mistakes (Figure 1.3.2)
- systematic errors
- random errors.

Note that the word 'error', when used in physics, does not mean that a blunder has been made in a measurement, but rather 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.

FIGURE 1.3.2 An example of a mistake, rather than an uncertainty, which occurred in Paris in 1895.

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.

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 (Figure 1.3.3)
- zero error (the equipment not being reset to zero before use) (Figure 1.3.4).

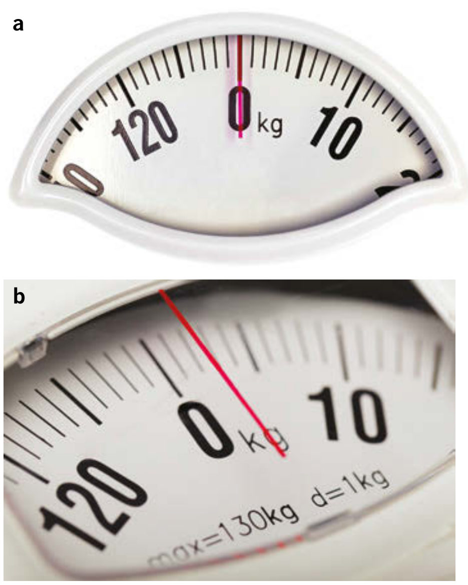


FIGURE 1.3.3 (a) The correct reading of 0 kg appears on the image when the scale is viewed from directly in front. (b) An incorrect reading of 2 kg appears on the image because of parallax error. This occurs when reading an analog scale at an angle.

FIGURE 1.3.4 Three examples of zero error on analog instruments: (a) voltmeter, (b) ammeter and (c) a digital instrument (an electronic balance).

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.

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

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 they can be reduced by repeating the experiment many times, removing any outliers, and finding the average of the values.

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.

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

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.

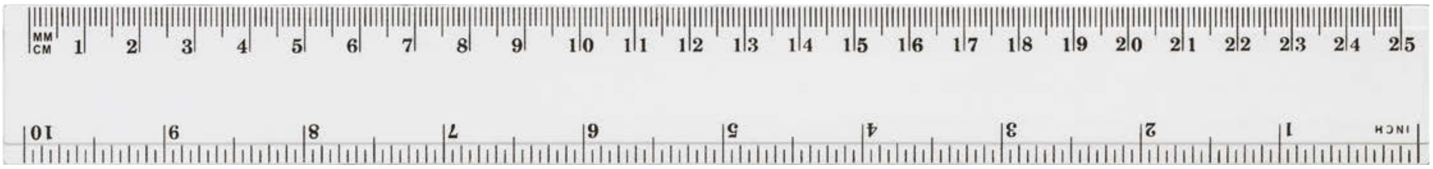
The precision that can be read off a single instrument is called the limit of reading. This is the smallest visible graduation on an analog instrument, or, if a digital instrument is used, then the limit of reading is usually the smallest decimal place given on the screen.

For most analog instruments, the **absolute measurement uncertainty** (also known as the absolute certainty), 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 a ruler (Figure 1.3.5a). 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 (Figure 1.3.5b).

a



b

FIGURE 1.3.5 (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.

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.

Usually, the absolute uncertainty in a measurement will have one significant figure, or two significant figures if the first digit is 1. This is because the uncertainty of a measurement is an estimate, and writing more than two significant figures is therefore meaningless. Some examples are given in Table 1.3.2.

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 1.3.2 Examples of measurements and their absolute uncertainties

Measurement and absolute uncertainty	Comments
48.2 ± 1.0°C	The absolute uncertainty is written to two 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 two decimal places, with one significant figure for the uncertainty. This measurement of time may have been recorded using a digital device such as a data logger 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 1.3.3 summarises the limit of reading and absolute uncertainty of common analog instruments used in a high school physics lab.

TABLE 1.3.3 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 (Figure 1.3.6).
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 for 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 s 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 uncertainty is the smallest possible decimal place that is displayed.
analog voltmeter	analog	depends on the scale of the instrument	half of the smallest increment on the display	3.4 ± 0.5 V	In this example the smallest increment on the device is 1 V.
analog ammeter	analog	depends on the scale of the instrument	half of the smallest increment on the display	2.14 ± 0.05 A	In this example the smallest increment on the device is 0.1 A.

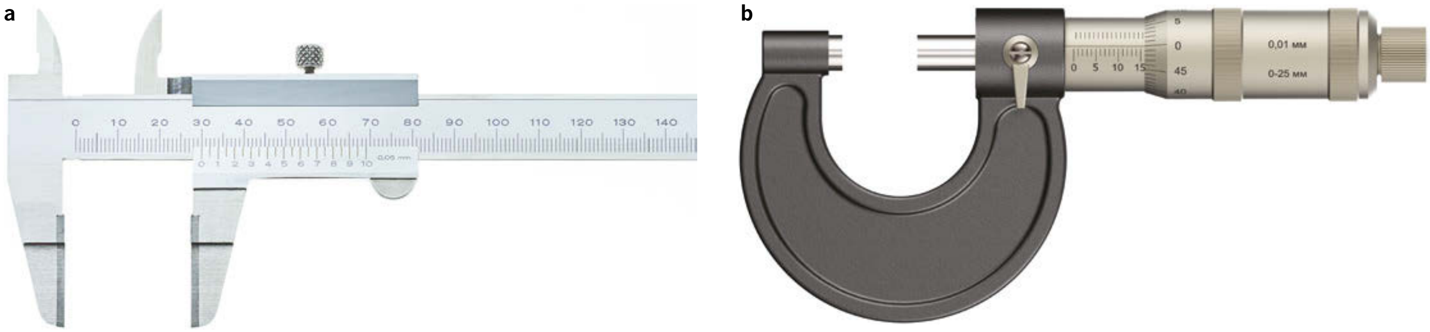


FIGURE 1.3.6 (a) The Vernier calliper and (b) micrometer use screws to determine the measurement.

How to write a measurement and its absolute uncertainty are 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 placeholders, as the uncertainty.
5. Add the unit of measurement for the quantity.

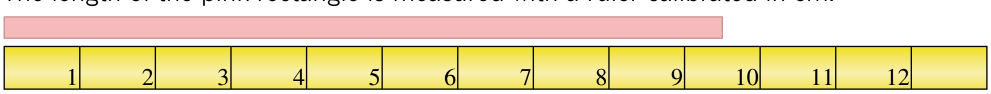
> The absolute uncertainty should be written to one or two significant figures, which then determines to how many decimal places the measurement is written.

Worked example 1.3.4

READING MEASUREMENTS

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

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



Thinking	Working
The pink rectangle is approximately midway between 9 cm and 10 cm in length, so the best estimate for this is 9.5 cm.	Length L = 9.5 cm
The limit of reading is 1.0 cm so this is the uncertainty in a cm ruler.	ΔL = ±1.0 cm
Write the measurement and the uncertainty.	L = 9.5 ± 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°C
The limit of reading is 0.1°C so the uncertainty is half of this: 0.05°C.	ΔT = ±0.05°C
Write the measurement and the uncertainty.	T = 40.14 ± 0.05°C

Worked example 1.3.4 *continued*

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

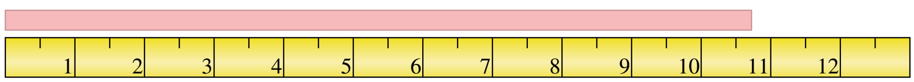
Thinking	Working
This temperature measurement is done using a digital thermometer, so the temperature is simply read off the screen at 36.4°C.	Temperature $T = 36.4°C$
The uncertainty in this measurement is then 1 of the smallest decimal value: ±0.1°C	$\Delta T = \pm 0.1°C$
Write the measurement and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

➤ Try yourself 1.3.4

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 liquid is measured in a measuring cylinder calibrated in mL.

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

Determining the 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:

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

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

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

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 1.3.5

UNCERTAINTIES IN THE MEAN OF A SET OF MEASUREMENTS

The strength, *B*, of the magnetic field at a distance of 1.0 cm from a neodymium bar magnet was measured at seven points along its long axis and recorded in T, using a digital magnetic field sensor with an uncertainty of ±0.1 T. The results were:

1.3, 1.2, 0.9, 1.1, 1.1, 1.2 and 1.1.

Calculate the mean (average) value for the strength of the magnetic field of the bar magnet and its absolute uncertainty.

Thinking	Working
First, calculate the mean of the set of measurements. Note that the mean has not been rounded to the correct number of decimal places at this stage.	$B = \frac{1.3 + 1.2 + 0.9 + 1.1 + 1.1 + 1.2 + 1.1}{7}$ $= \frac{7.9}{7}$ $= 1.128571$ T
Find the uncertainty in the mean using the difference between the maximum and minimum values, divided by 2.	$\Delta B = \pm\left(\frac{1.3 - 0.9}{2}\right)$ $= \pm\left(\frac{0.4}{2}\right)$ $= \pm$ 0.2 T
This value is larger than each individual uncertainty, so it will now be the final absolute uncertainty of the mean. The uncertainty also has one significant figure, so no rounding of the uncertainty needs to be done. It has one decimal place, so the mean will be rounded to also have one decimal place as the final value.	$B = 1.1 \pm 0.2$ T

➤ Try yourself 1.3.5

UNCERTAINTIES IN THE MEAN OF A SET OF MEASUREMENTS

The resulting voltage, *V*, of six trials of an electromagnetic induction experiment was measured using an analog voltmeter with the smallest increment on the device being 0.01 V. The results were:

7.23, 7.41, 7.39, 7.29, 7.40 and 7.29.

Calculate the mean (average) voltage produced in this experiment and the absolute uncertainty in the mean.

PROPAGATING UNCERTAINTIES

Propagating uncertainties means combining the uncertainties in one set of data with the uncertainties in another data set. To help with these calculations, an uncertainty can be written in 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 $= \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100\%$

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

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 the final value of the uncertainty of a measurement, the absolute uncertainty should always be used.

Table 1.3.4 shows some examples of writing the absolute uncertainty as a fractional uncertainty and percentage uncertainty.

TABLE 1.3.4 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°	$\frac{1.0}{5.0} = 0.2$	$\frac{1.0}{5.0} \times 100\% = 20\%$

Often in physics is it 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 the 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 $\Delta y = \Delta a + \Delta b$.
- If a and b are two measured values with absolute uncertainties of Δa and Δb, and their difference is $y = a - b$, then $\Delta y = \Delta a + \Delta b$.

This means that it does not matter whether the operation is addition or subtraction, as the absolute uncertainty is the total sum of the individual uncertainties.

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

Worked example 1.3.6

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation:
(4.1 ± 0.2) nC + (9.7 ± 0.4) nC

Thinking	Working
Ignore each uncertainty and add the measurements.	Let x be the sum of the two quantities. $x = 4.1 + 9.7 = 13.8$ nC
This is an addition operation, so add the absolute uncertainties.	$\Delta x = 0.2 + 0.4 = 0.6$ nC
The absolute uncertainty can only have one significant figure because the first digit is not 1. The absolute uncertainty also has one decimal place, so x will also have one decimal place.	$x = 13.8 \pm 0.6$ nC

➤ Try yourself 1.3.6

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation: $(8.144 \pm 0.005) \times 10^{-20}$ N s – $(3.41 \pm 0.01) \times 10^{-20}$ N s

Multiplying or dividing uncertainties

If an operation involves 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 $\frac{\Delta a}{a}$ 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 $\frac{\Delta y}{y}\% = \frac{\Delta a}{a}\% + \frac{\Delta b}{b}\% + \frac{\Delta c}{c}\%$, where $\frac{\Delta a}{a}\%$ is the percentage uncertainty in a.

This means that it doesn't matter whether the operation is multiplication or division, as the percentage or fractional uncertainties are always added. 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 1.3.7

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation:
(16.8 ± 0.5) J s $\times$ (4.14 ± 0.01) s^{-1}

Thinking	Working
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. $x = 16.8 \times 4.14 = 69.552$ J
This is a multiplication operation, so the absolute uncertainties will need to be converted into percentage uncertainties.	$16.8 \pm 0.5\,\text{cm} = 16.8 \pm \frac{0.5}{16.8} \times 100\%\,\text{J s} = 16.8 \pm 2.98\%\,\text{J s}$ $4.14 \pm 0.01\,\text{s}^{-1} = 4.14 \pm \frac{0.01}{4.14} \times 100\%\,\text{s}^{-1} = 4.14 \pm 0.2415\%\,\text{s}^{-1}$
The percentage uncertainties are now added.	$\Delta x\% = 2.98\% + 0.2415\% = 3.2215\%$
The percentage uncertainty is now converted back into an absolute uncertainty.	$\Delta x = 3.2215\%$ of 69.552 J $= \frac{3.2215}{100} \times 69.552$ $= 2.2406$ J
The absolute uncertainty does not have 1 as its first digit, therefore only one significant figure can be quoted: $\Delta x = 2$. The absolute uncertainty therefore has no decimal places so x will also have no decimal places.	$x = 70 \pm 2$ J

➤ Try yourself 1.3.7

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation: (4.1 ± 0.5) V $\div$ $(9.44 \pm 0.08) \times 10^{-3}$ A

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 $y = a^n$, then:

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

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 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.

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

> When propagating uncertainties, perform any addition and subtraction calculations first.

Worked example 1.3.8

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 $c = \frac{a^2}{b^3}$.

Thinking	Working
First, ignore each uncertainty and perform the calculation for c. Don't forget the units.	$c = 4.52^2 \div 2.0^3 = 2.5538\ \text{m}^2\,\text{s}^{-3}$
This is a multiplication operation, so the absolute uncertainties will need to be converted into percentage uncertainties.	$a = 4.52 \pm 0.02$ m $= 4.52 \pm \frac{0.02}{4.52} \times 100\%$ m $= 4.52 \pm 0.4425\%$ m $b = 2.0 \pm 0.2$ s $= 2.0 \pm \frac{0.2}{2.0} \times 100\%$ s $= 2.0 \pm 10\%$ s
To obtain the final percentage uncertainty, the individual percentage uncertainties are multiplied by the absolute values of the powers of a and b given in the formula.	$\Delta c\% = 2 \times 0.4425\% + \lvert -3\rvert \times 10\%\ \text{m}^2\,\text{s}^3$ $= 0.885\% + 30\%\ \text{m}^2\,\text{s}^3$ $= 30.885\%\ \text{m}^2\,\text{s}^3$
Now convert the percentage uncertainty into an absolute uncertainty.	$\Delta c = 30.885\%$ of 2.5538 $= \frac{30.885}{100} \times 2.5538$ $= 0.7887\ \text{m}^2\,\text{s}^{-3}$
The absolute uncertainty does not have 1 as its first digit, therefore it must be rounded to one significant figure: $\Delta c = 0.8$. The absolute uncertainty therefore is written with one decimal place to match the number of decimal places in the uncertainty.	$c = 2.6 \pm 0.8\ \text{m}^2\,\text{s}^{-3}$

➤ Try yourself 1.3.8

MIXED UNCERTAINTY CALCULATIONS

If $a = 3.6 \pm 0.6$ kg, $b = 9.91 \pm 0.01$ m, and $c = 4.9 \pm 0.5$ kg, find d when $d = \sqrt{\frac{b^2}{c - a}}$.

1.3 Review

SUMMARY

- All measurements made in physics experiments are subject to a level of uncertainty, or doubt, as 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 the measuring 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 always add.
- When multiplying or dividing measurements, the individual percentage uncertainties always add.
- 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 the following:
   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 Kirsten measured the charge on four different pieces of metal using a digital device, but did not check that the device was set to zero at the start of each measurement.
   b Jackson 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 Shiva sometimes forgot to reset the balance to zero between weighing trolleys used in a motion experiment.

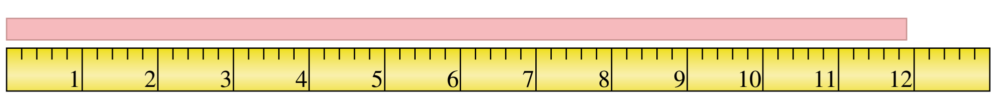
3 State the absolute uncertainty of the following instruments.
   a a cm ruler
   b an electronic balance giving a reading down to the nearest 0.001 g
   c an analog needle voltmeter graduated in 10 volt intervals

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.



1.3 Review *continued*

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

a $(6.626 \times 10^{-34}) \pm (9.8149 \times 10^{-36})$ J s

b $(0.001\,783\,30 \pm 1.512 \times 10^{-5})$ MeV

Analysis

8 Differentiate between precision and accuracy.

9 Marney asks to borrow your precious ruby for a day to show her family. You are a bit worried, so you carefully have your ruby weighed on a scale that reads 16.19 g. The scale's precision is claimed to be ±0.01 g. The next day you weigh the returned ruby again, getting 16.16 g. Determine whether this is your ruby.

10 The magnetic field strength, *B*, inside a straight piece of wire is given by the formula:

$$B = \frac{\mu_0 NI}{L}$$

where

I is the current through the wire (A)

L is the straight length of the wire (m)

N and μ_0 are constants.

If the percentage uncertainty in I is ±5% and the percentage uncertainty in L is ±2%, calculate the percentage error in B.

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

12 Calculate A and ΔA, if $A = \pi r^2$ and $r = 4.12 \pm 0.05$ m.

13 The constant electric field between two parallel charged metal plates is found by dividing the force on a single charged particle by the charge on that particle. A small charge of constant value is placed between the two metal plates and the force on it is measured at different points between the plates.

Particle's charge ($\pm 0.1 \times 10^{-18}$ C)	4.5	4.6	4.5	4.4	4.6
Force on particle ($\pm 0.02 \times 10^{-13}$ N)	2.25	2.31	2.19	2.20	2.28

Calculate (with their uncertainties):

a the average charge on the particle

b the average force on the particle

c the electric field between the metal plates.

14 If $w = 4.52 \pm 0.02$ m, $x = 2.0 \pm 0.2$ m, and $y = 3.0 \pm 0.6$ m, calculate z when $z = \left(\frac{w-x}{y}\right)^2$.

1.4 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, and 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 1.4.1 shows an example of a typical graph used in physics, complete with error bars and line of best fit.

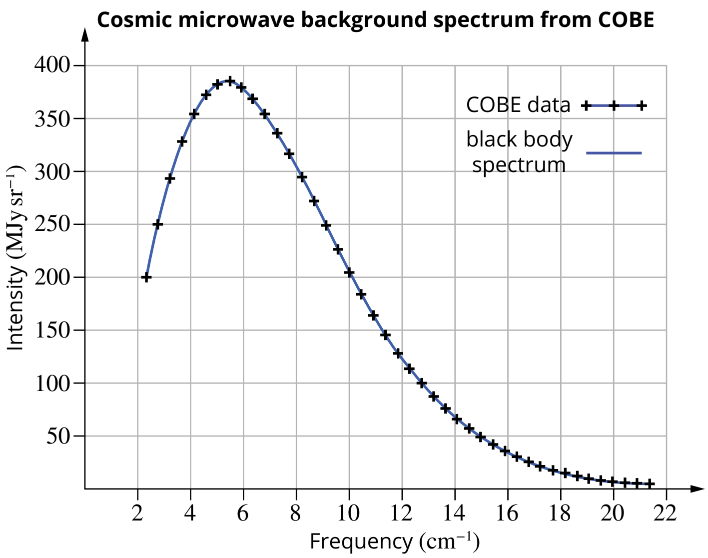


FIGURE 1.4.1 One of the best fits of data to theory is the intensity of microwaves coming from deep space against their frequency taken by the COBE satellite in the 1990s.

The shape of a curve can be used to suggest a possible relationship between the dependent and independent variables. Figure 1.4.2 shows a hypothetical relationship between Bloxists and Dubars. The number of Bloxists measured is plotted against the rate of Dubars. The shape of the graph and the index of the trend line suggest there is an inverse relationship. The trend line passes through each error bar, so the inverse relationship between Bloxists and Dubars appears to be real.

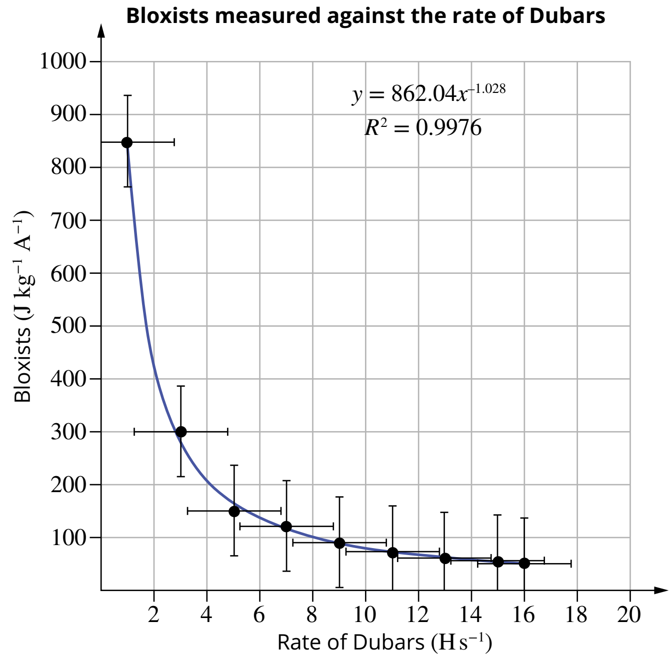


FIGURE 1.4.2 Hypothetical Bloxists graphed against the hypothetical rate of Dubars showing how the shape of a graph and its error bars can suggest a particular relationship between variables.

Graphs can display 'holes' or missing data, and therefore where more measurements need to be taken, especially around rapidly changing values. Figure 1.4.3 shows many data points located around the 0.5 phase value, taken to confirm the curvature of the data.

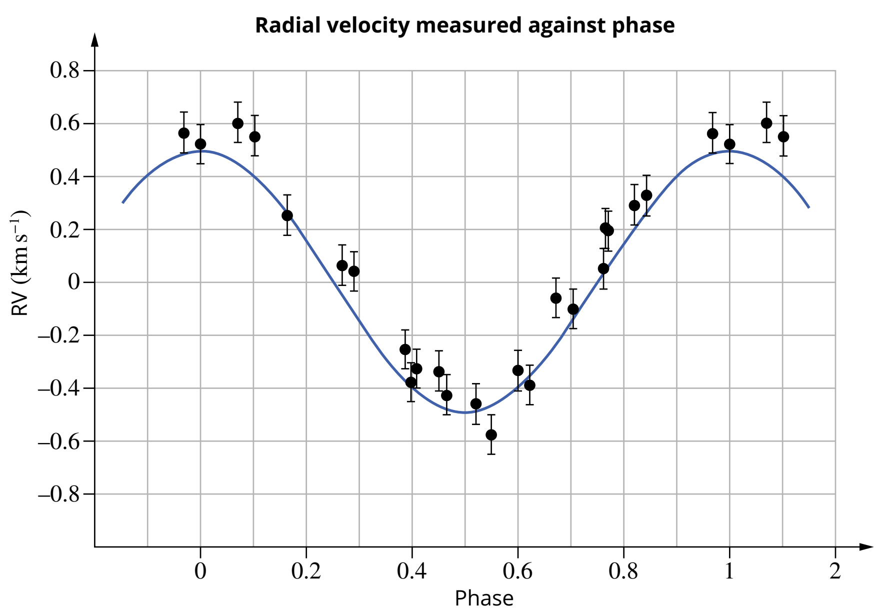


FIGURE 1.4.3 The radial velocity curve and *y*-axis error bars for an exoplanet orbiting the star Tau Boötis. Many data points were taken around the 0.5 phase values in order to confirm that that point was an important part of the best-fit curve.

DRAWING GRAPHS IN PHYSICS

There are some 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 label 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 (a horizontal line) and dependent (a vertical line) values. They are drawn as a horizontal line centered on the data point indicating the uncertainty of the independent variable left and right of the value, and as a vertical line centred on the data point above and below the value indicating the uncertainty of the dependent variable. The error bars for *x* and *y* form an error rectangle that the true measurement is located within (Figure 1.4.4).

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

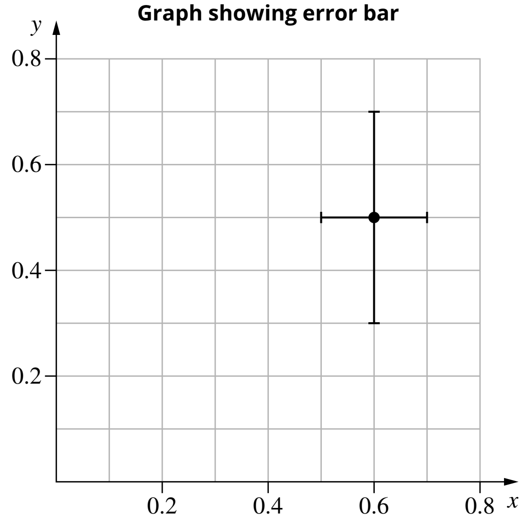


FIGURE 1.4.4 This error bar has an *x*-value of 0.6 ± 0.1, and a *y*-value of 0.5 ± 0.2.

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 1.4.5 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.

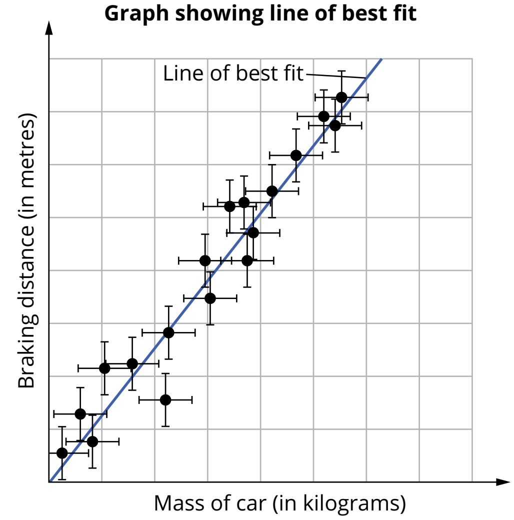


FIGURE 1.4.5 A graph showing the line of best fit passing through the data, as well as the y-intercept.

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

TYPES OF GRAPHS SEEN IN PHYSICS

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

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 (Figure 1.4.6). The general equation of a straight line is:

$$y = mx + c$$

where

m is the gradient

c is the y-intercept.

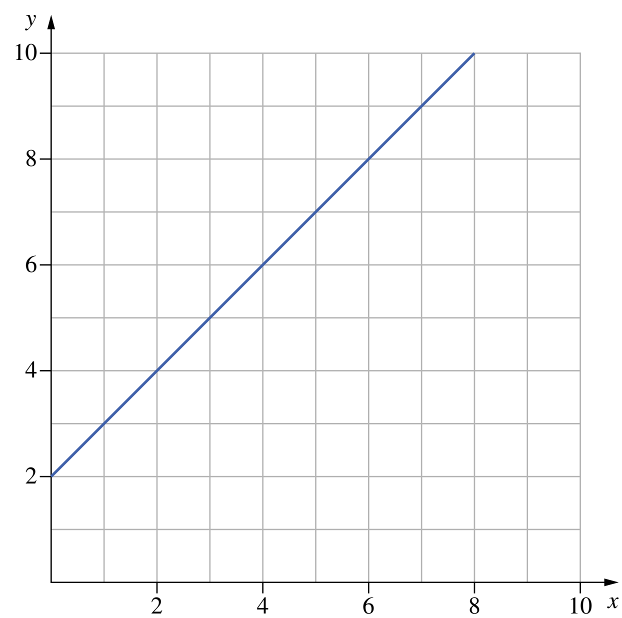


FIGURE 1.4.6 The linear, or straight line, graph. In this example, the equation of the line is $y = x + 2$, with a gradient of 1 and y-intercept of 2.

Examples of linear relationships in physics include that between the energy of a photon of light and its frequency, and the force on a charged particle between two parallel metal plates and the charge on the particle. 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 1.4.7 is $y = 2x$.

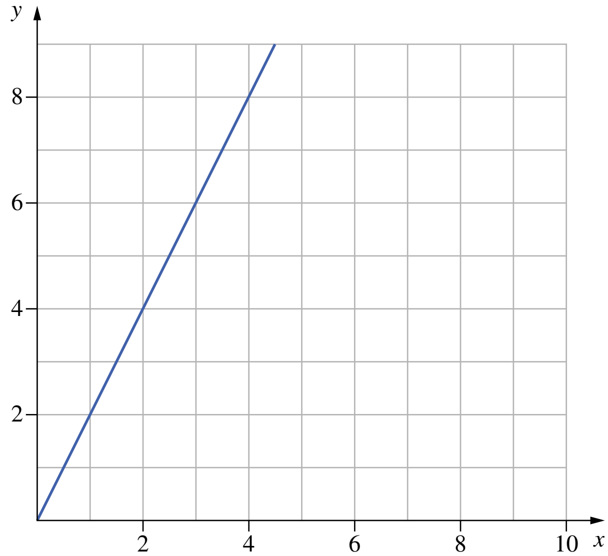


FIGURE 1.4.7 An example of a direct proportion. The equation of the line is $y = 2x$. The line passes through the origin and has a gradient of 2.

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 variables increase at an increasing rate (Figure 1.4.8). The general equation of a parabola is:

$$y = kx^2$$

where k is a constant.

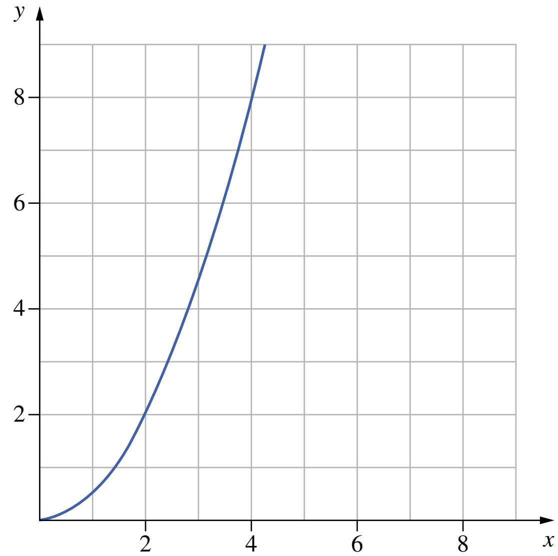


FIGURE 1.4.8 An example of a parabolic or squared graph. The equation of the parabola is $y = 0.5x^2$.

Examples of parabolic relationships in physics include that between the position of a projectile and the time when launched at an angle to the horizontal, and the centripetal acceleration of an object moving in a circle of constant radius and its velocity.

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 (Figure 1.4.9). The general equation of a hyperbola is:

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

where *k* is a constant.

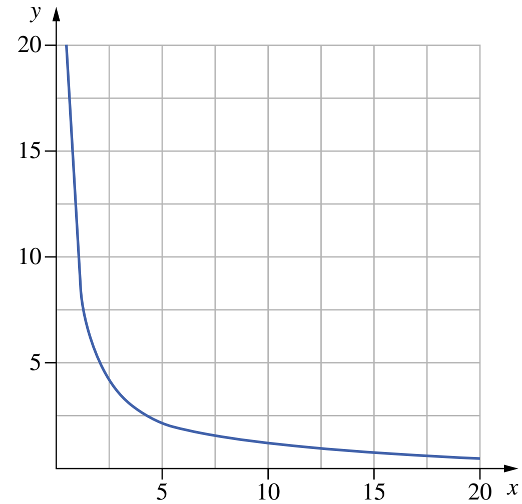


FIGURE 1.4.9 An example of a hyperbola, or inverse, graph. The equation of the hyperbola is $y = \frac{10}{x}$.

Examples of hyperbolic relationships in physics include that between the wavelength of a photon and its momentum, and the magnetic field strength inside a solenoid and the length of the solenoid.

Periodic or sine and cosine graphs

These graphs represent relationships that oscillate between a maximum and minimum value over a period of time (Figure 1.4.10). 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).

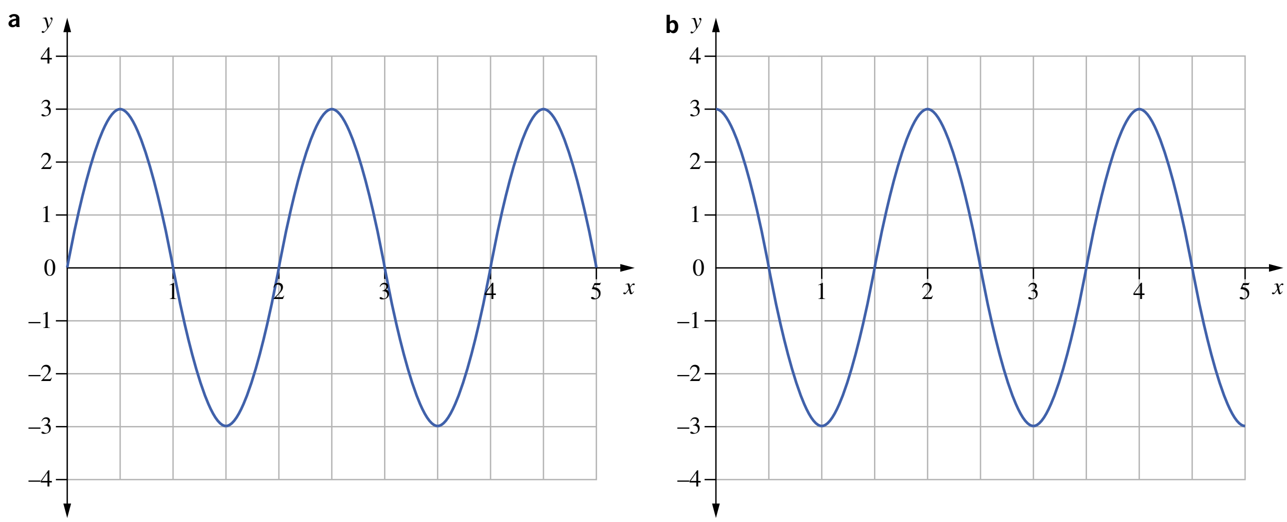


FIGURE 1.4.10 Examples of (a) a sine graph with equation $y = 3\sin \pi x$ and (b) a cosine graph with equation of $y = 3\cos \pi x$. The variable *x* is measured in radians in each case.

Examples of sine and cosine relationships in physics include that between the position of a mass on a spring and time, and between the current from an alternating current supply and time.

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 (Figure 1.4.11). The equation of an exponential decay graph is:

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

where

A and k are constants

e is the mathematical constant 2.71828…

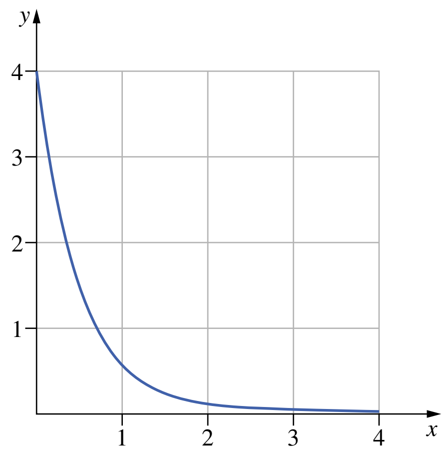


FIGURE 1.4.11 The exponential curve. In this example the equation of the curve is $y = 4e^{-2x}$ indicating that the initial value of the graph is 4.

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

Some examples of exponential curves seen in physics are those representing the decay of a radioactive sample over time, and those representing the amplitude of a wave that experiences damping (reduction in amplitude) over time. Table 1.4.1 summarises the common graphs seen in physics.

TABLE 1.4.1 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
linear	$y = mx + c$	increasing if $m > 0$ decreasing if $m < 0$	constant
directly proportional	$y = mx$	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

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.

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 $F = ma$.

What 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 in Table 1.4.2 and used to find a value for the acceleration due to gravity, *g*. Note that uncertainties were noted but have been removed for this example.

TABLE 1.4.2 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

A graph of the raw data shows a parabolic relationship, with time on the *x*-axis and displacement on the *y*-axis (Figure 1.4.12).

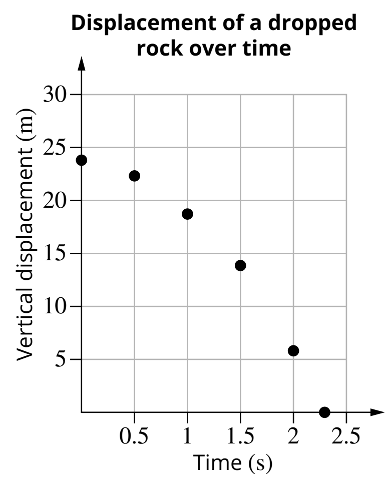


FIGURE 1.4.12 The graph shows a parabolic relationship between the vertical displacement of an object falling under Earth's gravity and time.

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 $y = mx + c$ (Figure 1.4.13). You then match the variables s to y and t^2 to x (shown in blue) and you can see the gradient and y-intercept of the linearised t^2 graph (shown in red).

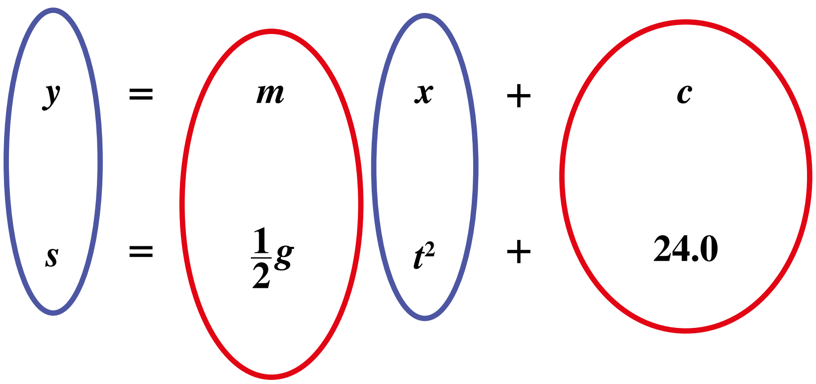


FIGURE 1.4.13 Linearising an equation

To linearise the quadratic equation $s = \frac{1}{2}gt^2 + 24.0$ you equate to the general equation of a 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 1.4.3, 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 1.4.3 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 1.4.14 shows this as a very good linear fit to the data (R^2 of 0.9994). The linear trend line is also shown.

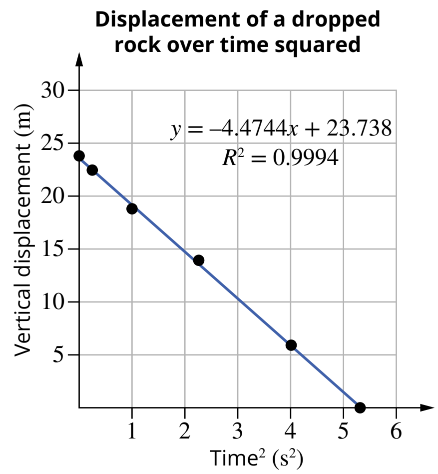


FIGURE 1.4.14 The linearised graph of vertical displacement against time^2 allows the gradient and *y*-intercept to be used to calculate the acceleration due to Earth's gravity.

From the trend line, the gradient is −4.4744 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 m s^{-2} is much lower than the expected value of the acceleration due to Earth's gravity, *g*, which is −9.81 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 shows 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 1.4.15 shows how this does not work if there is no relationship between the variables.

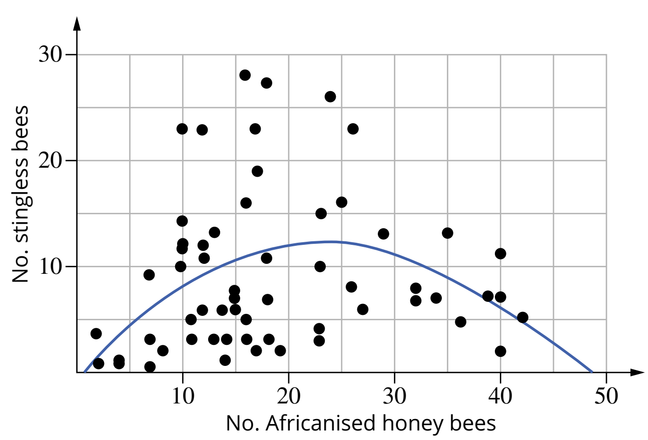


FIGURE 1.4.15 An extremely poor line of best fit to data that was actually published in the journal *Science* in 1978. Can you see the duck?

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 1.4.1

LINEARISING DATA

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

i state what variable would need to be graphed on the horizontal and vertical axes to linearise these equations

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

a $F = \frac{mv^2}{r}$ (F 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, F, will not be modified.	New x-axis variable = v^2 New y-axis variable = F (unchanged)
ii $F = \frac{m}{r}v^2 + 0$ The y-intercept is zero. The coefficient of v^2 is $\frac{m}{r}$.	y-intercept = 0 Gradient = $\frac{m}{r}$

b $\lambda = \frac{h}{p}$ (λ on the y-axis and p on the x-axis produce a hyperbola.)

Thinking	Working
i p is on the x-axis and the graph is a hyperbola, so the new x-axis variable will be $\frac{1}{p}$. The y-axis variable, λ, will not be modified.	New x-axis variable = $\frac{1}{p}$ New y-axis variable = λ (unchanged)
ii $\lambda = h\left(\frac{1}{p}\right) + 0$ The y-intercept is zero. The coefficient of $\frac{1}{p}$ is h.	y-intercept = 0 Gradient = h

➤ Try yourself 1.4.1

LINEARISING DATA

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

i state what variable 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 $E_k = \frac{hc}{\lambda} - W$ (E_k on the y-axis and λ on the x-axis produce a hyperbola.)

b $F = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{r^2}$ (F on the y-axis and q on the x-axis produce a parabola.)

Table 1.4.4 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 1.4.4 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
linear	$y = mx + c$	already linear	already linear	no change	no change
directly proportional	$y = mx$	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	N/A
		x	$\frac{1}{y}$	$\frac{1}{k}$	N/A
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

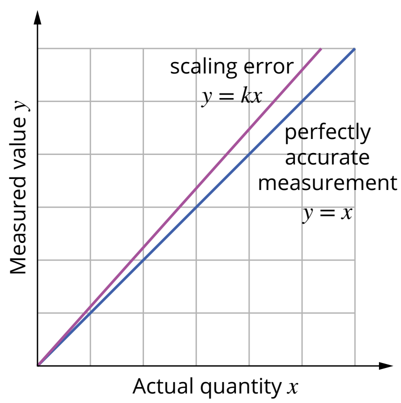


FIGURE 1.4.16 The recorded measurements are k times their real values. This means that the instrument's scale did not match the scale indicated on the display or on the graduated marks.

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 1.4.16. 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 1.4.17. All measurements along the y-axis are offset by the same value.

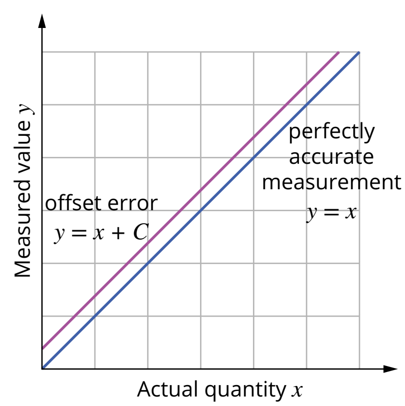


FIGURE 1.4.17 The recorded measurements need to be reduced by C to give the real values. This means that the instrument was not fully reset to zero before measurements were made.

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 processed or raw 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 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 so software is available that will do this automatically.

Graph of distance travelled by toy car

Figure 1.4.18 shows an example of a linear graph, the best fit trend line and the maximum and minimum lines.

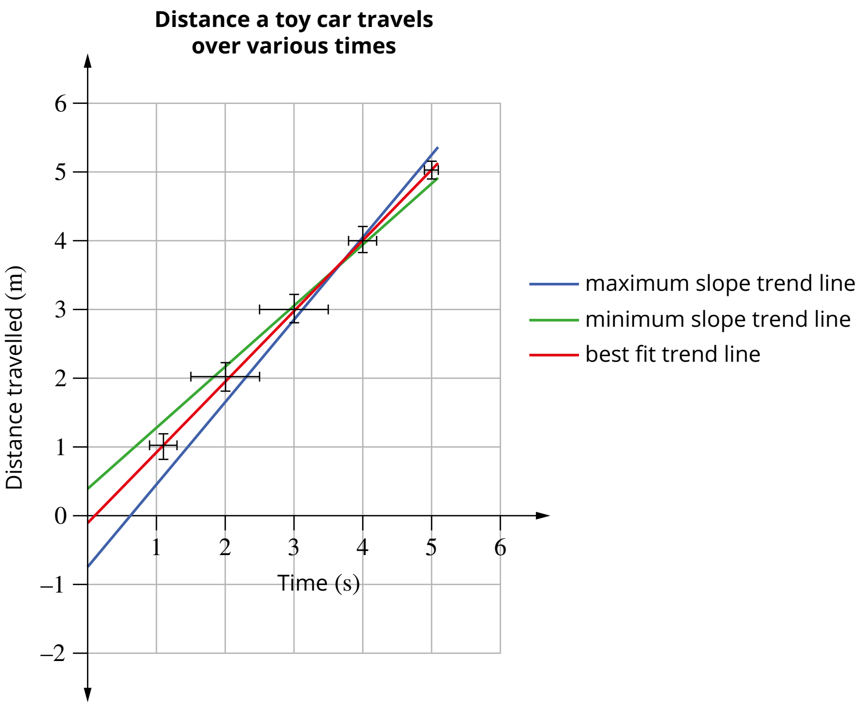


FIGURE 1.4.18 An example of a linear graph showing the best fit line, error bars, and maximum and minimum lines. The minimum and maximum lines are used to determine the uncertainty in the gradient and y-intercept.

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 1.4.18 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 gradient, and maximum and minimum y-intercept, 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 e35, the uncertainty of the gradient can be found by using:

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

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

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

Using the data from Figure 1.4.18, the uncertainties of the gradient and y-intercept are:

$$\Delta\text{gradient} = \frac{1.19 - 0.881}{2}$$
$$= 0.1545\,\text{m s}^{-1}$$

$$\Delta(y\text{-intercept}) = \frac{0.407 - -0.753}{2}$$
$$= 0.58\,\text{m}$$

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

gradient = $1.02 \pm 0.16\,\text{m s}^{-1}$

y-intercept = $-0.1 \pm 0.6\,\text{m}$.

Note that in this example:

- the gradient represents speed. The toy car is travelling at a constant speed of $1.02 \pm 0.16\,\text{m s}^{-1}$.
- 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 1.4.5 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 1.4.5 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 1.4.19 shows the line of best fit as the blue dotted line, with the green and red dotted lines being the maximum line and minimum lines, respectively. The equations of each are also shown, along with the R^2 value for the line of best fit.

From the line of best fit (blue):

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

y-intercept = 1.9725 g.

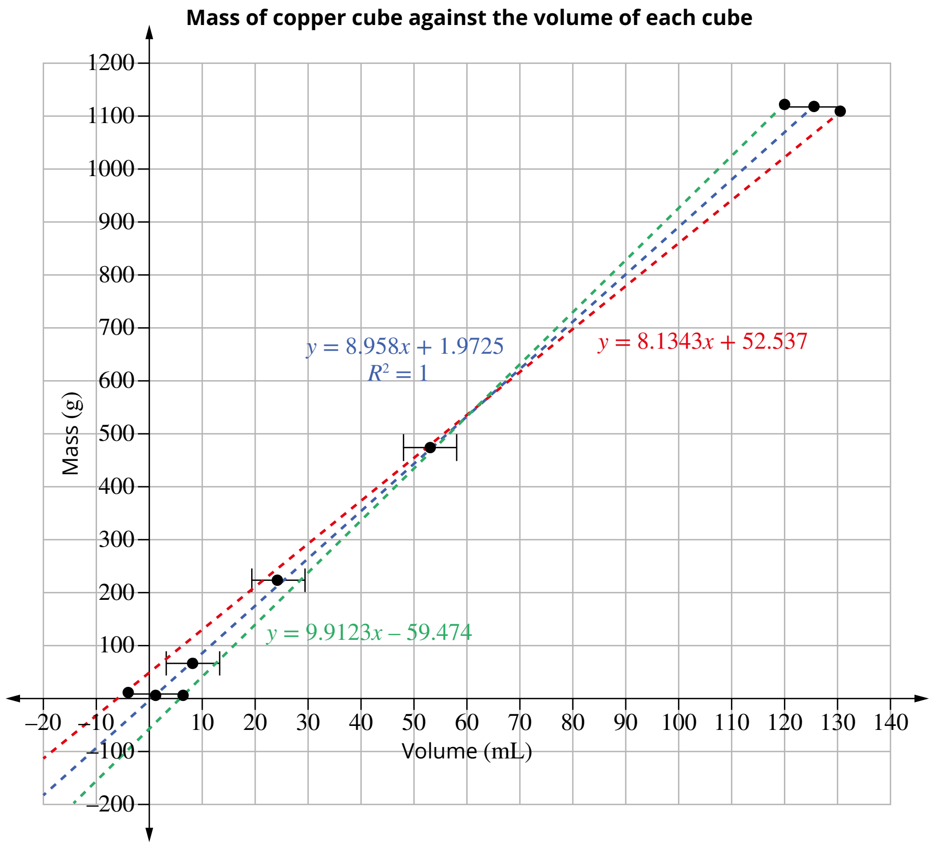


FIGURE 1.4.19 The complete graph, error bars and maximum and minimum lines for mass and volume data of copper cubes. The dots at the extremities of the lines were used to help draw the maximum and minimum lines.

From the graph:

$$\Delta\text{gradient} = \frac{9.9123 - 8.1343}{2}$$
$$= 0.889 \text{ g mL}^{-1}$$

$$\Delta(y\text{-intercept}) = \frac{52.537 - -59.474}{2}$$
$$= 56.006 \text{ g}$$

Note that in this example:

- the gradient represents the density of copper, which is 9.0 ± 0.9 g mL^{-1}. This is a reasonably precise measurement with a 10% uncertainty, and the discrepancy between this value and the accepted value ($\rho_{copper} = 8.96$ 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.

1.4 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 used 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 non-linear 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* is 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.

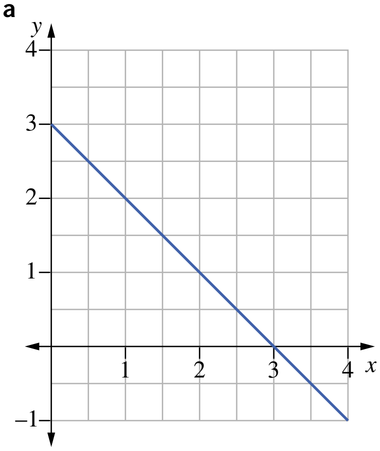
KEY QUESTIONS

Retrieval

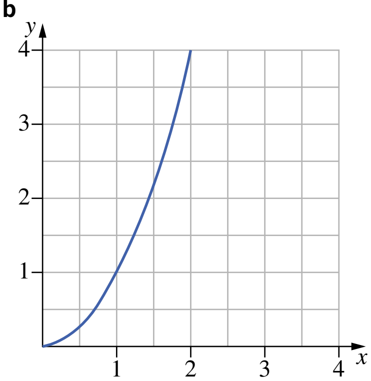
1 Recall how systematic errors are shown on a graph.

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

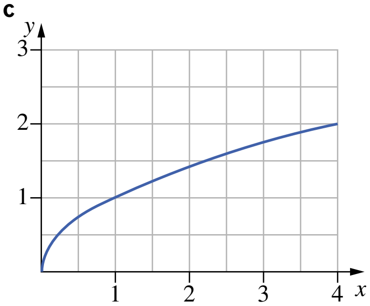
a



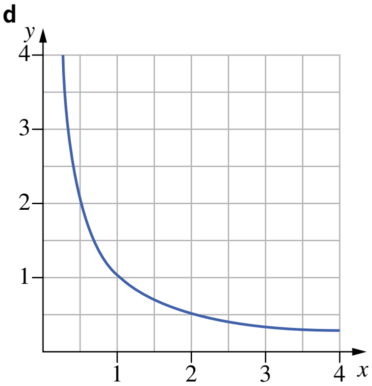
b



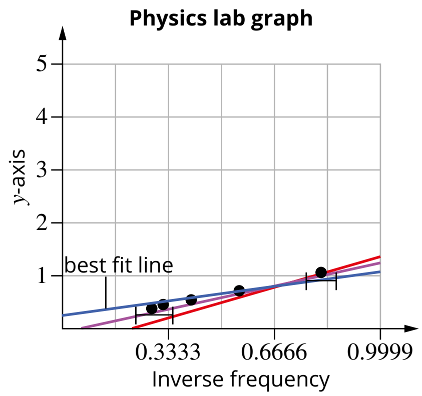
c



d



3 Consider the graph shown below.



a List the mistakes or poor techniques in this graph.

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

Comprehension

4 Ruby 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 Ruby why this is the case and suggest some improvements to her data.

5 If theory suggests that the *y*-intercept of a line is zero, describe what this should look like 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 three formulas used in physics. A description of the shape of the graph when the raw data are graphed is shown in brackets. Assume that all other symbols are constant.

- **i** Describe what modified variables, if any, need to be plotted on each axis to produce a linear graph.
- **ii** Identify what the gradient and *y*-intercept become in each case.

a $P = A\sigma T^4$ (*P* on the *y*-axis and *T* on the *x*-axis produce a rapidly rising curve).

b $a = \frac{4\pi r}{T^2}$ (*a* on the *y*-axis and *T* on the *x*-axis produce a hyperbola).

c $n_2 \sin\theta_2 = \sin\theta_1$ (θ_2 on the *y*-axis and θ_1 on the *x*-axis produce a near-straight line)

10 Kay and Glenn performed an experiment to determine the strength of a bar magnet, *B*, placed at a constant distance away from a single loop of wire ($L = 10.0 \pm 0.1$ cm long) carrying a current, *I*. They measured the force, *F*, on the wire using an electronic balance when the current through the loop of wire was varied and obtained the following results.

Current through loop of wire, *I* (±0.1 A)	Force on wire, *F* (±0.01 N)
1.0	0.13
2.0	0.23
3.0	0.38
4.0	0.50
5.0	0.60

The relationship between the force experienced by the wire placed near the bar magnet is given by $F = BIL$.

a Draw a graph of the data in the table. Include a line of best fit and error bars.

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

c Use your answer to part b to calculate the value of the strength of the bar magnet, and its uncertainty.

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

11 Zoe researches the period, *T*, and average orbital radius, *r*, of several planets in our solar system and records them in the table below.

Planet	Period *T* (±10^5 s)	Average orbital radius *r* (±10^6 km)
Mercury	7 600 000	58 000 000
Venus	19 400 000	108 000 000
Earth	31 500 000	150 000 000
Mars	59 400 000	228 000 000

The relationship between *T* and *R* for our solar system is found by:

$$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$$

where *G* is the universal gravitational constant, 6.67×10^{-11} N m^2 kg^{-2}, and *M* is the mass of the Sun in kg (when all other units are SI).

a Draw a graph of the data in the table, with *r* as the independent variable (in m) and *T* as the dependent variable (in s). Include a line or curve of best fit and error bars.

b Linearise the data by identifying new modified variables for the *x*- and *y*-axes.

c Draw the new straight line using the new modified variables. Include the modified error bars on your graph.

d Draw the maximum and minimum lines.

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

f Use your answer to part **e** to calculate the value of the mass of the sun, and its uncertainty.

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

PART B STUDENT EXPERIMENT (IA2)

The QCAA requires students to complete a student experiment in Unit 3 Physics. The student experiment assessment 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 you 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 your own experiment. It is recommended that during the class practical you record your 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 Physics.

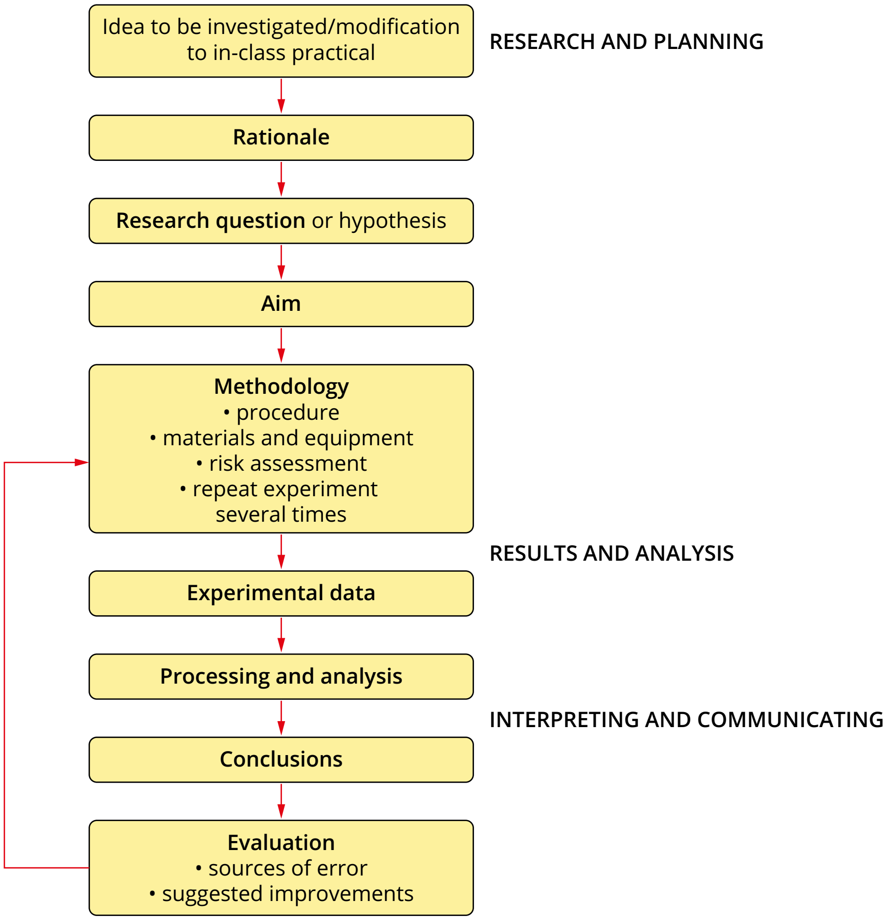
The student experiment may be presented in:

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

A summary of the ISMG for the student experiment (IA2) is provided below. The table includes the objectives and marking for this summative internal assessment.

Criteria	Assessment objectives	Demonstrated by	Marks
Research and planning	• apply understanding • investigate phenomena	• 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 • consideration of 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 below.



Note that although protocol dictates that a scientific report should include an aim, for the purposes of the student experiment (IA2) the inclusion of an aim will not be awarded any marks and inclusion will count against the assessment piece word count.

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: 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 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 much more 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

Criterion: Analysis of evidence

Objectives
These are the objectives being assessed. Your work must demonstrate these objectives. Definitions of the objectives can be found in the syllabus glossary. How the objectives will be assessed is described below.

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 data correctly and in a way that helps answer the research question • thoroughly identifying relevant relationships, trends, 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
• basic processing of data to demonstrate an adequate application of algorithms and representations of data • Identifying obvious relationships, trends, patterns to demonstrate effective analysis of evidence • rudimentary identification of uncertainty and limitations of evidence • collecting relevant data to demonstrate an effective investigation	3–4
• processing data incorrectly or processing data in a way that does not relate to the investigation • identifying incorrect or irrelevant relationships, trends, patterns to demonstrate ineffective analysis of evidence • identifying uncertainty or limitations of evidence incorrectly or to a degree that does not help resolve the investigation • collecting insufficient and irrelevant data to demonstrate an ineffective investigation	1–2
• descriptors not addressed	0

Descriptor
Each dot point in each performance level descriptor is called a descriptor. The descriptors contain all the characteristics required to achieve that level of performance. They outline the evidence that teachers will search for in your work.

Performance level descriptor
The performance level descriptor is the whole of the left-hand cell in each performance level. It is made up of all the descriptors in that level.

Performance level
Together, the performance level descriptor and the mark are known as the performance level. Once the descriptors for a particular performance level descriptor have been assessed, a performance mark is awarded. You can only be awarded one of the marks in the corresponding 'Performance mark' column. If all the descriptors of the performance level descriptor are demonstrated in your response, then the upper mark is awarded. Otherwise the lower mark is awarded.

Performance mark
The performance mark is the mark awarded to the response for the particular criterion. It is related to the quality of the response as measured against the performance level descriptor.

In the modules that follow, you will find a guide to a scientific method (Modules 1.5–1.7) followed by an outline on producing a scientific report (Module 1.8).

1.5 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 of 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 on ongoing draft of scientific work from which the final scientific report is written.

IDENTIFYING AN EXPERIMENT AND DEVELOPING A RESEARCH QUESTION

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 (Figure 1.5.1).

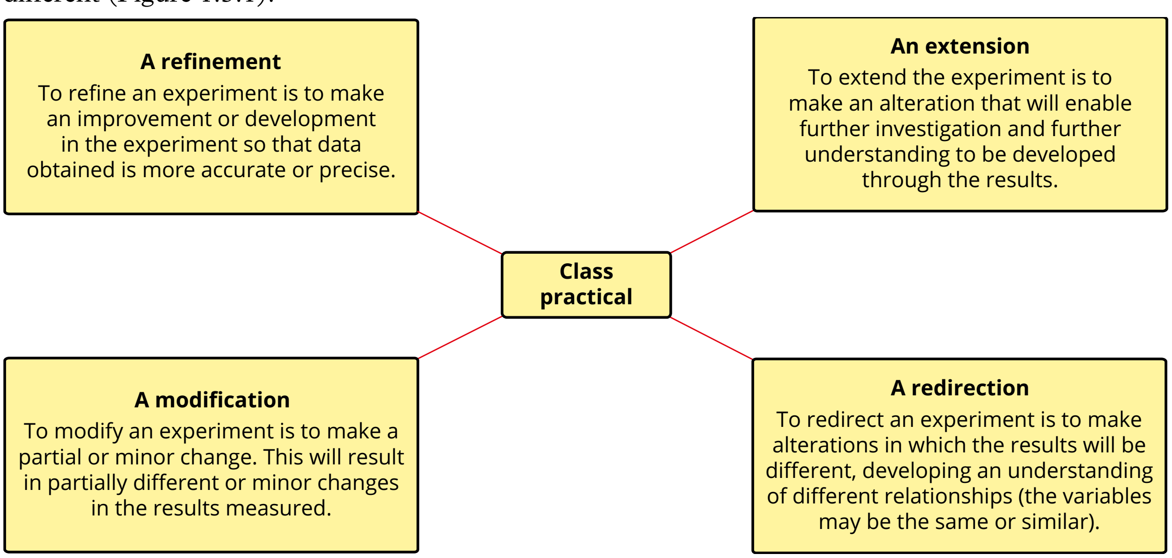


FIGURE 1.5.1 Chart showing possible changes to a class practical when developing a student experiment

Identify an experiment

During the class practical, record observations, points of interest, errors, and ideas for improvement or variables that you believe are significant to the experiment. Choose one of these observations to alter: **modify**, **refine**, **extend** or **redirect**. 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 a topic/observation 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 1.5.1 shows examples of modifying, refining, extending or redirecting practicals into a topic of interest for a student experiment.

TABLE 1.5.1 Examples of ideas for changes to a class practical

Class practical	Modification, refinement, extension or redirection	Student experiment idea
Measuring the strength of the magnetic field near a straight piece of wire	Extension and modification	Measure how the thickness of the wire affects the strength of the magnetic field. or Measure how the perpendicular distance away from the wire affects the strength of the magnetic field.
	Modification and refinement	Measure the strength of the magnetic field when the apparatus is placed in a medium other than air.
Conducting an experiment to determine the value of the acceleration due to Earth's gravity using centripetal force apparatus	Extension and modification	Investigate how the radius of motion affects the calculations of the acceleration due to Earth's gravity. or Investigate how the hanging mass (i.e. stationary mass) affects the calculations of the acceleration due to Earth's gravity.
	Modification and redirection	Measure the angle that the swinging mass makes with the horizontal and determine its effect on the calculations of the acceleration of Earth's gravity.
Using 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 thickness of a razor blade.

The Queensland General Senior Syllabus, Physics 2019 requires the student experiment report to justify the alteration of the methodology from the class practical. 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 (Figure 1.5.2). 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).

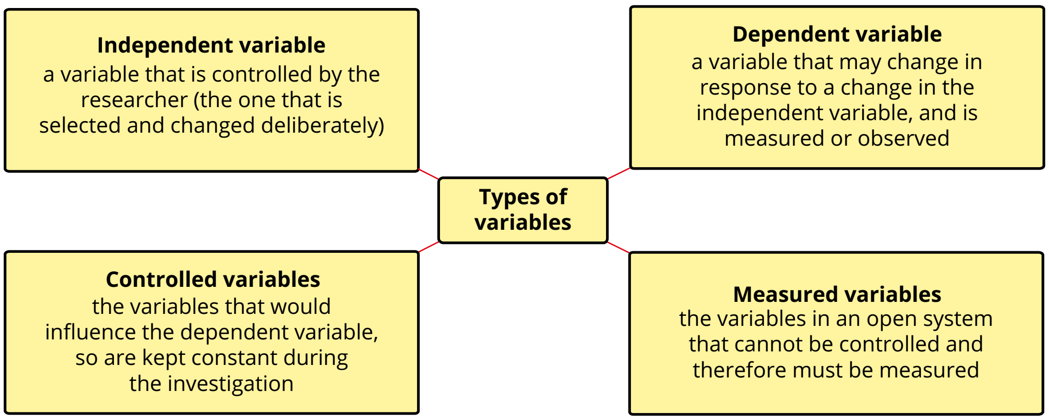


FIGURE 1.5.2 The four types of variables in experiments

Developing a research question

A research question is defined as a question that directs the scientific inquiry. 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 research question determines the experiment and the experiment is testing the question. A research question should:

- be specific and relevant to the class practical and have specific measureable variables defined
- 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 1.5.3.

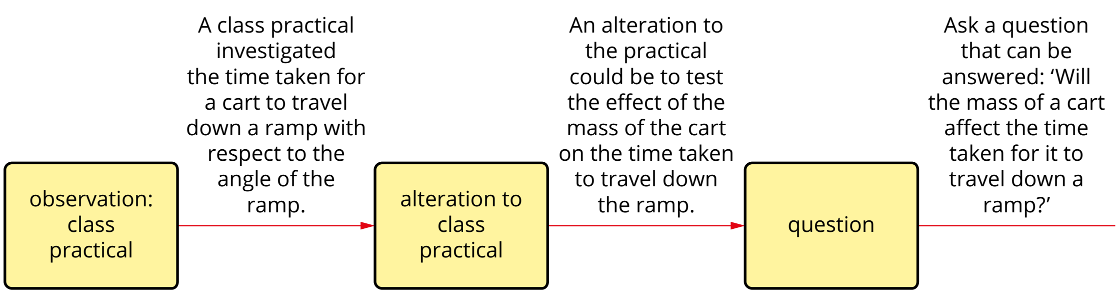


FIGURE 1.5.3 The process from class observation of a practical, to altering the practical and developing a possible question

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; at this stage, do not reject ideas that might seem improbable.

Figure 1.5.4 demonstrates the process of question refinement and the resultant question that will guide the student experiment.

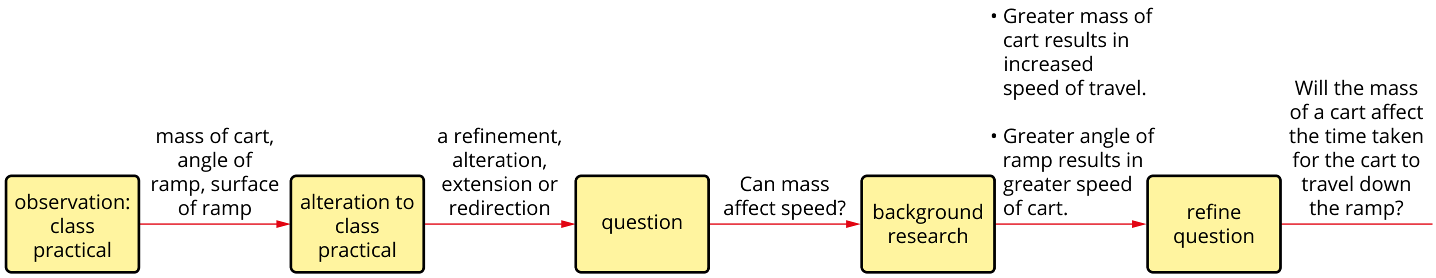


FIGURE 1.5.4 The process of refining a question in a student experiment

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:

Independent variable **Dependent variable**

'Will the wavelength of light that is shone onto the surface of a metal affect the current through a circuit?'

As the research question is constructed, it should have the following characteristics:

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

Table 1.5.2 shows examples of research questions with links between guiding words and command verbs.

TABLE 1.5.2 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 temperature have on the induced voltage produced by a generator?	Identify and describe specific evidence, reasons and examples from a variety of possibilities. *Identify* and *describe*
Will	**Will** a motor rotate at a higher rate if the current through it is increased or decreased?	Identify and describe giving reasons for effectiveness. *Identify* and *describe*
How	**How** does the angle between the magnetic field and current-carrying wire affect the force on the wire?	Identify and describe in detail a process or mechanism. Give examples using evidence and reasons. *Identify* and *describe*
Why	**Why** does the angle of release affect the range of a projectile?	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 light the same for each colour of the rainbow?	Evaluate. Justify, giving reasons and evidence. *Evaluate*, *assess*, *justify*
Can	**Can** you charge a perspex rod using a sheet of glass?	Evaluate and assess. Is it possible? Give reasons, suggest possible alternatives. *Evaluate*, *assess*, *justify*, *create*
Do/does	**Does** the strength of Earth's gravitational field depend on the height above sea level?	Evaluate. Justify using reasons and evidence for and against. *Evaluate*, *assess*, *justify*

Formulating a hypothesis

A hypothesis can be developed from the research question. A hypothesis is a statement that proposes a relationship between variables, 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 for developing a question (Figure 1.5.5).

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.

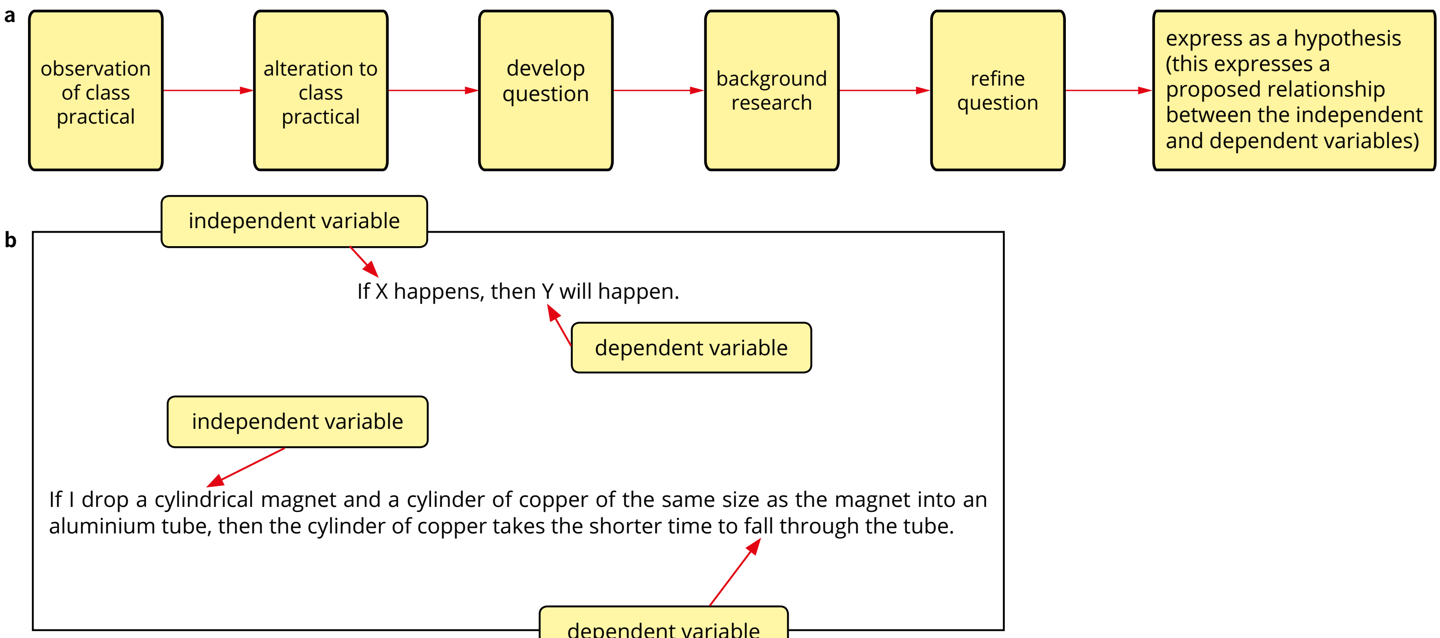


FIGURE 1.5.5 (a) Steps to refining a research question or hypothesis. (b) To formulate a hypothesis, write in terms of the dependent and independent variables.

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 1.5.5 could also be worded in the following ways:

1. A magnet will take longer to fall through an aluminium tube than a piece of copper.
2. When dropped through an aluminium tube, a magnet will take longer to fall than a piece of copper.

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

There are many benefits of hypotheses. The proposed relationship between variables set out in a hypothesis gives guidance as to the experimental method that needs to be adopted. A hypothesis may also suggest what variables to control for and what other variables should be measured. It also guides our approach to analysing the results, and can even suggest the limitations of the experimental method and how it might be improved.

EVALUATING YOUR RESEARCH QUESTION

When a research question has been developed, it should be evaluated and refined before progressing. Follow the prompts in the flow chart in Figure 1.5.6 to refine and improve the research question.

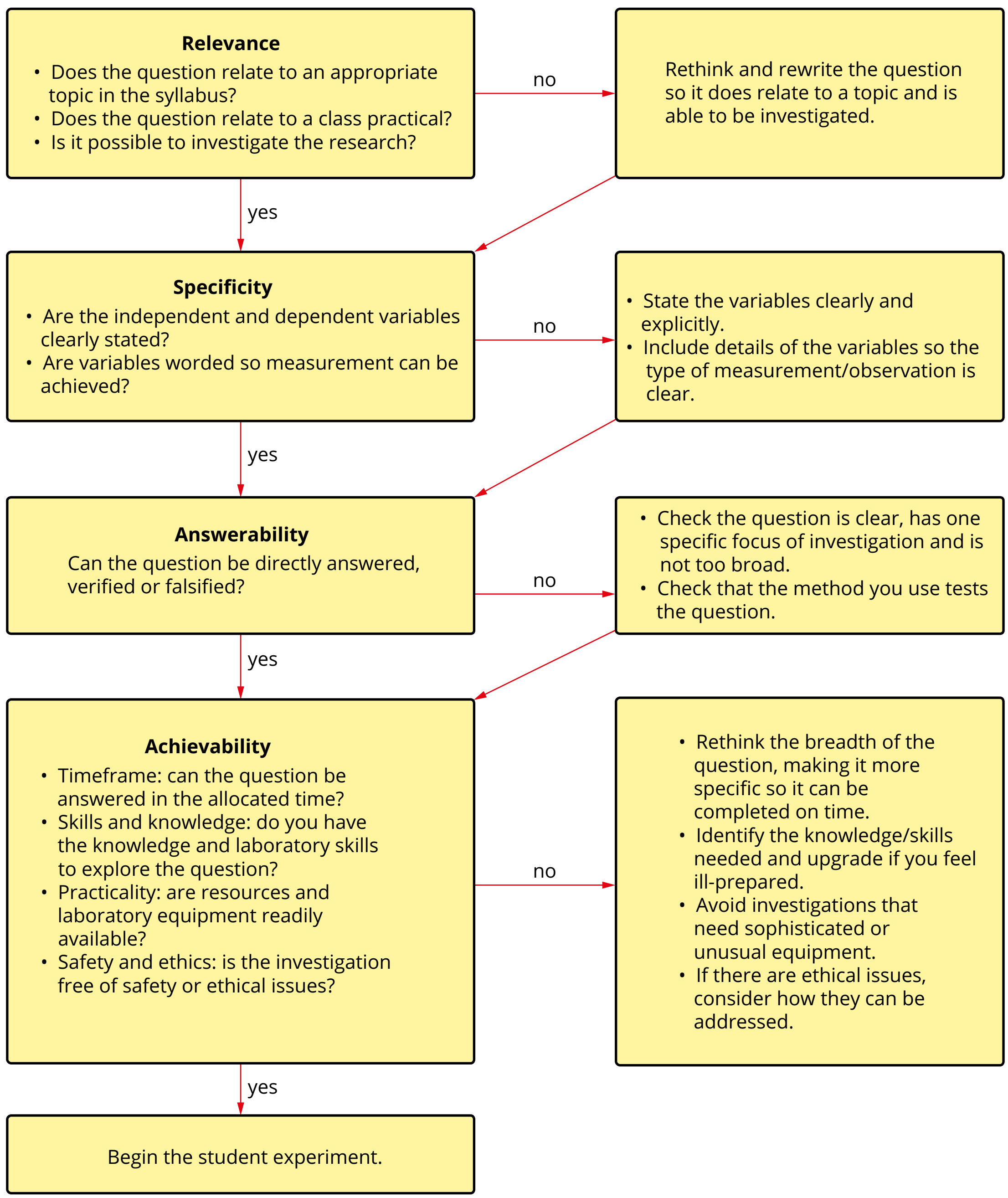


FIGURE 1.5.6 Steps for refining and improving the research question

Examples of research questions and hypotheses

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

Research question: Is the relationship between magnetic force and the velocity of a charged particle linear? **Hypothesis**: The relationship between the velocity of a charged particle and the magnetic force on it is linear.
Research question: Will increasing the launch angle of a projectile increase the flight time of the projectile? **Hypothesis**: Increasing the launch angle of a projectile will also increase the time the projectile is in the air.
Research question: Does increasing the angle of a track allow cyclists to ride around a bend at a higher maximum velocity? **Hypothesis**: A track placed on an angle will allow a cyclist to ride faster around a bend than on a flat track.

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. 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 variable
- 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 ISMG for the student experiment (IA2) research and planning criterion states that students are required to demonstrate:

- 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.

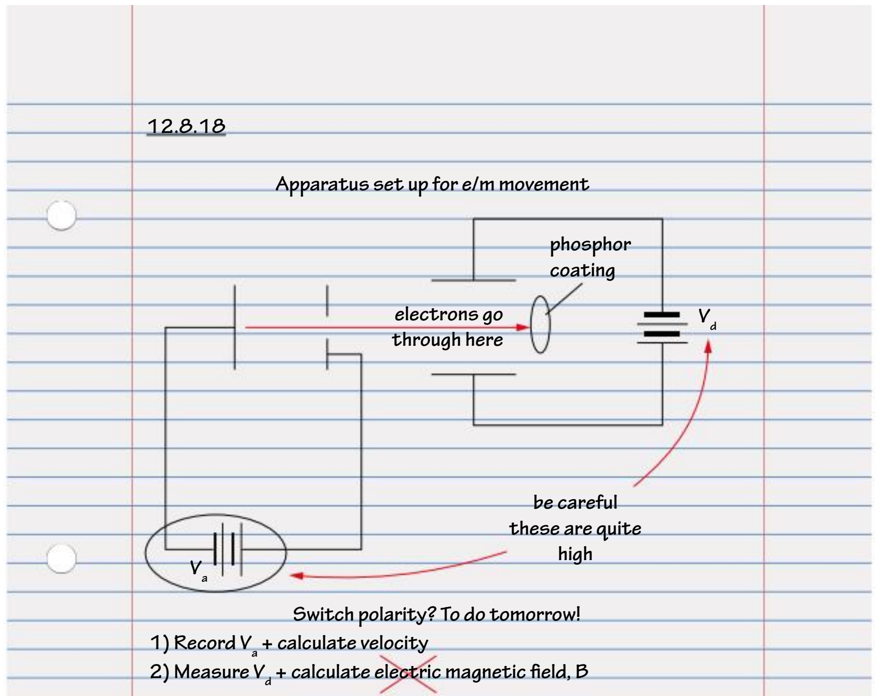
Furthermore, the syllabus expects background scientific information to be used in a rationale for the experiment to:

- explicitly justify the modifications to the methodology (alterations to the class practical)
- explain the 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.

There is a lot of information to record during a student experiment and it is best to 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 your thoughts in the scientific journal keeps a record of all information you collected during the process of the scientific method (Figure 1.5.7). 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 1.5.7 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 have their own titles. 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, defined the variables, developed knowledge and understanding of the relevant concepts and relationships, then 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 (methodology) and schedule 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, although, 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 was not influenced by other variables that should have been kept constant
- the degree, or scope, to which your findings can be generalised to broader 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 it 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 (Figure 1.5.8).

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.

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

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

Quantitive data: can be measured.

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

Discrete data

Variables can only take particular values.

Example 1: the number of springs connected together

Example 2: the energy levels in atoms

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 1.5.8 Qualitative and quantitative data

Measurement of temperature requires an instrument and provides quantitative data for temperature. It is not appropriate to record qualitative data for temperature, e.g. cold, warm or hot (Figure 1.5.9).

a

b

c

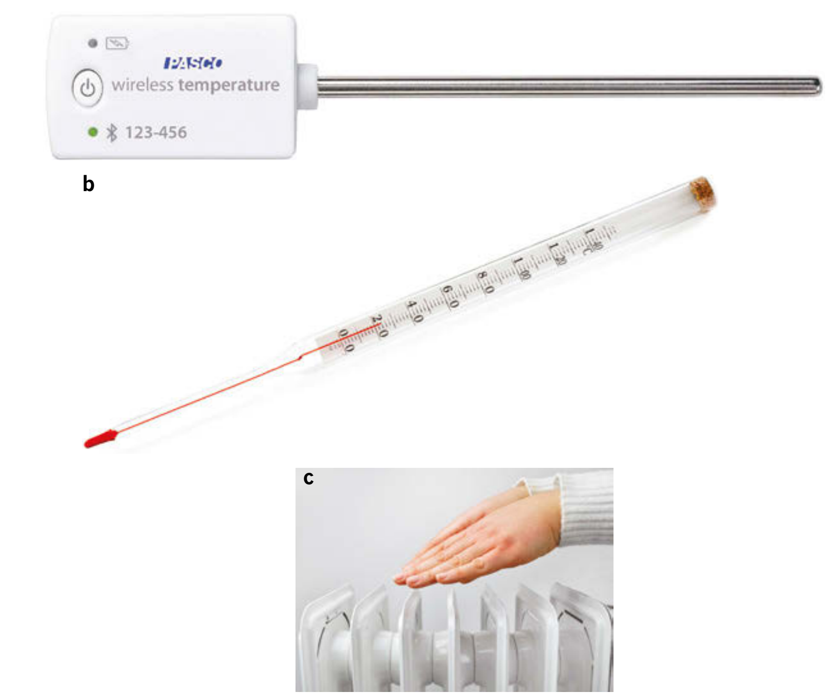


FIGURE 1.5.9 (a) A wireless temperature sensor and (b) a liquid thermometer will measure temperature empirically and provide quantitative data that can be analysed statistically. Processing empirical data can produce discrete, explicit and comparative analysis. (c) Describing the heat radiating from a heater is an example of qualitative data, based on personal observation. Qualitative data cannot be statistically analysed.

Depending on the experiment, it may be appropriate to record a qualitative observation (e.g. brightness of light), or a quantitative observation, such as voltage (Figure 1.5.10).

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 magnetic field. A way to eliminate the possibility that random factors affect the results and cause uncertainty is discussed in Module 1.3. 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.

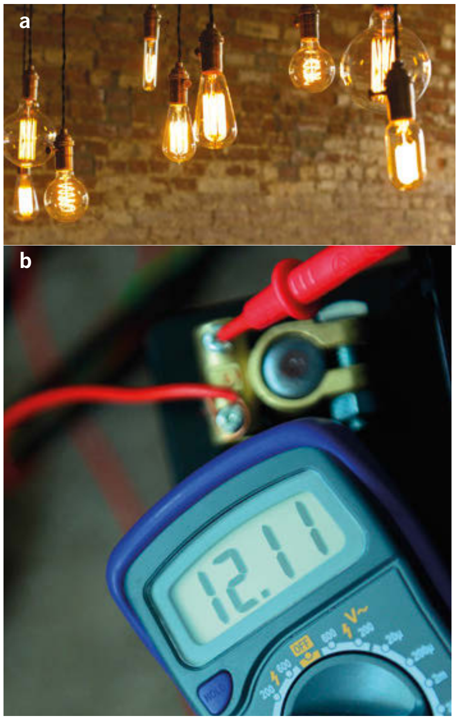


FIGURE 1.5.10 (a) When recording qualitative data, describe in detail how each variable will be defined. For example, if recording the brightness of light globes, photographs are a good way of clearly defining what each assigned term represents. (b) This multimeter is measuring an AC voltage of 0.4 volts. This is an example of a continuous variable that is quantitative data.

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 1.5.11). 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 1.3)
- 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 affects the:

- representation of the phenomenon
- natural variation, errors and uncertainty
- results by offering more evidence to support the experimental results
- 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 are also important in obtaining reliable (repeatable) data.

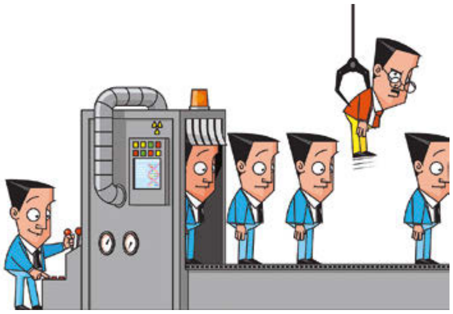


FIGURE 1.5.11 If you can reproduce your results, they are reliable.

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 give 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, the ability to connect independent sensors to any device has enabled simple and highly effective electronic data acquisition over extensive periods of time, anywhere.

Data acquisition can be achieved by using sensors, or probes, and recording data to a standalone device, computer, tablet (Figure 1.5.12) 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.

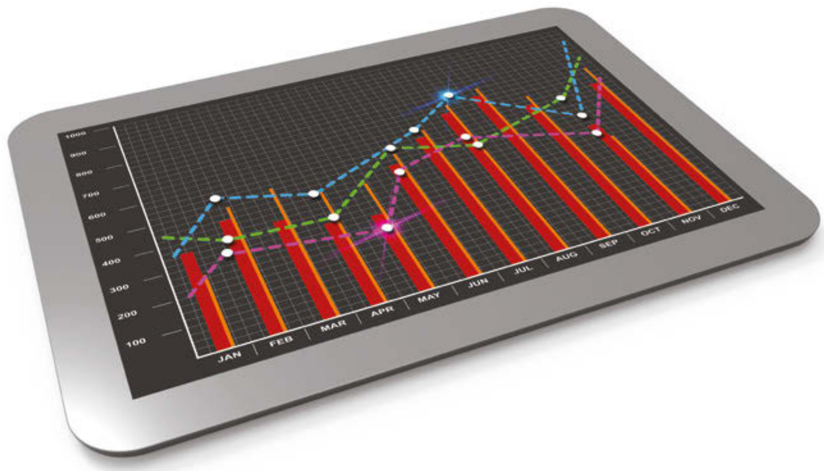


FIGURE 1.5.12 Data acquisition software produces real-time graphs that can be downloaded or printed.

Many smart watches and apps in phones include digital sensors (Figure 1.5.13) 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. With the many different probes available, there are many applications.

FIGURE 1.5.13 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 and send it directly to a computing device. There are many sensors, probes and instruments available that can measure a vast variety of phenomena in a single device (Figure 1.5.14a).

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 (Figure 1.5.14b).

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 (Figure 1.5.14c). 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 (Figure 1.5.14d). Video can be linked directly for synchronising with data or used separately and then be imported into suitable software after the event for detailed analysis.

FIGURE 1.5.14 (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) Probes 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, providing the temperature of skin on contact.

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

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

Uses of electronic data acquisition

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, and the mechanic can access these data when servicing the car, or on a console on the steering wheel (Figure 1.5.15). Control units are also used for diagnostic testing of equipment in aeroplanes, commercial air-conditioners and office equipment, such as photocopiers, and in vehicles to provide data on speed and engine operation.

FIGURE 1.5.15 Data acquisition is used throughout many industries. It provides informative feedback to manufacturers during the assembly of vehicles and many devices (especially electronics) for quality control and assurance.

FIGURE 1.5.16 When planning an investigation you need to identify, assess and control hazards.

RISK ASSESSMENT

When planning for an experiment or investigation in 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. A **risk assessment** is 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, the 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 1.5.16)
- what clothing you should wear, such as a lab coat and goggles.

The following hierarchy of risk controls is shown in Figure 1.5.17. It is organised from the most effective to least effective. The most commonly used risk control measure that addresses most risks is personal protective equipment (PPE). The least common, but most protective, control measure is eliminating all risk from the scientific investigation.

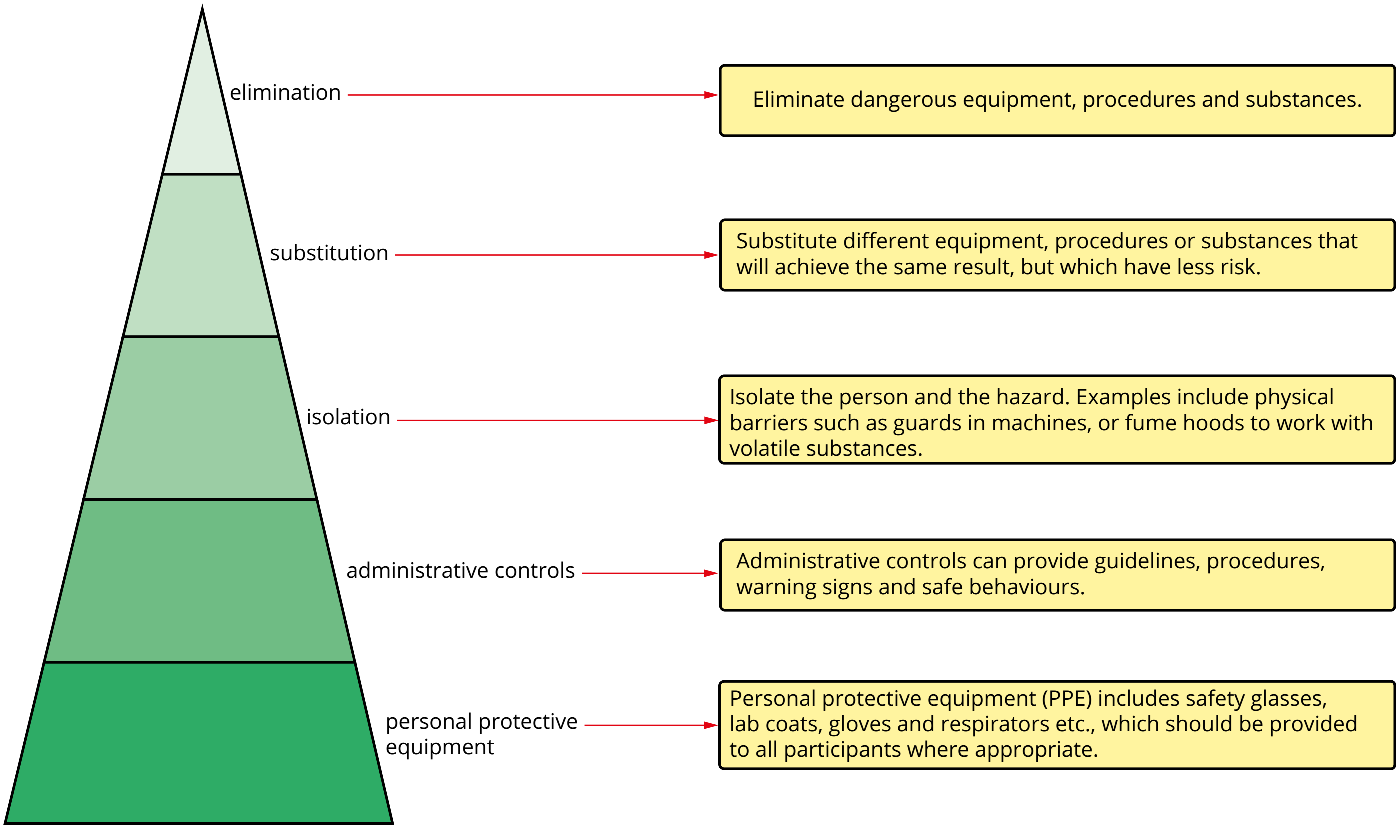


FIGURE 1.5.17 The hierarchy for risk control is shown in this pyramid, marked from bottom to top in order of increasing importance.

Personal protective equipment

Everyone who works in a laboratory wears PPE to help keep them safe, such as:

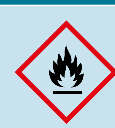
- safety glasses
- shoes with covered tops
- disposable gloves when handling certain chemicals
- a disposable apron or a lab coat if there is risk of damage to clothing.
  Examples of PPE are shown in Figure 1.5.18.

FIGURE 1.5.18 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. Some common pictogram codes and their meanings are shown in Table 1.5.3.

TABLE 1.5.3 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: can cause discomfort, pain or itchiness	Flammable	Danger: The hazard can include 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 1.5.19). The SDS contains important safety and first aid information about each chemical. 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 1.5.19 An example of part of an SDS for liquid nitrogen showing the pictogram for a compressed gas to alert the reader to any potential hazards when using the substance. The SDS also includes measures to reduce risk of harm.

Ethical considerations

When planning an investigation, researchers should always identify all possible ethical issues and, if necessary, consider ways to 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 wider society?
- Does one party benefit over another; for example, 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, refining the research question or as understanding of the variables develops. Scientists often employ an experimental methodology that has been refined numerous times over several years.

> 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 or resource limitation. Refinements also reduce error and uncertainty as the experimenter becomes aware of these problems.

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.

Figure 1.5.20 on page e78 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, and the limitations of the investigation can be 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 1.8.

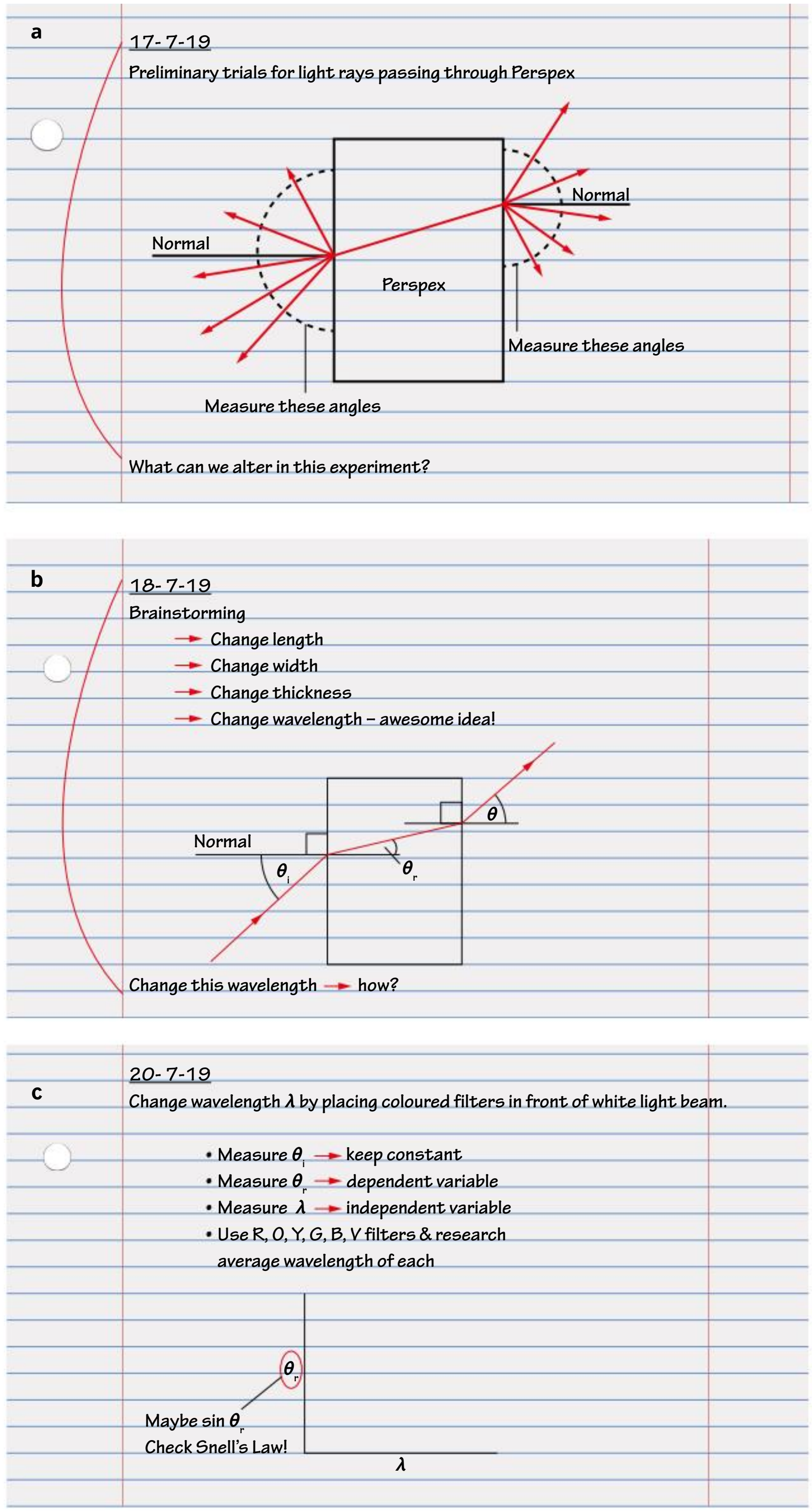


FIGURE 1.5.20 Demonstrating the alteration and refinement of a class practical into an experiment written in a student's journal. (a) The observations made during the class practical. (b) The recordings of ideas and possible alterations to the class practical form the student's development of an experiment. (c) The refinement of the student's idea for the experiment. The refinement was based on research.

1.5 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 order 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 Define the following types of variable:
- independent variable
- controlled variable
- dependent variable.

Comprehension

2 Represent each of the three inferences below as a hypothesis that could be tested using a motor in an experiment.
a The motor rotates at a higher rate when there is more current passing through it.
b The motor does not move when there is no current passing through it.
c No motion is seen when the voltage applied to the motor is less than 4.0 V.

1.5 Review *continued*

3 Write a research question for each of the following observations.
   a Silk is much better than wool at charging a perspex rod.
   b The acceleration of electrons in a magnetic field is higher than that of protons.
   c The Hubble Space Telescope can only be seen once per week from a given location.

4 Explain the difference between quantitative and qualitative data.

5 Identify which of the following pieces of information about a sheet of aluminium foil are qualitative, and which are quantitative. Place a tick in the appropriate column.

Information	Qualitative	Quantitative
shiny appearance		
has a work function of 4.1 eV		
will conduct electricity		
will conduct thermal energy		
is ductile		
surface area of 100 cm^2		
metallic smell		
has a resistivity of 27 nΩ m		

6 Identify the independent, dependent and controlled variables that would be needed to investigate each of the following research questions.
   a Will an increase in temperature result in an increase in the rate of heat loss in a transformer?
   b Will increasing the radius of a planet increase its acceleration due to gravity?
   c Will the intensity of the diffracted light be reduced if the slit through which the light passes is narrowed?
   d Will the deflection angle of electrons increase if the intensity of the external magnetic field is increased?

7 In a practical investigation, Abby measures the voltage output from a generator by increasing the number of turns of wire around the armature.
   a Explain how the output voltage could be a discrete value.
   b Explain how the output voltage could be continuous.

8 Explain the reasons for having an SDS for each chemical used in the laboratory.

9 Describe the appropriate action to take if you came into contact with a chemical substance with the following label on the container.

Analysis

10 Evaluate which is the best research question from the three options below. Explain your choice.
   A Will a higher atomic number of a singly-ionised atom cause a smaller deflection angle when fired perpendicularly at the same velocity into a constant external magnetic field?
   B Will shiny metals produce more photoelectrons in the photoelectric effect than dull metals?
   C Will the diffraction pattern of green laser light become clearer when a narrower slit is used?

1.6 Conducting an experiment

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

- determine what relevant data is needed to test a research question
- determine what is considered to be sufficient data to test a research question
- select appropriate equipment to collect relevant and sufficient data.

Once you have defined the variables and planned the methodology, you can conduct the experiment. Experiments rarely run according to plan.

CONDUCTING THE EXPERIMENT

While conducting the experiment, you must control the variables and maintain the conditions to ensure the measured or recorded raw data is valid and reliable. Others must be able to repeat your experiment 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 your experimental results. The more precise the instrument, the more accurate the measurements and the more reliable your 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 the 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 (Table 1.6.1).

TABLE 1.6.1 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 touch	 Measurung the temperature using a digital thermometer (sensor) with known precision and uncertainty

Safety precautions

Always use safe procedures and 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.

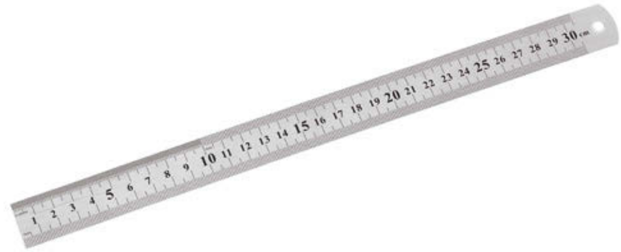
You must follow your school's and teacher's safety and risk assessment guidelines. Completing the risk assessment may require completing a form or completing an online process.

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 1.6.2 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, or the analysis and interpretation of the data will not be reliable or valid in relation to the research question or hypothesis.

TABLE 1.6.2 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

Collection of sufficient data

The term 'sufficient' is defined in 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 also 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 where the curve reaches a maximum or minimum point (Figure 1.4.3 on page e42).

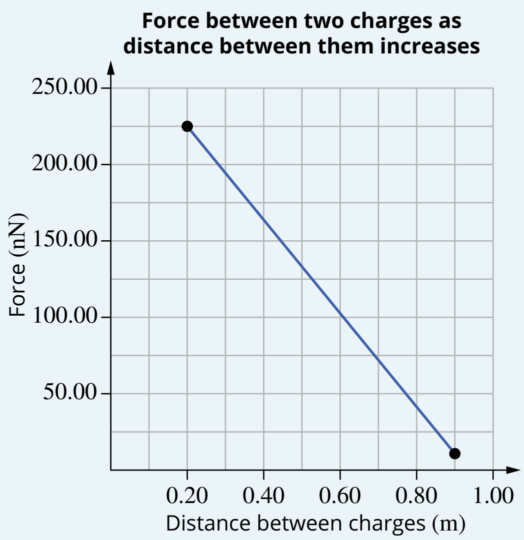
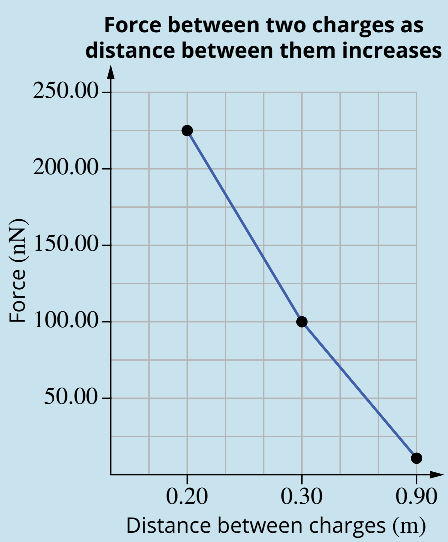
Together, the number of replicates and individual samples determine the sample size. This is vital to achieving and determining a valid interpretation of the data.

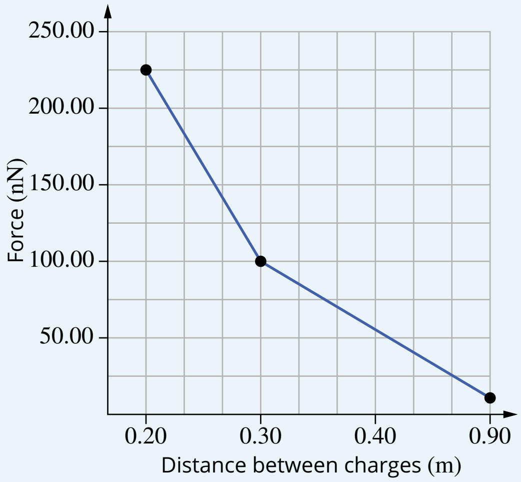
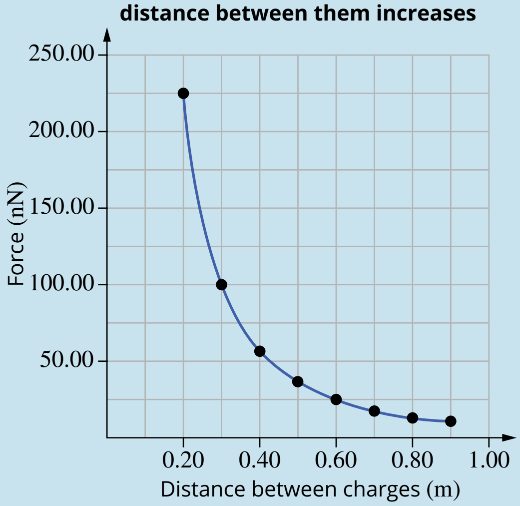
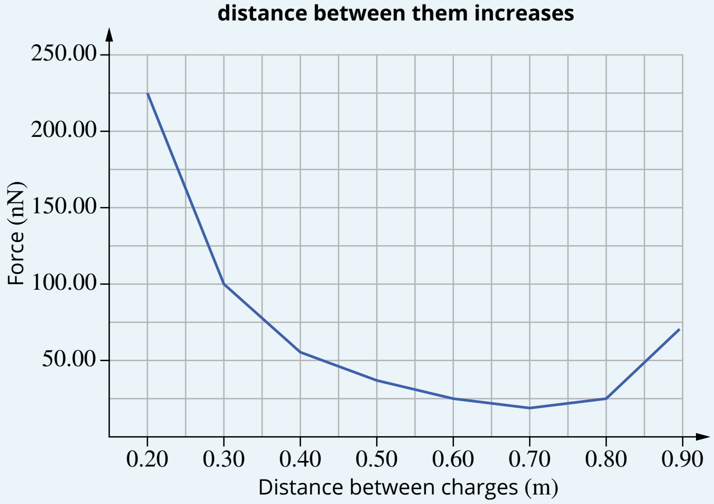
Table 1.6.3 shows examples of various sample sizes and the effect on the results of the experiment. The results are from an experiment into the effect of how distance between two charges affects the force between them.

Collection of 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, then it is not relevant, and therefore is not to be measured.

TABLE 1.6.3 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. (Note: with a graph of only two data points, any function—linear or curved—could match the data.
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.

<table>
<tr><th>Examples of analysed data</th><th>Effect of sample size on analysis</th></tr>
<tr><td>Line graph showing limited sample points and an uneven scale
Force between two charges as distance between them increases

</td>
<td>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.</td></tr>
<tr><td>Scatter graph with appropriate number and distribution of sample points
Force between two charges as distance between them increases

</td>
<td>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. This graph shows how a larger sample size indicates a correct relationship between variables.</td></tr>
<tr><td>Line graph based on data that had no replicates
Force between two charges as distance between them increases

</td>
<td>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.</td></tr>
</table>

1.6 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.
- Equipment used during an experiment should enable you to collect and measure relevant data to address the research question.

KEY QUESTIONS

Retrieval

1 State why it is important to choose appropriate equipment and instruments to conduct experiments.

Comprehension

2 Explain how the precision of equipment can affect scientific conclusions.

Analysis

3 Clancey recorded the data below to test the following null hypothesis: The length of the wire wound around a solenoid affects the magnetic field inside the solenoid. Assess on whether or not sufficient and relevant data was collected.

Length of wire (m)	Thickness of the wire (mm)	Current through the wire (A)	Length of solenoid (cm)	Diameter of solenoid (cm)	Type of wire	Magnetic field inside the solenoid (μT)	Brand of wire
0.50	0.31	0.02	12	3.4	copper	40.0	Ruby and Macey's House of Wire
1.00	0.31	0.02	12	3.4	copper	20.0	P & L
1.50	0.31	0.02	12	3.4	copper	13.3	P & L

1.7 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, they 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 1.4 for specific guidance on producing quality and appropriate graphs and to Module 1.8 for details regarding representing results.

IDENTIFYING ERRORS

Most practical investigations have errors, or uncertainties, associated with them (Figure 1.7.1).

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, such as in 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 1.8.

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 you want to see. Bias will result from using analysis tools (e.g. statistics) inappropriately and will lead to invalid conclusions and academic fraud. Quality scientific analysis processes the raw data as it is and is open to any result.

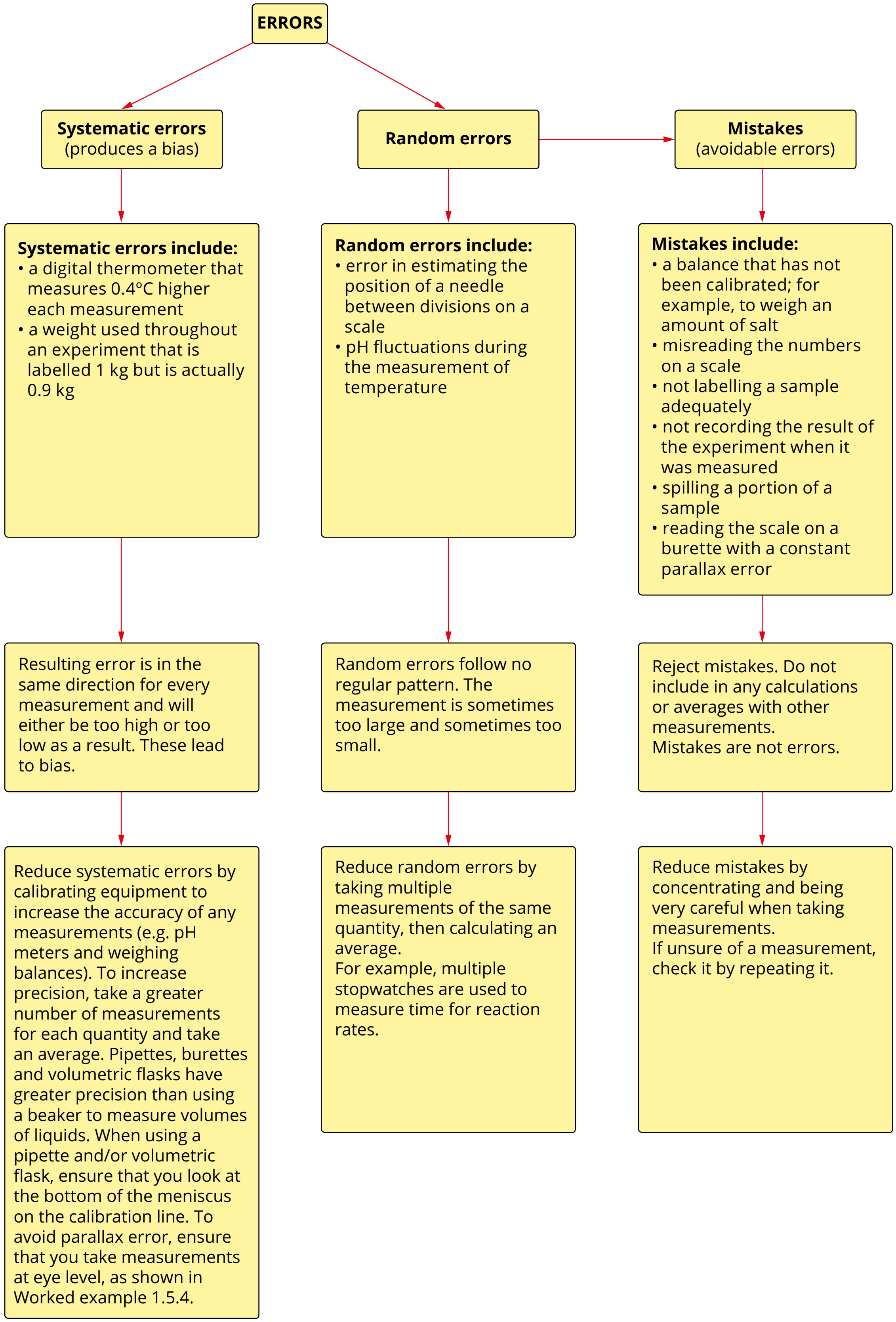


FIGURE 1.7.1 Types of errors that can be made in an experiment

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 instrumentation and how much is due to nature.

The precision and uncertainty of the instruments must always be displayed as a range of data next to the results (e.g. measurement ±Δ measurement). See Module 1.3 for more explanation. If calculations are performed with the results, then the appropriate calculations must also be done with the uncertainties. When the total uncertainty is known, then it can 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, 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 1.7.1 shows the mean value of the acceleration due to Earth's gravity (g) at six different locations along the coast of Queensland. The absolute uncertainty in the mean is calculated using the methods outlined in Module 1.3. The value of the absolute uncertainty in the mean is ±0.004 $m\,s^{-2}$, but as the individual uncertainties are larger than this value, the uncertainty in the mean is taken as ±0.005 $m\,s^{-2}$. There seems to be a pattern that the more northerly the location is, the lower the value of g at that location. But, since the uncertainty of ±0.005 $m\,s^{-2}$ covers the value of g at all of the locations except Cape York, the inference cannot be fully supported by the data.

This data suggests that the instrument used to measure g needs to be of a higher precision (i.e. lower uncertainty) so that the differences between the measured values of g and their respective uncertainties do not overlap. If the methodology controlled the extraneous variables appropriately and nothing unforeseen influenced the results, then you can interpret the difference between the values of g at those locations 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
- tendency (e.g. mean), which is the potential variation in instrumental measurements due to the instrument's design or increments.

TABLE 1.7.1 The values (and their uncertainties) of the acceleration due to Earth's gravity measured at several locations along the coast of Queensland

Sea level locations along the Queensland coast	Value of g ($m\,s^{-2}$)
Gold Coast	9.790 ± 0.005
Whitsunday Islands	9.788 ± 0.005
Cairns	9.785 ± 0.005
Cape York	9.783 ± 0.005
Weipa	9.785 ± 0.005
Fraser Island	9.790 ± 0.005
mean	**9.787 ± 0.005**

Analysing validity and theoretical relationships

Process the results and data 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. Once the quality of the data is understood, then the validity can be analysed in relation to established theoretical concepts.

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 the 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 they are 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 during the experiment in the journal becomes invaluable. When the results do not occur as expected, the observations provide a clue or a basis for what concepts or relationships need more research. 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, write the scientific report, summarising the scientific work and methods used in the experiment.

1.7 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 attempts to explain the observed results.

KEY QUESTIONS

Retrieval

1 Recall the two types of data.

2 Define 'systematic error'.

3 Define 'random error'.

Comprehension

4 Explain the difference between processing data and interpreting data.

Analysis

5 Izzy and Holly want to test the shielding strength of copper by comparing the strength of Earth's magnetic field inside and outside a copper 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 the uncertainties.

Trial number	Earth's magnetic field outside the copper box (μT)	Earth's magnetic field inside the 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

1.8 Communicating and writing a scientific report

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

- identify and explain the sections of a scientific report
- write a scientific report.

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.

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.

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 1.8.1 provides some examples of the differences in the understanding of words in common language and in scientific language.

TABLE 1.8.1 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	To proceed or arise as a consequence, effect, or conclusion; to have an issue or result	The recorded evidence of the sample during experimentation or observation	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 statistics 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.

- 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 concise report 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 1.8.2 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 1.8.2 Communicating concepts in various ways

Concept	Communication	Commentary of communication
Outline the basic structure of a proton.	A proton is made up of three even-smaller particles.	This is fluent and concise, however it lacks scientific terms or language to convey in-depth understanding.
	Protons are small particles that are made up of even tinier particles. These tinier particles are called quarks, and neutrons, also in the nucleus of an atom, are also made up of them.	This is fluent but not concise. There is repetition (e.g. 'tiny' and 'small' have the same meaning, and 'made up' is stated twice). It also uses many words without using scientific terms to provide detail and understanding. It may also be confusing as it lacks structure. This may be useful language in the journal when learning about a topic, but not in the scientific report.
	Protons are known as hadrons, which is a class of subatomic particles that are comprised of three quarks. In every proton, two up quarks are joined to a down quark via the strong nuclear force mediated by another particle called the gluon.	This is fluent and concise. Much in-depth understanding is communicated through scientific terms that 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 scientific reports. A report 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. There is no single convention for scientific report writing. Table 1.8.3 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 your teacher about which headings are preferred, and how to align your scientific report and its headings to the syllabus.

TABLE 1.8.3 Scientific report sections and appropriate titles and information

Scientific report section title	Common title alternatives	Expected information within the section
title	n/a	• a specific statement that outlines the expected relationship between independent and dependent variables, or a question asking about the relationship between the independent and dependent variables
abstract	n/a	• a summary of the entire experiment or investigation in a single paragraph outlining the main information for each section: background information, method, results, analysis and conclusion • usually 1–3 sentences per section, often less rather than more
introduction	• background information • background research • literature review	• information already known or inferred from previous experimentation and scientific literature specific to the research question • explains the current scientific knowledge about the relationship between the independent and dependent variables and any other variables that may alter the relationship • must also refer to the original experiment and justify the modification that was made
method • sampling technique • preparation • experiment	• procedure	• an outline of the exact details for other scientists to repeat the experiment, including specific details about instruments, equipment models and precision, techniques used and all the information required for others to repeat the experiment and, hopefully, achieve 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 • must show all the required information to answer the research question
conclusion • analysis • interpretation • discussion • evaluation	• interpretation • discussion • evaluation • sources of error • suggestion for improvements/ modifications	• an explanation of the results that includes the 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	n/a	• 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 1.8.4)—science uses this language convention
- scientific language—the terms used are specific to concepts, models and theories
- objective, unbiased language—avoid subjective and emotional or persuasive writing (Table 1.8.5).
- concise language—avoid unnecessary repetition and express ideas succinctly. Scientific language allows more details, knowledge and understanding to be communicated in fewer words. Use shorter sentences that are less wordy (Table 1.8.6).

TABLE 1.8.4 Examples of first-person and third-person narrative

First person	Third person
I firstly tied a rubber stopper of known mass onto one end of a piece of fishing line, and a brass cradle of 200 g to the other end.	First, a rubber stopper of known mass was tied to one end of a piece of fishing line. A brass cradle of mass 200 g was tied to the other end.
After the current was switched on, I found that …	After the current was turned on, the results showed …
My colleagues and I found …	Researchers found …

TABLE 1.8.5 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 was stuffed 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 / research question or hypothesised / theorised …

TABLE 1.8.6 Examples of wordy and concise language

Verbose language	Concise example
Due to the fact that …	Because …
Anog and Walsh undertook an investigation into …	Anog and Walsh 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. For the report to be concise, there should not be any repetition. The report must remain within the required word count or length. Being fluent and concise 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, the following sentences provide the details of the idea and the final sentence concludes it. 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 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, and are often used in physics.

Editing your report

Editing your report is an important part of the process. After editing your report, save new drafts 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, placing it 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 with your teacher for in-text referencing and for the 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 citied (or in-text referenced) in the scientific report.

The sources must be listed at the end of the report in alphabetical order (by 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 the full details of the source in a reference list. In the APA style, in-text citations include the first author's last name and the 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

It is imperative that your final scientific report addresses all the characteristics in the performance-level descriptors of the student experiment ISMG (IA2). Before you begin the scientific report it would be best to plan the sections and titles and then assign the ISMG (IA2) characteristics to each section. As outlined earlier, there is no single convention for the scientific report, and the student experiment ISMG (IA2) 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 maybe 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 IA2 is not exceeded.

1.8 Review

SUMMARY

- A scientific report has the following features.
  - Title: a specific statement that outlines the expected relationship between independent and 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 variables, 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 used and all the information required for others to repeat the same experiment
  - Results: the relevant data, observations and results relating to the experiment
  - Conclusion: an explanation of the results, including quality of experimentation, 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

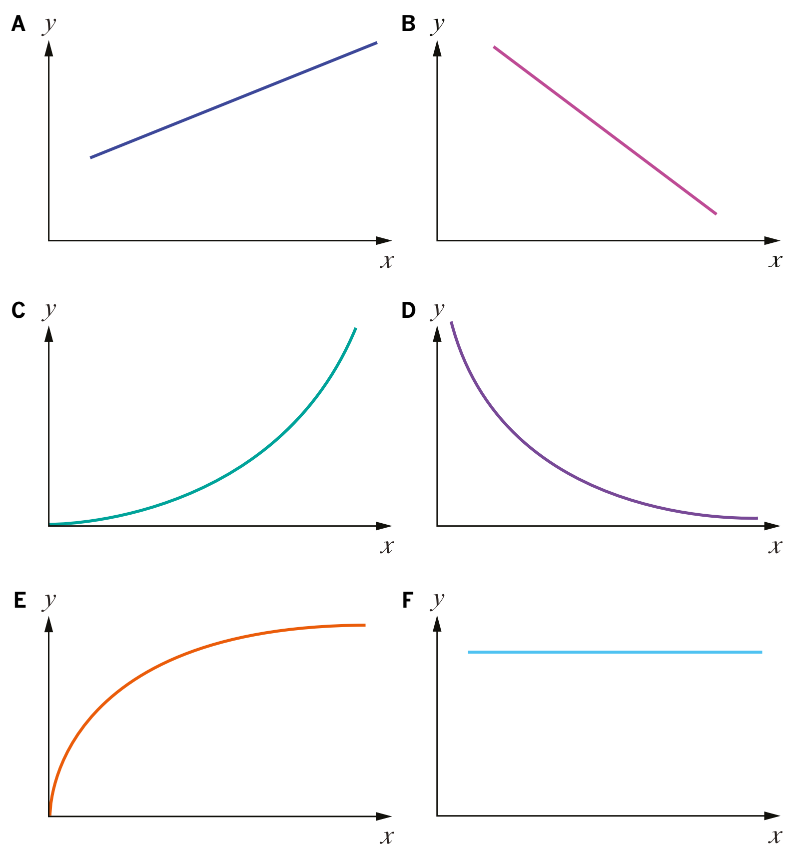
4 Consider the graphs on the right and answer the following questions.

a Identify the graph(s) that shows that the dependent variable increases at a constant rate.

b Identify the graph(s) that shows that the dependent variable increases at an increasing rate.

c Identify the graph(s) that shows that the dependent variable increases at a decreasing rate.

d Identify the graph(s) that describes the following observation.
You are measuring the time of flight of a projectile launched at a constant angle above the horizontal with various initial velocities. Data is collected and you observe the time of flight to increase at a steady rate as the initial velocity increases.



e Describe the relationship between the dependent variable and the independent variable in graph F.

5 Outline what might cause a sample size to be limited in an investigation.

6 Max is about to perform an experiment on light and matter and considered this investigation hypothesis:
An increase in the intensity of blue light shone onto a piece of aluminium metal connected in a photoelectric circuit will increase the current produced.
Improve Max's response to the hypothesis by making it more concise:
When the intensity was 7.8 $nW\,m^{-2}$, the current was 3.9 nA, and when the intensity was 3.9 $nW\,m^{-2}$, the current was 1.9 nA.

PART C RESEARCH INVESTIGATION (IA3)

The QCAA requires students to complete a research investigation in Unit 4 Physics.

The research investigation assessment (IA3) requires students to investigate a claim by drawing on secondary evidence from scientific texts. Students use research conventions to analyse and interpret the evidence and reach a justifiable conclusion about the claim. The research requires students to locate and use information beyond the scope of their knowledge and the data they have been given.

The research investigation requires you 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 Physics.

The 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.

A summary of the ISMG for the research investigation (IA3) is provided below. The table includes the objectives and marking for this summative internal assessment.

Criteria	Assessment objectives	Specifications	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 with 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.

A summary of the objectives and marking for the 'Research and planning' criterion, of the summative internal assessment: research investigation, IA3, is provided below.

Criterion: Research and planning

Objectives
These are the objectives being assessed. Your work must demonstrate these objectives. Definitions of the objectives can be found in the syllabus glossary. How the objectives will be assessed is described below.

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 that shows clear and well-thought-out development linking the original claim to the final research question • developing a clearly defined research question that is connected to the original claim • using relevant sources that enable a scientifically justified response to the research question to be constructed	5–6
• applying an understanding of the subject matter in an adequate way that demonstrates links from the claim to the research question • developing a research question that is connected to the claim • using resources that are related to the research question	3–4
• applying a basic understanding that does not provide logical reasons to connect the research question to the original claim • developing a research question that is not related to the original claim • using insufficient resources or sources that do not enable a conclusion about the research question to be made	1–2
• descriptors not addressed	0

Descriptor
Each dot point in each performance level descriptor is called a descriptor. The descriptors contain all the characteristics required to achieve that level of performance. They outline the evidence that teachers will search for in your work.

Performance level descriptor
The performance level descriptor is the whole of the left-hand cell in each performance level. It is made up of all the descriptors in that level.

Performance level
Together, the performance level descriptor and the mark are known as the performance level. Once the descriptors for a particular performance level descriptor have been assessed, a performance mark is awarded. You can only be awarded one of the marks in the corresponding 'Performance mark' column. If all the descriptors of the performance level descriptor are demonstrated in your response, then the upper mark is awarded. Otherwise the lower mark is awarded.

Performance mark
The performance mark is the mark awarded to the response for the particular criterion. It is related to the quality of the response as measured against the performance level descriptor.

In the modules that follow, you will find a guide to a research investigation report.

1.9 Developing a research question from a claim

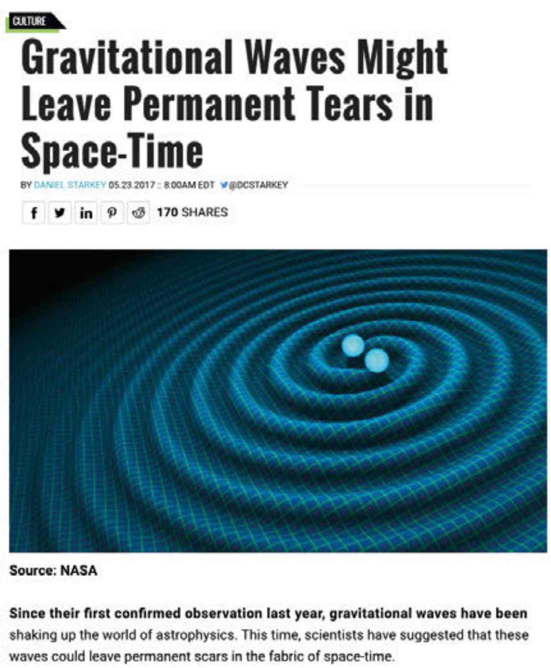
BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- analyse a claim to identify the scientific concepts, variables and measureable terms in it
- develop a research question 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, making it necessary to gather evidence so that you can evaluate the claim. An example of a claim is shown in the title of an article in Figure 1.9.1.


CULTURE

Gravitational Waves Might Leave Permanent Tears in Space-Time

BY DANIEL STARKEY 05.23.2017 :: 8:00AM EDT @DCSTARKEY

170 SHARES

Source: NASA

Since their first confirmed observation last year, gravitational waves have been shaking up the world of astrophysics. This time, scientists have suggested that these waves could leave permanent scars in the fabric of space-time.

FIGURE 1.9.1 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 the 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 1.9.1 outlines an example of analysing and categorising elements of a claim.

TABLE 1.9.1 Two examples of analysing and classifying the elements of a claim

Example 1		
Claim	A bullet fired from a gun into the air will fall at a velocity high enough to cause injury should it hit a person.	**Classifying the elements of a claim** **Projectiles** • known concepts: velocity (speed and direction) • initial upwards velocity • final downwards velocity **Air resistance** • measureable known concept • related to shape of projectile, its velocity and the medium through which the projectile is moving **Injury to people** • data needed on what defines 'injury' • could be measured in controlled experiments • final downwards velocity typically not high enough to cause injury due to air resistance
Source and context of claim	A 1994 *Journal of Trauma* article claims that 118 people were treated for falling bullet wounds (38 of them died) when New year's eve celebrators fired bullets into the air between 1985 and 1992.	
Elements	• Projectiles • Air resistance • Injury to people	

Example 2		
Claim	It is 'well-known' that lightning does not strike the same place twice.	**Classifying the elements of a claim** **Electric charge** • exists as positive and negative charges • negative charge is attracted to positive charge • large forces are involved when unlike charges are separated **Electric field** • provides the forces involved in lightning discharge • movement of air and ice is thought to be responsible for charge separation setting up the electric field • fields are strongest around sharp metallic points, e.g. antennae **Dielectric breakdown** • electric field reaches a maximum value then positive and negative charge rapidly move together • this motion drains the clouds of one type of charge creating large currents • charge drains to the point on the ground where the electric field is strongest, typically near antennae and aerials
Source and context of claim	This is a very old superstition that is thought to have been first published by P.H. Myers about the story of a US park ranger who was struck by lightning seven times between 1942 and 1977.	
Elements	Electric charge • Electric field • Dielectric breakdown	

If you unpack the claim into elements such as related terms and concepts, variables and measureable quantities, you can formulate questions using the claim.

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

Extrapolate and expand the claim further into possible scientific elements. Each of these elements can then be used to formulate a question (Table 1.9.2). It is best to formulate a number of questions related to the claim and write them all down in your journal. Each question must enable a response that will evaluate the validity and 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 them. 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.

Here are some guidelines to help you formulate a question.

1 Find the dependent variable in the claim, or refine the claim by rephrasing it into something measurable.

2 Choose an element of the claim to become the independent variable, or identify the independent variable in the material.

3 Phrase a question to ask if the independent variable will influence, cause or correlate with the dependent variable.

4 Write 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 1.9.2 to see examples of questions formed from the elements of the claims from Table 1.9.1.

A hypothesis is an optional feature that you may wish to write to 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.

TABLE 1.9.2 Two examples of questions formulated from the claims in Table 1.9.1

Example 1	
Claim	A bullet fired from a gun into the air will fall at a velocity high enough to cause injury should it hit a person.
Elements of a claim	**Projectiles** • known concepts: velocity (speed and direction) • initial upwards velocity • final downwards velocity **Air resistance** • measureable known concept • related to shape of projectile, its velocity and the medium through which the projectile is moving **Injury to people** • data needed on what defines 'injury' • could be measured in controlled experiments • final downwards velocity typically not high enough to cause injury due to air resistance
Formulated questions	**a** How much air resistance is there on a falling bullet? **b** How does the initial velocity relate to the final velocity of a bullet? **c** Can the damage caused by a falling bullet be quantified?

Example 2	
Claim	It is 'well-known' that lightning does not strike the same place twice.
Elements of a claim	**Electric charge** • exists as positive and negative charge • negative charge is attracted to positive charge • large forces are involved when unlike charges are separated **Electric field** • provides the forces involved in lightning discharge • movement of air and ice is thought to be responsible for charge separation setting up the electric field • fields are strongest around sharp metallic points, e.g. antennae **Dielectric breakdown** • electric field reaches a maximum value then positive and negative charge rapidly move together • this motion drains the clouds of one type of charge, creating large currents • charge drains to the point on the ground where the electric field is strongest, typically near antennae and aerials
Formulated questions	**a** How much current is generated during a typical lightning strike? **b** What type of structures are typically struck many times by lightning?

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 of developing a research question is often somewhat cyclical (Figure 1.9.2).

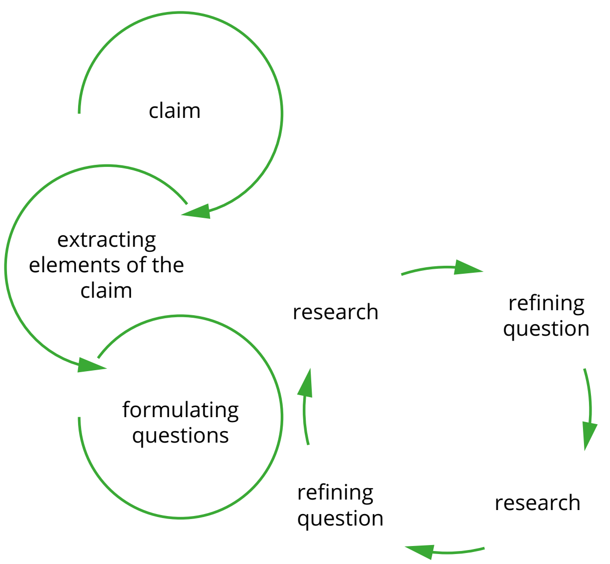


FIGURE 1.9.2 A chart of a common process for developing a research question. The cycle of researching and refining the research question can be repeated as many times as necessary until you are satisfied with the investigation question.

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 your journal and make note of any ideas that may arise related to the question. As your knowledge and understanding about the variables is developed, refine the question to be more specific.

The research question and the development of the research question from the claim using research, scientific concepts, knowledge and understanding, is related to the following 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.
- selection of adequate, applicable and pertinent resources.

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 1.9.3 compares formulated research questions that were refined.

TABLE 1.9.3 Development of the original formulated questions into research questions

Example 1			
Claim	A bullet fired from a gun into the air will fall at a velocity high enough to cause injury should it hit a person.		
Formulated questions	**a** How much air resistance is there on a falling bullet?	**b** How does the initial velocity relate to the final velocity of a bullet?	**c** Can the damage caused by a falling bullet be quantified?
Refined research question	**a** How much does air resistance slow down a vertically falling bullet that is released from rest when compared to its initial muzzle velocity?	**b** Is there a relationship between the initial velocity of a bullet fired vertically into the air and the final downwards velocity of the same bullet?	**c** Can plasticine models be used to directly measure the kinetic energy of a vertically falling bullet?

Example 2		
Claim	It is 'well-known' that lightning does not strike the same place twice.	
Formulated questions	**a** How much current is generated during one typical lightning strike?	**b** What type of structures are typically struck many times by lightning?
Refined research question	**a** How much current is generated during one dielectric breakdown as set up in a high school laboratory?	**b** Do high-curvature objects attract lightning more than low-curvature objects?

You will use your the research recorded in the journal to write the considered rationale for the research question, and display 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 (Figure 1.9.2).

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 the 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.

1.9 Review

SUMMARY

- A claim is an assertion made without any accompanying evidence to support it.
- Research questions can be developed from a claim by identifying the underlying scientific concepts and variables in the 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 Derive a research question for the following claims.

a Bismuth metal increases the strength of an external magnetic field.

b Quarks are the smallest pieces of matter than exist in the universe.

c Red light is better for seeing in low light conditions.

1.10 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 who apply scientific research to their industry
- articles in science magazines, newspapers and on websites.

The research investigation must include a reference list of cited sources. The sources 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; applicable and pertinent; having a direct bearing on'. Figure 1.10.1 points out the features of sources deemed 'sufficient' and 'relevant'.

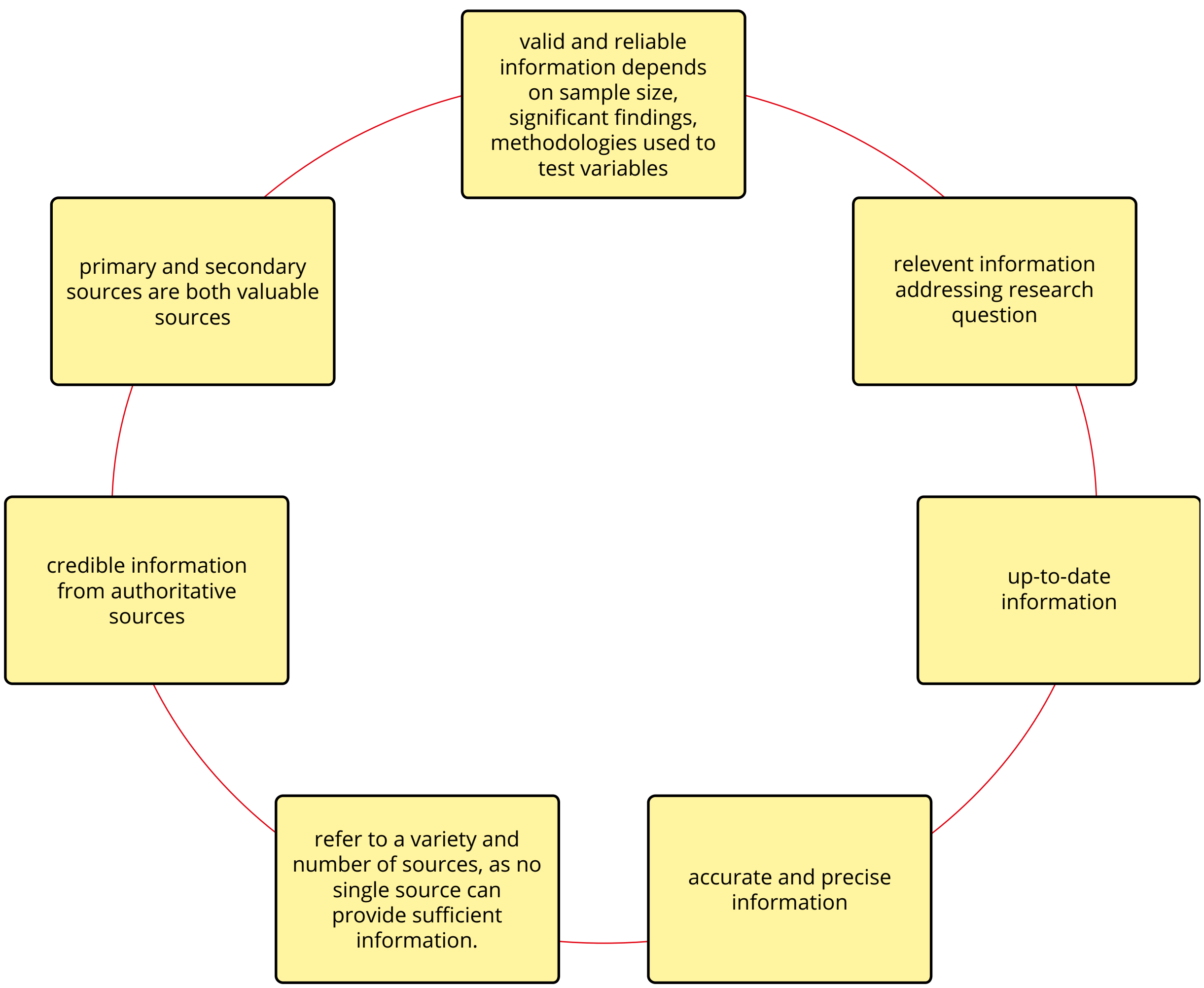


FIGURE 1.10.1 Features of sources suitable for the research investigation

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 to an event, or the scientist who conducted the research. Only the original observer has 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. Because it is second-hand information, its 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 the source is primary or secondary.
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 other sources?
   - Does the author have credible qualifications and expertise?
   - Is the methodology valid and were the variables controlled or measured?

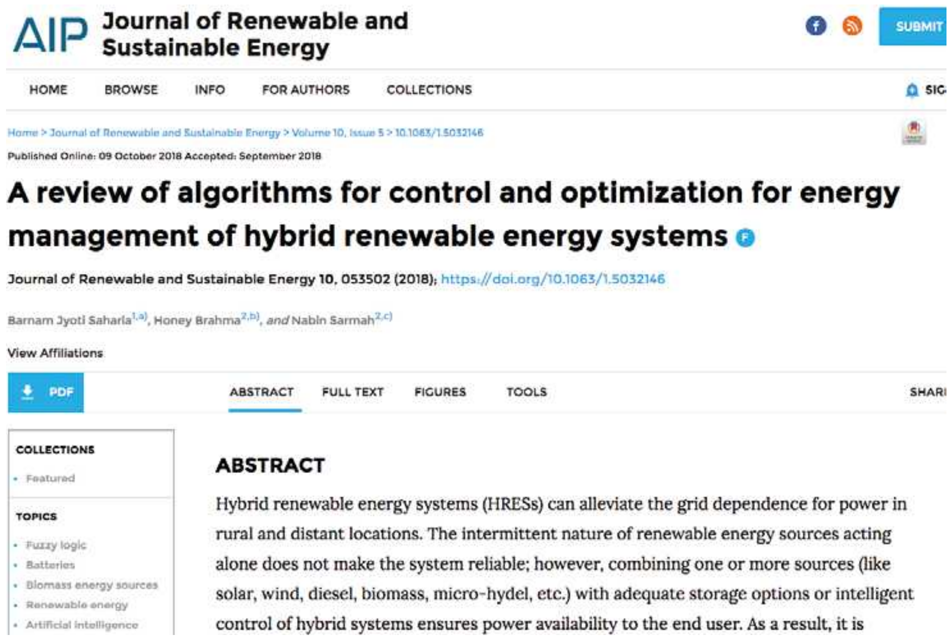
Table 1.10.1 summarises the characteristics of primary and secondary sources. Sometimes the same type of source may be classified as both a primary and a secondary source, depending on when and by whom it was written. For example, a scientist's journal article on a how a gamma ray laser can be used to 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 1.10.1 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 1.10.2).


AIP Journal of Renewable and Sustainable Energy

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Published Online: 09 October 2018 Accepted: September 2018

A review of algorithms for control and optimization for energy management of hybrid renewable energy systems

Journal of Renewable and Sustainable Energy 10, 053502 (2018); https://doi.org/10.1063/1.5032146

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- Artificial intelligence

ABSTRACT

Hybrid renewable energy systems (HRESs) can alleviate the grid dependence for power in rural and distant locations. The intermittent nature of renewable energy sources acting alone does not make the system reliable; however, combining one or more sources (like solar, wind, diesel, biomass, micro-hydel, etc.) with adequate storage options or intelligent control of hybrid systems ensures power availability to the end user. As a result, it is

FIGURE 1.10.2 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, an introduction, sections for method, results and analysis, a conclusion and ending with 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 1.10.3 provides ideas for accessing scientific journals. NASA ADS is another service that allows access to physics and astronomy abstracts.

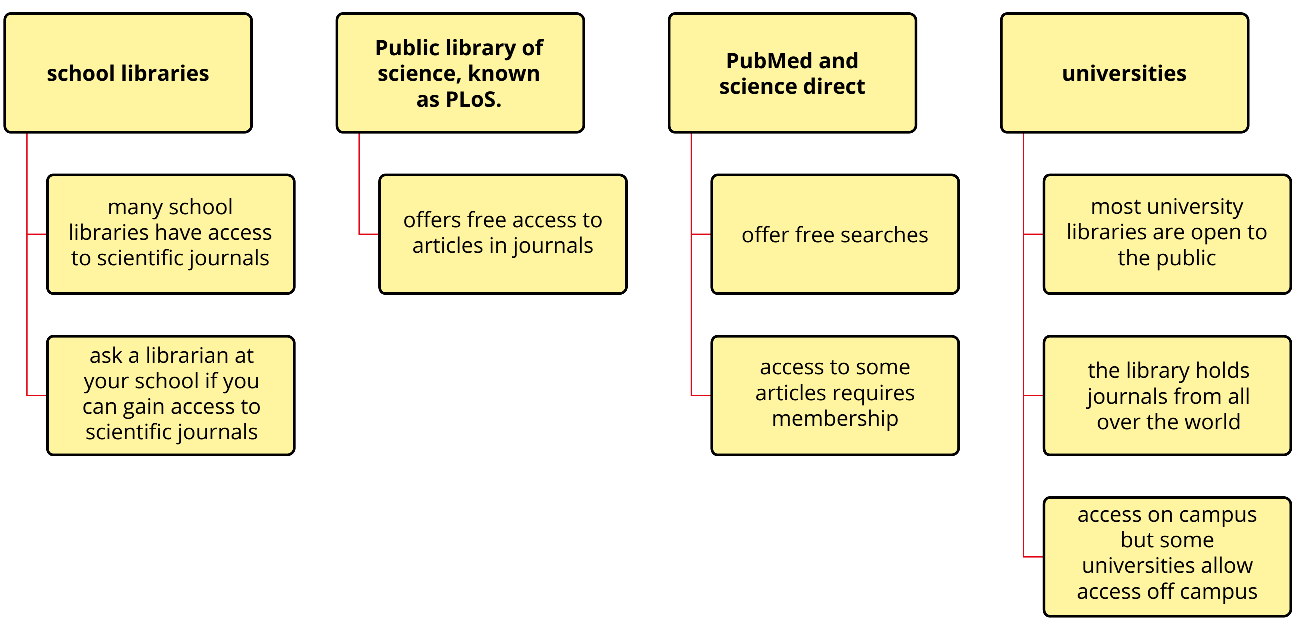


FIGURE 1.10.3 Suggestions and information on accessing scientific journal articles

Scientific articles are excellent sources of information, but they also have their drawbacks as sources for the research investigation. Table 1.10.2 outlines some advantages and disadvantages of using articles in scientific journals for the research investigation.

TABLE 1.10.2 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 the 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 • requires 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 this book. 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 1.10.4).

FIGURE 1.10.4 A science magazine you might find in your school library.

Table 1.10.3 outlines some advantages and disadvantages of non-fiction books as sources for your research.

TABLE 1.10.3 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 are provided by scientific organisations such as CSIRO, AIP (Australian Institute of Physics), IOP (Institute of Physics), NASA and some universities. Many government and privately funded science organisations as well as non-for-profit scientific organisations publish material online. 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 that the information may not be valid or reliable. Use the earlier guidelines to help you evaluate sources. Table 1.10.4 outlines advantages and disadvantages of using the internet to find information.

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, related terms and other 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 1.10.4 Advantages and disadvantages of online resources

Advantages	Disadvantages
• quick and easy to access • allows access to hard-to-find information • access to the whole world; millions of websites • information is potentially more up-to-date • may be interactive and use animations to enhance understanding	• 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 • may not be reliable, valid or credible

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, especially for novice learners. 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.

The following tables explain step-by-step how to evaluate a claim about high altitude skydivers.

SOURCE EVALUATED: How a skydiver jumped without a parachute—on purpose—and lived.
Scientific research article https://www.scientificamerican.com/article/how-a-skydiver-jumped-without-a-parachute-on-purpose-and-lived/

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	second-hand	It is an article written for scientifically literate community in the journal *Scientific American*.
Validity	Does it contain information that is specifically related to the claim?	yes	Outlines information directly related to air resistance and a falling skydiver in relation to velocity, acceleration and displacement of a projectile.
	Is the evidence and information pertinent to the variables in the research question?	yes	Some data on velocity, displacement and time of the skydiver's fall in SI and imperial units.
Reliability	Is it current/recent information?	yes	Published 2 August 2016.
	Is it up-to-date in its understanding of relationships?	partially yes	Some information on the theory of projectiles and air resistance is included but it is not at a high mathematical level.
	Is the evidence equivalent to other sources?	n/a	No other sources are quoted in this article.
	Check credibility and consider the author's qualifications and expertise.	no	No information about this author is given.
	Try to find the sample size.	n/a	This article is not about an experiment with data.
	Try to establish what variables were controlled or measured.	known	Variables were height of fall, time of flight, horizontal distance covered, wind speed and direction.

A judgement could be made about this source such as:
The information and evidence was published by an author 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, but requires more actual data to be useful. This article would be a good starting point for research.

continued over page

Skillbuilder *continued*

SOURCE EVALUATED: How do you measure the Stratos space Jump?
https://www.wired.com/2012/07/how-do-you-measure-the-stratos-space-jump/

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	second-hand	The journalist uses official data from Red Bull Stratos to put together information on the physics (for the lay person) of Felix Baumgartner's jump from the edge of space in 2012.
Validity	Does it contain information that is specifically related to the claim?	yes	This article has a lot of good data and references.
	Is the evidence and information pertinent to the variables in the research question?	yes	It provides data on speed, time and altitude
Reliability	Is it current/recent information?	yes	Article published in May 2012
	Is it up-to-date in its understanding of relationships?	yes	Discussion of air resistance and terminal velocity
	Is the evidence equivalent to other sources?	yes	Probably better than the first article as it has more data, but it is still a secondary source.
	Check credibility and consider the author's qualifications and expertise.	yes	Author is a physics lecturer at a US university.
	Try to find the sample size.	n/a	As this was a one-off event, the sample size is one.
	Try to establish what variables were controlled or measured.	no, mostly	Most variables in the fall were not controlled.

The judgement of this second source could be as follows:
The second article is better than the first article as there is more data available to analyse, but it is still a secondary source and a website rather than a formal scientific article in a journal. The problem with this claim is that the data is privately owned by Red Bull Stratos and is difficult to find without going through a commercial website. Further research is required to find the actual data but there should be *Physics Teacher* and *Physics Education* journal articles available with more robust physics concepts.

1.10 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 or witness to an event, or by the scientist who conducted the research.
- A secondary source is a document that refers to or analyses a primary source.

KEY QUESTIONS

Retrieval

1 State whether each of the following is a primary or a secondary source.

a a newspaper article about global warming

b a report on an experiment performed to investigate how the intensity of light affects the diffraction pattern when light is passed through a narrow slit

c an interview with an astrophysicist who calculated the orbit of the interstellar visitor ‘Oumuamua to our solar system

d a website with information about interplanetary travel by humans

Comprehension

2 Explain the difference between a primary and secondary resource.

Analysis

3 Freya is learning about the orbits of planets in other solar systems, and is 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 for her 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 6th June 2017.

d ‘Nightfall’, a short science-fiction story by Isaac Asimov, first published in 1941

1.11 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 will be 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 world-wide to catalogue and file information. When trying to find previous work completed, most people search their memory as to 'when' they completed the work. They think 'I'm sure I did the research on "Y" after I found the information on "X" last week'. So the date of your research will become a simple yet effective filing system.

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 information 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 are 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. The value and benefit they offer later could include:

- saving you time by:
  - not researching 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
- providing links between concepts in the future that are currently unknown
- providing answers (or partial answers) to future issues, conceptual blocks and questions
- developing 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 1.11.1 is an example of a journal entry.

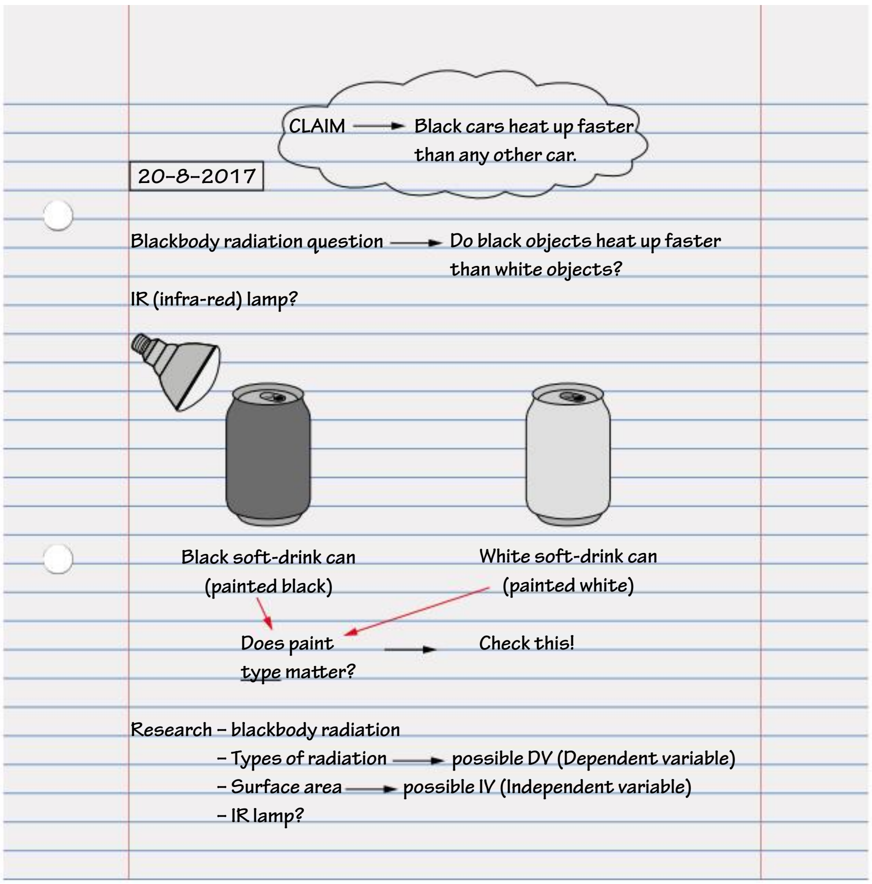


FIGURE 1.11.1 This journal entry records the date, title and information. There will be numerous journal entries on any given date, and most will have their own titles. The same titles will appear on different entry dates as research continues on that topic.

Many professionals use a couple of cataloguing systems 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.

Research background information

Information taken from a source should be re-written or summarised in your own words in the journal. Avoid copying information verbatim so that you are not tempted to plagiarise when you write up the research investigation.

It can be difficult sometimes to re-word 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 journal should be detailed with extended explanations that you will fully comprehend when you refer back to them at a future date.

Worked example 1.11.1

REWORDING INFORMATION FROM SOURCES

A resource for information states that: 'Electrons, when entering a region of a magnetic field, with a perpendicular velocity, are deflected at +90°, while protons are deflected at an angle of –90°. This is due to their opposite charges.' Rewrite this information in your own words.	
Thinking	**Working**
Swap the order of information, so that the reason (opposite charges) comes before the object (the deflection angles).	Due to the opposite sign of their charges, electrons and protons are deflected in opposite directions when entering a magnetic field at right angles.
Change numerous words such adjectives, verbs, adverbs and nouns.	Electrons will be deflected in the opposite direction to protons because their charge is opposite to the charge on a proton.
Gather more data so you can elaborate on the information and provide explanations.	Electrons and protons are charged objects, so they will experience the Lorentz force acting upon them. This force states that any charged object will experience a force at right angles to the direction of its motion into the magnetic field and at right angles to the direction of the magnetic field.

➤ Try yourself 1.11.1

REWORDING INFORMATION FROM SOURCES

A resource for information states that:

'Neutrons have no charge, and so will not be deflected at all when they enter a magnetic field.'

Rewrite this information in your own words.

Personal explanations and interpretation

The journal is a valuable tool that is personal to you. Hence it should be written and displayed in formats that you understand and with information that will help you 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. Details are not limited to just facts; they 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 capture more comprehensive details. Figure 1.11.2 presents the same information in a few different ways.

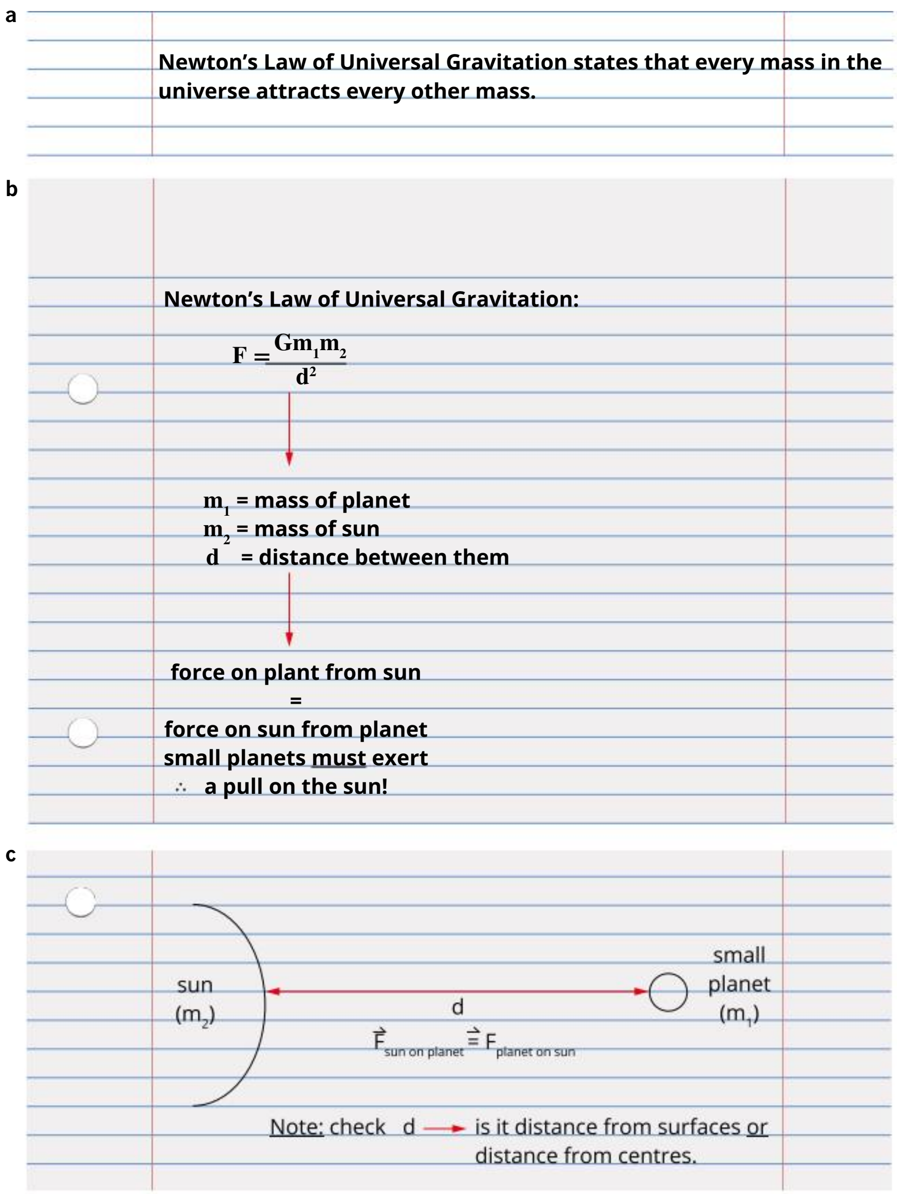


FIGURE 1.11.2 (a) Sample page from a journal explaining Newton's law of universal gravitation in the claim that small planets exert a pull on the Sun. (b) Sample page from a journal explaining Newton's law of universal gravitation in a flow chart to elaborate on the above claim. (c) Sample page from a journal explaining Newton's law of universal gravitation in a diagram.

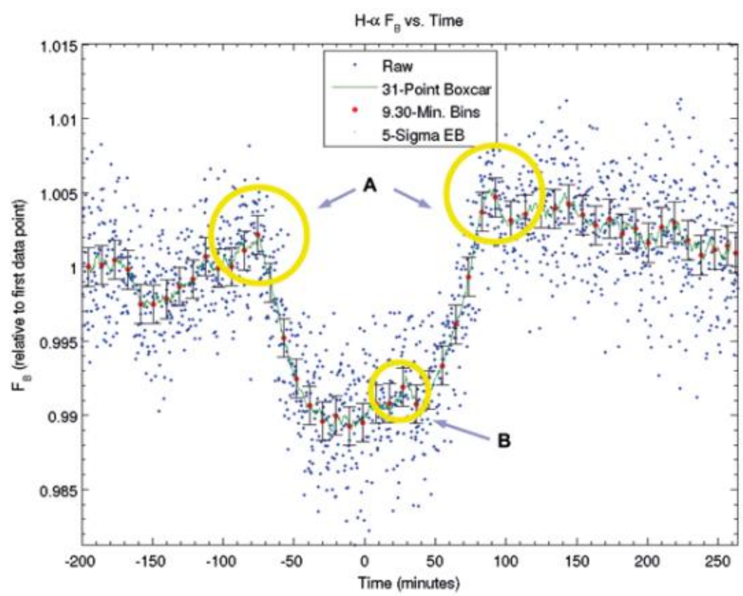
RESULTS, DATA AND EVIDENCE

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:

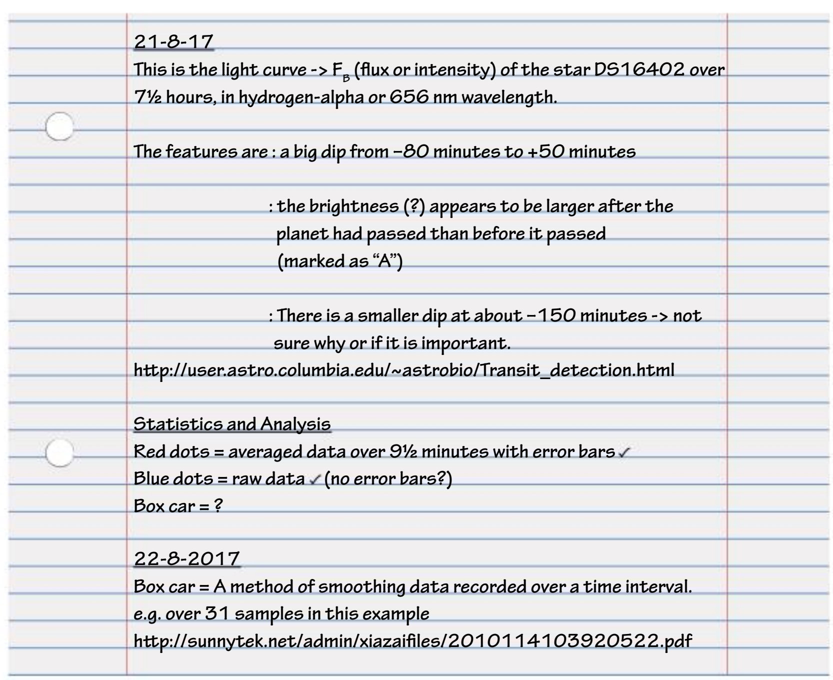
- specific details and your own interpretation of significant values
- the trend or pattern
- the comparison or difference between one set of values and another
- the statistics used to establish significance and also the author's interpretation
- notes written in your own words.

Figure 1.11.3 shows examples of research evidence and how they can be reinterpreted for a journal entry. Figure 1.11.3a is the original evidence the student found through research and Figure 1.11.3b 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/201011410392O522.pdf

FIGURE 1.11.3 (a) An example of representing evidence using graphs and statistics. This data is of the light curve of a 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 that evidence.

When making journal entries it is important for your understanding and analysis of statistical method (e.g. understanding an 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 recheck 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)

1.11 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 State how you record information from a source in your journal.

Comprehension

2 Explain the benefit of keeping a scientific journal.

Analysis

3 Paraphrase the following:
  a David and Matthew were using sheets of aluminium foil of different thicknesses to determine the relationship between thickness and current produced when light is shone on the foil. They found that there was a slight increase in the current produced with thicker sheets.
  b Wendy and Julian found that the percentage of impurities found in various grades of glass can be determined by analysing the angle of refraction of laser light. The more inconsistent the angle of refraction, the more impure was the glass.
  c A study by geophysicists found that the value of Earth's acceleration due to gravity was greatly affected by the density of rock and the depth of the crust at the location investigated. The denser rock yielded higher values of the acceleration due to gravity, but the type of rock was not investigated.

1.12 Writing a research investigation report

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 in length. 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 is provided in Module 1.8. 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 1.12.1. This module will focus on the literature review.

TABLE 1.12.1 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 about 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 the 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 in a logical development of ideas • Uses subheadings
Empirical essay	It is very similar to a literature review.	
Annotated bibliography	Notes, comments and explanations about a number of sources, e.g. books and articles. An evaluation of a claim after investigating how other sources treat the claim.	• Citation • Introduction to the citation • Aims, research methods, scope • Discussion of usefulness to your research topic • Limitations • Conclusions • Reflection—explain how the citation contributes to your topic or fits in with your research
Poster	An oral presentation accompanies the poster. The 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 through the presentation of information in a logical sequence in which the author 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 of the topic
- provide an overview of key concepts (relevant to the research question)
- identify important relationships between variables (specifically those 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 critically analyses 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 critically analyses 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 explain the statistical processing used (in particular, analysing the methodologies, samples, results, data processing and analysis)
- contain only relevant sources and content
- organise the structure of the review to logically inform and convince the reader—plan the introduction, body and conclusion.

There is no hard-and-fast rule about the number of articles that you should consult for the research investigation. The term 'sufficient' is defined by the 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 a justified conclusion to be drawn about the research question and explores both sides of the argument, then the number of sources is sufficient. Relevant research 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 thoroughly identify the limitations of the research because this may affect the extent to which information (primary or secondary) is relevant 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 supported by sound reasons or evidence. Therefore, you must apply your scientific understanding and conceptual knowledge to the evidence that you have examined. The following factors should be discussed.

- 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 the information may also include an evaluation of the methodology used by the authors to obtain their data or information.

Conclusion and evaluation

In conclusion, the discussion needs to include an understanding of the features of the evidence that limit its ability to be used. For example, was the sampled population reflective of 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 comparison was impossible?

The above questions require a justified discussion evaluating the reliability and validity of 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 the validity, accuracy, precision and reliability of the 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. The suggestions presented 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 than others. The journal will also help you make decisions on which figures, data and evidence to include, and also 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 not exceeded.

Planning the research investigation report will help address the ISMG characteristics. Figure 1.12.1 illustrates how planning can to be done to ensure the ISMG is addressed.

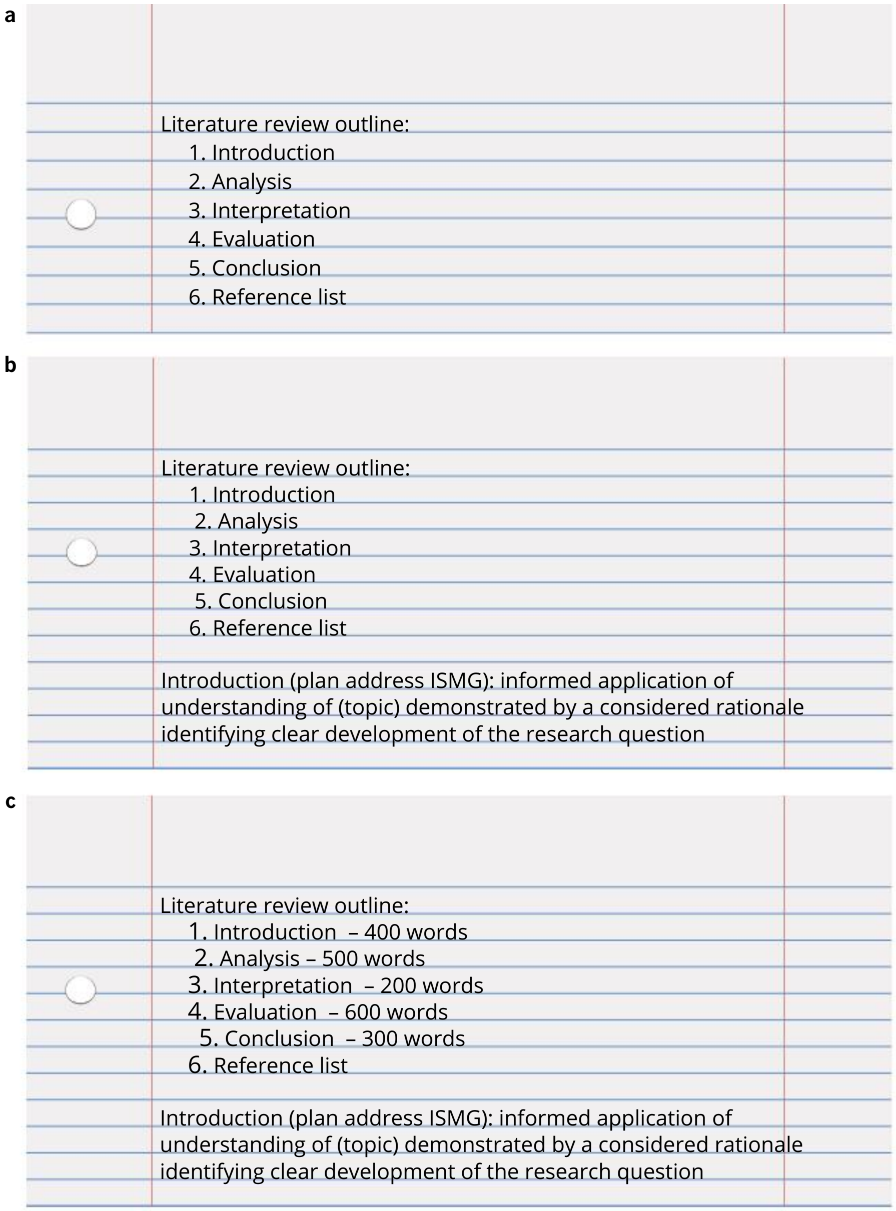


FIGURE 1.12.1 Planning the literature review: (a) an outline of the planned research investigation report to ensure the ISMG is addressed, (b) assigning the ISMG descriptors to the sections in the planned outline, (c) showing the word count planned

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 each draft of the report after you have completed it; this is an important part of the process. Save new drafts with a different file name and always back up your files to 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).

1.12 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.

PART D EXAMINATION (EA)

The examination is set externally by the Queensland Curriculum and Assessment Authority (QCAA) and covers both Unit 3 and Unit 4 of the syllabus. The examination accounts for 50% of the total mark. The examination consists of two papers.

The QCAA defines 'examination' as 'a supervised test that assesses the application of a range of cognitions to one or more provided items such as questions, scenarios and/or problems'. Students complete their responses individually, under supervision and in a set time.

The assessment objectives are to:

1 describe and explain
2 apply understanding
3 analyse evidence and identify trends, patterns, relationships, limitations and uncertainties in data
4 interpret evidence, analyse and draw evidence-based conclusions.

The table below outlines key information about each paper. Look at the table carefully and make yourself familiar with the unique features of each paper.

Examination	Papers 1 and 2	
Types of items	• multiple choice • single-word • sentences • paragraphs	• calculating using algorithms • interpreting using graphs, tables or diagrams • responding to unseen data and/or stimulus
Syllabus coverage	• Units 3 and 4	
Assessment objectives	1 describe and explain 2 apply understanding	3 analyse evidence 4 interpret evidence and draw conclusions
Conditions	• perusal (reading) time: 10 minutes • writing time: 90 minutes	
Equipment	• approved graphics calculator permitted • seen physics formula and data booklet provided	
Marks	• constitutes 50% if total assessment	

Careful and thorough preparation for the examination may help reduce some of the anxiety and stress you may experience in the lead-up and during this assessment. Many students feel that their performance in the examination, as well as all assessments, is what will define them and determine their future career paths.

Remember, no matter how you feel about your performance, there is nothing you can do to change it. If you have not achieved the score that will gain you entrance into the course for your preferred career path, consider your options. Investigate different pathways to move towards your goal. Consider different courses. Seek advice from teachers, and especially your careers teacher. Sometimes the path to achieve a career goal is less direct.

It is very common and easy for students to become totally 'consumed' by the demands and pressures of their final year of school. But remember, there is life beyond Year 12.

Engage in positive 'self-talk'.

This guide provides you with practical suggestions and support to prepare for the examination. The guide takes a year-long approach to your preparation that includes:

1 **consolidating learning**—effective learning routines and strategies for use throughout the year
2 **revising and practising**—study practices and strategies in the weeks leading up to the examination
3 **sitting the exam**—strategies and hints for tackling the examination
4 **after the exam**—some considerations.

1.13 Examination preparation

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

- prepare yourself to successfully complete the examination (EA) summative external assessment.

Understanding the requirements of the course and knowing where to find supporting resources is a very important beginning. As you work through the syllabus material, it is also important that you take very good notes from classwork and homework. These notes will be the foundation of your revision and summary notes, so they should:

- be thorough, covering all aspects of the syllabus
- focus on key concepts
- be balanced and weighted so that major topics are given greater emphasis than minor topics
- include examples and applications
- include definitions of key terms
- include questions (and answers that have been checked)
- indicate if you are confident with the content or need some more help with it—'traffic light' your work with a green or red highlighter
- be legible so you can easily read them.

CONSOLIDATING LEARNING

Begin study early. It is easy to procrastinate and then find yourself rushing to revise and study at the last minute. Just-in-time is not a recipe for success. Learning is more effective if spread over a long period instead of a last-minute cram.

Time-management is important.

- Use your study time effectively.
- Use your leisure time effectively.

Learning requires discipline over the duration of the course. Repetitive and frequent revision of the course material helps to reinforce and deepen understanding and helps embed learning in long-term memory. Studying and revising can be overwhelming. Revise manageable chunks by dividing your work into smaller sections or topics.

During the year, get into the habit of revising completed sections of the course. The revision may be done, for example, at the end of a week, a topic, a chapter or at intervals that best suit you. Revise work from earlier in the year on a regular basis. Ask your teacher for copies of any past exams you have done, and use the answer/marking scheme to help you revise. It is easy to forget information if you don't keep revising it.

There are a number of revision strategies you might use. These are outlined below. Identify your own study strengths—what works best for you—then make effective use of these strengths.

Use these effective learning routines and strategies throughout the year.

1 Your teacher is your physics expert. He or she is an excellent resource and should be the first person to consult for support and help. Seek help during classes if you are struggling to understand concepts. If you encounter problems out of class time, it is a good idea to write down areas that you are struggling with, and consult your teacher at a later time. Remember to pinpoint specific concepts or questions. Ask your teacher to re-explain concepts and ask for more material and/or questions for practice.

2 Flash cards: make your own flash cards as this consolidates your learning. Each card is dedicated to a particular idea that could include a:

- definition—key term on one side with the definition on the back
- diagram—diagram on one side with a brief explanation on the back
- equation/formula—formula on one side with worked example on the back
- graph—graph on one side with summary of results on the back
- question—question on one side and the answer on the back.

Use the cards to test yourself. You can get a friend or family member to test you. Periodically reading the cards reinforces learning and entrenches concepts in long-term memory. Flash cards are an excellent tool for subject matter that must be remembered (Figure 1.13.1).

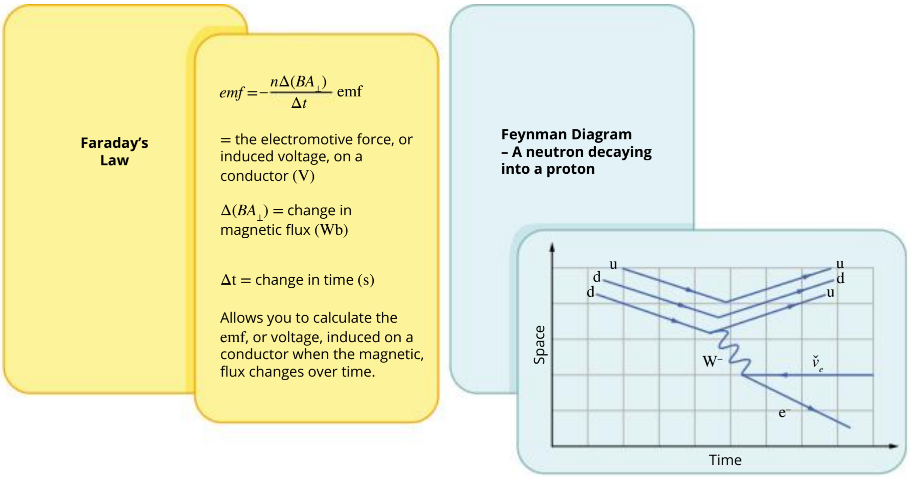


FIGURE 1.13.1 Flash cards are an excellent tool for remembering and testing yourself on factual material.

3 Trigger words: the key words associated with a topic/theme. Trigger words are useful in helping to generate other related words and ideas. This approach is helpful in preparing quick drafts to questions and concept maps to summarise whole topics.

4 Diagrams are useful memory triggers: draw first, explain second.

5 Test yourself: complete as many questions as possible, to test your learning. Hand write (not type) your answers. Writing is more valuable practice than just thinking about your answer. Writing is a good way to memorise material. Remember you will need to be able to write for 90 minutes in the allocated writing time in the exam (not type), and your writing must remain legible.

6 Summarise notes: consider your preferred learning style and take advantage of it to make revision notes. Summaries serve to help you identify the essential concepts and reinforce the learning. Keep in mind that any study notes you make are most effective when they are:

- clear
- to the point
- uncluttered.

These are some of the techniques you might apply to make summaries.

- Highlight or underline important points as you read your notes or text.
- Create headings or appropriate structures under which to organise dot points.
- Diagrams are useful to summarise concepts.
- Tables are good for comparisons (e.g. causes/effects, for/against).
- Create summary sheets.
- Use boxes, circles and colour to highlight points on your summary sheets.

- Create ways to remember key points (e.g. mnemonic devices like ROYGBV for the order of the colours in a rainbow from longest to smallest visible wavelength: red, orange, yellow, green, blue, violet).
- Compile a glossary of new terms. Use your own words, not those taken straight from the textbook. Your own words cement your understanding and help you remember new terms.
- Use other summary techniques such as scatter diagrams, mind maps or concept maps. These are all ways of organising key information (Figure 1.13.2).

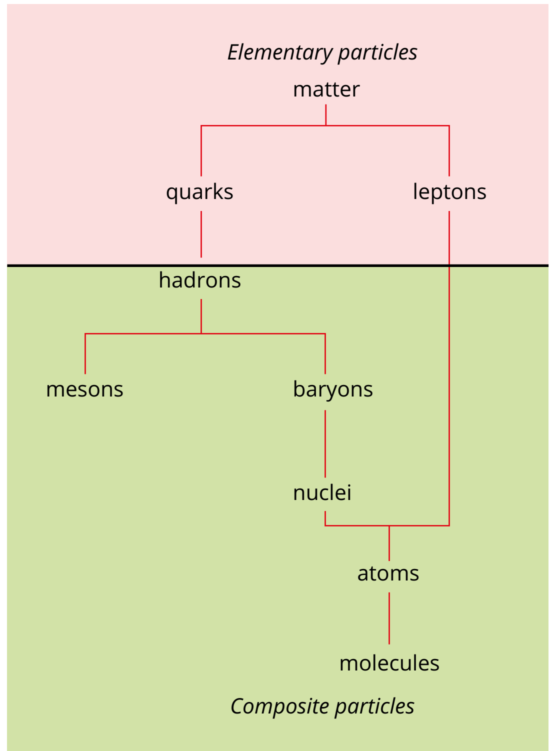


FIGURE 1.13.2 Visual representations in the form of concept maps are effective revision and study tools. Use a single page to map out the key words and ideas in the topic/chapter; use link lines to connect words and ideas; write along the link lines to explain the connections. Learning is consolidated as key concepts are represented in concise ways.

7 Check there are no gaps in your summary notes.
Use Chapter and Module openers and Module review summaries as a checklist for the key ideas in a chapter.
   - Tick those with which you feel confident.
   - Highlight those you need to revisit.
   - Re-read relevant sections of text.
   - Rewrite notes, definitions, equations etc. that you need to consolidate.

8 Form a small study group with friends. The group can meet face-to-face or on-line. Discuss and explain key points to each other. If you are struggling with a difficult concept, try to teach it to a friend. Ask a friend to teach it to you. You cannot explain something to another person until you have it clear in your own mind. Teaching and explaining something to someone else makes it clearer to you.

9 Practice questions—do lots of practice questions. Write down your answers so that you get practice expressing yourself. Verbalising or thinking the answer is not the same, and your responses may not always come out the way in writing the you want them unless you have plenty of practice.

10 Familiarise yourself with the Data Booklet. In the exam, you have access to the Data Booklet. Make sure that you use the Data Booklet throughout the year, as needed, to become familiar with when and how to use it. Print yourself a copy and keep on hand. You will use it more in some topics than in others.

REVISING AND PRACTISING

In the month and weeks leading up to the exam, most if not all the course will have been taught. Your focus should now shift to studying in preparation for the exam. You will be at an advantage if you have taken comprehensive notes throughout the year, made revision summaries, completed practice questions and generally made every effort to advance your understanding and skills.

Study practices and strategies in the weeks leading up to the examination can include the following.

Prepare a study timetable

On a study timetable, allocate time to study all the subject matter. The timetable may include daily study time across all your subjects and may specify sections of each subject to be covered daily. Although you may not stick strictly to the timetable, it is a guide to fitting everything in and allocating equal time to different subjects.

Prepare summary notes

You may have been making summary notes of sections of subject matter throughout the year. It is now time to consolidate all your learning across Units 3 and 4. Remember that different topics link with each other and it is only when a whole topic or unit is completed that these links become apparent. The summary notes you prepared previously can now be collated to serve as the foundation of a summary of the physics course.

Creating a revision summary

Creating a revision summary of Units 3 and 4 may be approached as follows:

- List all the topics and subtopics in the syllabus, including the subject matter statements—the chapter opening pages of your Student Book will guide you. You might choose to prepare a separate table for each topic, and use it to write your revision notes. The sample shown in Table 1.13.1 allows for key points, definitions and formulas for each subtopic. This layout may suit some students, but it may not suit you. Vary the labels and organisation to best suit you. For example, you may choose to include a column for worked examples and/or sample questions.

TABLE 1.13.1 A table for summarising and revising Topic 1 of Unit 4

Revision notes Unit 4 Revolutions in modern physics		
Topic 1 Special relativity		
	Key points	• key terms and definitions • diagrams
Frame of reference	Inertial frame of reference	• a reference frame that does not accelerate
Postulates of special relativity	Speed of light is the same for all inertial observers, AND laws of physics are the same for all inertial observers.	• speed of light • inertial reference frame
Simultaneity	Observers in their reference frame may not see events occur at the same time as an observer in another reference frame.	• event • simultaneous • inertial reference frame
Time dilation		
Length contraction		

- **Skim** through your Student Book and class notes. Identify key sections and terms. These can be added to your revision chart for later elaboration.
- **Re-read** all your class notes carefully for a section of work. Once you feel you understand and remember them, put the notes aside. Without referring back to the notes, start filling in the revision chart. You may need to keep referring back to your notes. Each re-reading of the notes will reinforce your learning. Create a manual, not electronic, revision chart. The exam is to be handwritten, so it is a good idea to practise handwriting your notes as preparation.
- **Refer** to additional resources if there is anything you do not understand. This might mean checking the Student Book, asking your teacher, researching online or discussing with classmates. You can keep track of problem areas by writing questions in the margin of the revision table, highlighting parts of the revision notes you do not fully understand, or keeping a separate queries sheet.
- **Use abbreviations and symbols**, but remember that only standard symbols and abbreviations may be used in the physics exam. In order to save time and space on the revision chart, you can develop your own abbreviations.
- **Dot point notes, visuals, tables and graphs** are all useful ways of summarising information. Use these in your revision table as appropriate. It is often easier to bring to mind information in these forms than to try to visualise a large block of text. If you are a visual learner, it may be helpful to colour-code notes to emphasise different concepts. Rewriting notes, whether in note or visual form, helps you remember them.
- **Learn the subject matter**. In preparing the revision table, you read and re-read the subject matter, so your understanding continually improves. Practise rewriting the revision table without referring to the original one. Try making a summary of the revision table so that you are focusing on the real essential concepts. Discuss concepts with classmates to clarify your understanding. Give the revision chart to a family member and ask them to test you. These are all strategies that can be used to reinforce your learning.
- **Practise, practise, practise**. Remember the saying 'practice makes perfect' and complete as many test and exam papers as are available. Sitting an exam requires skill and the more practice you have in advance, the more prepared you will be. Take practice exams in the time limit allocated. Handwrite the answers to get practice at working quickly, writing your ideas legibly and expressing yourself clearly. Exam paper practice will show you what you know, but more importantly, what you do not know and need to revise again.
- **Traffic light your work**. On a list of the subject matter for Units 3 and 4, use green highlight for those concepts you are very familiar with and can answer medium to difficult questions on. Highlight in orange those concepts that you understand but can only answer the easy and some medium level questions. Use red highlight for those concepts you feel you can only answer basic questions and need help from your teacher or peers.
- The examination consists of two papers. For each paper, make sure you know:
  - the time allowance
  - the date and time of the exam
  - the type of questions to expect
  - the equipment and materials you are permitted to take in
  - the materials and equipment to be supplied for use in the exam.
- **Be prepared**. Do not cram the night before the exam. Re-read your revision table to refresh the subject matter that you have been learning over the last few weeks. Put new batteries into your calculator!

SITTING THE EXAM

Be prepared. Double-check the date, time and place of the exam. Turn up to the exam with plenty of time to spare. Running late will only stress you before you even get into the exam room. Remain calm and focused as you enter the room. At this stage it is too late to worry about your application through the year or your exam preparation.

There are some strategies to keep in mind in the exam that will improve your chances of doing well.

Perusal or reading time

Every exam allocates time for candidates to look over the paper. You are not permitted to pick up pens or pencils at all during this time, not even to write your identification on the answer booklet. Use this time wisely as it is valuable for you to get an overview of the paper.

- Check through all the paper quickly.
- Carefully read the instructions and re-read them.
- Plan how much time you will allocate to different sections of the paper.
- Decide which questions you are going to do in which order—do the easy questions first so you have more time to complete the harder ones.
- Start reading questions and answer them mentally.
- If a question is difficult, do not dwell on it. Move on to the next question. Sometimes another question can give clues to questions that appear difficult.
- Carefully read each question. In your head, translate into your own words what you are asked to do.
- Consider the marks allocated to each question. Plan to spend more time on questions that carry more marks.

Writing time

Commence writing as soon as you are permitted to.

Read questions carefully

If you find it helpful, underline key words in the question—this can be a useful strategy in identifying the focus of the question and giving direction about what is required in your answer. For questions with parts, read the whole question before starting to write your answer. This gives an overview of the question. Sometimes the information in one part of a question will provide a hint for another part. Avoid repeating the same information in different parts of the same question.

Interpret the questions

Read questions carefully and look for the key verbs, such as 'explain', 'compare' and 'determine', that tell you what you are expected to do. It may be helpful to highlight or underline key parts of questions. The questions in module, chapter and unit reviews of your Student and Activity books have been written using verbs from the syllabus. Practice exams you worked through also developed your skills in analysing questions. You should therefore be familiar with the style of questioning and will have had practice at interpreting questions. Make sure your answers address all parts of the question. Use scientific terms and give your answers to the correct number of significant figures and with a unit.

Show your working

Show *all* the steps you took to reach your solution for questions involving calculations. While there may be an error in one part of the calculation, you may still score some marks for correct method. Remember to always include the correct units in answers. Remember to correctly label all graphs (*x*- and *y*-axes, title, units). If you do work that you think is incorrect, simply put an X through it, instead of spending time erasing it completely.

Working with data

Read information carefully so that your answers are accurate. For graphs, read the labels and units on the axes and understand the relationship shown by the graph. The title of the graph will assist with this. Use a ruler for reading graphical data accurately. Always give the units as well as the numerical data in your answers.

When looking at tables, read the headings of rows and columns carefully so you can understand the contents of the table. They usually contain symbols and units of the data.

Refer to the Data Booklet where appropriate.

You should include the proper units for each number where appropriate. If you keep track of units as you perform your calculations, it can help ensure that you express answers in terms of the proper units. Depending on the exam question, you could lose marks if the units are wrong or are missing from the answer.

Answer all questions

An unanswered question cannot possibly earn you any marks. It is better to take an intelligent guess that might earn some marks than not to attempt an answer. When you have completed an answer, re-read the question. Check that you have addressed the question. An answer that includes correct information but does not answer the question will not earn any marks.

Many free-response questions are divided into parts such as a, b, c and d, with each part calling for a different response. Credit for each part is awarded independently, so you should attempt to solve each part. For example, you may receive no credit for your answer to part a, but still receive full credit for parts b, c, or d. If the answer to a later part of a question depends on the answer to an earlier part, you may still be able to receive full credit for the later part, even if that earlier answer is wrong.

Use the answer sheet

Some examinations will require you to complete a separate answer sheet for the multiple-choice questions. If your examination does, make sure that you mark your answers on this sheet, not only on the question paper. If you make an error, erase it carefully before filling in a new answer.

Answer writing tips

- Do not rewrite the stem of a question to answer the question. You can deceive yourself by feeling you've filled up the allocated space, without actually answering the question!
- Answer questions simply and concisely. Sometimes an answer is simply a one-word answer or a numerical reading from a graph. Where possible, use standard phrases that neatly encapsulate meanings rather than wordy explanations.

  Examples:
  - equilibrium
  - refraction
  - Standard Model
  - Twin Paradox
- **Never try for an each-way bet!**

  Example:
  - Question: State the number of quarks that comprise a meson.
  - Answer: 2 or 3.
- **Don't give extra information**. This is unnecessary and can lead to irrelevant or even contradictory information; it is also inefficient use of time.
- **Answer the question being asked**. Providing accurate information that doesn't address the question doesn't attract a score.

Example:

Question: Explain how Lenz's law is consistent with the principle of conservation of energy.

Answer 1: Lenz's law describes the direction of an induced current in a conductor. **No score.**

Answer 2: Lenz's law makes sure that the induced current produced does so in a way to counterbalance the energy loss or gain that created the induced current in the first place. **Scores.**

- If a question asks for an explanation, a single, short sentence answer will not be enough!

  Example:

  Question: Explain how Kepler's third law can be used to determine the mass of the Sun.

  Answer 1: By using period and distance. **No score.**

  Answer 2: The square of the period divided by the cube of the average orbital radius for each planet in our solar system is equal to a constant. That constant contains the mass of the Sun as a factor. **Scores.**

- Be clear about what you mean. There should be no room for interpretation!

  Example:

  - The direction of force in a mass moving in a circle is perpendicular to the other vectors. **No score.**
  - A perpendicular force on a moving object will cause the object to move in a different direction to the original direction it was moving in before the force was applied. **No score.**
  - A force directed at right angles to the direction of motion will cause the object to start moving in a circle. **Scores.**
- Use the **number of lines** provided as a guide about how much to write.
- Use the **number of marks** allocated to a question or part of a question as a guide about how many points to make. Consider whether you can add more details, clearer explanations, or make corrections to answers.
- Pay attention to spelling.
- Never leave blanks!
- Easier questions could be completed first.

Multiple-choice questions are designed to make you select between very similar items. Read all options carefully. If unsure which option is correct, identify those that are wrong. Answer every multiple-choice question, even if all you can do is guess. You should answer each multiple-choice question before you move on to the next one. You can mark a question to come back to later if you have time but you should still fill an answer before you move on. You should allow just over a minute for each question. If the question takes longer than that, take a guess and move on.

Difficult questions

If you find a question particularly difficult, skip it. Come back to it later if you have time.

You should **not** use the 'scattershot' or 'laundry list' approach—writing answers with as many equations or lists of terms as you can, hoping that the correct one will be among them, so that you can get partial credit. For questions that ask for two or three examples or equations, only the first two or three examples will be scored.

Mental blocks

Sometimes in conditions when you are under pressure, your mind can go blank. The information is there but temporarily not available to you. Take a few deep, slow breaths. Go back to the question. Try to visualise your notes on the revision tables you created. If this does not work, move on to another question and return to this question later.

Rechecking answers

If you have time, return to questions that you are unsure of. There is no need to check all answers if you run out of time. Re-read each question when you have finished answering—this will help you to be sure that you:

- have addressed every part of the question
- haven't made an error that could change the meaning of your response.

Stay for the allocated time

Never leave the exam early. Exams are generally designed to take the full writing time allocated to them. If you finish early, recheck for anything you may have missed. Check for blank pages and both sides of the page to make sure you haven't missed anything! Count the number of questions you have answered against the number listed on the front of the exam.

Don't skip a question, have a guess—no marks will be deducted for an incorrect answer but you may pick up marks for a partial response. Also, if you're unsure of a multiple-choice answer, try to eliminate one or more of the options then have a guess. You may be lucky!

Ignore students who leave the exam early. Just because they leave early does not mean they performed well. It often indicates they did not study enough and do not know the subject matter.

Remember:

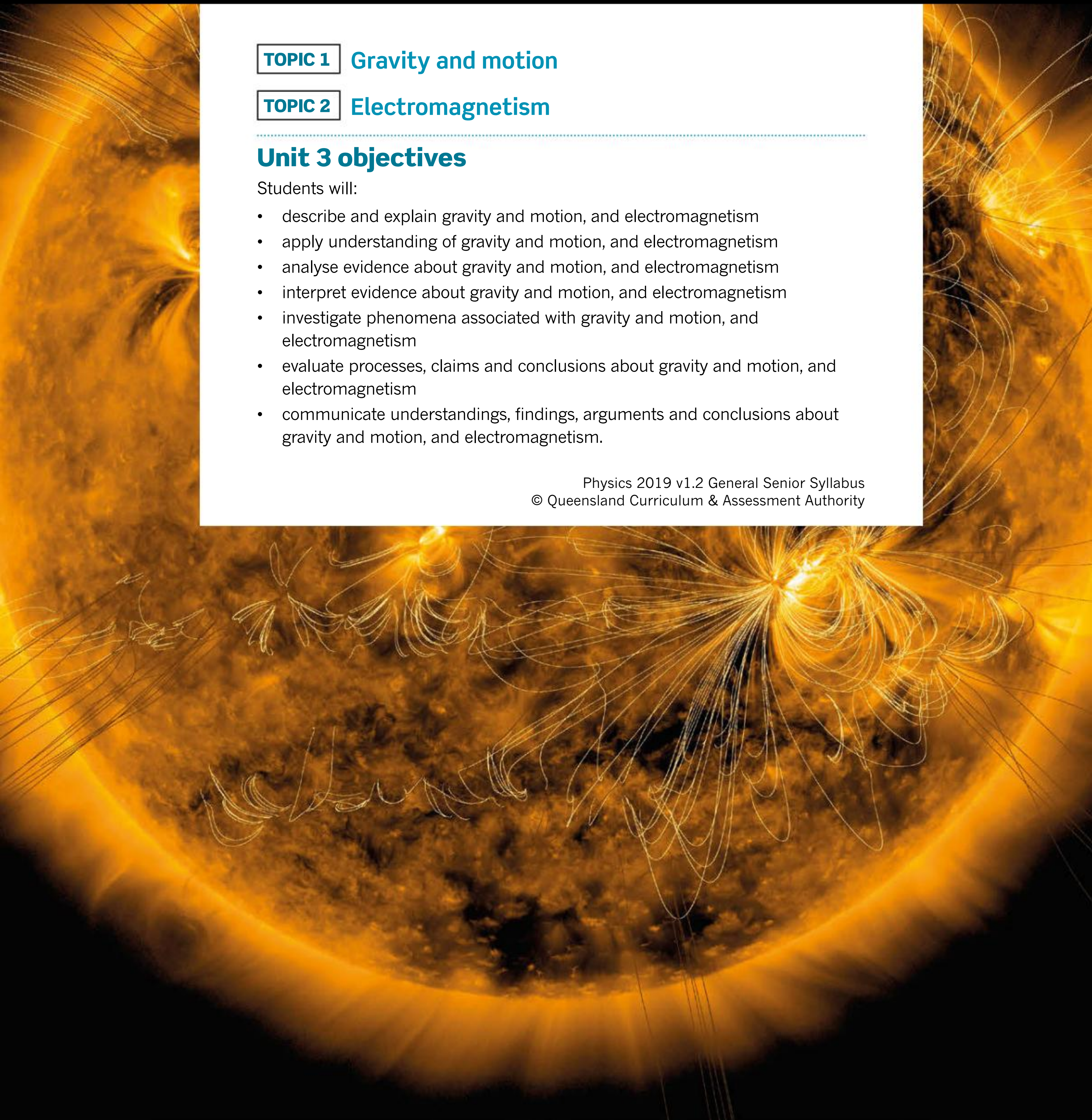
- You can only be asked about information that is included in this course!
- The exam is your opportunity to showcase your knowledge of this subject.

AFTER THE EXAMINATION

Once you have left the exam room, avoid talking to other exam candidates. Everyone has an opinion of their own personal performance. Listening to others can be unsettling. Whether you feel you performed well or are disappointed with your performance, it is now beyond your control. Remain calm. It is one exam result, in one subject, in one year of your life. No matter what happens, there are plenty of career pathways to pursue.

UNIT

3 Gravity and electromagnetism



TOPIC 1 Gravity and motion

TOPIC 2 Electromagnetism

Unit 3 objectives

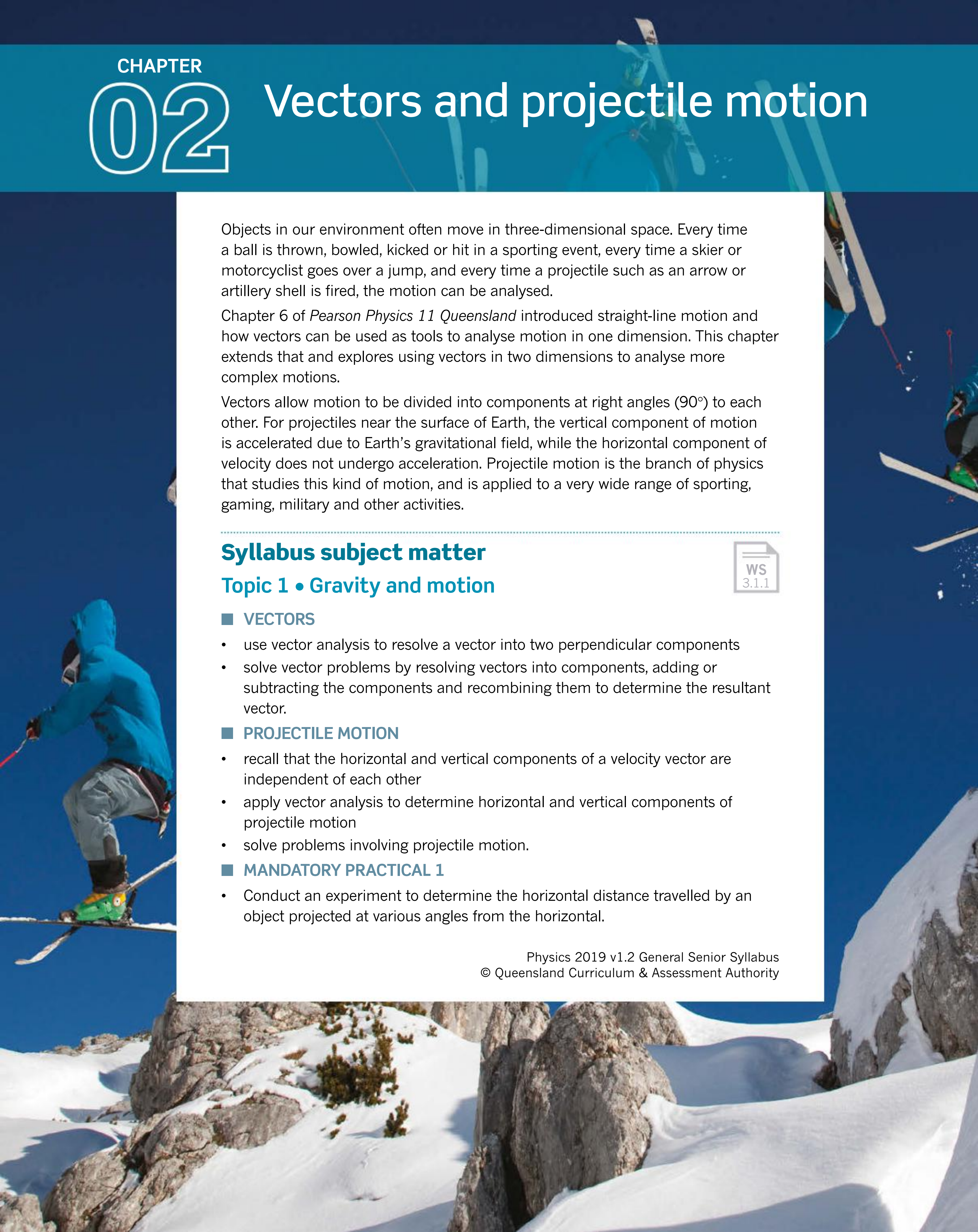
Students will:

- describe and explain gravity and motion, and electromagnetism
- apply understanding of gravity and motion, and electromagnetism
- analyse evidence about gravity and motion, and electromagnetism
- interpret evidence about gravity and motion, and electromagnetism
- investigate phenomena associated with gravity and motion, and electromagnetism
- evaluate processes, claims and conclusions about gravity and motion, and electromagnetism
- communicate understandings, findings, arguments and conclusions about gravity and motion, and electromagnetism.

Physics 2019 v1.2 General Senior Syllabus

CHAPTER 02

Vectors and projectile motion



Objects in our environment often move in three-dimensional space. Every time a ball is thrown, bowled, kicked or hit in a sporting event, every time a skier or motorcyclist goes over a jump, and every time a projectile such as an arrow or artillery shell is fired, the motion can be analysed.

Chapter 6 of *Pearson Physics 11 Queensland* introduced straight-line motion and how vectors can be used as tools to analyse motion in one dimension. This chapter extends that and explores using vectors in two dimensions to analyse more complex motions.

Vectors allow motion to be divided into components at right angles (90°) to each other. For projectiles near the surface of Earth, the vertical component of motion is accelerated due to Earth's gravitational field, while the horizontal component of velocity does not undergo acceleration. Projectile motion is the branch of physics that studies this kind of motion, and is applied to a very wide range of sporting, gaming, military and other activities.

Syllabus subject matter

WS 3.1.1

Topic 1 • Gravity and motion

VECTORS

- use vector analysis to resolve a vector into two perpendicular components
- solve vector problems by resolving vectors into components, adding or subtracting the components and recombining them to determine the resultant vector.

PROJECTILE MOTION

- recall that the horizontal and vertical components of a velocity vector are independent of each other
- apply vector analysis to determine horizontal and vertical components of projectile motion
- solve problems involving projectile motion.

MANDATORY PRACTICAL 1

- Conduct an experiment to determine the horizontal distance travelled by an object projected at various angles from the horizontal.

2.1 Vectors in two dimensions

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

- describe two-dimensional vectors in the horizontal and vertical planes.

Vectors require magnitude, units and direction to make sense. Some examples of vectors include **displacement**, velocity, **acceleration** and force. Arrows are used to represent vectors, where the length of the vector is proportional to the magnitude of the vector, and the direction of the arrow indicates the direction of the vector.

In Units 1 and 2, you learnt the difference between scalars and **vectors**, and explored vectors in one dimension. When vectors are in one dimension, it is relatively simple to understand direction. However, some vectors will require a description in a two-dimensional plane. These planes could be:

- horizontal, which can be defined using north, south, east and west
- vertical, which can be defined in a number of ways including up, down, left and right.

The description of the direction of these vectors is more complicated. Therefore, a more detailed convention is needed for identifying the direction of a vector. There is a variety of conventions, but they all describe a direction as an **angle** from a known reference point.

HORIZONTAL PLANE

The horizontal plane is one that is looked down on from above. Examples include looking at a house plan or map placed on a desk.

For a horizontal, two-dimensional plane, two common methods are used to describe the direction of a vector: full circle (or true) bearing and quadrant bearing.

- A full circle (or true) bearing describes north as zero degrees true. This is written as 0°T. In this convention, all directions are given as a clockwise angle from north. As an example, 95°T is 95° clockwise from north.
- In a quadrant bearing, all angles are referenced from either north or south and are between 0° and 90° towards east or west. In this method, 30°T becomes N30°E, which can be read as 'from north turn 30° towards east'.

Using these two conventions, north-west (NW) would be 315°T using a full circle bearing, or N45°W using a quadrant bearing. Figure 2.1.1 demonstrates these two methods.

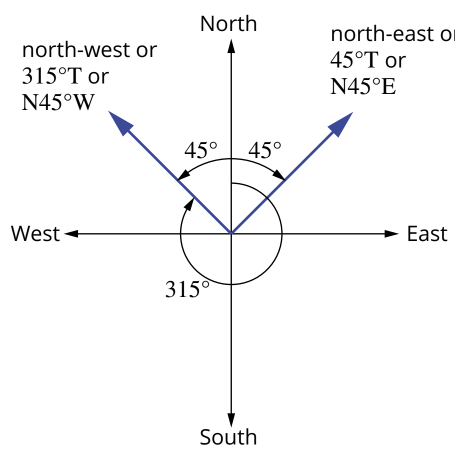


FIGURE 2.1.1 Two horizontal vector directions, viewed from above, using full circle bearings and quadrant bearings

VERTICAL PLANE

For a vertical, two-dimensional plane the directions are referenced to vertical (upwards and downwards) or horizontal (left and right) and are between 0° and 90° clockwise or anticlockwise. For example, a vector direction can be described as '60° clockwise from the left direction'. The same vector direction could be described as '30° anticlockwise from the upwards direction'. The opposite direction to this vector would be '60° clockwise from the right direction or 30 degrees anticlockwise from the downwards direction'. This example is illustrated in Figure 2.1.2.

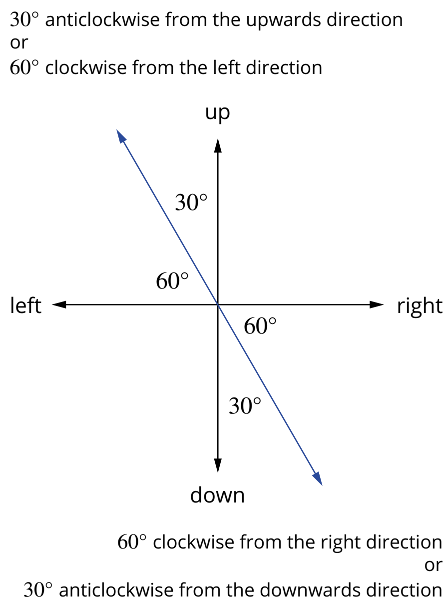
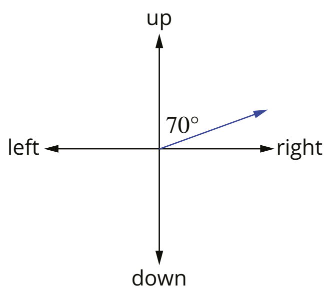


FIGURE 2.1.2 Two vectors in the vertical plane

Worked example 2.1.1

DESCRIBING TWO-DIMENSIONAL VECTORS

Describe the direction of the following vector using an appropriate method.

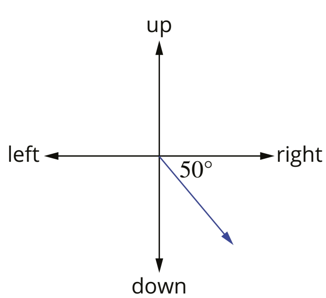


Thinking	Working
Choose the appropriate points to reference the direction of the vector. In this case using the vertical reference makes more sense, as the angle is given from the vertical.	The vector can be referenced to the vertical.
Determine the angle between the reference direction and the vector.	In this example there is 70° from the upwards direction to the vector.
Determine the direction of the vector from the reference direction.	From vertically up, the vector is clockwise.
Describe the vector using the sequence: angle, clockwise or anticlockwise from the reference direction.	This vector is 70° clockwise from the upwards direction.

➤ Try yourself 2.1.1

DESCRIBING TWO-DIMENSIONAL VECTORS

Describe the direction of the following vector using an appropriate method.



2.1 Review

SUMMARY

- For a horizontal two-dimensional plane, the direction of a vector can be described using:
  - a full circle (or true) bearing (e.g. 315°T)
  - a quadrant bearing (e.g. N45°W).
- For a vertical two-dimensional plane, the direction of a vector can be described using:
  - upwards and downwards
  - left and right
  - an angle between 0° and 90° clockwise or anticlockwise (e.g. 60° clockwise from the left direction or 30° anticlockwise from the upwards direction).
- The direction of two-dimensional vectors in the horizontal plane can be described using a full circle bearing or a quadrant bearing. Vectors in the vertical plane can be described using angles measured clockwise and anticlockwise from the vertical or horizontal.

KEY QUESTIONS

Retrieval

1 State two ways in which a horizontal two-dimensional vector can be described.

2 Identify two things needed to describe the direction of a vertical two-dimensional vector.

3 State the opposing direction to each of the following two-dimensional descriptions.

a up
b north
c left
d down
e west

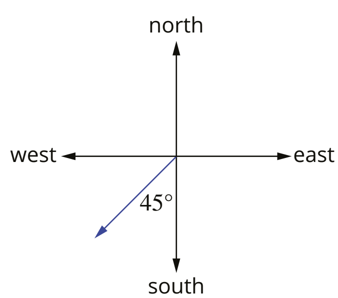
4 State another way of describing the direction 270°T.

Comprehension

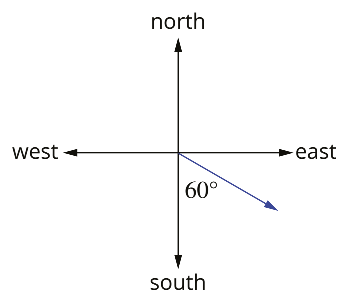
5 Describe the following vectors using:

i full circle bearings
ii quadrant bearings.

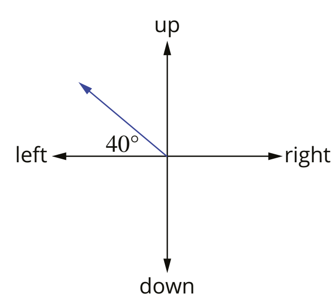
a



b



6 Describe the following vector using appropriate conventions.



2.2 Adding vectors in two dimensions

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

- add vectors in two dimensions
  - graphically using a scale and a protractor
  - geometrically using trigonometry or Pythagoras.

In *Pearson Physics 11 Queensland* you learnt how to add vectors in one dimension. Adding vectors that are in one dimension means finding the resultant vector for a number of vectors that are in the same line. This technique can be applied both graphically and algebraically.

It is also possible to find the resultant of two or more vectors that are in two dimensions. The vectors can be in any direction, as long as they are all in the same plane. In two dimensions, simple algebra cannot be used to add vectors. Instead, geometry must be used. In this section, you will learn how to add vectors in two dimensions graphically or using geometry.

METHODS OF ADDING VECTORS IN TWO DIMENSIONS

To add vectors in two dimensions, all of the vectors must be in the same plane. The vectors can go in any direction within the plane, and can be separated by any angle. The examples in this section illustrate vectors in the horizontal plane, but the same strategies apply to adding vectors in the vertical plane.

The direction conventions that suit the horizontal plane best are the north, south, east and west convention, or the forwards, backwards, left and right convention (Figure 2.2.1).

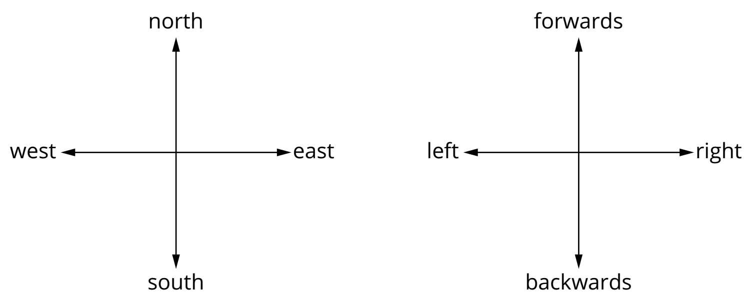


FIGURE 2.2.1 The direction conventions for the horizontal plane

Graphical method of adding vectors

The magnitude and direction of a resultant vector can be determined by measuring an accurately drawn scaled vector diagram. There are two main ways to do this:

- head to tail method
- parallelogram method.

Head to tail method

To add vectors at right angles to each other using a graphical method, use an appropriate scale and then draw each vector head to tail. The resultant vector is the vector that starts at the tail of the first vector and ends at the head of the last vector. To determine the magnitude and direction of the resultant vector, measure the length of the resultant vector and compare it to the scale, then measure and describe the direction appropriately.

In Figure 2.2.2, the vectors 30.0 m east and 20.0 m south are added head to tail. The resultant vector, shown in red, is measured to be about 36 m according to the scale provided. Using a protractor, the resultant vector is measured to be in the direction 34° south of east. This represents a direction of S56°E when using quadrant bearings.

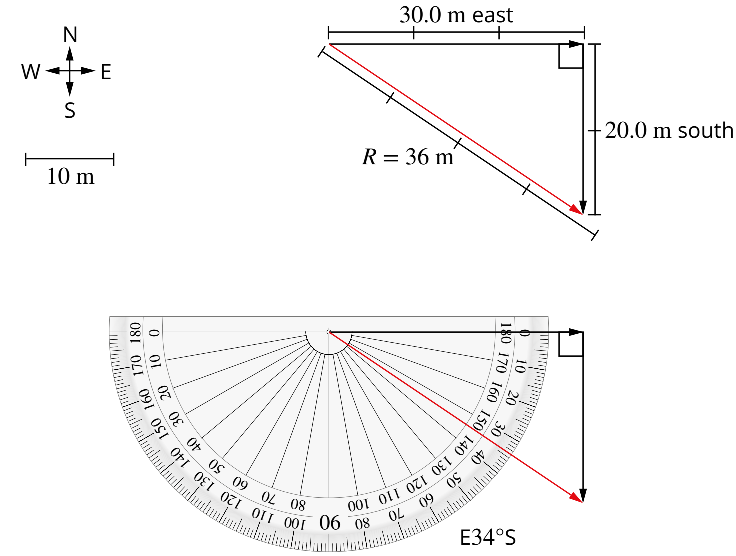


FIGURE 2.2.2 Two vectors can be added at right angles using the graphical method.

If the two vectors are at angles other than 90° to each other, the graphical method is ideal for finding the resultant vector. In Figure 2.2.3, the vectors 15 N east and 10 N S45°E are added head to tail. The magnitude of the resultant vector is measured to be about 23 N. The direction of the resultant vector is measured by a protractor from east to be 18° towards the south, which should be written as S72°E.

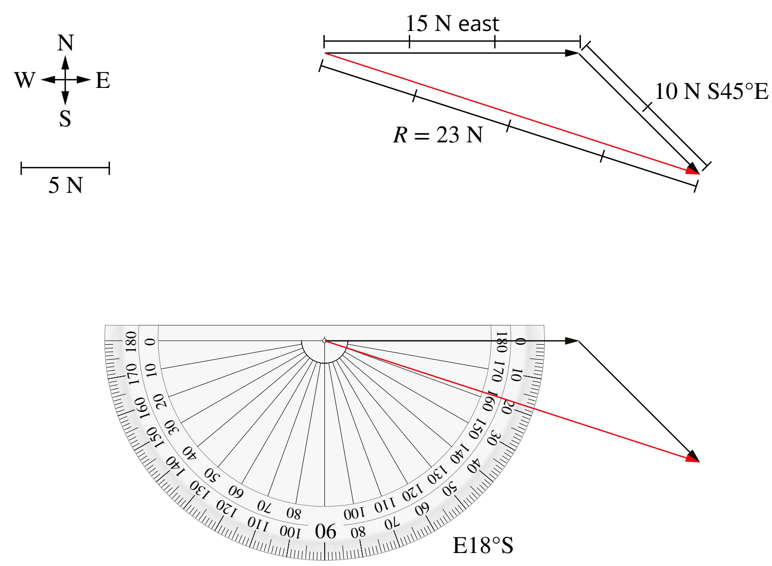


FIGURE 2.2.3 Two vectors not at right angles are added using the graphical method.

Parallelogram method

An alternative method for determining a resultant vector is to construct a parallelogram of vectors. In this method, the two vectors to be added are drawn tail to tail. Next, a parallel line is drawn for each vector as shown in Figure 2.2.4. In this figure, the parallel lines have been drawn as dotted lines. The resultant vector is drawn from the tails of the two vectors to the intersection of the dotted parallel lines. The magnitude and direction of the resultant vector are then measured using a ruler and a protractor.

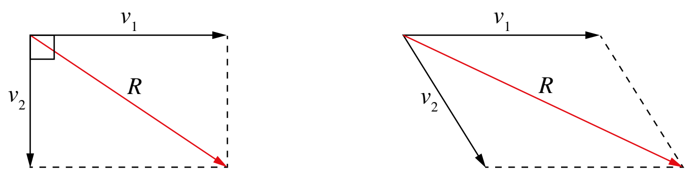
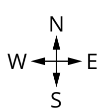


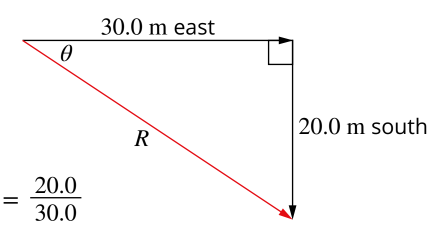
FIGURE 2.2.4 Two vectors can be added using the parallelogram of vectors method.

Geometric method of adding vectors

Graphical methods of adding vectors in two dimensions only give approximate results as they rely on comparing the magnitude of the resultant vector to a scale and measuring the direction with a protractor. A more accurate method to **resolve** vectors—i.e. to find their **components** in two **perpendicular** directions—is to use **Pythagoras' theorem** and trigonometry. These techniques are referred to as geometric methods. Geometric methods can be used to calculate the magnitude of the vector and its direction. Pythagoras' theorem and trigonometry can only be used for finding the resultant vector of two vectors that are at right angles to each other.

In Figure 2.2.5, two vectors, 30.0 m east and 20.0 m south, are added head to tail. The resultant vector, shown in red, is calculated using Pythagoras' theorem to be 36.1 m. The angle between the east vector and the resultant vector is calculated using trigonometry to be 33.7°; i.e. in the direction S56.3°E. This result is more accurate than the answer determined on page 8.





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

$R^2 = 30.0^2 + 20.0^2$

$= 900 + 400$

$R = \sqrt{1300}$

$= 36.1 \text{ m}$

$\tan\theta = \dfrac{20.0}{30.0}$

$\theta = \tan^{-1} 0.6667$

$= 33.7°$

E33.7°S (or S56.3°E)

FIGURE 2.2.5 Two vectors at right angles can be added using the geometric method.

Pythagoras' theorem

Pythagoras' theorem is $a^2 + b^2 = c^2$, where c is the hypotenuse (the longest side) and a and b are the two shorter sides of a right-angled triangle. The hypotenuse is easily recognised as it is directly across from (opposite) the right angle of the triangle.

Trigonometric ratios

Most students learn the mnemonic SOHCAHTOA in their maths classes. It is often pronounced soh-cah-toa and provides a way to remember the trigonometric ratios:

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

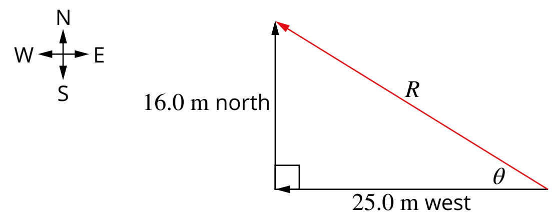
$\cos\theta = \dfrac{\text{adjacent}}{\text{hypotenuse}}$

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

Worked example 2.2.1

ADDING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the resultant displacement vector that represents a child running 25.0 m west and 16.0 m north. Refer to Figure 2.2.1 on page 7 for sign and direction conventions if required.

Thinking	Working
Construct a vector diagram showing the vectors drawn head to tail. Draw the resultant vector from the tail of the first vector to the head of the second vector.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the resultant vector.	$R^2 = 25.0^2 + 16.0^2$ $= 625 + 256$ $R = \sqrt{881}$ $= 29.7\ \text{m}$
Using trigonometry, calculate the angle from the west vector to the resultant vector.	$\tan\theta = \frac{16.0}{25.0}$ $\theta = \tan^{-1} 0.640$ $= 32.6°$
Determine the direction of the vector relative to north or south.	$90° - 32.6° = 57.4°$ The direction is N57.4°W.
State the magnitude and direction of the resultant vector.	$R = 29.7\ \text{m}$, N57.4°W

➤ Try yourself 2.2.1

ADDING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the resultant force when forces of 5.0 N east and 3.0 N north act on a tree.
Refer to Figure 2.2.1 on page 7 for sign and direction conventions if required.

2.2 Review

SUMMARY

- Two-dimensional vector addition refers to vectors in a plane.
- Vectors in two dimensions can be added graphically with a scale and a protractor.
- An alternate method of adding vectors in two dimensions is to construct a parallelogram of vectors.
- Perpendicular vectors in two dimensions can be added using Pythagoras' theorem and trigonometry.

KEY QUESTIONS

Retrieval

1 Module 2.2 describes two approaches to finding the sum of two vectors: using Pythagoras' theorem and geometry to resolve them by calculation, and using a carefully constructed diagram to resolve them graphically. While both work in any situation, state which would be more convenient for resolving two vectors that are at a 38° angle to each other.

2 Describe, using a number and the appropriate unit, the resultant force acting on a book on a chair. The book is acted on by a 20.0 N force downwards and a 20.0 N upwards, as well as a 10.0 N force towards the back of the chair from someone pushing on it and a 10.0 N force forwards on the book from the back of the chair it is sitting on.

Comprehension

3 Sketch and state the resultant force when a 33 N force acting horizontally and a 28 N force acting at 45° above the horizontal act on an object. Determine the resultant vector.

Analysis

4 Calculate the magnitude of the total force acting on an object if it has a gravitational force of 30.0 N downwards acting on it and a force due to a strong wind of 8.0 N is acting eastwards on it.

5 Calculate the resultant distance travelled and the displacement, *d*, if David walks 210.0 km east and then turns right and walks 87.0 km south.

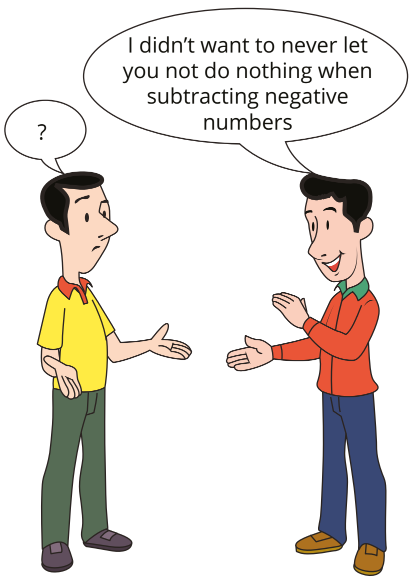
2.3 Subtracting vectors in one and two dimensions

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

- subtract vectors in two dimensions
  - graphically using a scale and a protractor
  - geometrically using trigonometry or Pythagoras.

In *Pearson Physics 11 Queensland* you also learnt how to subtract vectors in one dimension. 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 and add the vectors together graphically or algebraically.

In two dimensions, simple algebra cannot be used to subtract vectors. Instead, geometry must be used. In this section, you will learn how to subtract vectors in two dimensions graphically or using geometry.



When a change in a vector occurs, the magnitude and/or the direction of the vector can change.

A change in any quantity, Δx, is always given by the final value of x_f minus the initial value of x_i:

$$\Delta x = x_f - x_i$$

SUBTRACTING VECTORS IN TWO DIMENSIONS

Changing **velocity** in two dimensions can occur when turning a corner, such as walking at $3\,\text{m s}^{-1}$ west and then turning to travel at $3\,\text{m s}^{-1}$ north. Although the magnitude of the velocity is the same, the direction has changed.

A change in velocity in two dimensions can be determined using either the graphical method or the geometric method described in Module 2.2. The initial velocity must always be reversed before it is added to the final velocity.

The two-dimensional direction conventions were introduced in the previous section in Figure 2.2.1 on page 7.

Graphical method of subtracting vectors

To subtract vectors using the graphical method, use a direction convention and a scale and draw each vector.

Using velocity as an example, the steps to do this are as follows:

- Draw the final velocity first.
- Draw the opposite of the initial velocity head to tail with the final velocity vector.
- Draw the resultant change in velocity vector, starting at the tail of the final velocity vector and ending at the head of the opposite of the initial velocity vector.
- Measure the length of the resultant vector and compare it to the scale to determine the magnitude of the change in velocity.
- Measure an appropriate angle to determine the direction of the resultant vector.

Figure 2.3.2a shows the velocity vectors for travelling $3\,\text{m s}^{-1}$ west and then turning and travelling $3\,\text{m s}^{-1}$ north. The opposite of the initial velocity is drawn as $3\,\text{m s}^{-1}$ east.

To determine the change in velocity, the final velocity vector is drawn first, then from its head the opposite of the initial velocity is drawn (Figure 2.3.2b). The magnitude of the change in velocity (resultant vector) is shown in red. It is measured to be about $4.3\,\text{m s}^{-1}$ according to the scale provided. Using a protractor, the resultant vector is measured to be in the direction N45°E.

Geometric method of subtracting vectors

The graphical method of subtracting vectors in two dimensions only gives approximate results, as it relies on comparing the magnitude of the change in velocity vector to a scale and measuring its direction with a protractor.

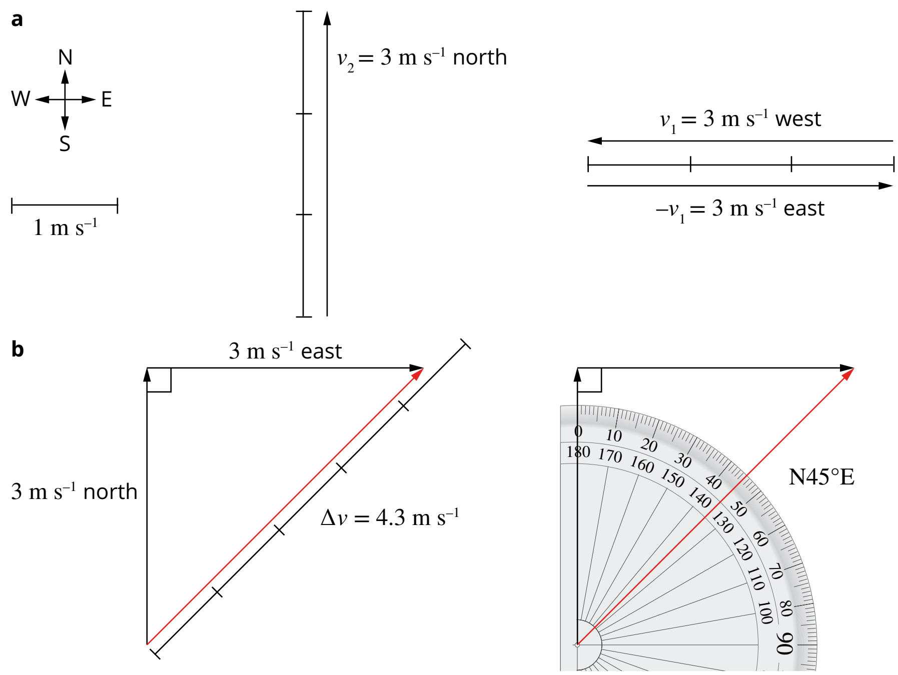
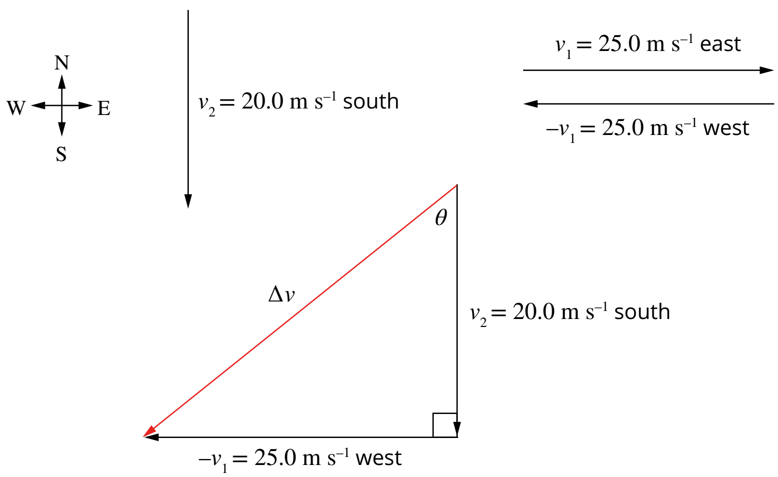


FIGURE 2.3.2 (a) The opposite of the initial velocity 3 m s^{-1} west is drawn as 3 m s^{-1} east. (b) Subtracting two vectors at right angles, using the graphical method.

A more accurate method for subtracting vectors is to use Pythagoras' theorem and trigonometry.

Figure 2.3.3 shows how to calculate the resultant velocity when changing from 25.0 m s^{-1} east to 20.0 m s^{-1} south. The initial velocity of 25.0 m s^{-1} east and the final velocity of 20.0 m s^{-1} south are drawn. Then the opposite of the initial velocity is drawn as 25.0 m s^{-1} west. The final velocity vector is drawn first, then from its head the opposite of the initial velocity is drawn. The resultant velocity vector, shown in red, is calculated using Pythagoras' theorem to be 32.0 m s^{-1}. The direction of the resultant vector is calculated using trigonometry to be S51.3°W.

The resultant vector is 32.0 m s^{-1} S51.3°W.



$$R^2 = 25.0^2 + 20.0^2 \qquad \tan\theta = \frac{25.0}{20.0}$$

$$= 625 + 400 \qquad \theta = \tan^{-1} 1.25$$

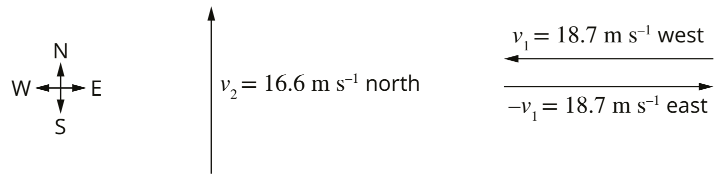
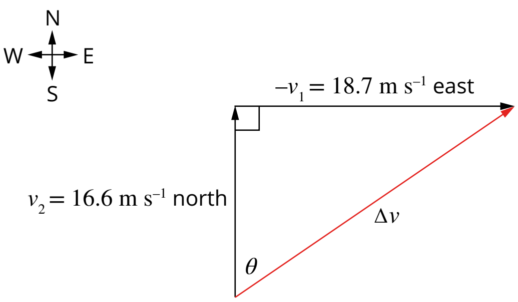
$$R = \sqrt{1025} \qquad = 51.3°$$

$$= 32.0 \text{ m s}^{-1} \qquad \text{S51.3°W}$$

FIGURE 2.3.3 Subtracting two vectors at right angles, using the geometric method

Worked example 2.3.1

SUBTRACTING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the change in velocity of Clare's scooter as she turns a corner if she approaches it at 18.7 m s^{-1} west and exits at 16.6 m s^{-1} north.	
Thinking	**Working**
Draw the final velocity vector, v_2, and the initial velocity vector, v_1, separately. Then draw the initial velocity in the opposite direction.	
Construct a vector diagram drawing v_2 first and then from its head draw the opposite of v_1. The change of velocity vector is drawn from the tail of the final velocity to the head of the opposite of the initial velocity.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the change in velocity.	$R^2 = 16.6^2 + 18.7^2$ $= 275.26 + 349.69$ $R = \sqrt{625.25}$ $= 25.0\ \text{m s}^{-1}$
Calculate the angle from the north vector to the change in velocity vector.	$\tan\theta = \frac{18.7}{16.6}$ $\theta = \tan^{-1} 1.16$ $= 48.4°$
State the magnitude and direction of the change in velocity.	$\Delta v = 25.0\ \text{m s}^{-1}$ N48.4°E

➤ Try yourself 2.3.1

SUBTRACTING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Determine the change in velocity of a ball as it bounces off a wall. The ball approaches at 7.0 m s^{-1} south and rebounds at 6.0 m s^{-1} east.

2.3 Review

SUMMARY

- To find the difference between, or the 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 in two dimensions can be determined:
  - graphically using a scale and a protractor
  - geometrically using Pythagoras' theorem and trigonometry.

KEY QUESTIONS

Retrieval

1 State whether the following is true or false: To subtract vector B from vector A, we change the sign of vector A and add the resulting vector to vector B.

Comprehension

2 Describe the steps for subtracting a distance of 20 km left from 17 km upwards.

Analysis

3 Calculate the resultant force when a force of 27 N west is subtracted from a force of 18 N north.

4 Tom hits a tennis ball against a wall. The ball travels towards the wall at 35.0 $m s^{-1}$ at an angle of 45° upwards, and rebounds at 32.5 $m s^{-1}$ at an angle of 45° upwards. Calculate the change in velocity of the ball.

5 Calculate the change in the velocity of a jet that makes a turn after taking off, changing its velocity from 345 $m s^{-1}$ south to 406 $m s^{-1}$ west.

6 Calculate the change in the velocity of a golf ball that Yvette hits and, when it strikes a tree, changes its velocity from 42.0 $m s^{-1}$ east to 42.0 $m s^{-1}$ north.

7 Calculate the change in the velocity of a yacht that tacks during a race, changing its velocity from 7.05 $m s^{-1}$ south to 5.25 $m s^{-1}$ west.

2.4 Vector components

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

- resolve vectors into their components in two perpendicular directions
- use geometrical methods to resolve vectors into their components
- use trigonometry to resolve vectors into their components
- combine vectors in two perpendicular directions to find a resultant vector.

Modules 2.2 and 2.3 explored how vectors can be combined to find a resultant vector. In physics there are times when it is useful to break one vector up into two vectors that are at right angles to each other. For example, if a force vector is acting at an angle up from the horizontal (Figure 2.4.1), this vector can be considered to consist of two independent vertical and horizontal components.

The components of a vector can be found using trigonometry.

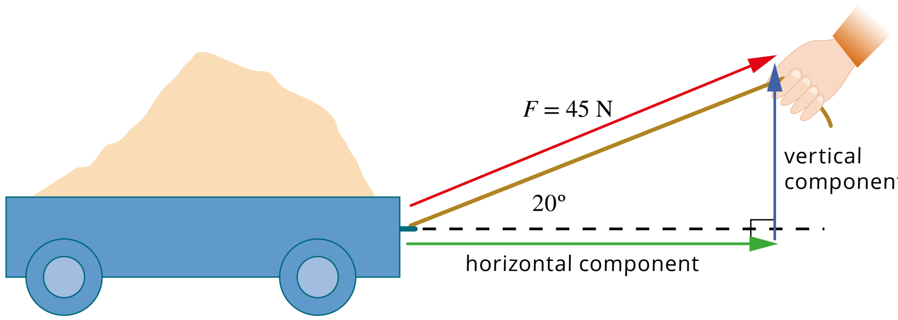


FIGURE 2.4.1 The pulling force acting on the cart has a component in the horizontal direction and a component in the vertical direction.

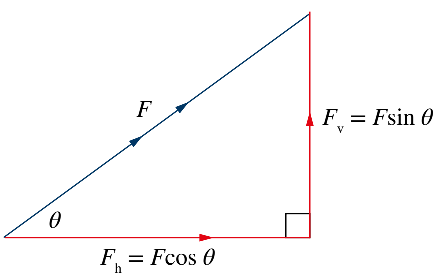


FIGURE 2.4.2 The perpendicular components (shown in red) of the original vector (shown in blue). The original vector is the hypotenuse of the triangle.

You may see the vertical component described as F_v with v meaning vertical, or as F_y with y meaning y-axis. Likewise, you may see the horizontal component described as F_h with h meaning horizontal, or F_x with x meaning x-axis.

FINDING PERPENDICULAR COMPONENTS OF A VECTOR

Vectors at an angle are more easily dealt with if they are broken up into perpendicular components, that is, two components that are at right angles to each other. These components, when added together, give the original vector. To find the components of a vector, a right-angled triangle is constructed with the original vector as the hypotenuse. This is shown in Figure 2.4.2. The hypotenuse is always the longest side of a right-angled triangle and is opposite the 90° angle. The other two sides of the triangle are each shorter than the hypotenuse and form the 90° angle with each other. These two sides are the perpendicular components of the original vector.

Geometric method of finding vector components

The geometric method of finding the perpendicular components of vectors is to construct a right-angled triangle using the original vector as the hypotenuse. The magnitude and direction of the components are then determined using trigonometry. A good rule to remember is that no component of a vector can be larger than the vector itself. In a right-angled triangle, no side is longer than the hypotenuse. The original vector must be the hypotenuse and its components must be the other two (shorter) sides of the triangle.

Figure 2.4.3 shows a force vector of 50.0 N (drawn in black) acting on a box in a direction 30.0° up from the horizontal to the right. The horizontal and vertical components of this force must be found in order to complete further calculations.

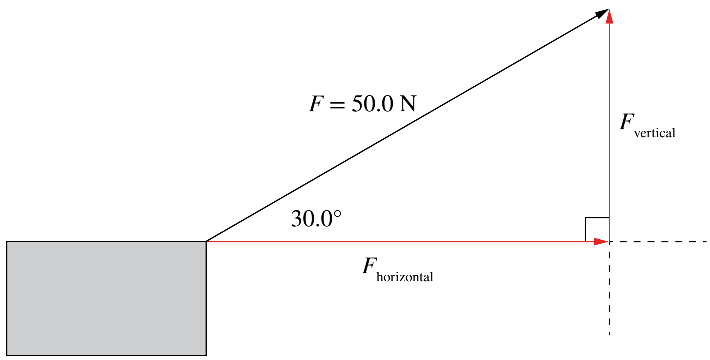


FIGURE 2.4.3 A force vector is broken into horizontal and vertical components.

The horizontal component vector is drawn from the tail of the 50.0 N vector towards the right, with its head directly below the head of the original 50.0 N vector. The vertical component vector is drawn from the head of the horizontal component to the head of the original 50.0 N vector.

Using trigonometry, the horizontal and vertical components of the force are calculated as follows:

Horizontally:

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

$\text{adj} = \text{hyp}\cos\theta$

$F_h = 50.0 \times \cos 30.0°$

$= 43.3$ N horizontally to the right

Vertically:

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

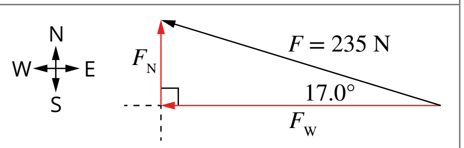
$\text{opp} = \text{hyp}\sin\theta$

$F_v = 50.0 \times \sin 30.0°$

$= 25.0$ N vertically upwards

Worked example 2.4.1

CALCULATING THE PERPENDICULAR COMPONENTS OF A FORCE

Determine the perpendicular components of a 235 N force acting on a bicycle at a direction of 17.0° north of west. Use direction conventions.	
Thinking	**Working**
Draw F_W from the tail of the 235 N force along the horizontal direction, then draw F_N from the head of F_W to the head of the 235 N force.	
Calculate the west component of the force F_W using $\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$	$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$ $\text{adj} = \text{hyp}\cos\theta$ $F_W = 235 \times \cos 17.0°$ $= 225$ N west
Calculate the north component of the force F_N using $\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$	$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$ $\text{opp} = \text{hyp}\sin\theta$ $F_N = 235 \times \sin 17.0°$ $= 68.7$ N north

➤ Try yourself 2.4.1

CALCULATING THE PERPENDICULAR COMPONENTS OF A FORCE

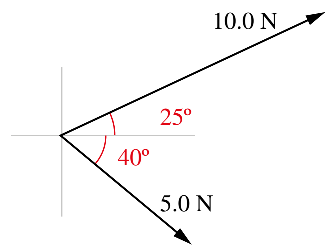
Determine the perpendicular components of a 3540 N force acting on a trolley in a direction of 26.5° anticlockwise from the left. Use direction conventions.

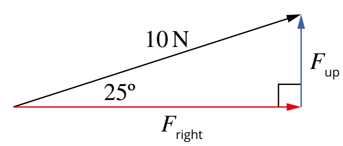
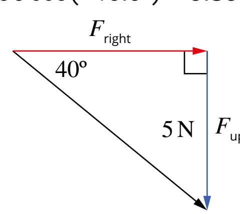
So far in this chapter we have generally added and subtracted vectors that are at right angles to one another. Resolving vectors into their components in two directions at right angles to each other can also allow us to add and subtract vectors that are not at right angles to one another.

Worked example 2.4.2

ADDING VECTORS THAT ARE NOT PERPENDICULAR

Resolve the two vectors in this figure into their components in the horizontal and vertical directions and then add them to find the resultant.



Thinking	Working
Taking the 10.0 N vector first, the components will be given by: $F_{up} = F_{10} \sin \theta°$ $F_{right} = F_{10} \cos \theta°$	$F_{up} = 10.0 \sin 25.0° = 4.23$ N upwards $F_{right} = 10.0 \cos 25.0° = 9.06$ N right 
Taking the 5.00 N vector second, the components will be given by: $F_{up} = F_5 \sin \theta°$ $F_{right} = F_5 \cos \theta°$ As the angle is below the horizontal, we write it with a negative sign.	$F_{up} = 5.00 \sin(-40.0°) = -3.21$ N upwards $F_{right} = 5.00 \cos(-40.0°) = 3.83$ N right 
Next we can add the components in each direction.	$F_{up} = 4.23 + (-3.21) = 1.02$ N upwards $F_{right} = 9.06 + 3.83 = 12.89$ N right
Finally, we use Pythagoras' theorem to calculate the magnitude.	$F_{net} = \sqrt{(F_{up})^2 + (F_{right})^2}$ $= \sqrt{1.02^2 + 12.89^2}$ $= 13$ N
Use trigonometry to calculate the angle of the resultant force vector.	$\theta = \tan^{-1}\left(\frac{1.02}{12.89}\right) = 4.52°$ The resultant force is 12.9 N right, 4.52° up (or 12.9 N at 4.52° to the horizontal).

➤ Try yourself 2.4.2

ADDING VECTORS THAT ARE NOT PERPENDICULAR

Calculate the sum of a displacement of 20.0 km north and a displacement of 14.0 km N33.0°E.

2.4 Review

SUMMARY

- Vectors can be resolved into two perpendicular components.
- Components can be horizontal and vertical or in the *x* and *y* directions, or in two other named directions, such as north and east.
- Trigonometry is used to resolve vectors into their components.
- Components of different vectors in the same direction can be added or subtracted.
- Perpendicular vector components can be recombined to find a resultant vector.

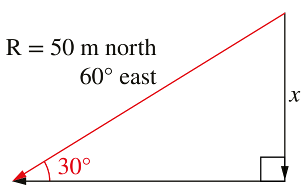
KEY QUESTIONS

Retrieval

1 Name the theorem used to find the magnitude when two perpendicular vectors are added.

Comprehension

2 Calculate the value of *x* in this figure.



Analysis

3 A force of 3000 N is acting at 40 degrees west of south. Calculate the magnitude of the southwards component of this force.

4 Calculate the change in Zehn's position down the field and across the field, when Zehn walks 47.0 m in the direction of S66.3°E across a hockey field.

5 Calculate the force that each tug boat applies to a cargo ship in the following situation. The cargo ship has two tugs attached to it by ropes. One of the tugs is pulling directly north, while the other tug is pulling directly west. The pulling forces of the tugboats combine to produce a total force of 235 000 N in a direction of N62.5°W.

6 Determine the perpendicular components of the following forces. In part **d**, use the horizontal and vertical directions.

a 100.0 N S60.0°E
b 60.0 N north
c 300.0 N 160.0°T
d 3.00×10^5 N 30.0° upwards from the horizontal

7 Calculate the horizontal and vertical components of a 30.00 N force that is applied along a rope at 60.0° to the horizontal and used to drag an object across a yard.

8 Calculate the horizontal and vertical components of following force vectors acting on the same object and add them to find the resultant force acting on the object: 28 N at 18° to the horizontal and 17 N at 168° to the horizontal (i.e. left and slightly upwards if we use the convention that right is the positive direction).

2.5 Projectile motion

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

- describe the interaction of acceleration and velocity in projectile motion
- understand that the vertical component of motion and the horizontal component of motion are independent of each other
- resolve projectile motion into vectors in the horizontal and vertical directions
- complete calculations of distances, heights and times for projectile motion.

THE FLIGHT OF A BALL

Rarely does a ball travel in a straight line on the sports field. Whether it is due to the spin on the ball caused by a racquet, the dimples of a golf ball breaking air flow or the wind catching a netball and pulling it off course, the flight of any two balls is rarely the same. The path of the ball can be difficult to predict, even for the experienced sportsperson. However, there are some things that every sports ball will have in common while in flight. Once a theoretical understanding of the ideal flight of a ball is understood, the effects of air resistance, drag and spin can be investigated.

In this module, you will apply the equations of straight line motion and your understanding of acceleration under the force of gravity to investigate the flight of projectiles.

Investigating movement in two dimensions

Analysing the flight of a ball, or any object in flight, involves considering the movement of the object in both the horizontal and the vertical directions. For example, consider the bouncing ball in Figure 2.5.1. The ball is bouncing up and down as well as moving sideways.

Figure 2.5.1 shows a single bounce of a ball across a smooth flat surface. The circles represent the position of the ball at equal time intervals during the bounce. The arrows at each position give an indication of how the vertical and horizontal position of the ball changes at each point throughout the bounce. So, for example, the biggest change in vertical position is near the start and end of the bounce.

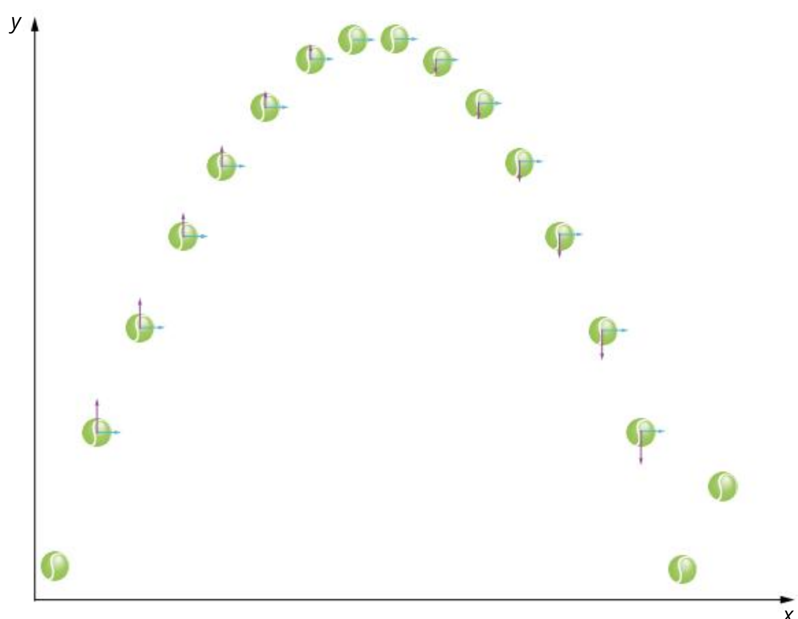


FIGURE 2.5.1 The path of a bouncing ball, from left to right, with arrows showing the changes in its vertical and horizontal position

The bounce shown in Figure 2.5.1 can be further analysed by plotting the horizontal and vertical positions of the ball on separate graphs. The change in the position of the ball from the start of its motion (the origin) is shown in Figure 2.5.2. Graph (a) shows the horizontal displacement and graph (b) the vertical displacement from the origin. Note that the origin of the graph has been established on the left of the field of view. As the ball bounces towards the right, the horizontal position increases as the ball moves further from the origin. Height on the graph increases as the ball moves up and decreases as it moves down.

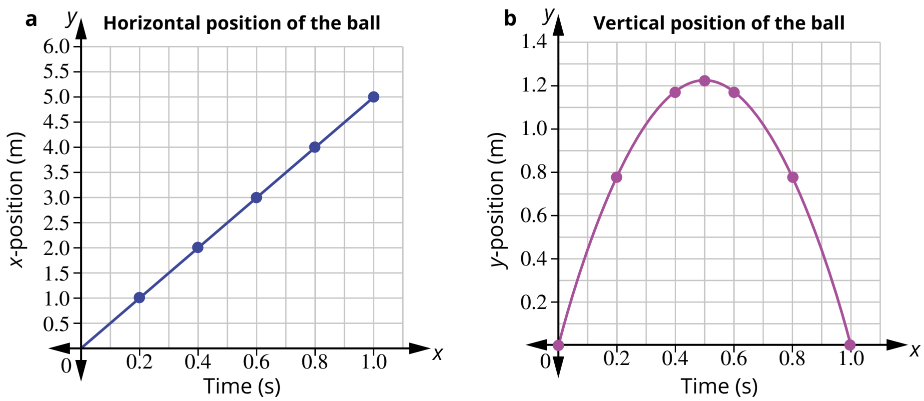


FIGURE 2.5.2 Graphs of the horizontal and vertical displacement of the ball from the origin

The graph of the horizontal position of the ball (Figure 2.5.2a) shows that:

- The distance from the origin increases as the ball moves away from the origin.
- The graph is a straight line with a regular interval between each point.
- In the horizontal direction, the straight line position–time graph indicates that the velocity of the ball is constant. There is no acceleration in the horizontal direction.

The graph of the vertical position of the ball (Figure 2.5.2b) is quite different. It shows that:

- The distance from the origin increases as the ball bounces higher, and then decreases as the ball returns to the ground.
- The graph is roughly parabolic in shape with a changing interval between each point: the points on the graph are closer together near the top of the bounce.
- The changing gradient of the position–time graph indicates that the velocity is changing. There is a force affecting the ball and the ball is accelerating.

Velocity–time graphs of horizontal and vertical motion can be used to confirm these conclusions and determine the size and direction of the acceleration found to be affecting the ball in the vertical direction (Figure 2.5.3).

The graph of horizontal velocity versus time (Figure 2.5.3a) confirms that the horizontal velocity is constant. Once the ball leaves the person's hands, and ignoring air resistance, there are no forces acting in a horizontal direction. The ball will continue to move at the same horizontal velocity as when it was first thrown. The positive value confirms that the ball is moving further from the origin.

In the vertical direction, the gradient of the velocity–time graph confirms that there is an acceleration, and hence a force, affecting the movement of the ball. The constant gradient of the graph (allowing for small measuring errors) indicates that this acceleration is constant. The negative slope indicates that the acceleration is acting downward. The graph also shows that the ball had a maximum velocity at the bottom of the motion, that is, at the start of the bounce and at the very end of the bounce. Finally, you can see that the velocity was at a minimum (zero) when at the maximum height of the bounce.

Ignoring air resistance, the only force that causes the vertical velocity of the ball to change is gravity. Gravity is constant and acts downward towards the ground, which matches the shape of the velocity–time graph (Figure 2.5.3b).

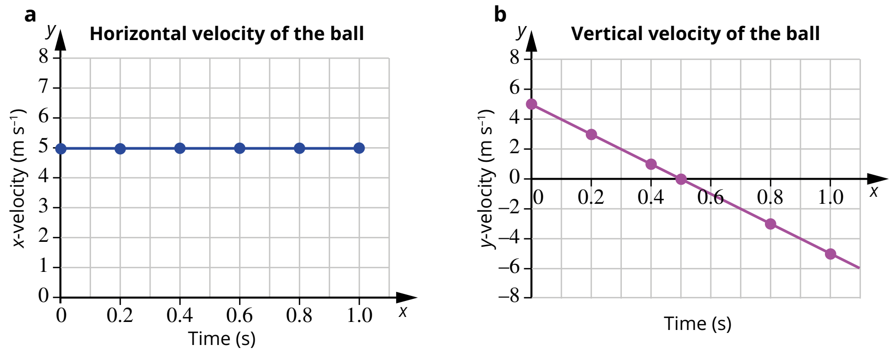


FIGURE 2.5.3 Graphs showing the velocity of the ball during a single bounce. (a) The horizontal velocity is constant. (b) The vertical velocity is changing at a constant rate, implying a constant acceleration.

As the only acceleration on the ball is vertical, this acceleration will not affect the horizontal motion. Another way of saying this is that the vertical and horizontal components of motion (velocity, displacement and acceleration) are independent of each other. A change in one of these values in one direction will not affect the value in the other direction. The only exception is time. Time is not a vector, so the time taken for the ball to travel horizontally will be the same as the time taken to travel vertically.

A spectacular example of this is that if a bullet is fired from a gun horizontally at the same time as another bullet is simply dropped, both bullets will hit the ground at the same time.

So in summary, and ignoring air resistance, an object in flight will:

- continue at a constant velocity in a horizontal direction equal to the velocity at which it left the point of release, since there is no force acting on the ball in a horizontal direction
- undergo constant acceleration downwards in a vertical direction equal to the acceleration due to gravity.

When launched upwards, an object in flight will have a maximum vertical velocity at the point of release. On returning to the same height, the vertical velocity will be of the same magnitude but in the opposite direction. It will have a zero vertical velocity at the point where it reaches its maximum height, after which it will begin to fall and the velocity will increase.

In the event that a ball is thrown directly horizontally or downwards, the horizontal velocity will remain constant once the ball is released, as there is no horizontal force acting on it. The vertical velocity will increase, as the ball is accelerated by gravity.

The resultant velocity of the object at any point will be the vector sum of the horizontal and vertical velocities of the object at that point.

This is shown diagrammatically in Figure 2.5.4. By adding the vertical and horizontal vectors that are shown in the figure, the resultant velocity of the ball can be determined.

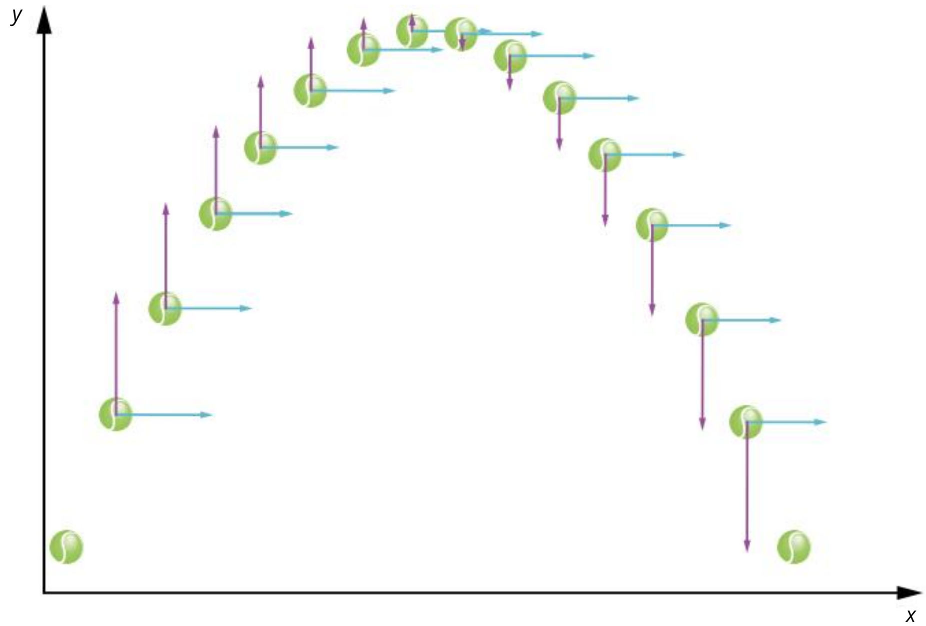


FIGURE 2.5.4 An annotated analysis of the ball from Figure 2.5.1 showing velocity vectors at each point. The horizontal velocity is constant while the vertical velocity vector shows the velocity decreasing while the ball is going up and increasing when the ball is falling.

Applying equations of motion to the flight of a ball

In Unit 2, the equations of motion were explained and applied to simple straight-line motion in one dimension. These same equations can be applied to the more complex two-dimensional motion of an object in flight. This is because two-dimensional motion, such as that of the bouncing ball, can be broken into vertical and horizontal components using the techniques described so far in this chapter.

PROJECTILES

A **projectile** is any object that is thrown or projected into the air and is moving freely; that is, it has no power source (such as a rocket engine or propeller) driving it. A netball as it is passed, a cricket ball that is hit for six, and an aerial skier flying through the air are all examples of projectiles. People have long argued about the path that projectiles follow; some thought they were circular or had straight sections. It is now known that, if projectiles are not launched vertically and if air resistance is ignored, they move in smooth parabolic paths, like that shown in Figure 2.5.5. This section considers projectiles that are launched horizontally and uses Newton's laws to solve problems involving this type of motion.

FIGURE 2.5.5 A multi-flash photograph of a golf ball that has been bounced on a hard surface. The ball moves in a parabolic path.

Projectile motion

It is a common misconception that when a projectile, such as a netball, travels forwards through the air, it has a forwards force acting on it. This is incorrect. There may have been some forwards force acting as the projectile was launched, but once the projectile is released, this forwards force is no longer acting.

In the vertical direction, a projectile accelerates due to the force of gravity, that is, at a rate of 9.8 m s^{-2} downwards.

In the horizontal direction a projectile has a uniform velocity, as there are no forces acting in this direction (if air resistance is ignored). So, the horizontal acceleration is zero.

In fact, if air resistance is ignored, the only force acting on a projectile during its flight is its weight, which is the force due to gravity, F_g. This force is constant and always directed vertically downwards. This causes the projectile to continually deviate from a straight-line path to follow a parabolic path (Figure 2.5.6). This motion is known as **freefall**.

Projectile motion is quite complex compared to straight-line motion. It must be analysed by considering the different components—horizontal and vertical—of the actual motion. The vertical and horizontal components of the motion are independent of each other and must be treated separately.

FIGURE 2.5.6 The motorcycle and rider are travelling in parabolic paths as they fly through the air.

Given that the only force acting on a projectile is the force due to gravity, F_g, it follows that the projectile must have a vertical acceleration of 9.8 m s^{-2} downwards throughout its motion.

Projectiles launched horizontally

Projectiles can be launched at any angle. The launch velocity needs to be resolved into vertical and horizontal components using trigonometry in order to complete most problems. For projectiles launched horizontally, calculating the vector components of the launch velocity is easy to do. That's because the initial vertical velocity is zero (but increases during the flight). The horizontal velocity is constant and is equal to the launch velocity. This can be verified using trigonometric ratios and a launch angle of 0°.

Solving problems with projectiles launched horizontally

1 Construct a diagram showing the projectile's motion to set the problem out clearly. Write out the information supplied for the horizontal and vertical components separately.
2 In the horizontal direction the velocity of the projectile is constant, so the only formula needed is $u_x = v_x = \frac{s_x}{t}$.
3 In the vertical direction, the projectile is moving with a constant acceleration ($9.8\,\text{m}\,\text{s}^{-2}$ down), and so the equations of motion for uniform acceleration must be used. These include:

$$v_y = u_y + gt$$
$$s_y = u_y t + \frac{1}{2} g t^2$$
$$v_y^{\,2} = u_y^{\,2} + 2gs_y$$

4 In the vertical direction it is important to clearly specify whether up or down is the positive or negative direction. Either choice will work just as effectively, but the same convention needs to be used consistently throughout each problem.
5 Pythagoras' theorem can be used to determine the actual speed of the projectile at any point.
6 If the velocity of the projectile is required, provide a direction with respect to the horizontal plane as well as the speed of the projectile.

It is easy to get the wrong idea about projectile motion when you watch cartoon characters running or driving off cliffs. In many cartoons, the character leaves the cliff and travels horizontally outwards, stopping in mid-air (Figure 2.5.7). Once they realise where they are, they immediately fall vertically downwards. This is not what happens in reality: the character starts falling in a smooth parabolic arc as soon as they leave the clifftop.

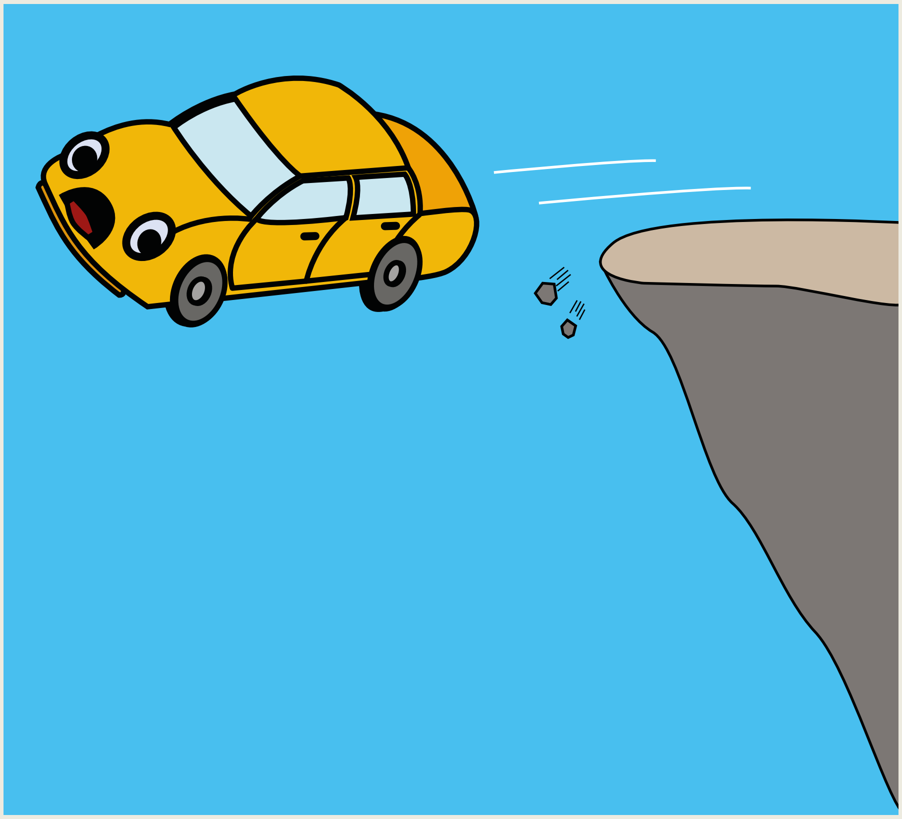
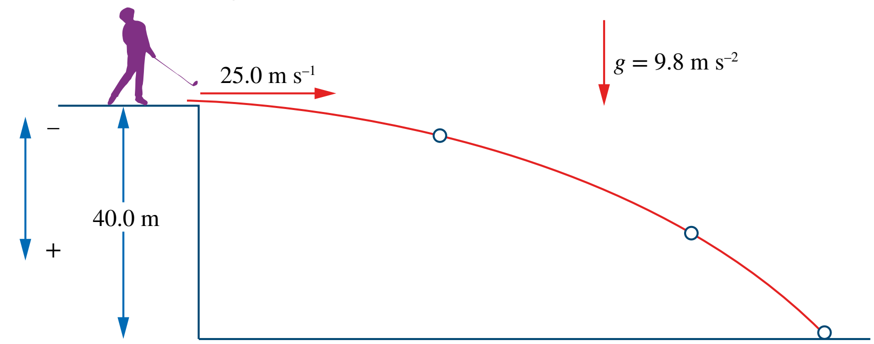


FIGURE 2.5.7 In real life, this car would start falling as soon as it leaves the clifftop and it would travel in a parabolic arc.

Worked example 2.5.1

PROJECTILE LAUNCHED HORIZONTALLY

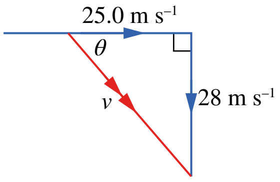
A golf ball of mass 150 g is hit horizontally from the top of a 40.0 m–high cliff with a speed of 25.0 m s^{-1}. Using $g = 9.8$ m s^{-2} and ignoring air resistance, calculate the following values.



a Calculate the time that the ball takes to land.

Thinking	**Working**
Mass does not affect the projectile's motion.	The 150 g mass value can be ignored.
Let the downwards direction be positive. Write down the information relevant to the vertical component of the motion. Note that the instant the ball is hit, it is travelling only horizontally, so its initial vertical velocity is zero.	Down is positive. Vertically: $u_y = 0$ m s^{-1} $s_y = 40.0$ m $g = 9.8$ m s^{-2} $t = ?$
In the vertical direction, the ball has constant acceleration, so use equations for uniform acceleration. Select the equation that best fits the information you have.	$s_y = u_y t + \frac{1}{2}gt^2$
Substitute values, rearrange and solve for t.	$40.0 = 0 + \frac{1}{2} \times 9.8 \times t^2$ $t = \sqrt{\frac{40.0}{4.90}}$ $= 2.857 = 2.9$ s

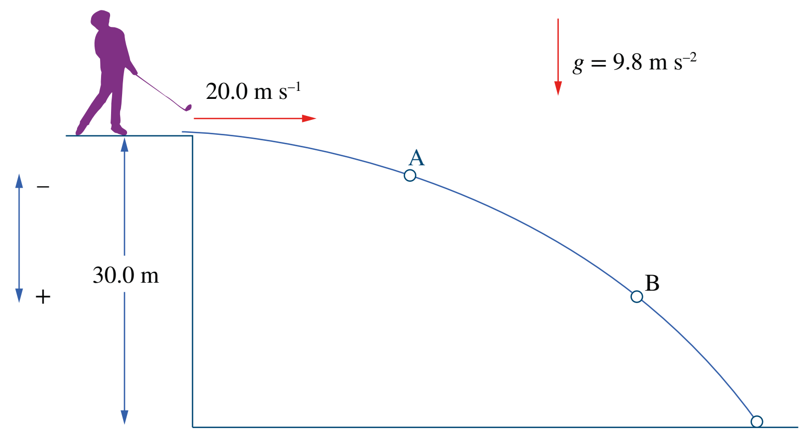
b Calculate the distance that the ball travels from the base of the cliff, i.e. the range of the ball.	
Thinking	**Working**
Write down the information relevant to the horizontal component of the motion. As the ball is hit horizontally, the initial speed gives the horizontal component of the velocity throughout the flight.	Horizontally: $v_x = 25.0\,\text{m}\,\text{s}^{-1}$ $t = 2.9\,\text{s}$ from part (a) $s_x = ?$
Select the equation that best fits the information you have.	$v_x = \frac{s_x}{t}$
Substitute values, rearrange and solve for *s*. Never round off a value until the final calculation, otherwise you will introduce a rounding error.	$25.0 = \frac{s_x}{2.9}$ $s = 25.0 \times 2.9$ $= 73\,\text{m}$ Note that the mass of the ball does not affect its motion. This is true for all objects in projectile motion or in freefall.

c Calculate the velocity of the ball as it lands.	
Thinking	**Working**
Find the horizontal and vertical components of the ball's speed as it lands. Write down the information relevant to both the vertical and horizontal components.	Horizontally: $u_x = v_x = 25.0\,\text{m}\,\text{s}^{-1}$ Vertically, with down as positive: $u_y = 0$ $g = 9.8\,\text{m}\,\text{s}^{-2}$ $s_y = 40.0\,\text{m}$ $t = 2.857\,\text{s}$ $v_y = ?$
To find the final vertical speed, use the equation for uniform acceleration that best fits the information you have.	$v_y = u_y + gt$
Substitute values, rearrange and solve for the variable you are looking for, in this case *v*.	Vertically: $v_y = 0 + 9.8 \times 2.857$ $= 28\,\text{m}\,\text{s}^{-1}$ down
Add the components as vectors.	
Use Pythagoras' theorem to work out the actual speed, *v*, of the ball.	$v = \sqrt{v_x^2 + v_y^2}$ $= \sqrt{25.0^2 + 28^2}$ $= \sqrt{1409}$ $= 38\,\text{m}\,\text{s}^{-1}$
Use trigonometry to find the angle, θ.	$\theta = \tan^{-1}\left(\frac{28}{25.0}\right)$ $= 48$
Indicate the velocity with a magnitude and direction relative to the horizontal.	The final velocity of the ball is $38\,\text{m}\,\text{s}^{-1}$ at 48° below the horizontal.

➤ Try yourself 2.5.1

PROJECTILE LAUNCHED HORIZONTALLY

A golf ball of mass 100.0 g is hit horizontally from the top of a 30.0 m high cliff with a speed of 20.0 m s^{-1}. Using $g = 9.8$ m s^{-2} and ignoring air resistance, calculate the following values.



a Calculate the time that the ball takes to land.

b Calculate the distance that the ball travels from the base of the cliff, i.e. the range of the ball.

c Calculate the velocity of the ball as it lands.

PROJECTILES LAUNCHED OBLIQUELY

The previous section looked at projectiles that were launched horizontally. More commonly, projectiles are launched at an angle to the horizontal direction, by being thrown forwards and upwards at the same time. An example of an oblique launch is shooting for a goal in basketball (Figure 2.5.8). Once the ball is released, the only forces acting are gravity pulling the ball down to Earth and air resistance, which retards the ball's motion slightly.

In this section, the principles covering horizontal projectile motion will still apply, as described by Newton's first law.

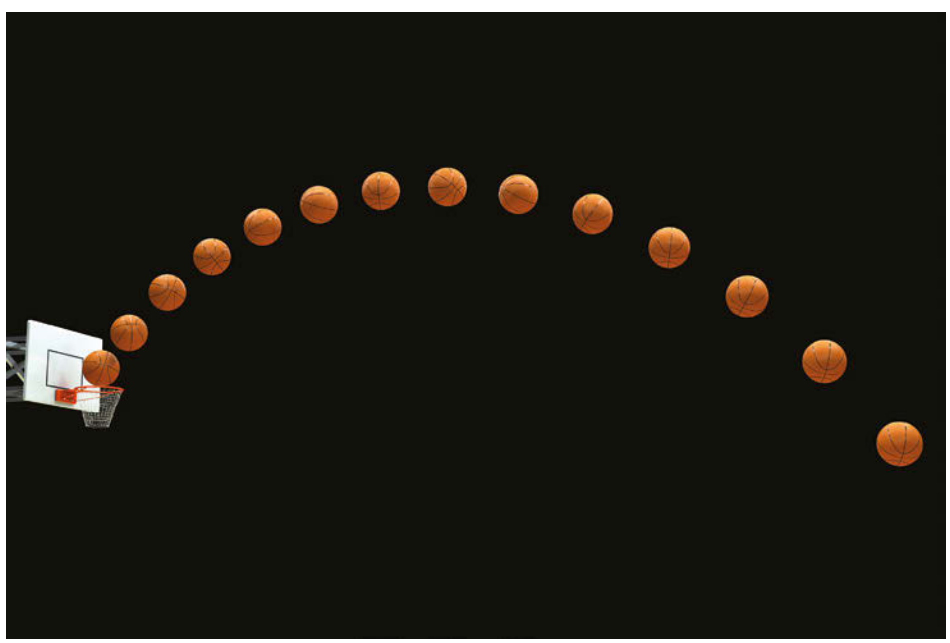


FIGURE 2.5.8 The basketball was thrown up towards the basket, travelling in a smooth parabolic path.

Projectiles launched at an angle

As with projectiles launched horizontally, if drag forces are ignored, the only force that is acting on a projectile that is launched at an angle to the horizontal is gravity, F_g.

Gravity acts vertically downwards and so it has no effect on the horizontal motion of the projectile. Recall that the vertical and horizontal components of the motion are independent of each other and once again must be treated separately.

In the vertical direction, a projectile accelerates due to the force of gravity, that is, at a rate of $9.8\,m\,s^{-2}$ downwards. The effect of the force due to gravity is that the vertical component of the projectile's velocity decreases as the projectile rises. It is momentarily zero at the very top of the flight and then it increases again as the projectile descends.

In the horizontal direction a projectile has a uniform velocity, since there are no forces acting in this direction (if air resistance is ignored).

Solving problems with projectiles launched at an angle

General rules for solving problems involving projectile motion were given in the previous section—see page 16 for a reminder.

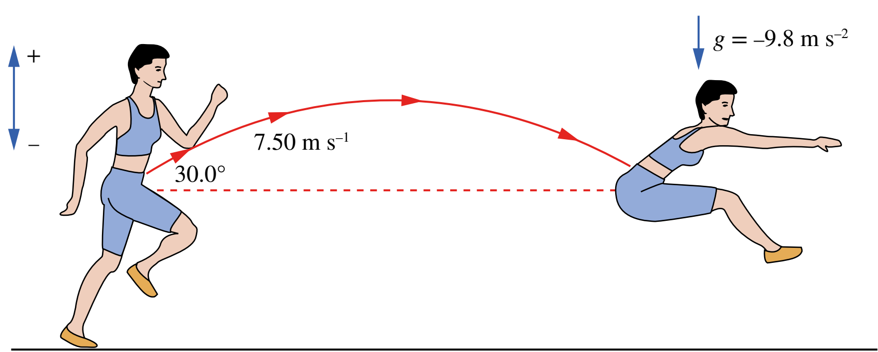
If a projectile is launched at an angle to the horizontal, the initial vertical velocity will not be zero, and trigonometry can be used to find both the initial horizontal and vertical components of the velocity. Pythagoras' theorem can be used to determine the actual velocity of the projectile at any point, as well as a direction with respect to the horizontal plane.

Worked example 2.5.2 will show you how this is done.

Worked example 2.5.2

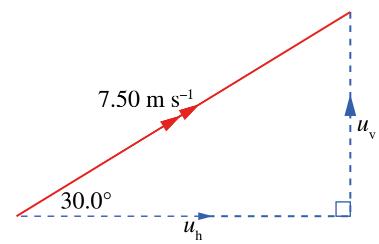
LAUNCH AT AN ANGLE

A 65.0 kg athlete in a long-jump event leaps with a velocity of $7.50\,m\,s^{-1}$ at an angle of 30.0° to the horizontal.



For the following questions, treat the athlete as a point mass, ignore air resistance and use $g = 9.8\,m\,s^{-2}$.

Worked example 2.5.2 *continued*

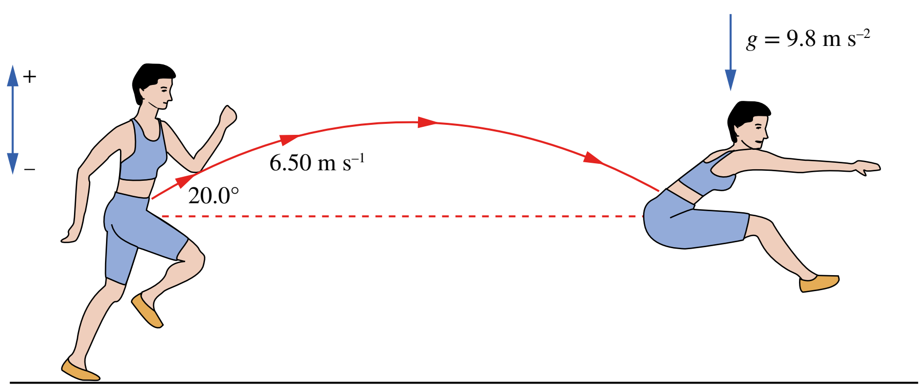
a Calculate the athlete's velocity at the highest point.	
Thinking	**Working**
Mass does not affect the projectile's motion.	The 65.0 kg mass value can be ignored.
First find the horizontal and vertical components of the initial velocity.	 Using trigonometry: $u_h = 7.50 \cos 30.0°$ $= 6.50\ m\ s^{-1}$ $u_v = 7.50 \sin 30.0°$ $= 3.75\ m\ s^{-1}$
At the highest point of the athlete's jump the vertical component of the velocity is zero, therefore the resultant velocity at this point is just the horizontal velocity.	At maximum height: $v_h = 6.50\ m\ s^{-1}$ horizontally to the right.
b Calculate the maximum height gained by the athlete during the jump.	
Thinking	**Working**
To find the maximum height that is gained, you must work with the vertical component of the velocity. Recall that the vertical component of velocity at the highest point is zero. As gravity acts in the opposite direction from the jump, the initial vertical velocity is made positive, and acceleration from gravity is made negative.	Vertically, taking up as positive: $u_v = 3.75\ m\ s^{-1}$ $g = -9.8\ m\ s^{-2}$ $v_v = 0$ $s_v = ?$
Substitute these values into an appropriate equation for uniform acceleration.	${v_v}^2 = {u_v}^2 + 2gs_v$ $0 = 3.75^2 + 2 \times -9.8 \times s_v$
Rearrange and solve for *s*.	$s_v = \frac{3.75^2}{19.6}$ $= 0.717\ m$

c Calculate the total time the athlete is in the air, assuming a return to the original height.	
Thinking	**Working**
The take-off height and landing height are the same.	The initial velocities in the *x* and *y* direction are the same as the final velocities in the *x* and *y* direction (with a negative value for the final *y* velocity).
As the motion is symmetrical, the time taken to complete the motion will be double that taken to reach the maximum height. First, the time it takes to reach the highest point must be found.	Vertically, taking up as positive: $u_v = 3.75\,\text{m s}^{-1}$ $g = -9.8\,\text{m s}^{-2}$ $v_v = 0$ $t = ?$
Insert these values into an appropriate equation for uniform acceleration.	$v_v = u_v + gt$ $0 = 3.75 - 9.8t$
Rearrange the formula and solve for *t*.	$t = \frac{3.75}{9.8}$ $= 0.383\,\text{s}$
The time to complete the motion is double the time it takes to reach the maximum height.	Total time $= 2 \times 0.383$ $= 0.766\,\text{s}$

➤ Try yourself 2.5.2

LAUNCH AT AN ANGLE

A 50.0 kg athlete in a long-jump event leaps with a velocity of $6.50\,\text{m s}^{-1}$ at 20.0° to the horizontal.



For the following questions, treat the athlete as a point mass, ignore air resistance and use $g = 9.8\,\text{m s}^{-2}$.

a Calculate the athlete's velocity at the highest point.

b Calculate the maximum height gained by the athlete's centre of mass during the jump.

c Calculate the total time the athlete is in the air, assuming a return to the original height.

PA 3.1.1

WS 3.1.2

WS 3.1.3

2.5 Review

SUMMARY

- If air resistance is ignored, the only force acting on a projectile is its weight, i.e. the force of gravity, F_g. This results in the projectile having a vertical acceleration of $9.8\,m\,s^{-2}$ down during its flight.
- Projectiles move in parabolic paths that can be analysed by considering the horizontal and vertical components of the motion.
- If a projectile is launched at an upward angle from a horizontal surface the flight will be symmetrical around the point of maximum height.
- The horizontal component and vertical components of motion are independent of each other, i.e. they do not affect each other.
- The following equations of motion for uniform acceleration must be used for the vertical component of the motion:

$$v_y = u_y + gt$$

$$s_y = u_y t + \tfrac{1}{2}gt^2$$

$$v_y^2 = u_y^2 + 2gs_y$$

- The horizontal velocity of a projectile remains constant throughout its flight if air resistance is ignored. Therefore, the following equation for average velocity can be used for this component of the motion:

$$u_x = v_x = \frac{s_x}{t}$$

- The vertical velocity of a projectile is zero at its highest point of motion.

KEY QUESTIONS

For the following questions, assume that the acceleration due to gravity is $9.8\,m\,s^{-2}$ and ignore the effects of air resistance unless otherwise stated.

Retrieval

1 Describe the horizontal velocity of a projectile throughout its flight, if air resistance is ignored.

2 State the position in the flight of a projectile when its vertical velocity is equal to zero.

Comprehension

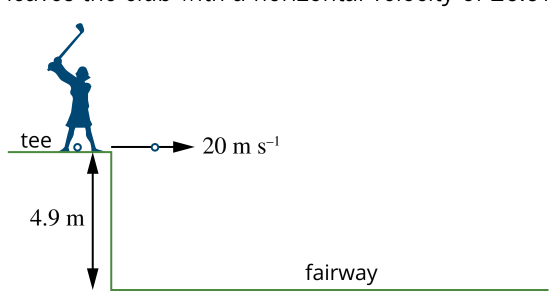
3 Describe the shape of the path of a projectile path if the horizontal and vertical components of its velocity are equal and air resistance is ignored.

Analysis

4 A marble travelling at $2.0\,m\,s^{-1}$ rolls off a jump, angled at 30° above horizontal, and takes 0.75 s to reach the floor.

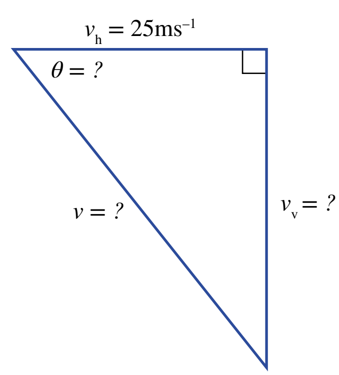
- **a** Calculate how far the marble travels horizontally before landing.
- **b** Calculate the vertical component of the speed of the marble as it lands.
- **c** Calculate the speed of the marble as it lands.

5 A golfer practising on a range with an elevated tee 4.9 m above the fairway is able to strike a ball so that it leaves the club with a horizontal velocity of $20.0\,m\,s^{-1}$.



- **a** Calculate the time taken for the ball to land on the fairway after being hit.
- **b** Calculate the horizontal distance the ball travels before landing on the fairway.
- **c** Calculate the acceleration of the ball 0.50 s after being hit.
- **d** Calculate the speed of the ball 0.80 s after it leaves the club.
- **e** Calculate the speed with which the ball hits the ground.

6 A tourist stands on top of a sea cliff that is 80.0 m high. The tourist throws a rock horizontally at $25.0\,m\,s^{-1}$ into the sea.



- **a** Determine the speed of the rock as it reaches the water.
- **b** Identify the angle at which the rock is travelling relative to the horizontal as it reaches the water.

7 A skateboard travelling at $4.0\,m\,s^{-1}$ rolls off a surface that is angled downward at 15° and that is 1.2 m high.

- **a** Determine how long the board takes to hit the ground.
- **b** Determine how far the board lands from the base of the bench.
- **c** Calculate the magnitude and direction of the acceleration of the board just before it lands.

MANDATORY PRACTICAL 1

Projectile motion—the effect of launch angle on range

MP 1

Aim

To investigate the relationship between the launch angle of a projectile, its motion and the range of the projectile.

Rationale (scientific background to the experiment)

A projectile is any object that moves, without propulsion, in free flight. If air resistance is ignored, the only force acting on a projectile during its flight is that due to gravity. This force is constant and is always directed vertically downwards. It causes the projectile to follow a parabolic path.

The motion of a projectile can be examined by looking at the horizontal and vertical components separately.

Vertically, a projectile will move with an acceleration due to gravity ($9.8\,m\,s^{-2}$ downwards at the Earth's surface).

In the horizontal component, velocity is uniform since, if air resistance is ignored, there are no forces acting in this direction.

If a projectile is launched at an angle to the horizontal, trigonometry can be used to find the initial horizontal and vertical components of the velocity. The equations of motion can then be used to calculate the horizontal distance travelled by the projectile.

Timing

40 minutes

Materials

- data-collection system
- projectile launcher (commercial or improvised, e.g. poly tube)
- projectile
- photogates and (optionally) a time-of-flight pad or stopwatch
- angle indicator
- tabletop or bench
- table clamp or burette stand and clamps
- A4 paper
- tape measure
- sticky tape
- carbon paper (optional)

Safety

Always wear safety glasses when using any kind of projectile launcher. Never look down the barrel of a mechanical projectile launcher.

Method

Risk assessment

Assessment of risks include chemical hazards and physical hazards. 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.

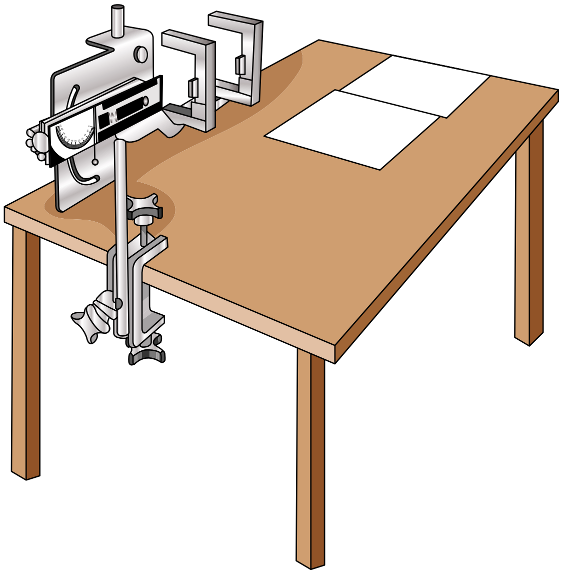
1 Start a new experiment on your data-collection system. Connect the photogates to your system following the manufacturer's instructions.

Note: If photogates aren't available to you, a stopwatch can be used to find the flight time. In estimating the uncertainty in the measurement, be sure to allow for your reaction time when both starting and stopping the watch.

2 Select 'velocity between gates' if prompted by your data-collection system.

Ensure the 'space between gates' parameter on your data-collection system is set to the measured space between your photogates.

3 Attach the projectile launcher to a table so that the projectiles travel across the longest part of the table. One suitable arrangement of launcher, photogates and table is shown in the set-up below. Use the equipment available to you to arrange the launcher to 'fire' down the length of the table and through the photogates. Be careful to avoid firing the projectile at classmates!



If a spring-loaded projectile launcher isn't available to you, a piece of curved 'poly pipe' supported by a retort stand can make a good alternative. Discuss, with the aid of diagrams, how you could do this.

4 Place sheets of paper end-to-end in a line across the length of the table in front of the projectile launcher, and secure them in place with tape.

5 Measure the height from the point the ball is released to the tabletop, and record this value in the Analysing section.

6 Mount the photogates on the launcher. Be sure to mount the first named photogate in your data-analysis software closest to the launcher.

Part 1—Distance versus angle

7 Set the launcher in the horizontal position with a launch angle of 0°. Record an estimate of the uncertainty in the measurement of the angle in the Analysing section.

8 Load a projectile into the launcher, and ensure that the launcher is set to its maximum compression or distance setting.

9 Launch the projectile, and note the point of impact on the paper.

10 Lay a sheet of carbon paper on top of the white paper over the point of impact, carbon side down, so that when a ball lands on it there will be a mark on the paper. Place a sheet of paper over the carbon paper to prevent damage to the carbon paper by the projectile.

If carbon paper is not available, look for a small indentation on the paper where the ball hits or use tracing paper heavily shaded with lead pencil. Highlight the point with a pencil or marker when the projectile lands.

What launch angle do you predict will yield the greatest horizontal range (distance)?

11 Start recording with the data collection system (or your stop watch) and launch the projectile.

Record the sampled ‘velocity between gates’ data point or time of flight, and enter the corresponding angle value in the table in the Analysing section.

12 Move the carbon paper, and measure the distance to the mark from the base of the launcher. Write the angle next to the mark on the paper.

13 Use the angle indicator on the launcher to position the launcher at the next angle, 10°.

14 Repeat the data collection steps, increasing the angle of inclination by 10° each time until you have recorded a data point every 10° from 0° to 80°.

15 Repeat the measurement for each angle an additional two times and find the average and uncertainty in the range.

16 Measure and enter the horizontal distance for each angle value into Table 1 in the Analysing section. Draw a graph of distance versus angle and a graph of velocity versus angle in the spaces provided.

Part 2—Time of flight

17 If a time-of-flight pad is available, remove one photogate and attach the time-of-flight pad. Alternatively, a handheld stopwatch or other timing mechanism can be used. Position the time-of-flight pad over the landing point recorded for an angle of 0° and reset the launcher to an angle of 0°.

Which angle do you think will give the greatest time of flight? Explain the reasons behind your prediction.

18 Start a new data-collection session. Launch the ball from the launcher and, using the time-of-flight pad or a stopwatch, record the time the ball is in flight in Table 2 of the Analysing section.

19 Use the angle indicator on the launcher to position the launcher at the next angle, and repeat the data-collection steps until you have recorded a data point every 10° from 0° to 80°. Record the time of flight for each angle in Table 2 of the Analysing section. Repeat each angle three times and find the average time and uncertainty in the range for each angle. Draw a graph of time of flight versus angle.

Variables

- Independent: launch angle
- Dependent: range of projectile
- Controlled: projectile shape, projectile mass, force of launch

Analysing

Raw and processed data

TABLE 1 Projectile data for launch angle versus distance

Angle (°) ±	Velocity ($m\,s^{-1}$)				Distance (m)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
				±				±
				±				±
				±				±
				±				±
				±				±
				±				±
								±
				±				±

TABLE 2 Projectile data for launch angle versus time of flight

Angle (°) ±	Time of flight (s)			
	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, and 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 Choose one of the angles other than 0°, and draw to scale a vector diagram for your projectile at the launch position showing both the horizontal and vertical component velocities. Show how you would determine the average initial velocity, and draw the net vector.

2 Calculate the horizontal and vertical components of velocity for each angle, and complete the columns in Table 3.

3 Use the horizontal distance and time of flight to calculate the average horizontal velocity for each angle, and fill in the corresponding column in Table 2. Why is this referred to as the *average* horizontal velocity?

4 Use the vertical velocity and the height of the launcher for each launch angle to calculate the theoretical time of flight of an object shot straight up. Record the results in Table 3.

TABLE 3 Projectile data calculations

Angle (°)	Horizontal velocity ($m\,s^{-1}$)	Vertical velocity ($m\,s^{-1}$)	Average horizontal velocity ($m\,s^{-1}$)	Theoretical time of flight (s)

➤ 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 How did the measured horizontal velocities from Table 1 compare to the calculated horizontal velocities from Table 3?

2 For any projectile launched horizontally, what can you state about the horizontal velocity?

3 Which launch angle will yield the maximum horizontal range?

Evaluation

4 Consider whether the reliability with which you could set and measure the angle of launch permitted reasonable conclusions to be drawn in this experiment. Discuss the effect of the uncertainty in your method on the reliability of your conclusion.

Improvements

5 Identify the major sources of error in this experiment and the steps taken to minimise them.

Extension

6 Are there launch angles that yield the same horizontal range? What are they and why is that the case?

➤ 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

02

KEY TERMS

acceleration
angle
component
displacement
freefall
perpendicular
projectile
Pythagoras' theorem
resolve
vector
velocity

KEY QUESTIONS

Retrieval

1 Identify which one or more of the following statements best describes a stone thrown horizontally at $5\,m\,s^{-1}$ as it falls towards a pond. Ignore air resistance.
- **A** Its speed increases.
- **B** It travels in a circular path.
- **C** There is a driving force acting on it.
- **D** The only force acting on it is gravity.

2 Identify the correct statement describing a javelin at the highest point of its path, after being launched at 40° above the horizontal.
- **A** It has zero acceleration.
- **B** It is at its minimum speed.
- **C** There are no forces acting on it since it is in freefall.
- **D** There are forwards and downwards forces acting on it.

3 Describe the horizontal velocity of a basketball as it is thrown towards the hoop in a shot for goal. Ignore air resistance.

4 State where the vertical velocity of a ball in flight will be at a minimum. Ignore air resistance.

Comprehension

5 Determine which one or more of the following answers correctly describes the path of golf balls hit on the Moon by American astronaut Alan Shepard in 1971.
- **A** The balls went into orbit.
- **B** The balls travelled in parabolic arcs.
- **C** The balls travelled in straight lines because there is no gravity.
- **D** The balls travelled much further than if they had been hit in an identical manner on Earth.

6 Determine which of the following statements best describes the comparison between the time that a ball takes to rise to its maximum height during its trajectory and the time it takes to fall back to the ground in this situation: A soccer ball was kicked by Sam. The ball rises into the air and returns to the ground at the same horizontal height some distance down the field. Ignore air resistance.
- **A** The time to rise is more than the time to fall.
- **B** The time to rise is less than the time to fall.
- **C** The time to rise is the same as the time to fall.
- **D** A comparison cannot be drawn from the information given.

Analysis

7 Using the information presented in question 6, determine which one of the following statements is correct, if the effects of air resistance are taken into account.
- **A** The ball's vertical acceleration would have increased.
- **B** The ball would have reached a greater maximum height.
- **C** The ball's horizontal velocity would have been continually decreasing.
- **D** The ball would have travelled a greater horizontal distance before striking the ground.

The following information relates to questions 8–10.

A rugby player place-kicks a ball from the kicking tee with an initial velocity such that the vertical component is $5.0\,m\,s^{-1}$ and the horizontal component is $10.0\,m\,s^{-1}$. Assume no air resistance and that the launch and landing heights are the same.

8 Determine the vertical and horizontal components of the ball's velocity at the point just before landing.

9 Calculate the value of the vertical component of the velocity 0.35 s after leaving the kicking tee.

10 **a** Calculate how long the ball will be in the air before landing.

b Calculate the horizontal distance the ball travels.

11 Charlie swims across a river that is flowing at a velocity of $1.3\,m\,s^{-1}$ south. He swims so that his direction of travel is due east, and his average velocity in swimming across the river is $0.43\,m\,s^{-1}$. Calculate the vector sum of Charlie's velocity and that of the river. Remember to specify both magnitude and direction in your answer.

12 Many well-planned cities in the United States have streets on a north–south and east–west grid. In one such city, Jenna drove 12 km west and then 2.8 km north to arrive at her destination. Determine the displacement between her origin and destination.

13 Determine the resultant force if a 20.0 N upwards force is subtracted from a 32 N force acting to the right.

14 Calculate the minimum speed (ignoring air resistance) at which a ball must leave a netballer's hands to score a goal. The netballer stands almost directly under the ring when shooting for a goal. She holds the ball at a height of 1.80 m and then shoots for goal. In order for the ball to clear the ring and drop in, it must reach a height of at least 3.30 m. Use $g = 9.8\,\text{m s}^{-2}$.

15 Calculate the total horizontal distance a ball travels when an AFL football player kicks a high torpedo punt kick towards the goal from the 50 metre line. The ball leaves his foot at an angle of 45° from the horizontal and with a speed of $23.0\,\text{m s}^{-1}$. Assume no air resistance.

16 Two identical tennis balls X and Y are hit horizontally from a point 2.0 m above the ground with different initial speeds: ball X has an initial speed of $5.0\,\text{m s}^{-1}$, and ball Y has an initial speed of $10.0\,\text{m s}^{-1}$.

a Calculate the time it takes for ball X to strike the ground.

b Calculate the time it takes for ball Y to strike the ground.

c Calculate how much further ball Y travels than ball X in the horizontal direction before bouncing.

17 An archer stands on top of a platform that is 20.0 m high and fires an arrow horizontally at $50.0\,\text{m s}^{-1}$.

a Calculate the speed of the arrow as it reaches the ground.

b Calculate the angle at which the arrow is travelling as it reaches the ground, relative to the horizontal.

18 A bowling ball of mass 7.5 kg travelling at $10.0\,\text{m s}^{-1}$ rolls off a horizontal table 1.00 m high.

a Calculate the ball's horizontal velocity just as it strikes the floor.

b Calculate the vertical velocity of the ball as it strikes the floor.

c Calculate the velocity of the ball as it reaches the floor.

d Calculate the time interval that elapsed between the ball leaving the table and striking the floor.

e Calculate the horizontal distance travelled by the ball as it falls.

f Draw a diagram showing the forces acting on the ball as it falls towards the floor.

19 Calculate the speed of a ball at its highest point if it is kicked by a rugby player taking a place kick with the ball at rest on the ground. The ball is kicked at 30.0° to the horizontal at $20.0\,\text{m s}^{-1}$.

20 A basketballer shoots for a goal by launching the ball at $15.0\,\text{m s}^{-1}$ at 25.0° to the horizontal.

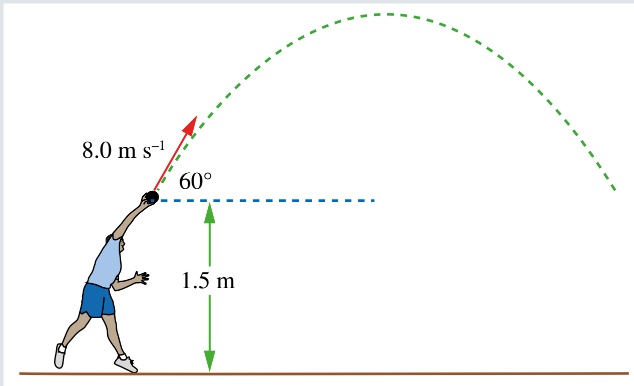
a Calculate the initial horizontal speed of the ball.

b Calculate the initial vertical speed of the ball.

c Describe the magnitude and direction of the acceleration of the ball when it is at its maximum height.

d Determine the speed of the ball when it is at its maximum height.

21 In a shot-put event a 2.0 kg shot is launched from a height of 1.5 m, with an initial velocity of $8.0\,\text{m s}^{-1}$ at an angle of 60.0° to the horizontal.



a Calculate the initial horizontal speed of the shot.

b Calculate the initial vertical speed of the shot.

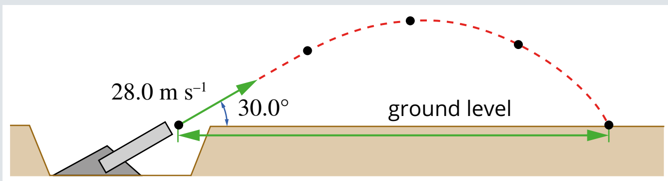
c Determine how long it takes the shot to reach its maximum height.

d Calculate the maximum height from the ground that is reached by the shot.

e Calculate the speed of the shot when it reaches its maximum height.

The following information relates to questions 22–26.

A senior physics class conducting a research project on projectile motion constructs a device that can launch a cricket ball. The launching device is designed so that the ball can be launched at ground level with an initial velocity of $28.0\,\text{m s}^{-1}$ at an angle of 30.0° to the horizontal.



22 Calculate the horizontal component of the velocity of the ball:

a initially

b after 1.0 s

c after 2.0 s.

23 Calculate the vertical component of the velocity of the ball:

a initially

b after 1.0 s

c after 2.0 s.

24 Determine the velocity of the cricket ball after 2.0 s.

25 Determine the speed of the ball as it lands.

26 Calculate the horizontal distance the ball travels before landing, that is, its range.

27 Calculate the net force acting on the stump in the following situation: A force of 2650 N is acting due east on the stump due to a rope from a tractor attempting to pull the stump out of the ground, while a force of 880 N is acting at an angle of N62°E on the same stump due to a car pulling on a rope attached to the stump.

Knowledge utilisation

28 Predict the angle to the horizontal that will result in a water stream travelling at the greatest distance through the air from a garden hose. The hose is held at ground level, with water travelling at 15 $m\,s^{-1}$.

29 Suppose the projectile launcher in the mandatory practical is placed at the edge of the table so that the projectile it fires falls to the floor. Determine the horizontal range on the floor if the projectile is fired at 1.9 $m\,s^{-1}$, assuming the ball is launched at 0.85 m high and the launcher is set to 65° upwards from the horizontal.

CHAPTER 03

Inclined planes

This chapter explores the forces on objects resting or moving on a surface that is at an angle to the horizontal. Types of forces covered in *Pearson Physics 11 Queensland*, as well as free-body diagrams and Newton's laws of motion, will be used to analyse inclined planes. Inclined planes are used to change the magnitude or direction of a force. They are experienced in many aspects of everyday life from walking up a hill to building skyscrapers.

Syllabus subject matter

Topic 1 • Gravity and motion

INCLINED PLANES

- solve problems involving force due to gravity (weight) and mass using the mathematical relationship between them
- define the term *normal force*
- describe and represent the forces acting on an object on an inclined plane through the use of free-body diagrams
- calculate the net force acting on an object on an inclined plane through vector analysis.

3.1 Inclined planes

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

- identify the forces acting on an object moving or resting on a surface at an angle to the horizontal, including the force due to gravity, friction and normal forces
- draw free-body diagrams to show the forces acting on an object on an inclined plane
- use vectors to analyse the net force acting on an object on an inclined plane.

REVIEW OF FORCES ACTING ON OBJECTS

In *Pearson Physics 11 Queensland* it was shown that a **force** is a push or a pull that can do one or more of the following to any object with mass:

- A force can change an object's velocity by changing its speed.
- A force can change an object's velocity by changing its direction of motion.
- A force can change the shape of an object.

Force is measured in newtons (N) and is a vector quantity, which means it requires a magnitude and direction to fully describe it.

> A force is a measure of the push or pull on an object.
>
> It is measured in newtons (N).
>
> It is a vector and so requires a magnitude and a direction to describe it fully.

There can be more than one force acting on an object at a time. The vector sum of these forces is known as the resultant force, or net force, F_{net}:

$$F_{net} = F_1 + F_2 + F_3 + \ldots$$

If there is no net force acting on an object, then the object will continue to move in a straight line at the same speed, or it will stay at rest. This is Newton's first law of motion.

If the net force is equal to zero, then the object is in equilibrium and it does not accelerate.

If the net force is not zero, then the object accelerates. The acceleration, a, of the object of mass m, is in the same direction as the net force and is given by Newton's second law:

$$a = \frac{F_{net}}{m}$$

or

$$F_{net} = ma$$

Forces always come in pairs known as the action force and the reaction force. This means that if a force from object A acts on object B then another force of the same magnitude but in the opposite direction will act on object A from object B. This is Newton's third law and is easily seen when you push on a heavy door to close it. You apply a force to close the door, but the door will also push back on you with the same force you gave the door.

WEIGHT

In *Pearson Physics 11 Queensland*, **weight** was shown to be a force on a massive object due to that object being in the presence of a gravitational field, e.g. Earth's gravitational field. Weight is different from mass in that mass is a scalar measure of how much material there is in the object (measured in kg) and weight is the gravitational force on that mass (a vector measured in N).

The mass of an object is the same everywhere in the universe, but its weight will change depending on the strength of the gravitational field the object is exposed to (you will learn more about this in Chapter 5). Any object with mass that is free to move in a gravitational field will experience an **acceleration due to gravity**, g.

Newton's second law of motion can be used to calculate the weight, F_g, of any mass in any gravitational field with an acceleration due to gravity g:

$$F_g = mg$$

g will vary depending on the location, but for objects on the surface of Earth, g is approximately $9.8\,\text{m}\,\text{s}^{-2}$ straight down towards the centre of Earth.

Weight is the force that acts on an object due to its mass in a gravitational field. It is given by:

$$F_g = mg$$

Worked example 3.1.1

WEIGHT AND MASS

Calculate the weight of Annie, a 44.3 kg student who is at rest on the surface of Earth.	
Thinking	**Working**
Annie's mass is given. The location is the surface of Earth, so the acceleration due to gravity is $g = 9.8\,\text{m}\,\text{s}^{-2}$.	$m = 44.3$ kg $g = 9.8\,\text{m}\,\text{s}^{-2}$ downwards
Weight is dependent on the variable g.	$F_g = mg$ $= 44.3 \times 9.8$ $= 434$ N downwards $= -430$ N

➤ Try yourself 3.1.1

WEIGHT AND MASS

Calculate the weight on the Moon of the 4932 kg lunar module that was used to land the Apollo 11 astronauts in 1969. The acceleration due to the Moon's gravitational field is $1.62\,\text{m}\,\text{s}^{-2}$.

THE NORMAL FORCE

The **normal force** is a very important force that acts on an object that is in contact with a surface. It is called the normal force because the direction of this force is always perpendicular (normal) to the surface, regardless of the angle of the surface to the horizontal. The normal force is sometimes referred to as a reaction force because it is what we 'feel' in response to our weight when we stand or sit down. If we are at rest on a horizontal surface, and no other forces are acting, our weight and the normal force acting on us are the same magnitude. These two forces will not be the same magnitude, however, if other forces act or the directions of the forces change, such as when flying in an aeroplane, or moving in an elevator.

Every object on Earth's surface has weight. This force is always present and should always be the first force considered when analysing forces.

A wooden crate of mass m located anywhere near the surface of Earth will have its weight, F_g, directed straight down (Figure 3.1.1).

If the wooden crate is resting (i.e. not moving) on the ground, it will also have its weight directed straight down (Figure 3.1.2).

This means the crate is pushing down on the Earth with a force equal to the weight of the crate. Newton's third law says that the Earth will then push back *up* onto the crate with a force of the same magnitude as F_g. This opposite force is known as the normal force, F_N, and is always perpendicular to the surface in contact with the object (Figure 3.1.3).

Note that the normal force only acts when the object is in contact with a surface. So there is no normal force in Figure 3.1.1 because the object is not in contact with a surface.

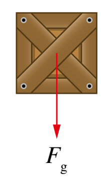


FIGURE 3.1.1 The weight, F_g, of an object anywhere near the surface of Earth is a force with its direction straight down.

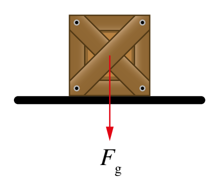


FIGURE 3.1.2 The weight, F_g, of an object resting on a horizontal surface is also a force with its direction straight down.

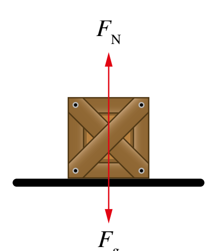


FIGURE 3.1.3 The normal force, F_N, is the force that pushes a mass upwards and is perpendicular to the surface in contact with the object.

> The normal force is a force that acts on an object when the object is in contact with a surface.
>
> The normal force always acts perpendicular to the surface.

> It is usually clear from the context whether or not something is a vector. Nonetheless, vectors can be represented using vector notation. In this book vectors are represented using italics, e.g. *F*, as are other variables and physical quantities. You might see a different type of vector notation in books and journals. This may include bold italics, such as ***F***, or a tilde or arrow above the letter such as $\tilde{F}$ or $\vec{F}$.

In the example shown in Figure 3.1.3, the forces acting on the crate are:

- weight, F_g, and
- normal force, F_N.

The crate is resting on the ground so the net force must be zero. Using Newton's second law:

$$F_{net} = \text{vector sum of all forces acting on the crate}$$

So,

$$F_{net} = F_N \text{ (as a vector)} + F_g \text{ (as a vector)}$$

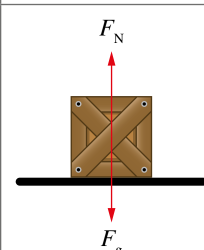
The weight and normal force are in a straight line because the surface the crate rests on is exactly horizontal. This means we can set the upwards force as positive and the downwards force as negative. So, the net force becomes:

$$F_{net} = F_N + F_g$$
$$\text{But } F_{net} = 0, \text{ so}$$
$$0 = F_N + F_g$$
$$\therefore F_N = -F_g$$

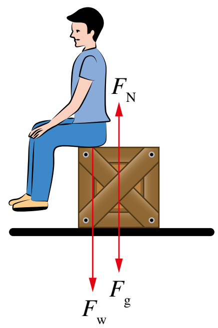
This shows that the normal force is the same size as the weight force but opposite in direction.

Worked example 3.1.2

NORMAL FORCE AND WEIGHT

A 18.2 kg wooden crate is resting on a horizontal concrete surface. Assume this takes place on Earth's surface.	
a Calculate the normal force that acts on the crate if the only other force acting on it is its weight.	
Thinking	**Working**
The mass of the crate is given and the acceleration due to Earth's gravity is 9.8 m s^{-2}.	m = 18.2 kg g = 9.8 m s^{-2} downwards
The surface is horizontal, so the force diagram will have weight straight down and normal force straight up. Draw a force diagram of this situation.	
Calculate the weight of the crate using $F_g = mg$.	$F_g = mg$ = 18.2 × 9.8 = 178 N downwards = −180 N
The crate is at rest, so the net force is equal to zero. This means that the sum of the weight and normal force as vectors is zero. Use a coordinate system so that any upwards forces are positive and any downwards forces are negative.	$F_{net} = F_N + F_g$ $0 = F_N + (-180)$ F_N = +180 N F_N = 180 N upwards

b Calculate the normal force that acts on the crate when a worker of mass 86.0 kg sits on top of it.

Thinking	Working
The mass of the crate and worker are given and the acceleration due to Earth's gravity is 9.8 m s^{-2}.	$m_c = 18.2$ kg $m_w = 86.0$ kg $g = 9.8$ m s^{-2} downwards
The surface is horizontal, so the force diagram will have the weight of the crate straight down, the weight of the worker straight down and the normal force straight up. Draw a force diagram of this situation.	 F_w is the force of the worker on the crate, i.e. the weight of the worker.
Calculate the weight of the crate and the worker using $F_g = mg$.	$F_g = m_c g$ $= 18.2 \times -9.8$ $= 180$ N downwards $= -180$ N $F_w = m_w g$ $= 86.0 \times -9.8$ $= 840$ N downwards $= -840$ N
The crate is at rest, so the net force is equal to zero. This means that the sum of the weight of the crate, the weight of the worker and the normal force as vectors is zero. Use a coordinate system so that any upwards forces are positive and any downwards forces are negative.	$F_{net} = F_N + F_g + F_w$ $0 = F_N + (-180) + (-840)$ $F_N = 180 + 840$ $= +1020$ N $= 1020$ N upwards

➤ Try yourself 3.1.2

NORMAL FORCE AND WEIGHT

Another wooden crate (of mass 12.4 kg) is on the same concrete floor. A worker, standing on the floor, attempts to lift the crate off the floor with a force of 94 N.

Calculate the normal force acting on the crate if the crate is at rest.

FREE-BODY DIAGRAMS

A diagram showing all of the forces acting on a single object is called a **free-body diagram**. Free-body diagrams are used to simplify the process of analysing the forces, and hence the resultant motion of a single object, by only showing forces that act directly on that particular object.

Usually, forces are drawn concurrently (i.e. from the same point on the object) and should show which force acts in which direction. Forces can be drawn to scale, but this is often not practical, and can introduce the possibility of measuring error. Forces have not necessarily been drawn to scale in this book. Sometimes the net force is shown alongside the diagram to indicate the direction of acceleration if the object is not in equilibrium.

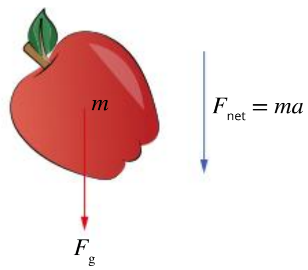


FIGURE 3.1.4 The free-body diagram of a falling apple with no air resistance or drag. Note that the net force is also shown next to the free-body diagram to show the direction of the net force.

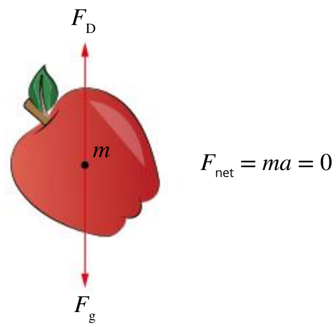


FIGURE 3.1.5 The free-body diagram of a falling apple with drag. In this example the drag is equal in magnitude to the weight so there is no net force and the apple falls with constant velocity.

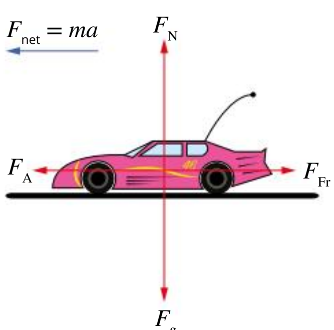


FIGURE 3.1.6 This free-body diagram of a remote-controlled car shows four forces acting (weight, normal force, friction and applied force) to give a net force to the left.

Drag and friction are forces that oppose the motion of the object. Drag acts to slow the motion of an object as it travels through air or a liquid. Frictional forces act to resist motion when two surfaces are in contact.

An example of a simple free-body diagram is that of a freely falling apple, of mass m, dropped from a high balcony. In this case the only force acting on the apple is its weight, if we ignore **drag** (Figure 3.1.4).

As there is only one force acting on the apple, the net force will be equal to the weight of the apple:

$$F_{net} = F_g$$
$$\therefore ma = mg$$

and

$$a = g$$

Hence the apple accelerates downwards at 9.8 m s^{-2}.

When drag is added to the falling apple, the free-body diagram could be as shown in Figure 3.1.5.

In this example the magnitude of the drag equals the magnitude of the weight (the lengths of the two vectors are the same), so there is no net force and the apple falls with constant velocity:

$$F_{net} = F_D + F_g$$
$$= 0$$
$$\therefore a = 0$$

Finally, an example of a free-body diagram of a remote-control car is shown to the left (Figure 3.1.6). The diagram shows four forces (weight, F_g, normal force, F_N, **frictional force**, F_f, and **applied force**, F_A) acting on the car. The forces sum to give a net force to the left, indicating that the car is accelerating directly to the left.

Note that left is taken as the positive direction along the horizontal.

$$F_{net} = F_A - F_f + F_N - F_g$$

As the car is not accelerating up or down:

$$F_N - F_g = 0$$

so that

$$F_{net} = ma = F_A - F_f$$

or

$$a = \frac{F_A - F_f}{m}$$

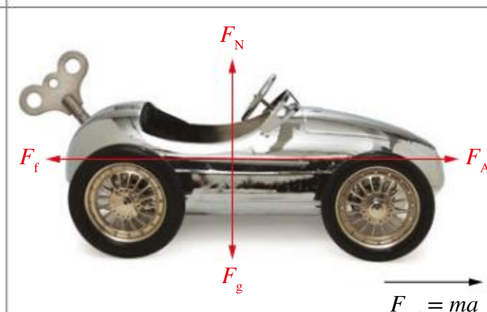
Worked example 3.1.3

FREE-BODY DIAGRAMS

A 0.125 kg wind-up toy is held motionless on a horizontal carpet. Max releases the toy and the unwinding of the internal spring causes the toy to accelerate towards the right until it hits a wall.

Friction acting on the toy is 0.007 50 N and the internal spring applies 0.0520 N of force to the toy.

a Draw a free-body diagram of the forces acting on the toy while the spring was unwinding.

Thinking	Working
There are four forces acting: friction, applied force, weight and normal force. Friction and applied force are drawn horizontally, and weight and normal force are drawn vertically, with both sets of forces at right angles to each other. A non-zero net force acts to the right.	

b Calculate the acceleration of the toy.	
Thinking	**Working**
There are several values given: friction, mass and applied force. Right is taken as the positive direction.	$m = 0.125\,kg$ $F_f = 0.007\,50\,N$ $F_A = 0.0520\,N$
The given acceleration is towards the right, so this means the weight and normal force cancel each other out. Newton's second law can now be used with the friction and applied force. Note that the applied force and net force are in the same direction so they will have the same sign.	$F_{net} = F_A + F_f$ $= ma$
Substite in the given values.	$F_{net} = 0.125 \times a$ $= 0.0520 - 0.007\,50$
Rearrange to give the acceleration of the toy.	$a = \frac{0.0520 - 0.00750}{0.125}$ $= 0.356\,m\,s^{-2}$
Write the acceleration as a vector with magnitude and direction.	$a = 0.356\,m\,s^{-2}$ to the right

In a free-body diagram only forces that directly affect the object are shown. These add up to give the net force on the object.

The net force, in turn, then determines the acceleration of the object using Newton's second law of motion, $F = ma$.

➤ Try yourself 3.1.3

FREE-BODY DIAGRAMS

A 66.0 kg student is standing in a lift on the ground floor of a building. She presses the button marked '2' to go up to her floor. The lift accelerates upwards at $0.820\,m\,s^{-2}$ for a few seconds before it then moves at a constant velocity.

a Draw a free-body diagram showing the forces that act on the student as the lift accelerates upwards.

b Calculate the normal force the student experiences as the lift accelerates upwards.

Brief descriptions of the common forces that can act on a massive object are shown in Table 3.1.1.

TABLE 3.1.1 Summary of the common forces that act on a massive object

Type of force	Symbol	Description	Where it acts
applied force	F_A	the force given to an object by an external push or pull, such as an engine	in the same direction as the push or pull
weight	F_g	the force on an object due to the presence of a gravitational field	always straight down on the surface of Earth towards the centre of Earth
normal force	F_N or N	the force on an object that is due to the contact between the object and the surface it is touching. The surface pushes back on the object due to Newton's third law of motion.	always perpendicular to the surface the object sits on
frictional force	F_f	the force on an object that opposes the motion of the object	always opposite to the direction of motion
tension	F_T or T	the force that acts along a string or wire when it is pulled tightly by forces at either end. It acts equally at all points in the string or wire.	along the string or wire, but away from the object
drag	F_D	air resistance, or the retarding force on an object due to its motion through a gas or liquid	always opposite to the direction of motion

INCLINED PLANES

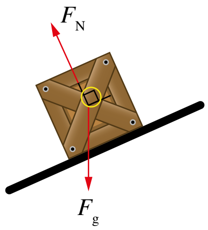


FIGURE 3.1.7 The weight of an object is always straight down, but the normal force is always perpendicular to the surface it is in contact with.

> The normal force is still perpendicular to the surface even if the surface is not horizontal.
>
> The weight is still straight down even if the surface is not horizontal.

If the crate shown in Figure 3.1.7 is on the ground but the ground itself is at an angle to the horizontal, the weight will still always act straight down, and the normal force still acts perpendicular to the surface.

In this case the weight and normal force are no longer in a straight line, and the magnitude of the normal force is no longer equal to the magnitude of the weight. The magnitude of the weight still has a negative value as its direction is straight down, but the normal force is no longer straight up. When this happens, components of the either the normal force or the weight must be calculated in order to fully analyse the situation.

In this situation, the crate can either be at rest, moving with a constant velocity, or accelerating along an **inclined plane**. All of Newton's laws of motion still apply; that is, the sum of all forces acting on the crate is equal to the mass of the crate multiplied by the acceleration of the crate, and that if the sum of forces acting on the crate is zero, then the crate will be stationary or moving at a constant velocity.

As the angle that the inclined plane makes with the horizontal increases, the normal force decreases. This is because there is a smaller and smaller force pushing perpendicular to the surface when the plane is at an angle to the horizontal, and zero when the plane is perpendicular to the horizontal (Figure 3.1.8).

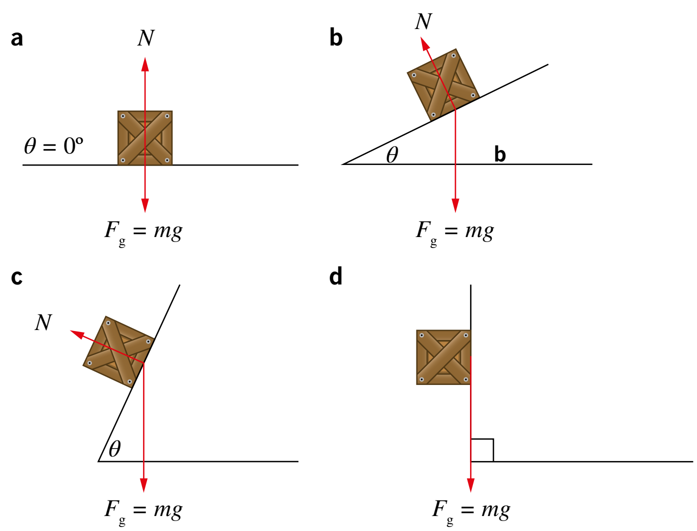


FIGURE 3.1.8 As the angle to the horizontal increases from 0° in (a), the magnitude and direction of the normal force changes, as in (b) and (c), until it is zero when the inclined plane is 90° to the horizontal. In all cases, the normal force is always perpendicular to the inclined plane.

In drawing free-body diagrams of objects on inclined planes, all forces are written according to a set of axes that are either parallel (the x-direction) or perpendicular (the y-direction) to the inclined plane (Figure 3.1.9). In defining the axes this way, it is only the weight that will need to be separated into components, as the normal force will always be perpendicular to the plane and any frictional forces will always act parallel to the plane (since the object's motion will either be up or down the incline).

To find the value of the normal force, the weight must be separated into components:

- F_{gy}, the component of F_g perpendicular to the plane (which will be equal to the normal force)
- F_{gx}, the component of F_g parallel to the plane.

These components are shown as a right-angled triangle in Figure 3.1.10 and with the full system of forces in Figure 3.1.11.

Note that the angle formed between the weight and the component of the weight perpendicular to the plane is the same as the angle the inclined plane makes with the horizontal.

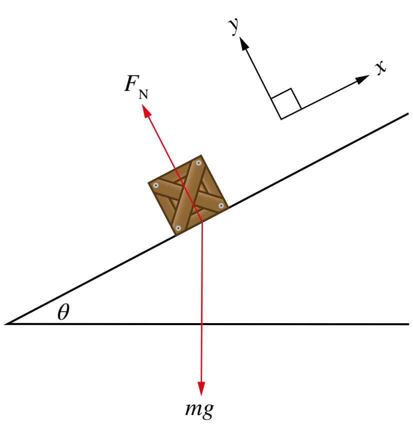


FIGURE 3.1.9 The forces acting on an inclined plane should be set up according to a pair of x- and y-axes, i.e. parallel (for the x-axis), and perpendicular (for the y-axis) to the inclined plane.

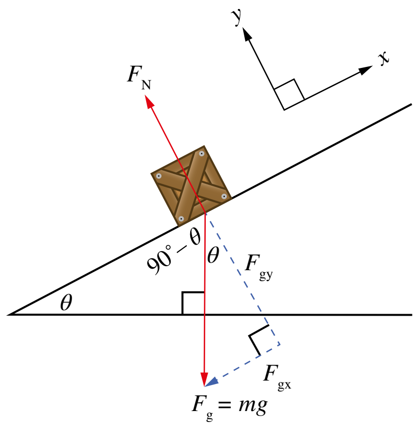


FIGURE 3.1.11 The angle formed between the weight and the component of the weight perpendicular to the plane is the same as the angle the inclined plane makes with the horizontal.

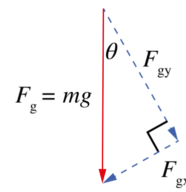


FIGURE 3.1.10 The components of weight parallel (F_{gx}) and perpendicular (F_{gy}) to the inclined plane are shown in purple. These vectors make a right-angled triangle, with the weight (F_g) as the hypotenuse.

As long as there are no other forces acting on the crate, the components of the weight can now be calculated.

Using trigonometry:

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{F_{gy}}{F_g}$$

or

$$F_{gy} = F_g \cos\theta$$

Using the definition of weight as $F_g = mg$, we can now write F_{gy} as:

$$F_{gy} = mg\cos\theta$$

and as this vector is exactly 180° to the normal force, it must be equal to the normal force:

$$F_N = F_{gy} = mg\cos\theta$$

The component of weight acting parallel to the plane, F_{gx}, is found using sine of θ in a similar way to give:

$$F_{gx} = F_g \sin\theta$$

The normal force, F_N, and the component of weight *perpendicular* to the plane, F_{gy}, are the only forces that act perpendicular to the plane and are balanced. Since they are equal, the net force will not be perpendicular to inclined plane. But the component of the weight *parallel* to the plane, F_{gx}, is not balanced so, unless there is another force acting parallel to the plane, the crate will accelerate down the plane.

Typically, there are at least two other forces acting on an object on an inclined plane and they are the applied force (if the object has an engine or can supply a force that helps the object to move in a forwards direction) and friction (which always opposes the motion of the object). These are added to the inclined plane force diagram to show the forces acting on a car accelerating up the plane (Figure 3.1.12).

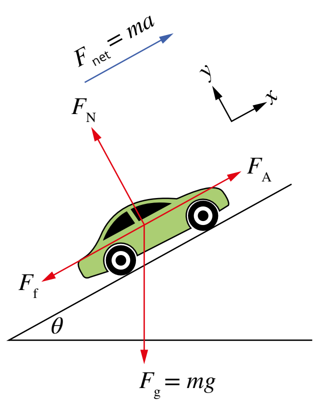


FIGURE 3.1.12 A full free-body diagram showing all of the typical forces acting on an object that is accelerating up an inclined plane. All forces, except weight, act directly along either the *x*- or *y*-axes shown in the top right corner.

The applied force and friction do not need to have their components resolved because they are already parallel to the inclined plane, i.e. along the *x*-axis.

A full free-body diagram showing all of the forces acting on an object on an inclined plane can now be drawn for three situations and Newton's second law used to analyse the motion of the object. These situations are when:

- the applied force is up the incline
- the applied force is down the incline
- there is no applied force.

In all situations, unless otherwise stated, the direction of acceleration (if any), will only be up or down the incline, not at an angle into the plane or out of the plane.

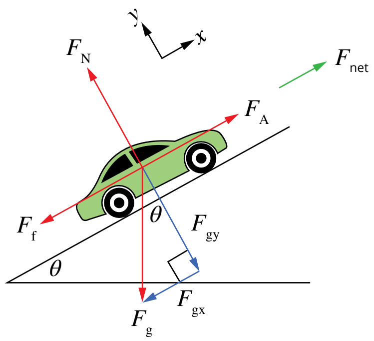


FIGURE 3.1.13 The full free-body diagram and weight components for the applied force directed up the inclined plane.

> The magnitude of the component of the weight acting parallel to the plane, F_{gx}, is equal to $mg\sin\theta$.
>
> The magnitude of the component of the weight acting perpendicular to the plane, F_{gy}, is equal to $mg\cos\theta$.

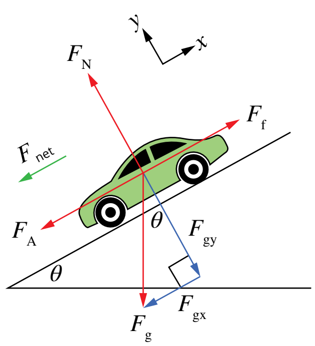


FIGURE 3.1.14 The full free-body diagram and weight components for the applied force directed down the inclined plane.

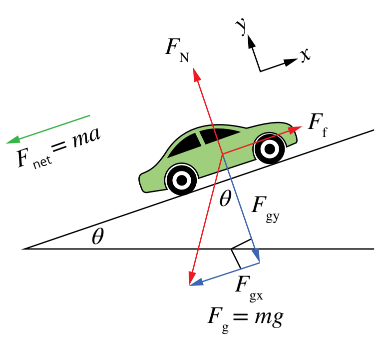


FIGURE 3.1.15 The full free-body diagram and weight components when there is no applied force along an inclined plane.

Applied force up the incline

A common scenario is that of the applied force acting up the incline as is the case of a car moving up a hill either with or without acceleration.

The free-body diagram of this situation is shown in Figure 3.1.13.

The components of weight can be written:

$$F_{gy} = F_g \cos\theta$$
$$F_{gx} = F_g \sin\theta$$

If the car is accelerating up the inclined plane, then the net force is parallel to the plane. This means that the component of the net force perpendicular to the plane must be zero, thus:

$$F_{\text{net perpendicular}} = F_N - F_{gy} = 0$$
$$\therefore F_N = F_{gy} = mg\cos\theta$$

The net force can now be written as a vector sum of all of the forces acting parallel to the plane:

$$F_{\text{net parallel}} = F_{net} = F_A - F_{gx} - F_f = ma$$

Remember that the direction up the incline is taken as positive and down the incline is taken as negative, so the applied force is the only acting force that has a positive value. Friction and F_{gx} have negative values. Then the acceleration of the car up the incline will therefore be:

$$a = \frac{F_{\text{net parallel}}}{m} = \frac{F_A - F_{gx} - F_f}{m}$$

Note that if the net force is equal to zero, then the car is either stationary, or moving up the incline with a constant velocity or down the incline with a constant velocity. This will happen if the applied force is equal to the frictional force plus F_{gx}:

$$\text{If } F_{\text{net parallel}} = 0$$
$$\text{then } F_A - F_{gx} - F_f = 0$$
$$a = 0,$$
$$\text{with } F_A = F_f + F_{gx}$$

Applied force down the incline

If the applied force from the car's engine is now down the inclined plane (i.e. the car is moving down a hill), the only difference from the above scenario is the direction of the applied force and friction (Figure 3.1.14).

The normal force and F_{gy} will still balance, and F_{gx} will still act down the incline, but now friction acts up the incline, since it opposes the motion of the car. The applied force is now in the *same* direction as the component of weight down the incline. This means that the overall acceleration of the car down the incline is:

$$a = \frac{-F_{\text{net parallel}}}{m} = \frac{(-F_A - F_{gx} + F_f)}{m}$$

As the component of weight acting down the incline is now being added to the applied force, this makes the acceleration of the car much larger than that of the car accelerating up the incline. This is why it is much easier to move downhill than uphill: you have a component of your weight helping you to go down the hill as well as your own applied force.

No applied force

If there is no applied force acting on an object (i.e. a car's engine is turned off, or an object is allowed to roll down a hill), then the free-body diagram of the inclined plane is simpler (Figure 3.1.15).

As long as friction is smaller than F_{gy}, the object will accelerate down the hill:

$$a = \frac{-F_{\text{net parallel}}}{m} = \frac{(-F_{gx} + F_f)}{m}$$

If the frictional force is equal to F_{gy}, the object will move down the incline at constant speed (or will remain at rest if it was already stationary).

In the ideal case where there is no friction acting, the value of the acceleration of the object moving down an incline can be used to measure the value of Earth's acceleration due to gravity. Galileo Galilei, in a series of very famous experiments in the 17th century, did this and showed that the time it took for an object to roll down an inclined plane is independent of its mass.

The acceleration of an object rolling down an inclined plane without friction and without any applied force is:

$$\begin{aligned} a &= \frac{F_{\text{net parallel}}}{m} = \frac{F_{gx}}{m} \\ &= \frac{F_g \sin\theta}{m} \\ &= \frac{mg\sin\theta}{m} \\ \therefore a &= g\sin\theta \end{aligned}$$

As the angle of the incline is increased, $\sin\theta$ gets closer and closer to 1. This means that the acceleration of an object gets closer and closer to $9.8\,\text{m}\,\text{s}^{-2}$. For smaller angles, the value of the acceleration is smaller and easier to measure.

Strategies for solving inclined plane problems

The following summarises strategies for solving inclined plane problems:

- List the information you are given.
- Draw a free-body diagram.
- Label each force acting on the mass. Typically these forces are:
  - normal force, F_N
  - weight, F_g
  - applied force, F_A
  - friction, F_f
  - tension, F_T or T
  - drag, F_D
- If the mass is accelerating, then there will be a net force in the direction of this acceleration.
- If the mass is not accelerating, then there will be zero net force.
- Remember that the net or resultant force is equal to the sum of all forces acting on the mass.
- Weight is typically the only force that requires its components to be resolved perpendicular and parallel to the incline. Use trigonometry to calculate these components.
- Finally, a question might ask for the final velocity, time or displacement of the mass moving along the inclined plane. As a reference, the four equations of motion are given here:

$$\begin{aligned} v &= u + at \\ s &= ut + \tfrac{1}{2}at^2 \\ v^2 &= u^2 + 2as \\ s &= \left(\frac{u+v}{2}\right)t \end{aligned}$$

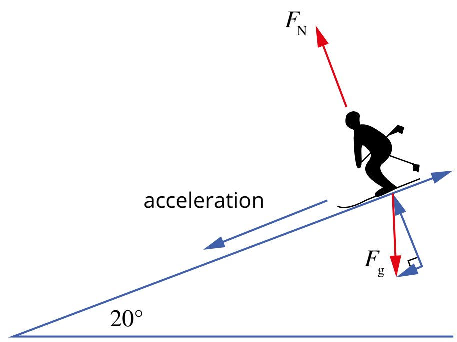
where:

s is the displacement along the inclined plane (m)
u is the initial velocity along the plane ($\text{m}\,\text{s}^{-1}$)
v is the final velocity along the plane ($\text{m}\,\text{s}^{-1}$)
a is the acceleration along the inclined plane ($\text{m}\,\text{s}^{-2}$)
t is the time taken for the acceleration (s).

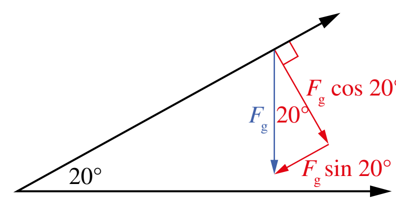
Worked example 3.1.4

INCLINED PLANES I

A skier of mass 50.0 kg is skiing freely down an icy slope that is inclined at 20.0° to the horizontal. Assume that friction is negligible and that the acceleration due to gravity is 9.8 m s^{-2}.



a Determine the components of the weight of the skier perpendicular to the slope and parallel to the slope.

Thinking	Working
The components of weight perpendicular and parallel to the slope are given by trigonometric equations.	
Calculate the weight of the skier.	$F_g = mg = 490$ N $m = \frac{490}{9.8} = 50$ kg
F_{gx} is the component of weight parallel to the slope.	$F_{gx} = F_g \sin 20.0°$ $= 490 \sin 20.0°$ $F_{gx} = 170$ N down the slope
F_{gy} is the component of weight perpendicular to the slope.	$F_{gy} = F_g \cos 20.0°$ $= 490 \cos 20.0°$ $F_{gy} = 460$ N perpendicular to the slope downwards

b Determine the normal force acting on the skier.

Thinking	Working
The normal force is equal in magnitude to the perpendicular component of weight, F_{gy}, but acts in the opposite direction.	$F_N = -F_{gy} = 460$ N perpendicular to the slope out of the plane

c Calculate the acceleration of the skier down the slope.	
Thinking	**Working**
The net force is down the slope, so this will be equal to the sum of all forces acting parallel to the slope. (The sum of all forces perpendicular to the slope add to zero.) The acceleration is then equal to the net force divided by the mass of the skier.	$F_{net} = ma =$ sum of forces parallel to slope $F_{net} = ma = F_{gx}$ $= 170$ So, $a = \frac{F_{net}}{m} = \frac{170}{50} = 3.36\,N$ $a = 3.4\,m\,s^{-2}$ down the slope

➤ Try yourself 3.1.4

INCLINED PLANES I

A much heavier skier of mass 85.0 kg skies freely down the same icy slope. Assume that friction is negligible and that the acceleration due to gravity is $9.8\,m\,s^{-2}$.

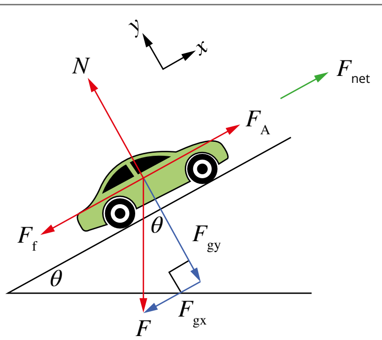
a Determine the components of the weight of the skier perpendicular to the slope and parallel to the slope.

b Determine the normal force acting on the skier.

c Calculate the acceleration of the skier down the slope.

Worked example 3.1.5

INCLINED PLANES II

An 850.0 kg car is accelerating up a road with a slope of 12.0° at $0.25\,m\,s^{-2}$. Calculate the force the engine provides to the car if the frictional forces on the car add to 500.0 N. Take g as $9.8\,m\,s^{-2}$.	
Thinking	**Working**
List what is given in the question, remembering that friction is a force that acts in a direction opposite to the motion.	$\theta = 12.0°$ $a = 0.25\,m\,s^{-2}$ $F_f = 500.0\,N$ down the slope. $m = 850.0\,kg$ $F_A = ?$
Draw a diagram of the car on the inclined plane showing all of the forces acting on it.	

Worked example 3.1.5 *continued*

Since the car is accelerating up the slope, all forces parallel to the slope need to be accounted for. This means that the parallel component of weight must be calculated. F_{gy}, the perpendicular component of weight, does not need to be calculated here since this force, and the normal force, do not contribute anything to the acceleration. (Those forces are at right angles to the net force.)	$F_g = mg$ $= 850.0 \times 9.8$ $F_g = 8300$ N straight down $F_{gx} = F_g \sin 12.0°$ $= 8300 \times \sin 12.0°$ $F_{gx} = 1700$ N down the slope
The car is accelerating up the slope, so Newton's second law can be written as: the net force is equal to the vector sum of friction, applied force and F_{gx}. The magnitudes of the vectors can now be written with any vector going up the slope taken as a positive value, and any vector going down the slope taken as a negative value.	$F_{net} = ma = F_A - F_f - F_{gx}$ And, using magnitudes of the vectors $F_{net} = ma = F_A - F_f - F_{gy}$
Substitute the values for m, a, F_f and F_{gx}.	$F_{net} = ma = F_A - F_f - F_{gy}$ $= 850.0 \times 0.25 = F_A - 1700 - 500.0$ $212.5 = F_A - 1700 - 500.0$ So, $F_A = 212.5 + 1700 + 500.0$ $= 2413$ N
Write the applied force as a vector with magnitude and direction.	F_A, the applied force, is 2413 N up the slope.

➤ Try yourself 3.1.5

INCLINED PLANES II

PA 3.1.2

> Calculate the acceleration of the car if the same car turns around and is now accelerating down the slope with the same frictional force and applied forces acting.
>
> Take g as 9.8 m s^{-2}.

3.1 Review

SUMMARY

- The weight, F_g, of an object is the force due to gravity. It acts straight down in all situations.
- A normal force, F_N, acts between an object and a surface, at right angles to the surface.
- On a horizontal surface, $F_N = -F_g$ and the object is not accelerating if there are no other forces present.
- On an inclined plane, F_N is equal and opposite to the component of the weight acting perpendicular to the plane, i.e. $F_N = -F_g \cos\theta$.
- A free-body diagram shows all the forces acting on a single object.
- Vectors are used to analyse the net force acting on an object on an inclined plane.

KEY QUESTIONS

Retrieval

1 State the formula for calculating the magnitude of the weight of an object.

2 Name the unit of weight.

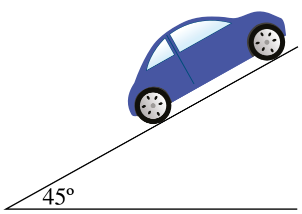
3 Identify the direction in which the weight of an object acts.

4 Identify the direction in which the normal force acts.

Comprehension

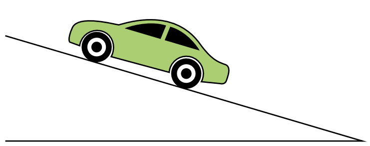
5 Explain why an object has to be in contact with a surface for a normal force to exist.

6 In 2009 in Wisconsin, USA, a car stalled and became stuck on a drawbridge while the drawbridge rose to an angle of 45° (see below). The frictional force between the car's tyres and the road stopped it from rolling down the drawbridge.



Describe how the car's weight, normal force and frictional force acting on the tyres of the car changed as the drawbridge rose. (Apparently the driver, uninjured, waited until the bridge came back down and drove off as if nothing had happened.)

7 The car in the image below is accelerating up the inclined plane under the power of its engine.



Draw a free-body diagram if there is friction acting on the car. Include the net force and *x*- and *y*-axes in your diagram.

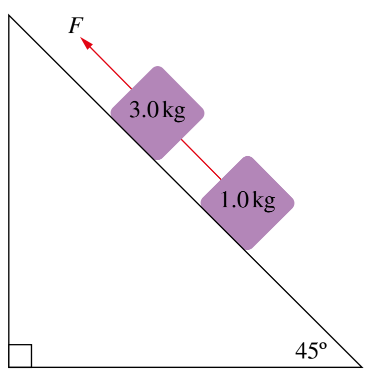
Analysis

8 Determine the force the engine must be applying to a 35 000 kg fully loaded bus being driven at a constant velocity up a 5.1° slope, if frictional forces add to 1600 N.

9 Two masses, 1.0 kg and 3.0 kg, are tied together with a light rope and pulled up a 45° frictionless incline with a force *F*, as shown below.

Determine the tension in the rope and the value of *F* if the acceleration of the system is 2.0 m s^{-2} up the incline.

Remember that tension is a force directed along a rope or chain that is away from the object the rope or chain is supporting. Draw free-body diagrams on each block showing the directions of each force.



Chapter review

03

KEY TERMS

acceleration due to gravity
applied force
drag
force
free-body diagram
frictional force
inclined plane
normal force
tension
weight

KEY QUESTIONS

Retrieval

1 Identify the situation in which weight is equal to the normal force.
- **A** in all situations
- **B** when the surface is at 0° to the horizontal
- **C** when the surface is at 45° to the horizontal
- **D** when the surface is at 90° to the horizontal

2 Identify the option that best describes the motion of a rubber ball rolling down a slope on which friction is negligible.
- **A** It moves with constant velocity.
- **B** It moves with constant acceleration.
- **C** It moves with increasing acceleration.
- **D** It moves with decreasing acceleration.

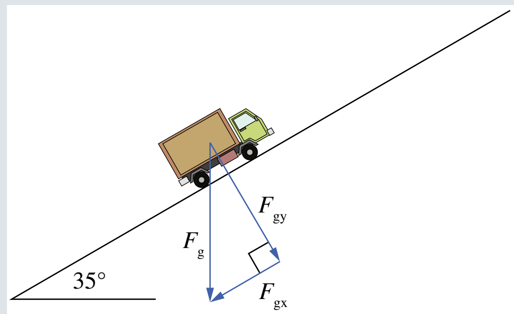
Comprehension

3 Recognise which of the following forces must balance in order for an object to remain stationary on a frictionless, inclined plane.
- **A** weight and normal force
- **B** weight and applied force
- **C** applied force and the component of weight parallel to the plane
- **D** applied force and the component of weight perpendicular to the plane

4 Recognise which of the following statements describes the forces acting on an object on a plane inclined at an angle θ, ($\theta > 0°$).
- **A** The normal force and the weight cancel out.
- **B** The normal force is equal in magnitude to the weight.
- **C** The normal force is always perpendicular to the surface.
- **D** In the absence of friction, a component of the normal force causes the object to accelerate down the slope.

5 Explain why it is much easier to ride a bicycle down a hill rather than up the hill.

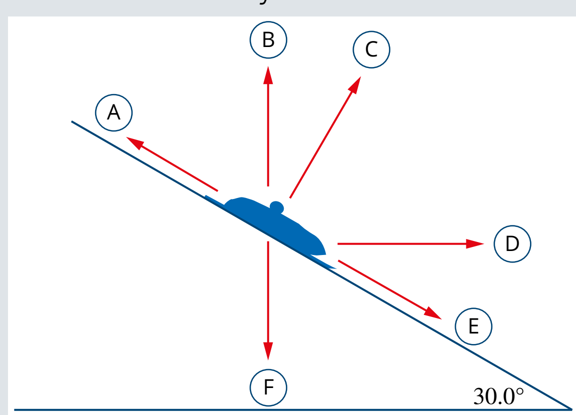
6 This is a partially drawn free-body diagram of a 2.58×10^3 kg broken-down truck resting on an inclined plane at an angle of 35° to the horizontal. Only the weight and its components are shown.



- **a** Describe the net force, and hence the acceleration, of the truck.
- **b** Complete the free-body diagram by drawing vectors representing the frictional force and normal force.
- **c** Calculate the magnitudes of the components of the weight parallel, F_{gx}, and perpendicular, F_{gy}, to the surface of the plane.
- **d** Calculate the magnitude of the normal force acting on the truck.

Analysis

7 Penny is riding in a bobsled that is sliding down a snow-covered hill with a slope of 30.0°. The bobsled is frictionless in situations where brakes are not applied. The total mass of the sled and Penny is 102 kg. Initially the brakes are on and the sled moves down the hill with a constant velocity.



- **a** Determine which one of the arrows A–F best represents the direction of the frictional force acting on the sled.

b Determine which one of the arrows A–F best represents the direction of the normal force acting on the sled.
c Calculate the frictional force acting on the sled.
d Calculate the magnitude of Penny's acceleration when she releases the brakes and the sled accelerates.
e Deduce how the acceleration of the bobsled will be affected when Penny rides the bobsled down the same slope with the brakes off, so friction can be ignored again. The sled now has an extra passenger so that its total mass is 144 kg.

8 A block is sliding down a frictionless slope that is inclined at 30.0° to the horizontal.
a Calculate the magnitude of the acceleration of the block.
b Compare the magnitude of the normal force that acts on the block with its weight.

9 Declan has a mass of 57 kg and he is riding his 3.0 kg skateboard down a 5.0 m long ramp that is inclined at an angle of 65° to the horizontal. Ignore friction when answering questions a–d.
a Calculate the magnitude of the normal force acting on Declan and his skateboard.
b Determine the net force acting on Declan and his board when no friction acts.
c Calculate Declan's acceleration as he travels down the ramp.
d Calculate his final speed as he reaches the bottom of the ramp, if Declan's initial speed is zero at the top of the ramp.
e Declan now stands halfway up the incline while holding the board in his hands. Friction now acts on Declan. Calculate the frictional force acting on Declan while he is standing stationary on the ramp.

Knowledge utilisation

10 The highest waterslide in the world is in Brazil. It is 49.0 m tall and is inclined at an angle of 60.0° to the horizontal. It is known that riders reach a speed of 91.0 km h^{-1} on this slide. Do not assume friction is negligible.
a Calculate the net force on a 70.0 kg teenager using the slide.
b Calculate the magnitude of the average frictional force opposing the teenager's motion.
c Determine the normal force acting on the teenager.

11 Belinda performed an experiment to measure the acceleration due to Earth's gravity using blocks of ice of mass 3.56 g. She allowed the ice blocks, initially at rest, to slide down an inclined ramp made of polished wood that rested on the surface of a table. She marked the starting position and final position on the ramp and measured the distance between them to be 1.90 m. She placed one end of the ramp on the surface of the table and the other end was clamped in a stand so that that particular end could be moved up or down, changing the angle of the ramp.

She recorded the angle between the surface of the table and the ramp and measured the time it took for an ice block to slide the full length of 1.90 m with a stopwatch. She then calculated the acceleration using the equation of motion:

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

with an initial velocity, u, of zero, displacement, s, of 1.90 m, and time, t, from the table.

This was repeated two more times and the average values of the times were calculated and recorded (as shown in the table below).

Angle (degrees)	Average time of ice block journey (s)	Average acceleration of the ice block (m s^{-2})
5.0	4.3	0.21
10.0	2.0	0.95
15.0	1.3	2.25
20.0	1.2	2.64
25.0	1.0	3.80
30.0	0.9	4.69

a Draw a free-body diagram of the forces acting on the ice block, including frictional forces.
b Prove that the acceleration, a, of the ice block down the ramp is given by:

$$a = g\sin\theta - \frac{F_f}{m}$$

where g is the acceleration due to Earth's gravity, m is the mass of the ice block, θ is the angle of the ramp to the horizontal, and F_f is the magnitude of the frictional force.
c Identify an assumption that Belinda made in using that particular equation of motion to determine the acceleration of the ice blocks.
d Plot a graph that shows how the acceleration of the ice block varies with the sine of the angle. Include a straight line of best fit.
e Determine the gradient and y-intercept of the line of best fit, including their units.
f Determine if the y-intercept shown on the graph is negative.
g Determine the following, using the gradient and y-intercept:
i the frictional force that acts on the ice block as it slides down the incline, F_f
ii the acceleration due to Earth's gravity, g.
h Identify one assumption that Belinda is making about the frictional force in this experiment.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CHAPTER

04 Motion in a circle

In Units 1 and 2, it was shown that the sum of all forces acting on an object of mass *m* caused it to change its velocity, i.e. accelerate. This acceleration was in the *same* direction as the net force and was calculated using Newton's second law:

$$a = \frac{F_{net}}{m}$$

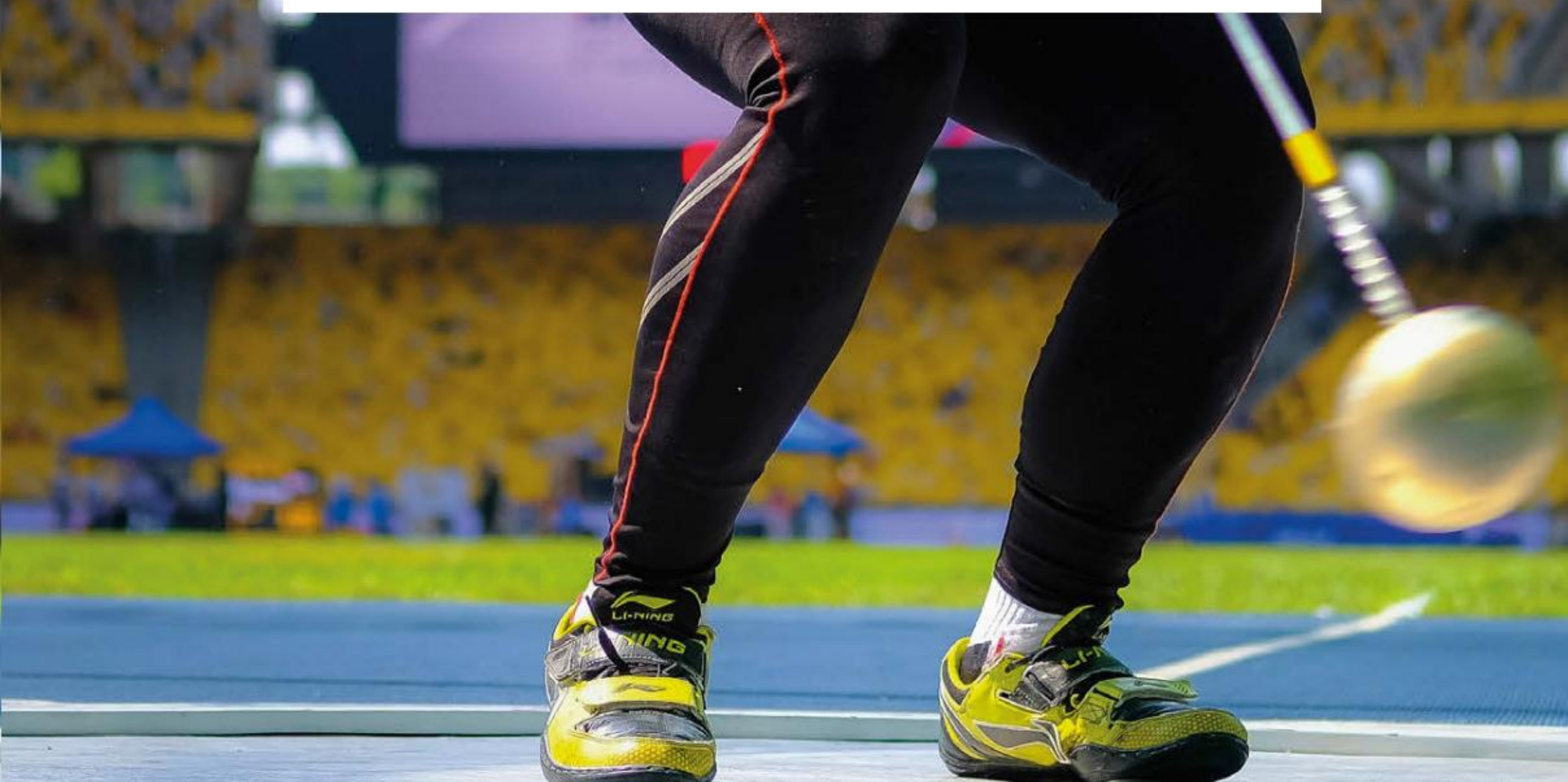
This chapter explores the idea that if a force is applied perpendicularly (at right angles) to the motion of an object, then the object will change direction. If this force is *continuously* applied at right angles to the motion of an object then the object will *continue* to change direction, i.e. it will move in uniform circular motion.

Syllabus subject matter

Topic 1 • Gravity and motion

CIRCULAR MOTION

- describe uniform circular motion in terms of a force acting on an object in a perpendicular direction to the velocity of the object
- define the concepts of average speed and period
- solve problems involving average speed of objects undergoing uniform circular motion
- define the terms *centripetal acceleration* and *centripetal force*
- solve problems involving forces acting on objects in uniform circular motion.



4.1 Circular motion

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

- define and solve problems using average speed, average velocity, period and frequency in motion around a circle
- define uniform circular motion as the motion of an object moving around a circle with a constant speed
- differentiate between average speed and average velocity
- solve problems involving the average speed of objects undergoing uniform circular motion.

From the motion of tiny gears in watches to the orbits of stars around the centre of the Milky Way galaxy, circular motion is very common. We have all experienced circular motion and the forces it involves as passengers in a car turning a corner, or watching a hammer thrower spin the hammer at the Olympic Games.

DESCRIBING CIRCULAR MOTION

In Figure 4.1.1, A is a point on the circumference of a circle of radius r that is moving with a velocity, v, in an anticlockwise direction.

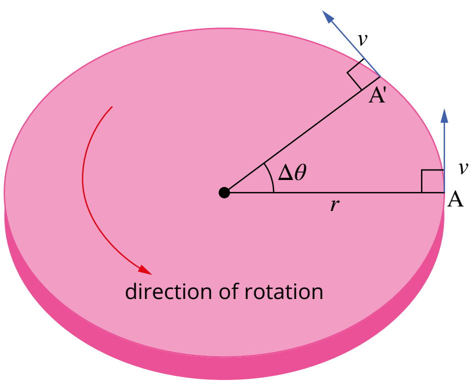


FIGURE 4.1.1 The mathematics of an object moving around a circle of radius *r* from point A to A', with a velocity *v*. Note that the direction of the velocity constantly changes.

Whenever an object moves with constant speed in a circle, it is changing three quantities:

- direction of its motion
- angle from its starting position
- distance from its starting point.

If A moves to A′ in a time t, then it will move through an angle $\Delta\theta$. The distance travelled by the object is therefore that arc of the circle moved in time t:

Distance from A to A′ = arc of AA′

$$= 2\pi r \times \frac{\Delta\theta}{2\pi} = r\Delta\theta \text{ if } \theta \text{ is in radians}$$

or

$$= 2\pi r \times \frac{\Delta\theta}{360} = \frac{r\pi\Delta\theta}{180} \text{ if } \theta \text{ is in degrees}$$

Recall from Units 1 and 2 that distance, a scalar quantity, is the total length of the path taken from the starting point to the finishing point. Displacement, a vector, is the length and direction of the shortest path (usually a straight line) from the starting position to the finishing position.

We know that the change in distance divided by change in time is the **average speed** of the object, v (or the magnitude of velocity). For an object that travels in a circle, the total distance travelled by the object is the circumference, $2\pi r$, and the total time taken for one full revolution, or cycle, is the **period** of the object, T, usually measured in seconds.

If the period of the object's motion is the time taken for one complete revolution, then the inverse of that is the number of revolutions the object completes in one second. This quantity is known as the **frequency**, f, of the motion. Frequency is measured in cycles or revolutions per second (s^{-1}), or hertz (Hz). Period and frequency are related by the rule:

$$T = \frac{1}{f}$$

and

$$f = \frac{1}{T}$$

Speed is distance divided by time and is a scalar quantity.

Velocity is displacement divided by time and is a vector quantity, i.e. velocity needs a direction as well as magnitude to fully describe it.

Some examples of objects that have different average speeds of rotation but the same period are shown in Figures 4.1.2 and 4.1.3.

Earth (Figure 4.1.2), rotates once every 23 hours, 56 minutes and 4.1 seconds, which is a period of 16 164.1 s and a frequency of 1.16058×10^{-5} Hz. A point on the equator rotates at $465\,\mathrm{m\,s^{-1}}$, while at the north and south geographic poles the rotational speed is zero.

Figure 4.1.3 shows the planet Jupiter. It is the fastest rotating planet in our solar system, completing one complete rotation every 9.925 hours (which is a frequency of 2.799×10^{-5} Hz), and appears noticeably flattened at the poles because of this rotation. On Jupiter's equator, an object will travel at $13\,\mathrm{km\,s^{-1}}$.

In Units 1 and 2 it was seen that the average speed, v, could be written as:

$$v = \frac{\text{total distance}}{\text{total time}}$$
$$= \frac{d}{t} = \frac{\text{circumference}}{\text{period}} = \frac{2\pi r}{T}$$

where:

v is the average speed around the circle ($\mathrm{m\,s^{-1}}$)

r is the radius of the circular path in m

T is the period of motion of the object around the circular path (s).

Similarly the **average velocity**, v, of an object is:

$$v = \frac{\text{final displacement}}{\text{total time}}$$
$$= \frac{s}{T}$$

where:

v is the average velocity around the circle ($\mathrm{m\,s^{-1}}$)

s is the displacement of the object (m)

T is the period of motion of the object around the circular path (s).

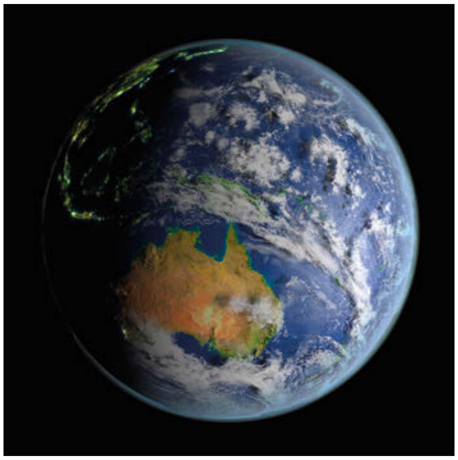


FIGURE 4.1.2 Earth's rotational speed differs depending on the latitude, or distance from the equator. At the equator, Earth rotates at about $465\,\mathrm{m\,s^{-1}}$.

FIGURE 4.1.3 Jupiter takes just under 10 hours to rotate once. As it is not one single solid object, different layers and latitudes will rotate with slightly different periods.

Units of circular motion

Note that in problems of circular motion, the rotational rate of the object is sometimes given in revolutions per minute (rpm) rather than $\mathrm{m\,s^{-1}}$. Before any values are substituted into the formulas, the values of rotation must first be converted into $\mathrm{m\,s^{-1}}$. Some common rotational units and their conversion factors are given in Table 4.1.1.

TABLE 4.1.1 Common units for circular motion

Unit	Symbol	Description	Is it an SI unit?	Conversion to SI unit
$\mathrm{m\,s^{-1}}$	v	how many metres the object moves in one second	yes	not applicable
$\mathrm{km\,h^{-1}}$	v	how many kilometres the object moves in one hour	no	divide by 3.6 to convert to $\mathrm{m\,s^{-1}}$
rpm	rpm	how many complete revolutions the object makes per minute	no	divide by 60 to convert to frequency
rps	rps	how many complete revolutions the object makes per second	no	same as frequency
angular frequency or $\mathrm{rad\ s^{-1}}$	ω	how many radians the object turns through in one second	yes	divide by 2π to convert to frequency
degree $\mathrm{s^{-1}}$	ω	how many degrees the object turns through in one second	no	divide by $\frac{180}{\pi}$ to convert to $\mathrm{rad\,s^{-1}}$ divide by 360 to convert to frequency
period	T	how long one complete revolution takes in seconds	yes	not applicable
frequency	f	how many revolutions, or cycles, are completed in one second	yes	not applicable

FIGURE 4.1.4 Formula 1 cars have engines that rotate at a maximum of 15 000 rpm.

Revolutions per minute are very commonly used to describe the rotational speeds of engines and motors. Since 2014, Formula 1 cars (Figure 4.1.4) can only use engines that are limited to 15 000 rpm. This corresponds to the piston moving inside the cylinder at 250 Hz and up to 75 km h^{-1}.

Worked example 4.1.1

UNITS OF CIRCULAR MOTION

The Windy Hill Wind Farm outside of Ravenshoe on the Atherton Tablelands in Queensland produces 12 MW of electricity. There are 20 turbines on the site and each has blades 20.0 m long that rotate at a maximum rate of 38 revolutions per minute.	
a Determine the frequency of the motion of the blade.	
Thinking	**Working**
Write down what is given and what is to be calculated.	r = 20.0 m rpm = 38 revs per minute T = ? s f = ? Hz v = ? in m s^{-1} and km h^{-1}
Convert the revolutions per minute to revolutions per second by dividing by 60. This will be equal to the frequency in Hz.	Revolutions per second = $\frac{38}{60}$ = 0.6333 rps, which is the frequency in Hz. So, f = 0.63 Hz
b Determine the period of the motion of the blade.	
Thinking	**Working**
Calculate the period by taking the reciprocal of frequency.	$T = \frac{1}{f} = \frac{1}{0.63} = 1.6$ s
c Calculate how fast the tip of one blade is moving in m s^{-1} and in km h^{-1}.	
Thinking	**Working**
How fast the tip of the blade is moving is the average speed of the blade. To find this, the circumference needs to be calculated.	$C = 2\pi r$ $= 2 \times \pi \times 20.0$ = 125.67 m
The average speed is the circumference divided by the period.	$v = \frac{125.67}{1.6}$ = 79 m s^{-1}
To find the average speed in km h^{-1} multiply by 3.6.	$v = 79 \times 3.6 = 280$ km h^{-1}
d Calculate how fast a point halfway along the blade moving in m s^{-1}.	
Thinking	**Working**
The average speed of a point halfway along the blade is also found using the circumference divided by the period, but the circumference is now calculated using r = 10.0 m instead of 20.0 m. Note that the radius is different but the period and frequency are the same, so the average speed will be smaller for a smaller radius.	$C = 2\pi r$ $= 2 \times \pi \times 10.0$ = 62.8 m $v = \frac{62.8}{1.6}$ = 39 m s^{-1} When the radius is halved, the average speed will also be halved.

➤ Try yourself 4.1.1

UNITS OF CIRCULAR MOTION

A typical internal hard disc drive (HDD) for a desktop computer can rotate at up to 7200 revolutions per minute.

a Determine the frequency of the HDD.

b Determine the period of the HDD.

c Calculate how fast, in $m\,s^{-1}$, a point on the edge of the HDD rotates if the diameter of the HDD is 8.89 cm.

d Calculate how fast a point 1.0 cm from the centre of the HDD moves in $m\,s^{-1}$.

Table 4.1.2 lists the typical rotational values of several objects that move in a circle.

TABLE 4.1.2 A range of objects and their typical rotational values

Motion	Revolutions per minute (rpm)	Frequency (Hz)	Period	Average speed of a point at the largest radius	Notes
rotation of the Milky Way galaxy at the Sun's distance from the centre	7.9×10^{-15}	1.3×10^{-16}	240 million years	$200\,km\,s^{-1}$	The rotation of the Milky Way galaxy is not constant and does not depend on the radius. It is still not known why.
Earth's motion around the Sun	1.9×10^{-6}	3.2×10^{-8}	1 year	$30\,km\,s^{-1}$	The average Earth to Sun distance is 149 600 000 km.
hour hand of a clock	1.4×10^{-3}	2.31×10^{-5}	12 hours	$12\,\mu m\,s^{-1}$	not applicable
minute hand of a clock	0.0167	2.78×10^{-4}	1 hour	$0.2\,mm\,s^{-1}$	not applicable
The Wheel of Brisbane	0.333	5.6×10^{-3}	3 min	$1.1\,m\,s^{-1}$	It has a radius of 30 m.
second hand of a clock	1	0.0167	60 s	$1\,cm\,s^{-1}$	not applicable
vinyl long playing record	33.3	0.56	1.8 s	$1.1\,m\,s^{-1}$	It has radius of 30 cm.
helicopter's rotor blades	480	8	0.13 s	$200\,m\,s^{-1}$	It has blades 4 m long.
washing machine	900	15	67 ms	$25\,m\,s^{-1}$	This is for a spin cycle.
typical 4-cylinder petrol car	2500	42	24 ms	$15\,m\,s^{-1}$	This is the average piston speed at cruising speed.
Airbus A380 Rolls Royce jet engine	12 200	203	4.9 ms	$3.8\,km\,s^{-1}$	It is the maximum speed recommended.
rotation speed of the flagella of *E. Coli* bacteria	16 000	270	3.7 ms	$34\,\mu m\,s^{-1}$	It is the maximum value recorded.
Pulsar PSR J1748−2446ad	43 000	716	1.40 ms	$7.2 \times 10^{7}\,m\,s^{-1}$ or 24% of the speed of light!	It is a rapidly rotating, very small, but dense star left over after a large star exploded. It is the fastest spinning pulsar known.
dentist's drill	400 000	6700	150 μs	$63\,m\,s^{-1}$	This is the typical high speed used for precision filing.

Worked example 4.1.2

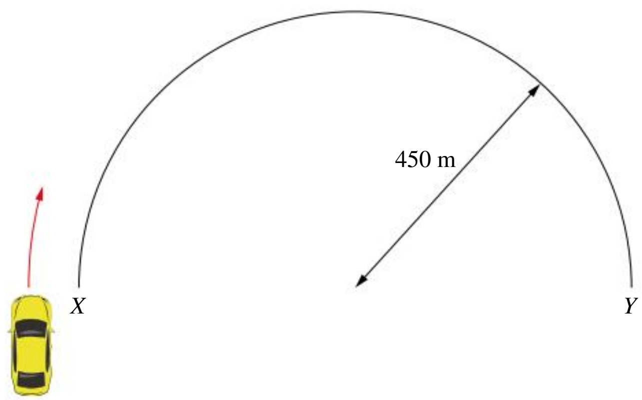
AVERAGE SPEED AND PERIOD AROUND A CIRCLE

A hammer is being thrown in a cage by an Olympic athlete who rotates 3.05 times each second. The total length of the athlete's arms and hammer is 2.1 m.	
a Calculate the distance travelled by the end of the hammer in one revolution.	
Thinking	**Working**
Write down what is given and what is to be calculated	rps = 3.05 revs per second $r = 2.1$ m $C = ?$ m $s = ?$ m $T = ?$ s $f = ?$ Hz $v = ?$ m s^{-1}
The distance covered by the end of the hammer in one revolution is the circumference of the circle the hammer traces.	$C = 2\pi r$ $= 2 \times \pi \times 2.1$ $= 13$ m
b Calculate the displacement of the hammer in one rotation.	
Thinking	**Working**
The displacement of the hammer is the distance between the end point and start point. In this case, the end point and start point are the same because of the circular motion of the hammer.	$s = 0$ m
c Determine the period of the hammer's motion.	
Thinking	**Working**
The period of the hammer's motion is the inverse of the frequency, i.e. the inverse of the number of revolutions per second.	revolutions per second = 3.05 $T = \frac{1}{3.05} = 0.328$ s
d Calculate the average speed of the hammer.	
Thinking	**Working**
The average speed of the hammer is the circumference divided by the period.	$v = \frac{C}{T}$ $= \frac{2 \times \pi \times 2.1}{0.328}$ $= 40.2$ m s^{-1}
e Calculate the average velocity of the hammer.	
Thinking	**Working**
The average velocity of the hammer is the displacement divided by the period.	$v = \frac{s}{T}$ $= \frac{0}{0.328}$ $= 0$ m s^{-1}

➤ Try yourself 4.1.2

AVERAGE SPEED AND PERIOD AROUND A CIRCLE

A car moves from X to Y along a semicircular path as shown. The radius of the path is 450 m and the time taken to complete the trip is 50.0 s.



a Determine the distance from X to Y along the path taken by the car.

b Determine the displacement of the car.

c Calculate the average speed of the car during the trip.

d Calculate the average velocity of the car during the trip.

CONDITIONS FOR MOTION IN A CIRCLE

Uniform circular motion refers to the constant *speed* of an object as it moves in a circular path. Keep in mind that velocity is a vector quantity that has a magnitude (i.e. speed) and a direction. Because the direction of the object is changing, the object's *velocity* is changing, but its speed is constant. In Units 1 and 2, acceleration was defined as the change in velocity over the change in time:

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{\Delta t}$$

where v_1 is the initial instantaneous velocity and v_2 is the final instantaneous velocity over time interval, Δt, that the velocity changed.

So, even if an object's speed is constant, it is still accelerating because its *direction* is changing.

And, since an object moving in a circle starts and finishes at the same point, its displacement is zero, hence its average velocity is zero, as seen in Worked example 4.1.2 above.

WS 3.1.4 WS 3.1.5

Average velocity is the displacement of an object divided by the time taken.

Instantaneous velocity is the velocity at one instant in time, or when the time taken to move a certain displacement is very small.

4.1 Review

SUMMARY

- The time taken for an object to complete one revolution around a circle is called the period, *T*, and is measured in seconds.
- The inverse of the period, or the number of complete rotations per second, is called the frequency, *f*. Frequency is measured in hertz (Hz) and is related to period by:

$$f = \frac{1}{T}$$

- For an object moving in a circle of radius *r*, the average speed, *v*, is the circumference of the circle divided by the period:

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

- For an object moving in a circle, the average velocity is zero if the object starts and finishes at the same point.
- Uniform circular motion is the motion of an object moving around a circle with a constant speed.
- An object moving at constant speed in a circle will be accelerating, since its velocity is changing.

KEY QUESTIONS

Retrieval

1 State the SI units of period, frequency, average speed and average velocity.

2 Define 'uniform circular motion'.

Comprehension

3 Explain the difference between average speed and average velocity of an object undergoing uniform circular motion.

4 Explain the difference between the period and frequency of an object undergoing uniform circular motion.

5 Explain how you could be accelerating even if you are moving at a constant speed.

Analysis

6 The Hubble Space Telescope makes an approximately circular orbit of Earth at an average altitude of 540 km above Earth's surface, and a period of 95.47 minutes. The radius of Earth is 6400 km.

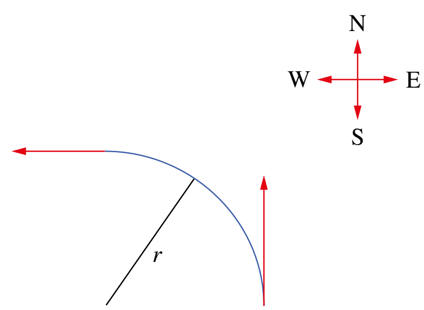
a Determine the distance travelled in one revolution around Earth.

b Determine the displacement around one revolution of Earth.

c Determine the average speed of the telescope.

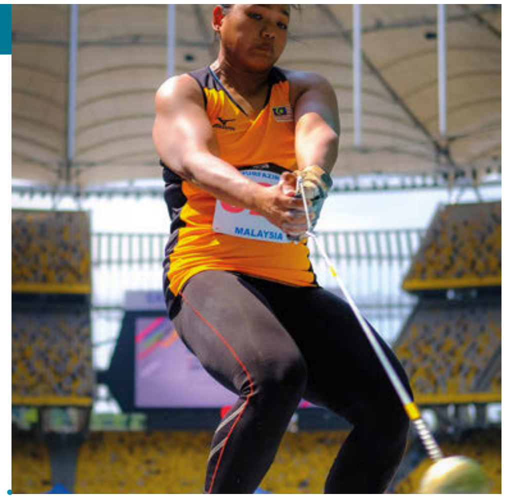
d Determine the average velocity of the telescope.

7 David takes a ride along a circularly curved track that has a radius of 1250 m as shown below. He starts the trip riding exactly due north and finishes facing due west. He travels at an average speed of 12.3 km h^{-1}. Calculate the average velocity of his trip.



8 Determine whether the average speed of an object moving in a circle ever equals the magnitude of the average velocity. Explain your answer.

4.2 Centripetal force



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

- recall that the velocity of an object moving in a circle is always perpendicular to the radius of the circle, i.e. at a tangent to the circle
- understand that motion around a circle involves a force that is always perpendicular to the velocity of the object
- define centripetal acceleration as the acceleration that keeps an object moving in uniform circular motion
- define centripetal force as the *net* force an object experiences that keeps it moving in uniform circular motion
- understand that centripetal acceleration and centripetal force are always directed towards the centre of the circle the object is moving around
- solve problems involving centripetal acceleration and centripetal force.

If the motion of an object moving in a circle were to be frozen, as in Figure 4.2.1, we would find that the velocity vector is always pointing in a direction at a tangent to its motion around the circular path, and at right angles to a line drawn to the centre of the path. The direction of the velocity shows where the object would move if the force causing it to move in a circle were to disappear.

This direction is continuously changing so that exactly one half of a rotation later the velocity vector is pointing in the opposite direction (Figure 4.2.2).

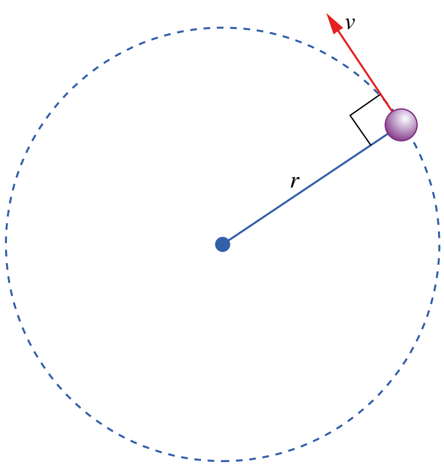


FIGURE 4.2.1 The velocity is always at a tangent, or 90°, to the radius of the circle around which the object is moving.

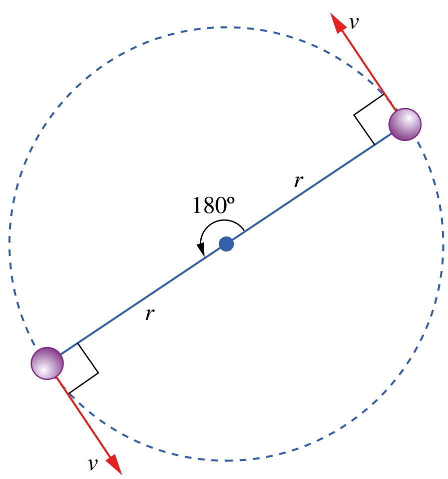


FIGURE 4.2.2 Exactly one half of a rotation later, the velocity of an object undergoing uniform circular motion has turned by 180°.

CENTRIPETAL ACCELERATION

In Figure 4.2.3, a particle is moving around a circle of radius r with uniform speed v. The velocities at two locations on the circumference on the circle, A and B, are v_1 and v_2 respectively. The velocity vectors v_1 and v_2 are always at a tangent to the circle, and at right angles to the radius. Remember that v_1 and v_2 have the same magnitude but different directions.

In order to quantify the acceleration of the particle, the time interval, Δt, over which the acceleration occurs must be kept as small as possible. This is because the velocities at A and B are the *instantaneous* velocities, not the average velocities. So, if Δt is very small, then the angle at which the velocity changed, $\Delta\theta$, must also be very small.

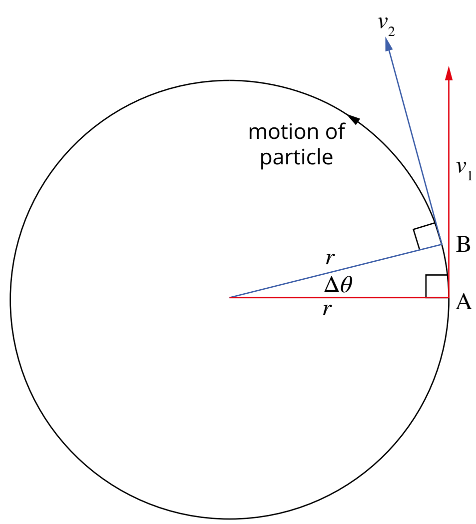


FIGURE 4.2.3 Vectors v_1 and v_2 have the same magnitude but different direction as the object moves around the circle.

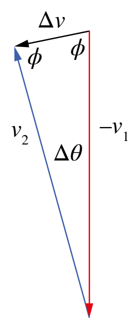


FIGURE 4.2.4 The isosceles triangle formed by adding v_2 to $-v_1$

As the particle is changing direction, it must be accelerating:

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{\Delta t}$$

To get Δv we use the subtraction of vectors:

$$\Delta v = v_2 - v_1 = v_2 + (-v_1)$$

Recall from Chapter 2 that subtracting a vector is the same as adding a vector that is negative, or adding the reverse by 180°.

To find $v_2 + (-v_1)$, vector addition is used, i.e. the tail of v_2 is moved to the head of $-v_1$ (Figure 4.2.4). This forms an isosceles triangle, with the angle at the apex being $\Delta\theta$. The base angles can be found using:

$$\phi + \phi + \Delta\theta = 180°$$

$$\therefore \phi = \frac{180° - \Delta\theta}{2}$$

or

$$\phi = 90° - \frac{\Delta\theta}{2}$$

We cannot use Pythagoras to find the magnitude of Δv since this triangle is not a right-angled triangle, so the sine rule is used instead:

$$\frac{\sin\phi}{-v_1} = \frac{\sin\Delta\theta}{\Delta v}$$

or

$$\frac{\sin\phi}{v} = \frac{\sin\Delta\theta}{\Delta v}$$

since the magnitude of $-v_1$ is just v.

Substituting $\phi = 90° - \frac{\Delta\theta}{2}$ into the sine rule above gives:

$$\frac{\sin\phi}{v} = \frac{\sin\Delta\theta}{\Delta v}$$

$$\frac{\sin\left(90° - \frac{\Delta\theta}{2}\right)}{v} = \frac{\sin\Delta\theta}{\Delta v}$$

$$\frac{\cos\frac{\Delta\theta}{2}}{v} = \frac{\sin\Delta\theta}{\Delta v}$$

$$\therefore \Delta v = \frac{v\sin\Delta\theta}{\cos\frac{\Delta\theta}{2}}$$

And now substituting Δv into the equation for acceleration with magnitudes only:

$$a = \frac{\Delta v}{\Delta t} = \frac{v\sin\Delta\theta}{\Delta t\cos\frac{\Delta\theta}{2}}$$

In the time Δt, the particle will trace out an arc from A to B. The length of the arc is given by the rule:

$$v = \frac{\text{arc length}}{\Delta t} = \frac{r\Delta\theta}{\Delta t}$$

so that

$$\Delta t = \frac{r\Delta\theta}{v}$$

Substituting into the equation for a:

$$\begin{aligned} a &= \frac{v\sin\Delta\theta}{\Delta t\cos\frac{\Delta\theta}{2}} \\ &= \frac{v\sin\Delta\theta}{\cos\frac{\Delta\theta}{2}} \div \Delta t \\ &= \frac{v\sin\Delta\theta}{\cos\frac{\Delta\theta}{2}} \div \frac{r\Delta\theta}{v} \\ &= \frac{v\sin\Delta\theta}{\cos\frac{\Delta\theta}{2}} \times \frac{v}{r\Delta\theta} \\ &= \frac{v^2\sin\Delta\theta}{r\Delta\theta\cos\frac{\Delta\theta}{2}} \end{aligned}$$

When an angle, x, is very small and measured in radians, the following approximations apply:

$$\sin x \approx x$$

and

$$\cos x \approx 1$$

The angle through which the velocity is changing from A to B, $\Delta\theta$, is very small, therefore:

$$\sin \Delta\theta \approx \Delta\theta$$

and

$$\cos\left(\frac{\Delta\theta}{2}\right) \approx 1$$

Finally, the acceleration of a particle moving with uniform circular motion with speed v around a circle with radius r is given by:

$$a = \frac{v^2 \sin \Delta\theta}{r\Delta\theta \cos \frac{\Delta\theta}{2}}$$

$$= \frac{v^2 \times \Delta\theta}{r \times \Delta\theta \times 1} = \frac{v^2 \times \cancel{\Delta\theta}}{r \times \cancel{\Delta\theta} \times 1}$$

$$\therefore a_c = \frac{v^2}{r}$$

This acceleration, a_c, is known as **centripetal acceleration** and is the resulting, or net, acceleration of a body that is moving in a circle of radius r, with a velocity v.

As it is a vector, centripetal acceleration requires a direction. For very small angles $\Delta\theta$, ϕ will be very close to 90° (Figure 4.2.5). Since each velocity vector is at a tangent to the circle, and ϕ is approaching 90°, then the change in velocity Δv—i.e. the acceleration—will be at right angles to the velocity vectors v_1 and v_2. A vector that is at right angles to a tangent must point towards the centre of the circle; hence, the direction of centripetal acceleration is directed towards the centre of the circle.

No matter where the object is, if it is moving in a circle then it will have a velocity vector at a tangent to the radius and a centripetal acceleration vector pointing towards the centre of the circle (Figure 4.2.6). These vectors are always at right angles to each other.

CENTRIPETAL FORCE

If the sum of all forces that act on an object cause it to move in a circle, then Newton's second law can be written using centripetal acceleration instead of linear acceleration. Using the magnitudes of the quantities involved:

$$F_{net} = \sum F_1 + F_2 + F_3 + \ldots$$

$$= F_c = ma_c = \frac{mv^2}{r} \text{ towards the centre of the circle}$$

This force is called the **centripetal force**, F_c. It is the resulting force that causes an object of mass m to move in a circle of radius r, with a velocity v.

Like centripetal acceleration, the centripetal force is directed towards the centre of the circle the object is moving around. If the force acts on an object at right angles to its uniform motion (i.e. constant speed), then the object will be continually changing direction, hence moving in a circle.

It is important to remember that the centripetal force is the resulting, or net, force that causes the circular motion of the object. There must always be a non-zero net force acting on an object for it to move in a circle.

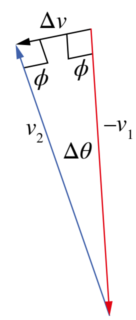


FIGURE 4.2.5 If $\Delta\theta$ is very small, then both angles ϕ are very close to 90°. Vector v_2 is at a tangent to the radius (Figure 4.2.3), therefore Δv is a vector that is pointing towards the centre of the circle.

The magnitude of centripetal acceleration is $a_c = \frac{v^2}{r}$. It is directed towards the centre of the circle that the object is moving around.

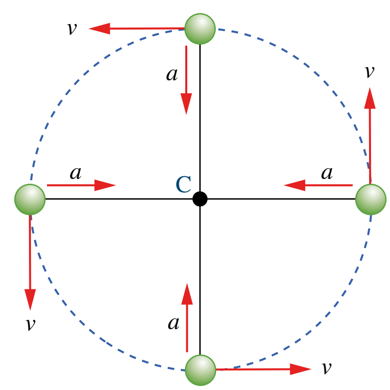


FIGURE 4.2.6 The centripetal acceleration of an object moving with uniform circular motion is always directed towards the centre of the circle, and at right angles to the object's velocity.

The magnitude of centripetal force is $F_c = \frac{mv^2}{r}$, and this is directed towards the centre of the circle that the object is moving around.

Examples of centripetal force in action

Some examples of forces that cause a net centripetal force are given below.

Turning a corner in a car

As a car turns a left corner, the tyres exert a frictional force on the road towards the right of the car's motion. By Newton's third law, the road must also exert a frictional force on the tyres in the opposite direction (the left) to the force exerted by the tyres on the road, causing the tyres and car to move to the left (Figure 4.2.7).

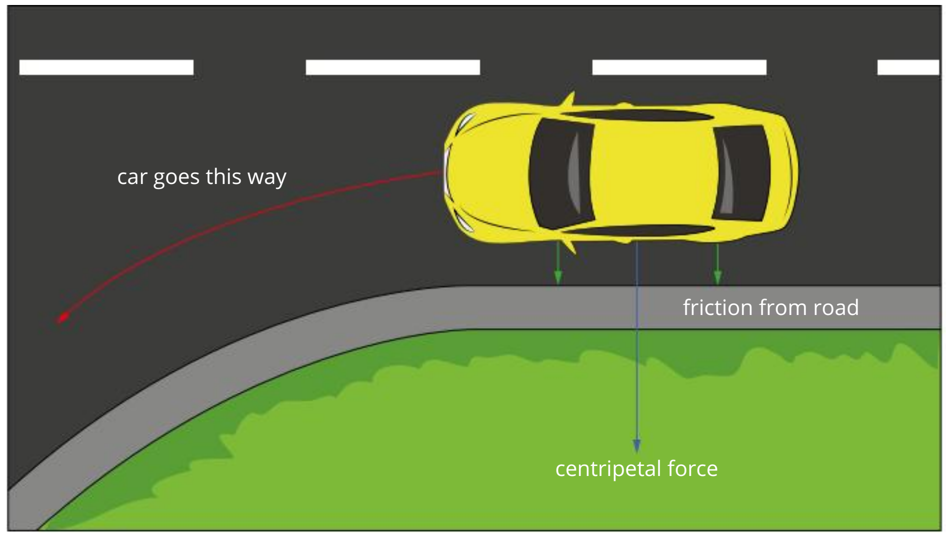


FIGURE 4.2.7 Cars turn corners when there is an unbalanced frictional force from the road pushing the car inwards. This inwards force is the centripetal force acting on the car.

If the force on the road from the tyres is larger than the friction between the tyres and the road, then the tyres will lose grip and the centripetal force (i.e. net force) from the tyres disappears. As there is no net force on the tyres, there will be no force on the car and the car will continue to move in a straight line rather than turning the corner (Figure 4.2.8).

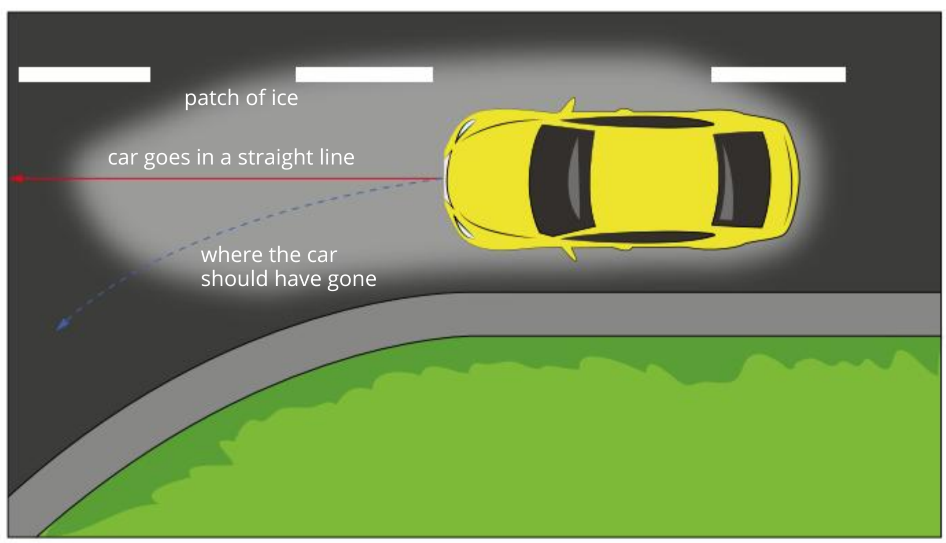


FIGURE 4.2.8 A car will skid off the road when trying to turn a corner when there is insufficient frictional force between the road and the tyres. In this case there is no centripetal force, thus the car continues to move in a straight line.

When turning a corner in a car, a passenger may experience a 'force' pushing them outwards. This is commonly, but incorrectly, referred to as 'centrifugal force'. This force does not exist (Figure 4.2.9).

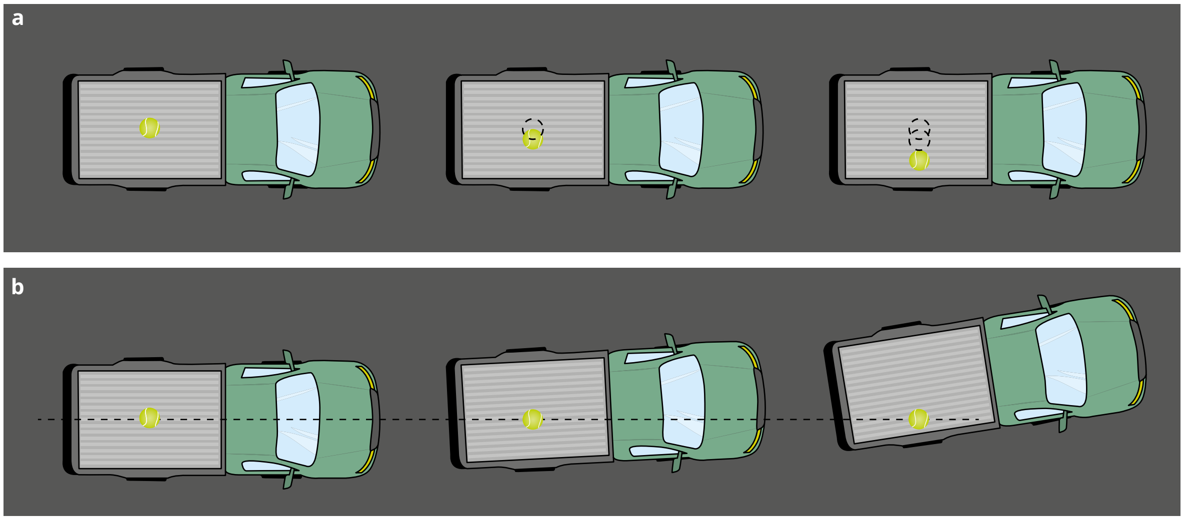


FIGURE 4.2.9 Two different points of view of a ball in the tray of a utility truck moving at a constant speed but turning left, as viewed (a) from above from the utility's point of view and (b) from the ball's point of view.

Figure 4.2.9a shows the motion of a ball in the tray of a utility truck that is turning left, from the point of view of the utility. The ball appears to violate Newton's laws, displaying a sideways force (the apparent 'centrifugal force') that is not the result of the interaction of a force with any other object. As nothing is causing this force, it doesn't actually exist. So what is causing the apparent motion of the ball?

Figure 4.2.9b shows the motion of the ball from its own point of view, or from the point of view of an outside observer watching the utility turn the corner. In this point of view the ball obeys Newton's first law, i.e. it will move in a straight line with the same speed until an unbalanced force acts upon it. No forces are being applied to the ball, so it continues moving in a straight line, shown with the dashed line in Figure 4.2.9b. It is the truck that is being forced to move left via friction with the road, and the ball is simply hit by the right side of the utility because the utility is turning into the path of the ball. Hence, there is no need for a centrifugal force to explain the ball's motion.

Orbits of planets and moons

The Earth pulls the Moon towards it with gravitational force at right angles to the velocity of the Moon around the Earth. Ignoring any forces from the other planets and the Sun, the gravitational force of the Earth on the Moon is the only force acting on the Moon (Figure 4.2.10). Hence, this must be equal to the centripetal force on the Moon causing it to continually change direction, thus circling or orbiting the Earth.

If Earth was to suddenly disappear, then there would be no centripetal force on the Moon and the Moon would continue to move in a straight line with constant speed, as per Newton's first law of motion (Figure 4.2.11).

Quite often, the velocity of an object moving in a circle is difficult to measure, and hence so too are the centripetal acceleration and centripetal force. One way around this is to avoid using the velocity of the object altogether and use the radius and period of the object, as these are usually much easier to measure.

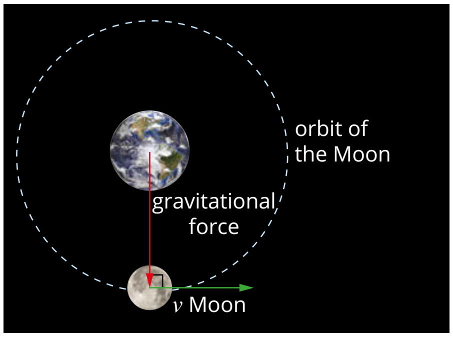


FIGURE 4.2.10 The gravitational force is the only force acting on the Moon and it acts at right angles to the Moon's velocity. This means that the net force is a centripetal force and it causes the Moon to continually move in a circle around Earth.

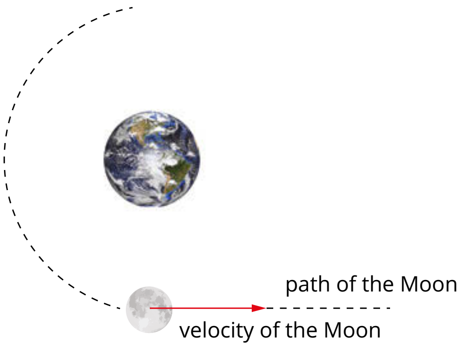


FIGURE 4.2.11 Without gravitational force acting on the Moon, there is no net force. By Newton's first law of motion, the Moon will simply move in a straight line at constant speed.

Another way to write centripetal acceleration and centripetal force is to use the rules dependent on the period and independent of the velocity of the object:

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

$$F_c = \frac{4m\pi^2 r}{T^2}$$

When speed, v:

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

is substituted into the rule for centripetal acceleration:

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

the magnitude of the centripetal acceleration can be written:

$$a_c = \frac{\left(\frac{2\pi r}{T}\right)^2}{r} = \frac{\left(\frac{4\pi^2 r^2}{T^2}\right)}{r}$$
$$= \frac{4\pi^2 r}{T^2}$$

hence, the magnitude of centripetal force becomes:

$$F_c = \frac{4m\pi^2 r}{T^2}$$

NEWTON'S SECOND LAW AND CIRCULAR MOTION

Remember that the net force is equal to the sum of all forces acting on an object:

$$F_{net} = \sum F_1 + F_2 + F_3 + \ldots$$

- If the net force on an object of mass m is not zero and is in the same direction as, or in the opposite direction to, the motion of the object, then Newton's second law states:

  $$F_{net} = ma$$

  and the object will accelerate or decelerate in the direction of its motion.
- If the net force on an object of mass m is not zero and is *at right angles to the motion of the object*, then Newton's second law states:

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

  and the object will continually be forced inwards and follow a uniform circular motion.
- If the net force on an object of mass m is equal to zero, then there is no acceleration on the object and it will continue to move in the same direction with the same speed.

Worked example 4.2.1

CENTRIPETAL FORCE AND ACCELERATION

The Moon has a mass of 7.3477×10^{22} kg and takes 27.322 days to orbit Earth at an average distance of 384 399 km.	
a Calculate the average speed of the Moon in its orbit around Earth.	
Thinking	**Working**
Write down what is given in the question and what you are being asked to calculate.	$T = 27.322$ days $r = 384\,399$ km $m_{Moon} = 7.3477 \times 10^{22}$ kg $v = ?$ $a_c = ?$ $F_c = ?$

The period and radius need to be changed to SI units.	$T = 27.322$ days $= 27.322 \times 24 \times 3600$ s $= 2\,360\,620.8$ s $r = 384\,399$ km $= 384399 \times 10^3$ m $= 3.84399 \times 10^8$ m
The average speed is the circumference of the circular orbit divided by the period.	$v = \frac{2\pi r}{T}$ $= \frac{2 \times \pi \times 3.84399 \times 10^8}{2\,360\,620.8}$ $= 1.0231 \times 10^3$ m s^{-1}
b Calculate the centripetal acceleration of the Moon.	
Thinking	**Working**
The centripetal acceleration is given by the formula $a_c = \frac{v^2}{r}$. Substitute the value for v from part a.	$a_c = \frac{v^2}{r}$ $= \frac{(1.0231 \times 10^3)^2}{3.84399 \times 10^8}$ $= 2.7230 \times 10^{-3}$ m s^{-2} towards Earth
c Calculate the centripetal force acting on the Moon.	
Thinking	**Working**
The centripetal force is the centripetal acceleration multiplied by the mass of the Moon.	$F_c = m a_c$ $= 7.3477 \times 10^{22} \times 2.730 \times 10^{-3}$ $= 2.0008 \times 10^{20}$ N towards Earth

➤ Try yourself 4.2.1

CENTRIPETAL FORCE AND ACCELERATION

Earth has a mass of 5.97×10^{24} kg and takes exactly 1 year to orbit the Sun at an average distance of 150 million km.

a Calculate the average speed of Earth in its orbit around the Sun.

b Calculate the centripetal acceleration of Earth.

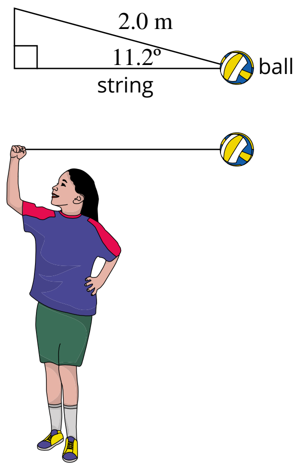
c Calculate the centripetal force acting on Earth.

When an object is twirled on the end of a string in a horizontal circle, it will always hang below the pivot point. If the object were to trace a horizontal circle at the same height as the pivot point, the string would be perpendicular to the direction of the object's weight, and there would be no component of tension in the string in the vertical direction to balance the weight of the object. Therefore, the object traces a circle lower than the pivot point and has both vertical and horizontal components. The vertical component balances the weight of the object, and the horizontal component provides the centripetal force to keep the object moving in a circle. The tension in the string is therefore greater than the centripetal force keeping the object moving in a circle.

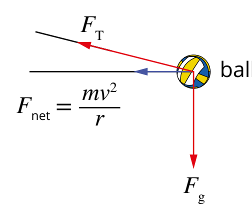
Worked example 4.2.2

HORIZONTAL CENTRIPETAL FORCE AND ACCELERATION

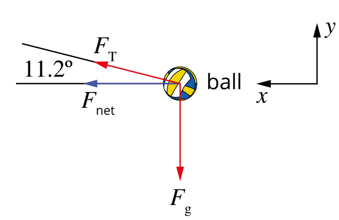
Jenny twirls a 230 g rubber ball connected to a 2.0 m long string above her head. The ball makes an angle of 11.2° to the horizontal plane, as shown below:

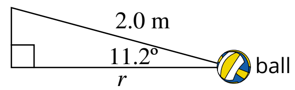
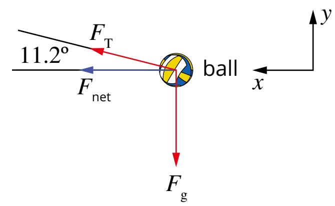


a Sketch a free-body diagram showing all forces acting on the ball.

Thinking	**Working**
Write down what is given in the question and what is being asked for.	String length = 2.0 m m = 230 g = 0.230 kg θ = 11.2° F_c = ? v = ? T = ?
Forces that act on the ball are tension in the string and the weight of the ball. No normal force exists because the ball is not in contact with a surface. Centripetal force is the vector sum of the tension and the weight of the ball.	

b Calculate the tension in the string.

Thinking	**Working**
The tension in the string is found using the vertical component of the tension and equating that with the weight of the ball. As the weight and vertical component of tension are along the *y*-axis, and there is no net force along the *y*-axis, then the magnitude of the weight will equal the magnitude of the vertical component of tension.	$\sin 11.2° = \frac{-F_g}{F_T} = \frac{m \times -g}{F_T}$ $\therefore F_T = \frac{0.23 \times 9.8}{\sin 11.2°} = 12\text{ N}$ The tension in the string is 12 N directed towards Jenny's hand.

c Calculate the centripetal force acting on the ball.	
Thinking	**Working**
Note that because the ball is twirled in a horizontal circle that is 11.2° below the centre of Jenny's hand, the radius of the circle is not 2.0 m. To find the radius of the circle, use the cosine of the angle.	 $\cos 11.2° = \frac{r}{2.0}$ $\therefore r = 2.0 \times \cos 11.2°$ $= 1.962\,\text{m}$
The centripetal force on the ball is found using the horizontal component of tension, since that force is unbalanced and thus equal to the centripetal force.	 $\cos 11.2° = \frac{F_c}{F_T} = \frac{F_c}{12}$ $\therefore F_c = 12 \times \cos 11.2°$ $= 11.8\,\text{N}$ F_c = 12 N, towards the centre of the circle of rotation (just below Jenny's hand).

d Calculate the speed of the ball.	
Thinking	**Working**
The speed of the ball can be found using the equation for centripetal force.	$F_c = \frac{mv^2}{r} = 11.8$ $\therefore v = \sqrt{\frac{11.8 \times 1.962}{0.23}}$ $= 10\,\text{m s}^{-1}$

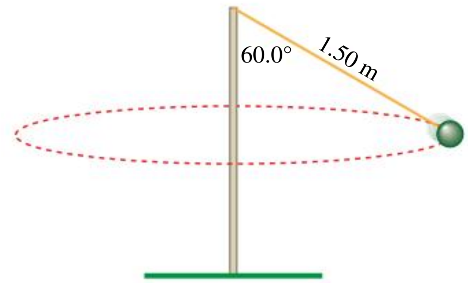
e Calculate the period of rotation of the ball.	
Thinking	**Working**
The period of rotation of the ball is found by using the speed of the ball and the radius of its rotation.	$v = \frac{2\pi r}{T}$ $\therefore T = \frac{2\pi r}{v} = \frac{2 \times \pi \times 1.962}{10}$ $= 1.2\,\text{s}$

f Calculate the initial speed of the ball if Jenny lets go of the string.	
Thinking	**Working**
If Jenny lets go of the string, the centripetal force is zero and hence the net force on the ball is now solely due to the weight of the ball. There is no longer a horizontal net force, thus the speed of the ball does not change. At the instant the ball is released, its motion will be in a horizontal direction with a speed equal to the rotational speed; however, Earth's gravity will act to make it accelerate downwards.	The speed of the ball will be $10\,\text{m s}^{-1}$.

➤ Try yourself 4.2.2

HORIZONTAL CENTRIPETAL FORCE AND ACCELERATION

During a game of totem tennis, the 150 g tennis ball is swinging freely in a horizontal circular path as shown below.



The cord is 1.50 m long and is at an angle of 60.0° to the vertical.

a Calculate the radius of the ball's circular path.

b Sketch a free-body diagram showing all the forces acting on the ball.

c Determine the net force acting on the ball.

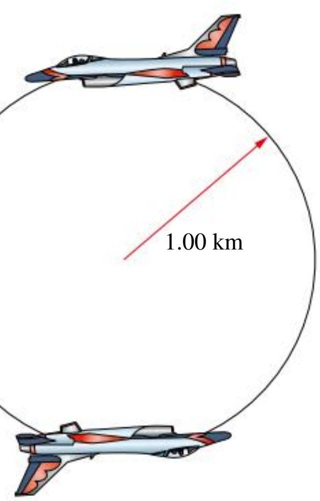
d Calculate the tension in the string.

e Calculate the speed of the ball.

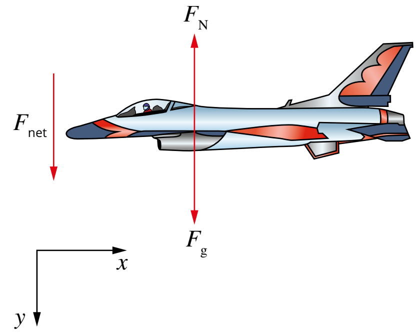
Worked example 4.2.3

VERTICAL CENTRIPETAL FORCE AND ACCELERATION

Justin flies a plane in a loop-the-loop of radius 1.00 km. The plane starts out flying upside down, straight and level, and then begins curving up along the circular loop. It is right-side-up when it reaches the top of the loop, as shown below.



Determine how fast the plane must be going at the top of its loop if Justin is to experience no force from the seat or seat belt.

Thinking	Working
Write down what is given in the question and what you are being asked to find out.	$r = 1.00\,\text{km}$ $v = ?$
To answer this question the forces acting on Justin at the top of the loop must be considered using a free-body diagram. These forces could be Justin's weight and the normal force from the seat.	
The plane is flying in a circular loop-the-loop, therefore the net force is equal to the centripetal force, which is equal to the sum of the normal force and Justin's weight. The question states that Justin experiences no force from the seat or seat belt, which implies that the normal reaction force on him from the seat and seat belt is zero.	$F_{net} = \frac{mv^2}{r} = F_N - F_g$ $F_N = 0$
Using the direction convention given, in which any force downwards is treated as a positive value and any force upwards is treated as a negative value, the magnitude of the forces can now be written.	$F_{net} = \frac{mv^2}{r} = -F_N + F_g$ $\frac{mv^2}{r} = 0 + F_g$ $\frac{mv^2}{r} = 0 + mg = mg$ $\therefore v = \sqrt{gr}$
Substituting in 1.00 km for *r* gives the velocity required.	$v = \sqrt{gr} = \sqrt{9.8 \times 1000}$ $= 99\,\text{m}\,\text{s}^{-1}$

➤ Try yourself 4.2.3

VERTICAL CENTRIPETAL FORCE AND ACCELERATION

Justin flies another loop-the-loop of the same radius, but this time the plane is upside-down and travelling at $221\,\text{m}\,\text{s}^{-1}$ as it reaches the bottom of the 1.00 km loop.

Determine how many times heavier Justin 'feels' (i.e. calculate the normal force acting on Justin, divided by his weight) at the bottom of the loop-the-loop. Justin's mass = 90.0 kg.

PA 3.1.3 PA 3.1.4

4.2 Review

SUMMARY

- To undergo motion around a circle, an object must experience a net inwards force that is always perpendicular to the velocity of the object.
- The centripetal acceleration, a_c, is the acceleration an object experiences that keeps it moving in uniform circular motion with speed, v, and period, T, around a circle of radius r:

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

- The direction of centripetal acceleration is always towards the centre of the circle the object is moving around.
- The centripetal force, F_c, is the *net* force an object of mass m experiences that keeps it moving in uniform circular motion with speed, v, period, T, and radius r:

$$F_c = \frac{mv^2}{r} = \frac{4m\pi^2 r}{T^2}$$

- Centripetal force is also always directed towards the centre of the circle the object is moving around.

KEY QUESTIONS

Retrieval

1 State the direction in which centripetal acceleration acts.

2 State the direction in which centripetal force acts.

3 Describe the relationship that must exist between the net force and the velocity of a moving mass for uniform circular motion to result.

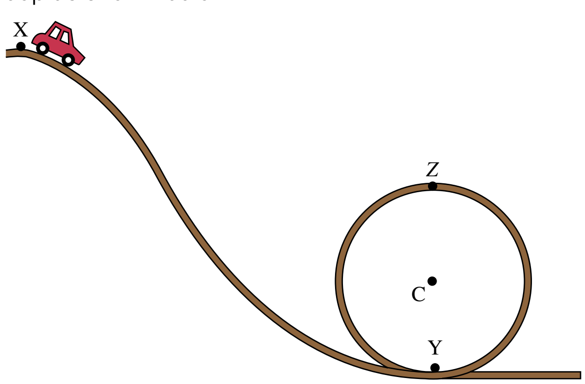
4 State the direction of the velocity vector of an object that moves in a circle.

Comprehension

5 Explain why the centripetal force is not necessarily a force that acts directly on an object moving in a circle.

6 Identify at which point in their rotation hammer and discus throwers need to release their projectiles in order for the projectile to land on the arena.

7 Maya arranges a toy car track with a circular vertical loop as shown below.



The car is released from rest from point X and travels inside the loop of centre C. Assume friction is negligible. Draw in the forces, including the net force, acting on the toy car at:

a point Y

b point Z.

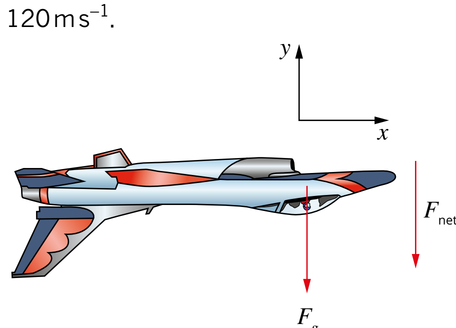
Analysis

8 Calculate the magnitude of the centripetal acceleration of a person standing on the surface of Earth at the equator. Use the radius of Earth at the equator as 6378 km.

Calculate this value as a percentage of the acceleration due to Earth's gravity, $9.8\,\text{m}\,\text{s}^{-2}$.

9 A cyclotron is a device used to accelerate subatomic particles to very high speeds in order for them to collide and create new particles. The cyclotron consists of an electromagnet and a circular tube for the particles to move along. Calculate the magnitude of the velocity of the protons if the electromagnet exerts a force of 7.50×10^{-13} N on a beam of protons, causing them to move in a circular path of radius 1.20 m. The mass of a proton is 1.67×10^{-27} kg.

10 A 75 kg pilot flies her plane in a circular vertical loop, as shown below in the free-body diagram. At the top of her loop, she notices she is floating freely upside-down, apparently weightless. Calculate the radius of the plane's loop if the airspeed indicator shows $120\,\text{m}\,\text{s}^{-1}$.



Chapter review

04

KEY TERMS

average speed
average velocity
centripetal acceleration
centripetal force
frequency
period
uniform circular motion

KEY QUESTIONS

Retrieval

1 Identify the formula that correctly describes the magnitude of centripetal force.

A $F_c = \frac{mr^2}{v}$ **B** $F_c = \frac{mv^2}{2}$

C $F_c = \frac{mv}{r}$ **D** $F_c = \frac{mv^2}{r}$

2 Identify what provides the centripetal force needed to keep something in an orbit around Earth.

3 Define 'centripetal force'.

4 Identify an example of a force that keeps an object moving in a circle.

Comprehension

5 After getting off a Ferris wheel at a local amusement park, Cameron remarks to a friend that he felt lighter than usual at the top of the ride. Select the option that explains why he might feel lighter at the top of the ride.

A He lost weight during the ride.
B The strength of the gravitational force was weaker at the top of the ride.
C The normal force at the top of the ride was larger than the gravitational force.
D The normal force at the top of the ride was less than the gravitational force.

6 Describe what would happen if there was no friction between the tyres of your bicycle and the road when you tried to go around a bend.

7 Explain why an object consisting of a ball tied to a piece of string and swung around a person's head can never trace out an exactly horizontal circle.

8 Explain why a hammer moves off in a straight line when the hammer thrower lets go.

Analysis

9 Angelina twirls a 7.00 kg hammer tied to the end of a 1.3 m rope in an approximately horizontal circle. The hammer moves at a rate of 1.0 revolutions per second.

a Calculate the average speed of the hammer as it travels around in its path.
b Calculate the centripetal acceleration of the hammer.
c Calculate the tension in the rope.

10 A turbocharger is a device that is used to increase the power and efficiency of a normal internal combustion engine. It works using a set of blades rotating at 250 000 rpm to draw air into the engine. The blades of a particular turbocharger are 6.0 cm in radius.

a Calculate the frequency of the blades.
b Calculate the period of the blades.
c Calculate the average speed of the tip of the blades.

11 The galaxy NGC 1365, in the constellation Fornax, shown below, is thought to have a supermassive black hole in its centre. This black hole has a mass two million times the mass of the Sun and is also the fastest spinning object ever measured, rotating at 85% of the speed of light.

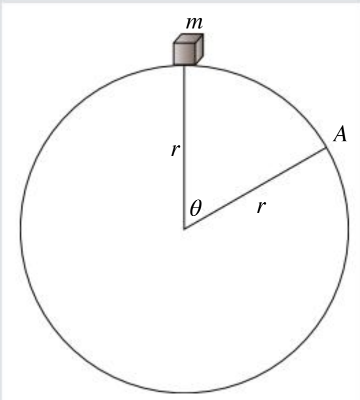
If the radius of the black hole is 1.6 million km and the speed of light is $3.00 \times 10^8\,\text{m s}^{-1}$:

a calculate the period of the black hole
b calculate the frequency of the black hole
c calculate the revolutions per minute of the black hole
d calculate the magnitude of the centripetal acceleration of the black hole.

12 A car goes over the crown of a hill whose road bed is considered to be an arc of a circle in a vertical plane of radius 40.0 m. Calculate the maximum speed at which the car may travel and not move tangentially off the road.

Knowledge utilisation

13 An object of mass m is just balanced on top of a frictionless sphere of radius r as shown below.

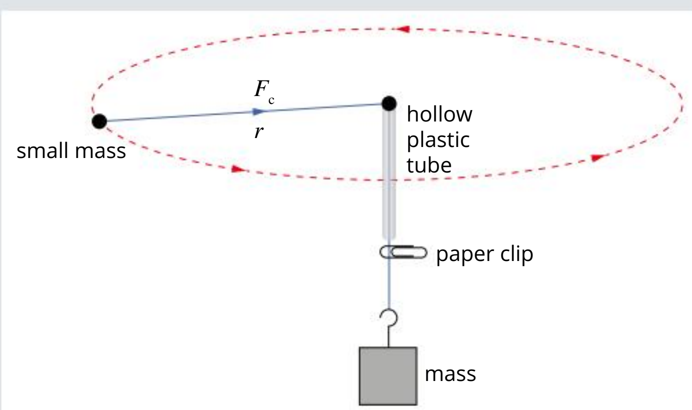


The mass is given a small push and it slides down the right-hand side of the sphere until it leaves the sphere at point A.

Determine the angle θ at which the mass leaves the sphere.

14 Rob performed an experiment to determine the value of the acceleration due to Earth's gravity, g. A known, but variable mass, m, connected to a light string was threaded through a small tube. Connected to the other end of the string was a small, but constant mass.

The small mass, M, was then twirled around so that the radius, r, of the motion was kept constant. A paperclip was attached to the string just underneath the end of the tube so the radius of the circular motion could be kept constant. This set-up is shown below.



The mass underneath the tube, m, was varied and the period, T, of one swing was recorded in the table below. The radius of the string was kept constant at 30.0 cm, and the small mass being twirled was kept constant at 50.0 g. Rob recorded the values in the table below:

Mass underneath tube, m (kg)	Period of one swing, T (s)
0.050	1.11
0.100	0.82
0.150	0.66
0.200	0.55
0.250	0.49
0.300	0.45

a Show that the weight, mg, of the mass underneath the tube can be written as:

$$mg = \frac{4\pi^2 Mr}{T^2}$$

b State the independent and dependent variables.

c Sketch a graph that shows how the period of the motion of the constant mass changes with the mass underneath the tube.

d Show the equation in part a so that T is the subject of the formula. This will give you the mathematical description of the graph in part **c**. Describe the shape of the graph.

e State which axis will be changed to linearise this graph, and what will be graphed to produce a straight line.

f Calculate the values of the new axis.

g Draw a graph of the new linearised data to produce a straight line.

h Calculate the values of the gradient and y-intercept of the line, including their units.

i State the theoretical value of the y-intercept.

j State the equation of the gradient.

k Determine a value for g by using the gradient or y-intercept.

CHAPTER

05 Gravity

Gravity is the force that drives the universe. It was gravity that first caused atoms to congregate together to form the first nebulas, stars and planets. An understanding of gravity is fundamental to understanding the universe.

This chapter centres on Newton's law of universal gravitation. This will be used to predict the size of the gravitational force experienced by an object at various locations on Earth and other planets. It will also be used to develop the idea of a gravitational field. And because the field concept is also used to describe other basic forces, such as electromagnetism, this will provide an important foundation for further study in physics.

Syllabus subject matter

Topic 1 • Gravity and motion

GRAVITATIONAL FORCE AND FIELDS

- recall Newton's Law of Universal Gravitation
- solve problems involving the magnitude of the gravitational force between two masses
- define the term *gravitational fields*
- solve problems involving the gravitational field strength at a distance from an object.

SCIENCE AS A HUMAN ENDEAVOUR

- Developing understanding of planetary motion

5.1 Newton's law of universal gravitation

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

- recall Newton's law of universal gravitation
- solve problems involving the magnitude of the gravitational force between two masses
- calculate the strength of the gravitational force between two masses
- calculate acceleration due to gravitational force.

Gravity is one of the four fundamental forces in the universe. Ordered from strongest to weakest forces, these four forces are:

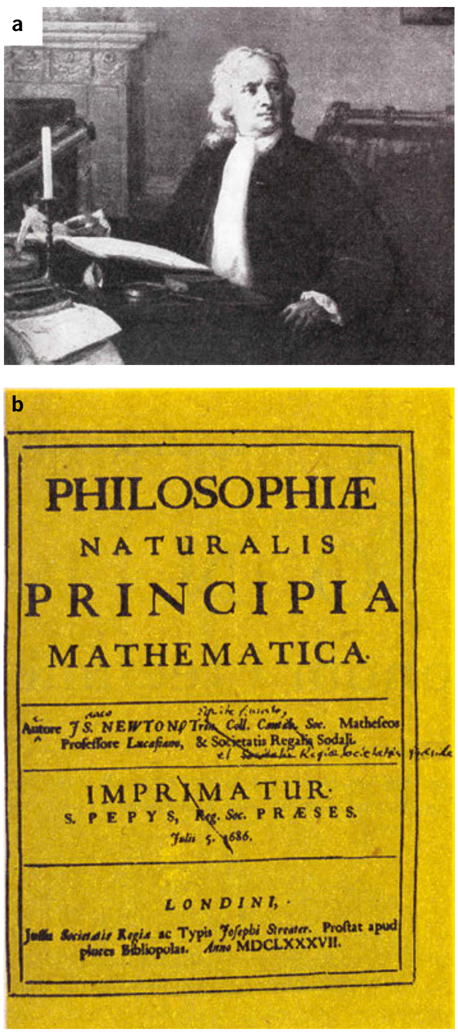
- strong nuclear force
- electromagnetic (EM) force
- weak nuclear force
- gravitational force.

Electromagnetic forces, which include light and magnetism, are covered in Unit 2 (Chapter 11) and Unit 3 (Chapters 8 and 9). Strong and weak nuclear forces act within the nucleus of atoms, as covered in Unit 1 (Chapter 3) and Unit 4 (Chapter 13).

The **gravitational force** (gravity) is by far the weakest force of the four. However, because it acts at great distances (unlike the two nuclear forces), and because it is always attractive (unlike the EM force), gravity is the force that drives the universe we live in.

UNIVERSAL GRAVITATION

Sir Isaac Newton's law of universal gravitation was introduced in his book *Philosophiæ Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy) in 1687 (Figure 5.1.1).



a

b

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

IMPRIMATUR
S. PEPYS, Reg. Soc. PRÆSES.

LONDINI,
Anno MDCLXXXVII.

FIGURE 5.1.1 (a) Sir Isaac Newton. (b) The *Principia* is one of the most influential books in the history of science.

Newton's law of universal gravitation says that any two bodies attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

Mathematically, Newton's law of universal gravitation is expressed as:

$$F_g = G\frac{m_1 m_2}{r^2}$$

where

F_g is the gravitational force (N)
m_1 is the mass of object 1 (kg)
m_2 is the mass of object 2 (kg)
r is the distance between the centres of m_1 and m_2 (m)
G is the gravitational constant, 6.67×10^{-11} (N m^2 kg^{-2})

The fact that distance r appears in the denominator of the equation indicates an inverse relationship. The greater the distance between the two objects, the smaller the force. As r is squared, this relationship is known as an **inverse square law**. The result is that as r increases, F_g decreases dramatically. Inverse square laws will reappear again later in the chapter, when gravitational fields are examined in detail, and also in Chapter 7.

Worked example 5.1.1

GRAVITATIONAL ATTRACTION BETWEEN SMALL AND LARGE OBJECTS

In *Principia*, Isaac Newton used this deceptively simple proof to show that the same force that acted on the orbiting Moon (orbital period about Earth = 27.3 days, average radius of the Moon's orbit about Earth = 3.84×10^8 m) also acted on a falling object (let's say, an apple) here on Earth (radius = 6.37×10^6 m).

Newton also showed that the force acting from the Earth on both the Moon and the apple was inversely proportional to the distance. Here, we will do the same.

Compare the force on a falling apple to the force of the Moon from the Earth's gravity.

Thinking	Working
Newton used the orbit of the Moon to confirm his law of inverse squares. Use the equation for the centripetal acceleration of an object travelling in a circle (from Chapter 4). Here, d is used instead of r for the radius of the Moon's orbit.	$a_c = \frac{v^2}{d}$ $= \frac{\left(\frac{2\pi d}{T}\right)^2}{d}$ $= \frac{4\pi^2 d}{T^2}$
Substitute the known values into the equation. Use: d (radius of the Moon's orbit) = 3.84×10^8 m T (period of the Moon's orbit) = 27.3 days = 2.36×10^6 s	$a_{c(\text{Moon})} = \frac{4\pi^2 d}{T^2} = \frac{4 \times \pi^2 \times 3.84 \times 10^8}{(2.36 \times 10^6)^2}$ $a_{c(\text{Moon})} = 2.72 \times 10^{-3}\ \text{m s}^{-2}$
Compare the acceleration of the Moon with that of a falling apple on Earth by calculating the ratio $\frac{g_{\text{Earth}}}{a_{\text{c Moon}}}$. Note the measured acceleration of a falling object (e.g. an apple) on Earth is: $g_{\text{Earth}} = 9.8\ \text{m s}^{-2}$ In Newton's time this value was well known. Galileo first measured this acceleration in 1604.	$\frac{g_{\text{Earth}}}{a_{\text{c (Moon)}}} = \frac{9.8}{2.72 \times 10^{-3}}$ ≈ 3600 The acceleration of the Moon in orbit is approximately 3600 times smaller than the acceleration of the falling apple.
Compare the two distances that the forces are acting over by calculating the ratio $\frac{d_{\text{Earth–Moon}}}{r_{\text{Earth}}}$	Calculate $\frac{d_{\text{Earth–Moon}}}{r_{\text{Earth}}}$ where: $d_{\text{Earth–Moon}} = 3.84 \times 10^8$ m $r_{\text{Earth}} = 6.37 \times 10^6$ m $\frac{d_{\text{Earth–Moon}}}{r_{\text{Earth}}} = \frac{3.84 \times 10^8}{6.37 \times 10^6}$ ≈ 60 The distance from Earth to the Moon is approximately 60 times greater than the distance from the centre of Earth to its surface.
Square the ratio of the distances to compare with the ratio of the accelerations.	Newton noted that the acceleration of a falling object on Earth was 3600 times greater than the acceleration of the Moon in orbit. He also noted that the distance to the Moon was 60 times greater than the radius of the Earth. And, of course, 60 squared is 3600. That is, said Newton, the same force from Earth acts on both the orbiting Moon and a falling object at Earth's surface. And the strength of that force is inversely proportional to the square of the distance.

➤ Try yourself 5.1.1

GRAVITATIONAL ATTRACTION BETWEEN SMALL AND LARGE OBJECTS

Apply Isaac Newton's calculations as if you were a Martian scientist comparing the acceleration of Mars's small, close-orbiting moon Phobos with the acceleration of a falling Martian apple.

Use 9.38×10^6 m as the radius of the orbit of Phobos, and 7 hours 40 minutes as the period of the moon's orbit. Use $3.71\,\text{m s}^{-2}$ as the acceleration of a falling apple on the Martian surface and 3.39×10^6 m as the radius of Mars.

Even the great Isaac Newton could not quantify the **gravitational constant** G when he developed his law of universal gravitation, because the mass of Earth was not then accurately known. All Newton could say was that the force was 'proportional' to the distance between two objects, with the component of proportionality being the product $G \times M_{\text{Earth}}$.

The value of G was first determined a century later by the British scientist Henry Cavendish, who used a sensitive torsion balance (a twisting wire) to find the gravitational attraction between two known masses held a small distance apart. By finding the constant G, Cavendish's experiment also enabled the first accurate measurement of the mass of the Earth.

Worked example 5.1.2

GRAVITATIONAL ATTRACTION BETWEEN SMALL OBJECTS

Mark has a mass of 90.0 kg and his dance partner Bec has a mass of 75 kg. The distance between their centres is 85 cm. Calculate the magnitude of the force of gravitational attraction between the dancers.

Thinking	Working
Recall the formula for Newton's law of universal gravitation.	$F_g = G\frac{m_1 m_2}{r^2}$
Identify the information required, and convert values into appropriate units where necessary.	$G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$ $m_1 = 90\,\text{kg}$ $m_2 = 75\,\text{kg}$ $r = 85\,\text{cm} = 0.85\,\text{m}$
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \frac{90 \times 75}{0.85^2}$
Solve the equation.	$F_g = 6.2 \times 10^{-7}\,\text{N}$ This force is of the order of a millionth of a newton. To give an idea of scale, that's about ten-thousandth the weight of a feather.

➤ Try yourself 5.1.2

GRAVITATIONAL ATTRACTION BETWEEN SMALL OBJECTS

In Henry Cavendish's 1798 experiment, a large lead mass was suspended beside a smaller mass so that the centres of the two balls were 230 mm apart. Ball 1 had a mass of 160 kg and ball 2 had a mass of 0.73 kg. Calculate the magnitude of the force of gravitational attraction between them.

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Gravitational forces between everyday objects are so small (as seen in Worked example 5.1.2) that forces are hard to detect without specialised equipment. Such forces are often considered to be negligible. For the gravitational force to become significant, at least one of the objects must have a very large mass—for example, a planet (Figure 5.1.2).

FIGURE 5.1.2 Gravitational forces become significant when at least one of the objects has a large mass, for example forces between Earth and the Moon. Note that distances are not shown to scale.

Worked example 5.1.3

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Calculate the magnitude of the force of gravitational attraction between the Moon and Earth given the following data:

$m_{Moon} = 7.35 \times 10^{22}$ kg

$m_{Earth} = 5.97 \times 10^{24}$ kg

$r_{Moon–Earth} = 3.84 \times 10^{8}$ m

Thinking	Working
Recall the formula for Newton's law of universal gravitation.	$F_g = G\frac{m_1 m_2}{r^2}$
Identify the information required.	$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2} $m_1 = 7.35 \times 10^{22}$ kg $m_2 = 5.97 \times 10^{24}$ kg $r = 3.84 \times 10^{8}$ m
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \frac{7.35 \times 10^{22} \times 5.97 \times 10^{24}}{(3.84 \times 10^{8})^2}$
Solve the equation.	$F_g = 1.98 \times 10^{20}$ N This force is close to 200 million trillion newtons.

➤ Try yourself 5.1.3

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Calculate the magnitude of the force of gravitational attraction between Earth and the Sun given the following data:

$m_{Earth} = 5.97 \times 10^{24}$ kg

$m_{Sun} = 1.99 \times 10^{30}$ kg

$r_{Sun–Earth} = 1.50 \times 10^{11}$ m

The forces in Worked example 5.1.3 are trillions of trillions times greater than those in Worked example 5.1.2, illustrating the difference in the gravitational force when at least one of the objects has a very large mass.

Explaining the structure of the universe

The greatest achievement of Newton's law of universal gravitation was to explain the observed movement of planetary bodies. The three laws of planetary motion laid down by Johannes Kepler in 1609 (considered in detail in Chapter 6) had accurately predicted the movement of the planets, but before Newton no-one knew *why* the planets followed these orbits.

Newton's simple law of universal gravitation mathematically explained the movement of planets in ellipses, and all other aspects of Kepler's laws. It explained the orbit of the Moon about Earth, Earth about the Sun, the moons around Jupiter, and all other observable planetary motion.

There is one exception. Isaac Newton's laws did not properly explain very subtle quirks in the orbit of Mercury. For that, we needed Albert Einstein (you will learn more about this in Module 5.2).

EFFECT OF GRAVITY

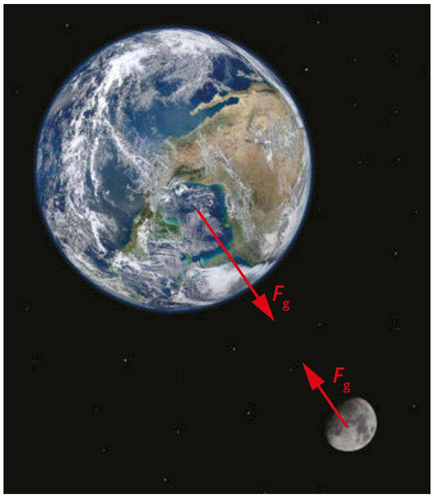


FIGURE 5.1.3 Earth and the Moon exert gravitational forces on each other.

Recall that according to Newton's third law of motion, all forces occur in equal action–reaction pairs.

An example of such a pair is shown in Figure 5.1.3. Earth exerts a gravitational force on the Moon and, conversely, the Moon exerts an equal and opposite force on the Earth.

Using Newton's *second* law of motion ($F = ma$), you can determine that the equal gravitational force between the two bodies results in a much smaller acceleration of the Earth than of the Moon.

Worked example 5.1.4

ACCELERATION CAUSED BY A GRAVITATIONAL FORCE

As you saw in Worked example 5.1.3, the force of gravitational attraction between the Moon and Earth is 1.98×10^{20} N. Calculate the acceleration of Earth and the Moon caused by this force. Compare these accelerations by calculating the ratio $\frac{a_{Moon}}{a_{Earth}}$.

Use the following data:

$m_{Moon} = 7.35 \times 10^{22}$ kg

$m_{Earth} = 5.97 \times 10^{24}$ kg

Thinking	Working
Recall the formula for Newton's second law of motion.	$F = ma$
Transpose the equation to make *a* the subject.	$a = \frac{F}{m}$
Substitute values into this equation to find the accelerations of the Moon and of Earth.	$a_{Moon} = \frac{1.98 \times 10^{20}}{7.35 \times 10^{22}} = 2.70 \times 10^{-3}\,\text{m s}^{-2}$ and the direction is towards Earth. $a_{Earth} = \frac{1.98 \times 10^{20}}{5.97 \times 10^{24}} = 3.32 \times 10^{-5}\,\text{m s}^{-2}$ and the direction is towards the Moon.
Compare the two accelerations by calculating the ratio $\frac{a_{Moon}}{a_{Earth}}$	$\frac{a_{Moon}}{a_{Earth}} = \frac{2.70 \times 10^{-3}}{3.32 \times 10^{-5}} = 81.2$ That is, the acceleration of the Moon due to the Earth is approximately 80 times greater than the acceleration of the Earth due to the Moon.

➤ Try yourself 5.1.4

ACCELERATION CAUSED BY A GRAVITATIONAL FORCE

The force of gravitational attraction between Earth and a rugby ball kicked into the air is 4.90 N. Calculate the acceleration of the ball, and of Earth, caused by this force. Compare these accelerations by calculating the ratio $\frac{a_{ball}}{a_{Earth}}$.

Use the following data:

$m_{ball} = 500.0$ g

$m_{Earth} = 5.97 \times 10^{24}$ kg

Gravity in the solar system

Accelerations caused by gravitational forces between astronomical bodies, as calculated in Worked example 5.1.3, created the motion of the solar system.

In the Earth–Moon system, the acceleration of the Moon is many times greater than that of Earth, which is why the Moon orbits Earth. Although the Moon's gravitational force causes a much smaller acceleration of Earth, it does have other significant effects, such as the tides.

Similarly, the Earth and other planets orbit the Sun because their masses are much smaller than the Sun's mass. However, the combined gravitational effect of the planets of the solar system (and Jupiter in particular) causes the Sun to wobble slightly as the planets orbit it.

WEIGHT AND GRAVITATIONAL FORCE

You will have seen previously (Unit 2 Chapter 7 and Unit 3 Chapter 3) that the weight of an object is calculated using the formula $F_g = mg$.

'Weight' is simply another name for the gravitational force acting on an object near Earth's surface.

Worked example 5.1.5 below shows that the formula for weight $F_g = mg$ and Newton's law of universal gravitation $F_g = G\frac{m_1 m_2}{r^2}$ give the same answer for the gravitational force acting on objects on Earth's surface. It is important to note that the distance used in these calculations is the distance between the centres of the two objects, which is effectively the radius of Earth.

Weight is the force due to gravity.

Mass is the amount of material contained in a body.

In distant space, far from any large body, your weight would be zero, but your mass would be the same as here on Earth (and so, for example, your inertia would be the same, if you were trying to change direction in space).

Worked example 5.1.5

GRAVITATIONAL FORCE AND WEIGHT

Compare the weight of a 30.0 kg child, calculated using $F_g = mg$, with the gravitational force on the child due to Earth, calculated using $F_g = G\frac{m_1 m_2}{r^2}$.

Use the following dimensions of Earth in your calculations:

$G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$

$g = 9.8\,\text{m s}^{-2}$

$M_{\text{Earth}} = 5.97 \times 10^{24}\,\text{kg}$

$r_{\text{Earth}} = 6.37 \times 10^{6}\,\text{m}$

Thinking	Working
Apply the weight equation.	$F_g = mg$ $= 30.0 \times 9.8$ $= 290\,\text{N}$
Apply Newton's law of universal gravitation.	$F_g = G\frac{m_1 m_2}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{5.97 \times 10^{24} \times 30.0}{(6.37 \times 10^6)^2}$ $= 294\,\text{N}$
Compare the two values.	Both equations give the same result (to within 2 or 3 significant figures).

➤ Try yourself 5.1.5

GRAVITATIONAL FORCE AND WEIGHT

Compare the weight of a 5.0 kg mass on Earth's surface calculated using the formulas $F_g = mg$ and $F_g = G\frac{m_1 m_2}{r^2}$. Use the following dimensions of Earth, where necessary:

$G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$

$g = 9.8\,\text{m s}^{-2}$

$m_{\text{Earth}} = 5.97 \times 10^{24}\,\text{kg}$

$r_{\text{Earth}} = 6.37 \times 10^{6}\,\text{m}$

Be aware that Newton's law of universal gravitation, $F_g = G\frac{m_1 m_2}{r^2}$, can also be expressed as $F_g = \frac{GMm}{r^2}$. This form will be introduced and used in Chapter 6.

Worked example 5.1.5 shows that the standard acceleration due to gravity at Earth's surface, g, can be derived directly from the dimensions of Earth. An object with mass m sitting on the surface of Earth is a distance of 6.37×10^6 m from its centre.

Given that Earth has a mass of 5.97×10^{24} kg, then:

$$\text{Weight} = Fg$$

$$mg = G\frac{m_{\text{Earth}}m}{(r_{\text{Earth}})^2}$$

$$g = G\frac{m_{\text{Earth}}}{(r_{\text{Earth}})^2}$$

$$6.67 \times 10^{-11} \times \frac{5.97 \times 10^{24}}{(6.37 \times 10^6)^2}$$

$$= 9.81\,\text{ms}^{-2}$$

This calculation shows that the acceleration of objects near the surface of Earth, g, is a result of Earth's mass and radius. A planet with a different mass or different radius will therefore have a different value for g.

The measured value for g is not constant everywhere on Earth. It is higher at the poles than at the equator, because of the slightly 'squashed' shape of the Earth (i.e. the distance from pole to centre is shorter than the distance from equator to centre). Also g varies according to nearby valleys, mountains and more dense or less dense rock. Globally, the average value for g is $9.8\,\text{m s}^{-2}$. You will learn more about variations in gravitational field strength in Module 5.2.

Likewise, if an object is above Earth's surface, the value of r will be greater and therefore the acceleration due to gravity will be smaller, following the inverse square law. This is why the strength of Earth's gravity reduces as you travel away from Earth.

Multi-body systems

So far, only gravitational systems involving two objects have been considered, such as the Moon and Earth.

In reality, objects experience a gravitational force from every other object around them. Usually, most of these forces are negligible and only the gravitational effect of the largest object nearby (i.e. in everyday life, Earth) needs to be considered.

When there is more than one significant gravitational force acting on a body, the gravitational forces must be added together as vectors to determine the net gravitational force (Figure 5.1.4).

For example, the gravitational forces acting on *you* right now include the pull of Earth, the pull of the Sun (about 1500 times smaller), the pull of the Moon (almost 200 times smaller again) and the pull of Jupiter (100 times smaller than that).

The direction and relative magnitude of the net gravitational force in a multi-body system depends on the masses and positions of all of the attracting objects (i.e. m_1, m_2 and m_3 in Figure 5.1.4).

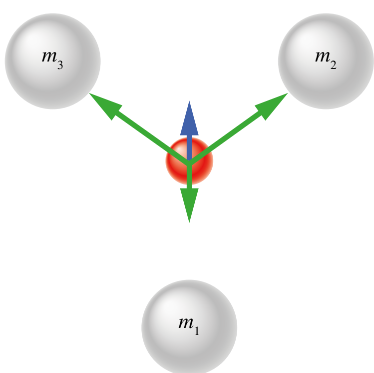


FIGURE 5.1.4 For three objects of equal mass ($m_1 = m_2 = m_3$) with the relative positions shown, the gravitational forces acting on the central red ball are indicated by the green arrows. The vector sum of the green arrows is indicated by the blue arrow. This will be the direction of the net (or resultant) gravitational force on the red ball due to the other three masses.

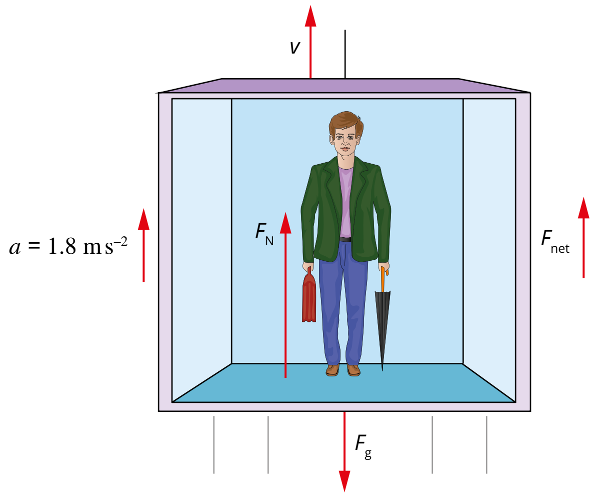
APPARENT WEIGHT

Scientists use the term 'weight' simply to mean 'the force due to gravity'. It is also correct to interpret weight as the contact force (or normal reaction force) between an object and Earth's surface. In most situations these two definitions are effectively the same. However, there are some cases—for example, when a person is accelerating up or down in a lift—when they give different results. In these situations, the normal force (F_N) is referred to as the **apparent weight**, as this is the force that the person will feel through their feet.

Worked example 5.1.6

APPARENT WEIGHT

A 50.0 kg person is standing in a lift that is accelerating upwards at 1.8 m s^{-2}. Calculate the weight and apparent weight of the person. Use g = 9.8 m s^{-2}.



Thinking	**Working**
Calculate the weight of the person using $F_g = mg$.	$F_g = mg = 50.0 \times 9.8 = 490$ N downwards
Calculate the force required to accelerate the person upwards at 1.8 m s^{-2}.	$F_{net} = ma = 50.0 \times 1.8 = 90$ N
The net force that causes the acceleration results from the normal reaction force (upwards) and the weight force (downwards). Since the lift is accelerating upwards, $F_N > F_g$. Recall that the normal reaction force gives the apparent weight.	$F_{net} = 90$ $F_N - F_g = 90$ $F_N - 490 = 90$ $F_N = 490 + 90$ F_N = apparent weight = 580 N upwards, since it in the same direction as the normal reaction force.

➤ Try yourself 5.1.6

APPARENT WEIGHT

Calculate the apparent weight of a 100.0 kg person in a lift that is accelerating downwards at 0.20 m s^{-2}. Use g = 9.8 m s^{-2}.

SCIENCE AS A HUMAN ENDEAVOUR

Hunting exoplanets

In recent years, scientists have been interested in discovering whether other stars have planets like those in our own solar system. One of the ways in which these 'extrasolar planets' (or 'exoplanets') can be detected is by the gravitational effect they have on their host star.

When any planet orbits a star, it causes the star to 'wobble' enough for this wobble to be detected on Earth. At the time of writing, thousands of exoplanets have been discovered using this technique. These exoplanets range in size from many times the mass of Jupiter to Earth-sized.

Consider Newton's law of universal gravitation: $F_g = G\frac{m_1 m_2}{r^2}$. You will see that the larger the mass of the planet, the greater the gravitational force between that planet and its host star, and therefore the more it will cause its host star to wobble. The inverse square relationship to distance means that the closer the planet's orbit is to the star, the greater the wobble too. So it won't be surprising to hear that the easiest exoplanets to spot are those known as 'hot Jupiters'—planets the mass of Jupiter or larger, and orbiting their star closer than Mercury orbits the Sun. These are the planets that exert the greatest forces on their host star.

These hot Jupiters were the first exoplanets to be discovered using the gravitational wobble method. In fact, before hot Jupiters were detected, astronomers didn't believe that planets that large could ever form so close to a star. So in 1995 the very first exoplanet discovered orbiting a regular star, 51 Pegasi b, revolutionised our understanding of how solar systems form.

Since then astronomers' instruments have improved and can now detect the gravitational tug of much smaller planets.

In fact, in 2016 it was discovered that Proxima Centauri, the star closest to us, has at least one planet not much larger than Earth tugging at the star in time with the planet's 11-day orbit. With such a small planet, the effect on the star's orbit is tiny—a change in velocity of only $1.4\,\text{m s}^{-1}$. The instrumentation used by astronomers is precise enough to identify such small changes in velocity.

Instruments at the new observatory at Mt Kent in southern Queensland will be able to detect even smaller gravitational wobbles in distant stars, changes as small as $1\,\text{m s}^{-1}$, or about the same as a very slow walking pace.

Queensland astronomer Jonti Horner (Figure 5.1.5) has discovered many exoplanets using gravitational wobble and other planet-hunting methods. But he is still impressed by the science behind these discoveries: 'Stars are trillions or quadrillions of kilometres away. Proxima Centauri, the nearest, is more than 40 trillion km distant. I find it astonishing we can measure something that is so distant and see a wobble that is comparable to the speed at which you or I would walk around the shops!'

FIGURE 5.1.5 Queensland astronomer Jonti Horner uses the gravitational pull on host stars to identify distant exoplanets.

Review

1 Explain the term 'hot Jupiters' and why they are reasonably easy for astronomers to detect.

2 Astronomers can discover planets orbiting distant stars by observing the effect of the exoplanet's gravitational pull on its host star. The huge exoplanet Hypatia has a mass of 1.68×10^{28} kg (almost 10 times the mass of Jupiter).

   a Calculate the magnitude of the gravitational force that the planet exerts on its host star, given that Hypatia orbits at an average distance of 195 000 000 km and the mass of its host star is 3.62×10^{30} kg.

   b Calculate the magnitude of the resulting acceleration of the planet's host star.

5.1 Review

SUMMARY

- All objects with mass attract one another with a gravitational force.
- The gravitational force acts equally on each of the masses.
- The magnitude of the gravitational force is given by Newton's law of universal gravitation: $F_g = G\frac{m_1 m_2}{r^2}$.
- Gravitational forces are usually negligible unless one of the objects is massive, e.g. a planet.
- The weight of an object on the Earth's surface is due to the gravitational attraction of Earth and, unless the object is accelerating, weight is equal to the normal reaction force: weight = $F_g = F_N$.
- The acceleration due to gravity of an object near the surface of Earth can be calculated using the dimensions of the Earth: $g = G\frac{m_{Earth}}{(r_{Earth})^2} = 9.8\,m\,s^{-2}$
- Objects can have an apparent weight that is greater or less than their normal weight. This occurs when they are accelerating vertically.

KEY QUESTIONS

Retrieval

1 Describe the relationships in Newton's law of universal gravitation. State what the force of attraction is proportional to. Determine what makes it greater and what makes it smaller.

2 Indicate what the symbol r represents in Newton's law of universal gravitation.

Comprehension

3 Describe what happens to the gravitational force acting between two masses m_1 and m_2 a distance r apart, in each case below.

a The mass of m_1 is doubled.

b The distance r is doubled.

c The distance r is quadrupled.

4 Explain why the acceleration of the Moon caused by the gravitational force of Earth is much larger than the acceleration of Earth due to the gravitational force of the Moon.

Analysis

5 Consider gravitational attraction between the Sun and Mars, given that the mass of the Sun is 1.99×10^{30} kg, the mass of Mars is 6.39×10^{23} kg and the average distance between the two is 2.28×10^{11} m.

a Calculate the gravitational attraction between the Sun and Mars.

b Calculate the acceleration of Mars.

6 On 14 April 2014, Mars came within 93.0 million km of Earth. At that point its gravitational effect on Earth was the strongest it had been for over 6 years. Use the following data to answer the questions below.

$$m_{Sun} = 1.99 \times 10^{30}\,kg$$
$$m_{Earth} = 5.97 \times 10^{24}\,kg$$
$$m_{Mars} = 6.39 \times 10^{23}\,kg$$

a Calculate the gravitational force between Earth and Mars on 14 April 2014.

b Calculate the force of the Sun on Earth, given that the distance between them is 150 million km.

c Compare your answers to parts **a** and **b** above by expressing the Mars–Earth force as a percentage of the Sun–Earth force.

d Calculate the distance r between Earth and Mars at the greatest distance between the two planets, where the gravitational force between Mars and the Earth is 5.03×10^{15} N.

7 Compare and explain the difference between the terms 'weight' and 'apparent weight', giving an example of a situation in which the magnitudes of these two forces would be different.

8 Two astronauts, Sandra and George, each of mass 150 kg (including their suits), float in outer space 1.00 m apart.

a Calculate the gravitational force between them.

b Calculate the resulting acceleration of each astronaut.

5.1 Review *continued*

9 Consider the force of gravity on Mercury, a small rocky planet.

a State the equation you would use to calculate gravitational acceleration on the surface of Mercury.

b Explain the effect the much smaller radius of Mercury has on gravitational acceleration. Mercury has a radius only a third of the radius of Earth.

c Explain the effect the much smaller mass has on gravitational acceleration. The mass of Mercury is much smaller than that of Earth.

d Calculate gravitational acceleration on the surface of Mercury, given that Mercury has a mass of 3.29×10^{23} kg and a radius of 2440 km.

e Calculate the weight of Hermes, a 75.0 kg astronaut standing on the surface of Mercury.

10 Calculate the weight of Aphrodite, a 75.0 kg astronaut standing on the surface of Venus, given that the planet has a mass of 4.87×10^{24} kg and a radius of 6050 km.

11 Calculate the apparent weight of a 50.0 kg person in a lift under the following circumstances. Use $g = 9.8\,\text{m s}^{-2}$.

a accelerating upwards at $1.24\,\text{m s}^{-2}$

b moving upwards at a constant speed of $5.0\,\text{m s}^{-1}$

12 In 1846, Newton's laws of gravity allowed astronomers to predict the existence of Neptune, the eighth planet in the solar system, based on variations in the orbit of Uranus.

a Calculate the maximum force between the two planets if the mass of Uranus is 8.68×10^{25} kg, the mass of Neptune is 1.02×10^{26} kg, and the shortest distance between the two planets is 1.63×10^{9} km.

b Compare this with the gravitational force of the Sun on Uranus if the mass of the Sun is 1.99×10^{30} kg and the distance from the Sun to Uranus is 2.87×10^{9} km.

5.2 Gravitational fields

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

- define 'gravitational fields'
- solve problems involving the gravitational field strength at distance from an object.

Newton's law of universal gravitation describes the force acting between two mutually attracting bodies. In reality, complex systems like the solar system involve a number of objects (e.g. the solar system has the Sun and planets (Figure 5.2.1)) that are all exerting attractive forces on each other at the same time.

In the 18th century, to simplify the process of calculating the effect of simultaneous gravitational forces, scientists developed a model known as the **gravitational field**. In the following centuries, the idea of a **field** was also applied to other forces and has become a very important concept in physics.

FIGURE 5.2.1 The solar system is a complex gravitational system.

GRAVITATIONAL FIELDS

A gravitational field is a region in which a gravitational force is exerted on all matter within that region. Every physical object has an accompanying gravitational field. For example, the space around your body contains a gravitational field because any other object that comes into this region will experience a (small) force of gravitational attraction to your body.

The gravitational field around a large object such as a planet is much more significant than that around a small object. Earth's gravitational field exerts a significant influence on objects on its surface and even up to thousands of kilometres into space.

Discovering Neptune

The planet Neptune was discovered through its gravitational effect on other planets and the application of Newton's law.

Two astronomers, Urbain Le Verrier of France and John Couch Adams of England, each independently identified that the observed orbit of Uranus varied significantly from predictions made based on the gravitational effects of the Sun and other known planets. Both astronomers suggested that this was due to the influence of a distant, undiscovered planet.

Le Verrier sent a prediction of the location of the new planet to Gottfried Galle at the Berlin Observatory and, on 23 September 1846, Neptune was discovered within 1 degree of Le Verrier's prediction (Figure 5.2.2).

a b

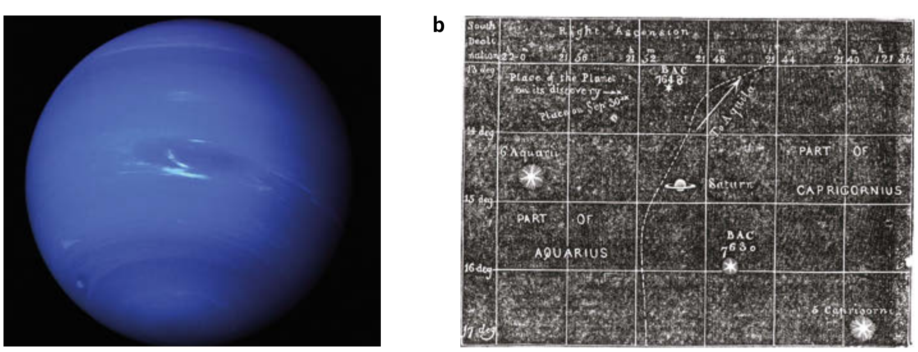


FIGURE 5.2.2 (a) Picture of Neptune taken by Voyager 2 in 1989. (b) This star chart published in 1846 shows the location of Neptune in the constellation Aquarius on its discovery, and its location one week later, on September 30.

Representing gravitational fields

Over time, scientists have developed a commonly understood method of representing fields using a series of arrows known as field lines (Figure 5.2.3). For gravitational fields, these are constructed as follows.

- The direction of the arrowhead indicates the direction of the gravitational force.
- The space between the arrows indicates the relative magnitude of the field:
  - closely spaced arrows indicate a strong field
  - widely spaced arrows indicate a weaker field.
- Parallel field lines indicate constant or uniform field strength.
- Gravitational field lines emanate from the source of the field.
- The lines never cross.

In theory, you could draw an infinite number of field lines, but in fact only a few are needed to represent the rest. The size of the gravitational force acting on a mass in the region of a gravitational field is determined by the strength of the field, and the force acts in the direction of the field.

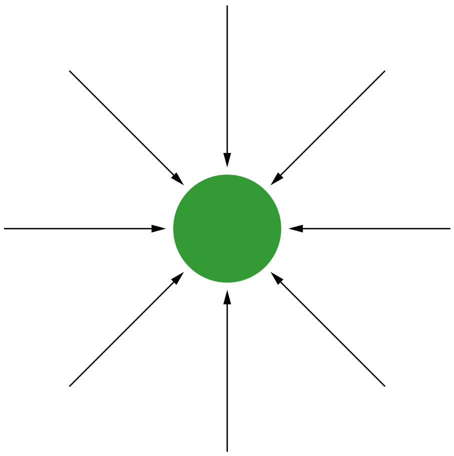
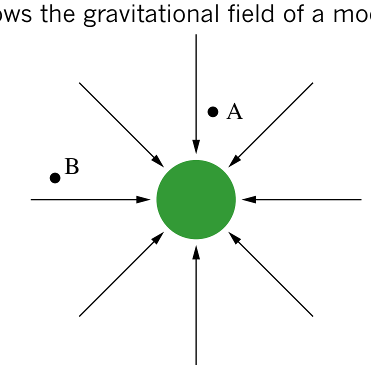


FIGURE 5.2.3 The arrows in this gravitational field diagram indicate that objects will be attracted towards the mass in the centre. The spacing of the lines shows that force will be strongest at the surface of the central mass and weaker further away from it.

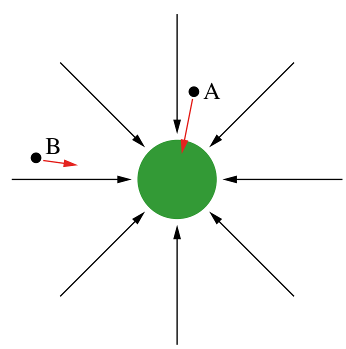
Worked example 5.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a moon.



a Use arrows to indicate the direction of the gravitational force acting at points A and B.

Thinking	Working
The direction of the field arrows indicates the direction of the gravitational force, which is inwards towards the centre of the moon.	

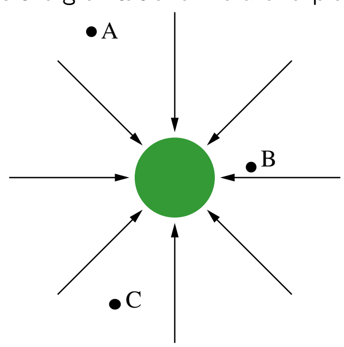
b Indicate the relative strength of the gravitational field at each point.

Thinking	Working
The closer the field lines, the stronger the force. The field lines are closer together at point A than they are at point B, as point A is closer to the moon.	The field is stronger at point A than at point B.

➤ Try yourself 5.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a planet.



a Use arrows to indicate the direction of the gravitational force acting at points A, B and C.

b Indicate the relative strength of the gravitational field at each point.

GRAVITATIONAL FIELD STRENGTH

In theory, gravitational fields extend infinitely out into space. However, since the magnitude of the gravitational force decreases with the square of distance, eventually these fields become so weak as to become negligible.

In Module 5.1, you calculated the acceleration due to gravity of objects near the Earth's surface using the dimensions of the Earth: $g = G\frac{M_{Earth}}{(r_{Earth})^2} = 9.8\,m\,s^{-2}$.

This acceleration is known as the standard acceleration due to gravity, and is usually indicated by the letter g or g_{Earth}. This value is also used as a measure of the strength of the gravitational field, in which case it is written with the equivalent units of $N\,kg^{-1}$ rather than $m\,s^{-2}$. This means $g_{Earth} = 9.8\,N\,kg^{-1}$.

These units indicate that objects on the surface of the Earth experience 9.8 N of gravitational force for every kilogram of their mass.

Accordingly, the familiar equation $F_g = mg$ can be rearranged so that the **gravitational field strength**, g, can be calculated:

$$g = \frac{F_g}{m}$$

where

g is gravitational field strength ($N\,kg^{-1}$)

F_g is the force due to gravity (N)

m is the mass of an object in the field (kg)

Worked example 5.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

When Maree hangs a 1.00 kg mass from a spring balance, the balance measures a downwards force of 9.8 N.

Calculate the gravitational field strength of the Earth at this location, according to this experiment.

Thinking	Working
Recall the equation for gravitational field strength.	$g = \frac{F_g}{m}$
Substitute in the appropriate values.	$g = \frac{9.8}{1.00}$
Solve the equation.	$g = 9.8\,N\,kg^{-1}$ downwards

> ℹ $g = G\frac{M}{r^2}$
>
> where
>
> g is the gravitational field strength ($N\,kg^{-1}$)
>
> G is the gravitational constant, $6.67 \times 10^{-11}\,N\,m^2\,kg^{-2}$
>
> M is the mass of the planet or moon (i.e. the central body; kg)
>
> r is the radius of the planet or moon (m)

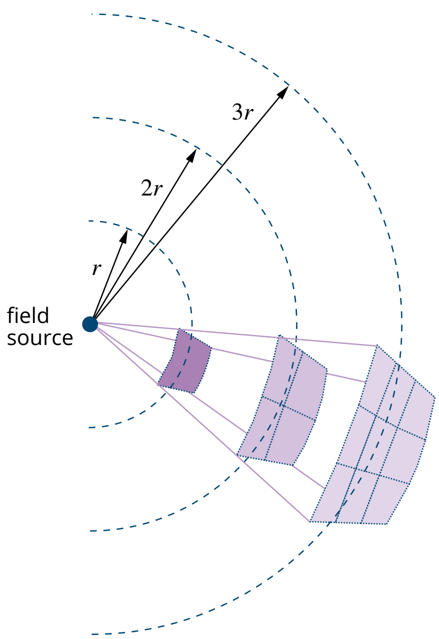


FIGURE 5.2.4 As the distance from the source of a field increases, the field is spread over an area that increases with the square of the distance from the source. This means that the strength of the field decreases by the same ratio.

➤ Try yourself 5.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

Dion uses a spring balance to measure the weight of a piece of wood as 2.53 N. If the piece of wood has a mass of 259 g, calculate the gravitational field strength indicated by this experiment.

As was shown earlier in this module and in Worked example 5.1.5, the formula for gravitational field strength, $g = \frac{F_g}{m}$, can be combined with Newton's law of universal gravitation, $F_g = G\frac{Mm}{r^2}$, to develop the formula for gravitational field strength:

$$g = \frac{F_g}{m} = \frac{G\frac{Mm}{r^2}}{m}$$

Therefore: $g = G\frac{M}{r^2}$

where

g is the gravitational field strength ($N\,kg^{-1}$)

G is the gravitational constant, $6.67 \times 10^{-11}\,N\,m^2\,kg^{-2}$

M is the mass of the planet or moon (i.e. the central body; kg)

r is the radius of the planet or moon (m).

The inverse square law

The concept of a field is a very powerful tool for understanding forces that act at a distance. It has also been applied to such forces as the electrostatic force between charged objects and the force between two magnets.

The study of gravitational fields introduces the concept of the inverse square law. From the point source of a field, whether it be gravitational or electric, the field will spread out radially in three dimensions. When the distance from the source is doubled, the field will be spread over four times the original area.

Figure 5.2.4 shows an increasing distance from the field source of r then $2r$ then $3r$. As you can see, a projection of one square at distance r increases to four squares (2^2) at distance $2r$ and increases to nine squares (3^2) at distance $3r$.

As the 'inverse' part of the inverse square law implies, at a distance $2r$ from the source the strength of the field will be reduced to a quarter of the field at distance r. The force the field would exert at that distance will also be reduced to a quarter. At a distance $3r$ from the source, the field will be reduced to one-ninth of the field at distance r, and so on.

> ℹ In terms of the gravitational field, the strength of the force varies inversely with the distance from the source of the field, squared:
>
> $F \propto \frac{1}{r^2}$
>
> where
>
> F is the force (N)
>
> r is the distance from the source of the gravitational field (m).
>
> This is referred to as an inverse square law. (Refer to the Skillbuilder on page 464 of *Pearson Physics 11 Queensland* for more information on proportional reasoning.)

One key difference between the gravitational force and other inverse square forces is that the gravitational force is always attractive, whereas like charges, or magnets with the same pole facing, repel one another.

Inverse square laws are an important concept in physics, not only in the study of fields but also in studying phenomena where energy is moving away from its source in three dimensions, such as in sound and other waves.

Variations in gravitational field strength of Earth

The gravitational field strength of Earth, g, is usually assigned a value of $9.8\,N\,kg^{-1}$. However, the field strength experienced by objects on the surface of Earth can vary—it can be between $9.76\,N\,kg^{-1}$ and $9.83\,N\,kg^{-1}$, depending on the location.

Several factors influence the varying gravitational field strength. Earth is not a perfect sphere, but is 'flattened' at the poles (Figure 5.2.5). This means objects near the equator are slightly further from the centre than objects at the poles, so the gravitational field is slightly weaker at the equator than at the poles.

Geological formations can also create differences in gravitational field strength, depending on their composition. Geologists use a sensitive instrument known as a **gravimeter** (Figure 5.2.6) that detects small local variations in gravitational field strength to indicate underground features. Rocks with above-average density, such as those containing mineral ores, create slightly stronger gravitational fields, whereas less-dense sedimentary rocks produce weaker fields.

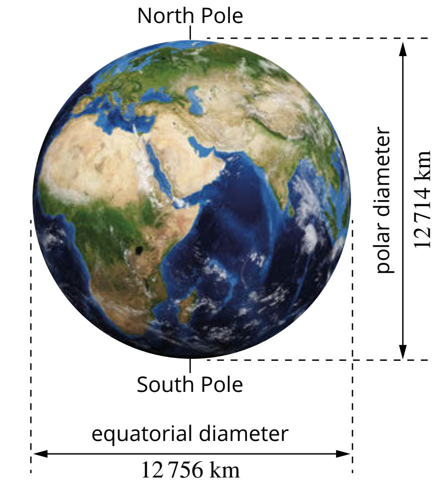


FIGURE 5.2.5 Earth is a flattened sphere, which means its gravitational field is slightly stronger at the poles than the equator.

FIGURE 5.2.6 A gravimeter can be used to measure the strength of the local gravitational field.

If Earth's surface is considered a flat surface as it appears in everyday life, then the gravitational field lines are approximately parallel, indicating a uniform field (Figure 5.2.7).

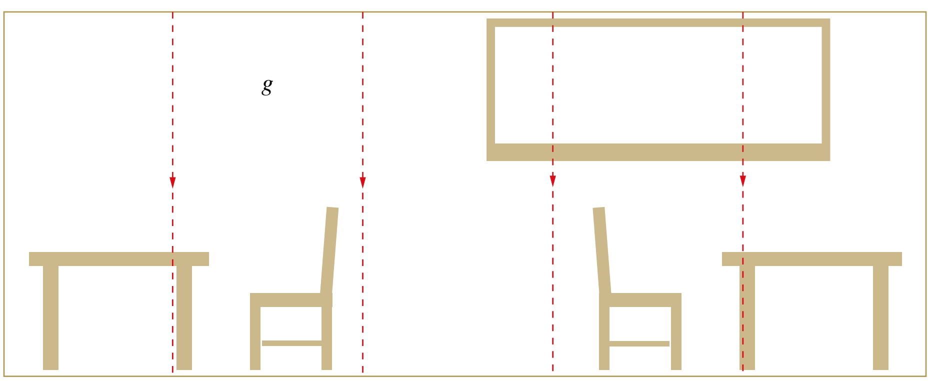


FIGURE 5.2.7 The uniform gravitational field, g, is represented by evenly spaced parallel lines in the direction of the force.

However, when Earth is viewed from a sufficiently large distance to see it as a sphere, it becomes clear that its gravitational field is not uniform at all (Figure 5.2.8). The increasing distance between the field lines indicates that the field becomes progressively weaker out into space.

This is because gravitational field strength, like gravitational force, is governed by the inverse square law:

$$g = G\frac{M_{Earth}}{(r_{Earth})^2}$$

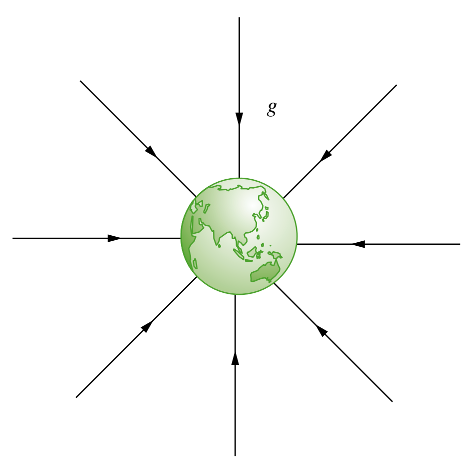


FIGURE 5.2.8 Earth's gravitational field becomes progressively weaker out into space.

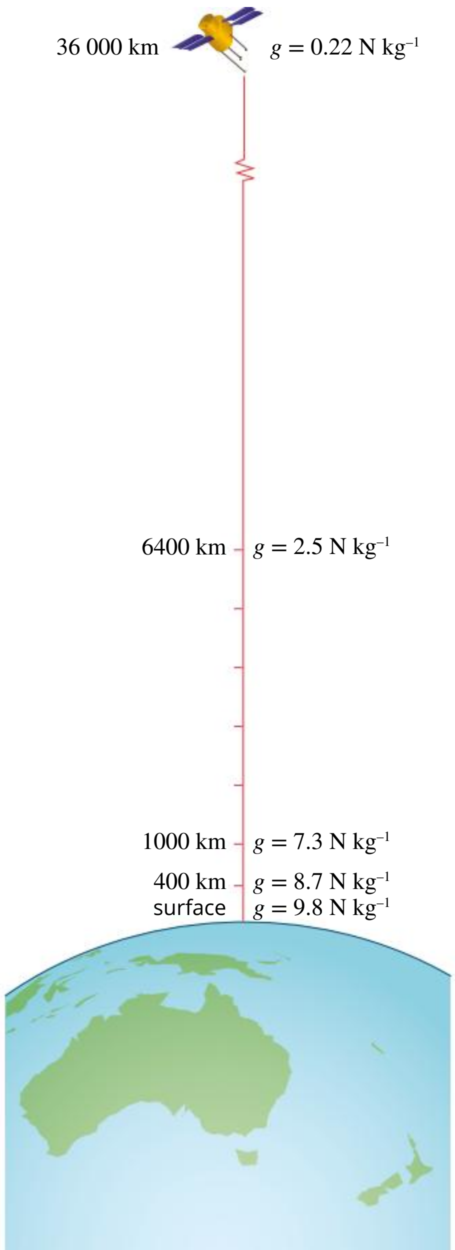


FIGURE 5.2.9 Earth's gravitational field strength is weaker at higher altitudes.

The gravitational field strength at different altitudes can be calculated by adding the **altitude** (height above the surface of Earth) to the radius of Earth to calculate the distance the object is from Earth's centre (Figures 5.2.9 and 5.2.10).

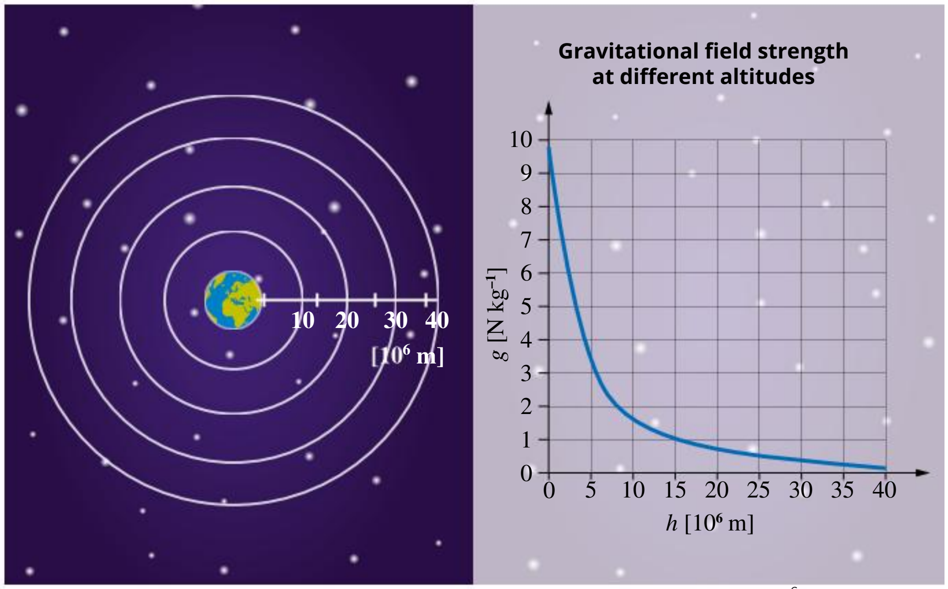


FIGURE 5.2.10 As the distance from the surface of Earth increases from 0 to 40×10^6 m, the value for g decreases rapidly from $9.8\,\text{N kg}^{-1}$, according to the inverse square law. The blue line on the graph gives the value of g at various altitudes (h).

$$g = \frac{GM_{\text{Earth}}}{(r_{\text{Earth}} + \text{alititude})^2}$$

Worked example 5.2.3

CALCULATING GRAVITATIONAL FIELD STRENGTH AT DIFFERENT ALTITUDES

Calculate the magnitude of Earth's gravitational field at the top of Mt Everest.

$r_{\text{Earth}} = 6.37 \times 10^6\,\text{m}$

$M_{\text{Earth}} = 5.97 \times 10^{24}\,\text{kg}$

height of Mt Everest = 8848 m

Compare the answer with average gravitational field strength at sea level, $9.8\,\text{N kg}^{-1}$.

Thinking	Working
Recall the formula for gravitational field strength.	$g = G\frac{M}{r^2}$
Add the height of Mt Everest to the radius of Earth.	$r = 6.37 \times 10^6 + 8848\,\text{m}$ $= 6.378 \times 10^6\,\text{m}$
Substitute the values into the formula.	$g = G\frac{M}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{5.97 \times 10^{24}}{(6.378 \times 10^6)^2}$ $= 9.79\,\text{N kg}^{-1}$
Compare the field strength at the height of Mt Everest with the global average at sea level by calculating the ratio $\frac{g_{\text{Everest}}}{g_{\text{average}}}$.	$\frac{g_{\text{Everest}}}{g_{\text{average}}} = \frac{9.79}{9.8}$ $= 0.9986$ The gravitational field strength at the top of Mt Everest is 99.9% of the average strength at sea level.

➤ Try yourself 5.2.3

CALCULATING GRAVITATIONAL FIELD STRENGTH AT DIFFERENT ALTITUDES

The International Space Station (ISS) orbits at an altitude of approximately 400 km. Calculate the magnitude of the gravitational field strength at this height.
h_{ISS} = 400.0 km
$r_{Earth} = 6.37 \times 10^6$ m
$M_{Earth} = 5.97 \times 10^{24}$ kg
Compare the answer with the average gravitational field strength at sea level, 9.8 N kg^{-1}.
Consider whether astronauts are 'weightless' at this altitude.

Gravitational field strengths on another planet or moon

The gravitational field strength on the surface of the Moon is 1.62 N kg^{-1}, which is much less than on Earth. This is because the Moon's mass is so much less than the mass of Earth, more than making up for its smaller radius.

The formula $g = G\frac{M}{r^2}$ can be used to calculate the gravitational field strength on the surface of any astronomical object, such as Mars (Figure 5.2.11).

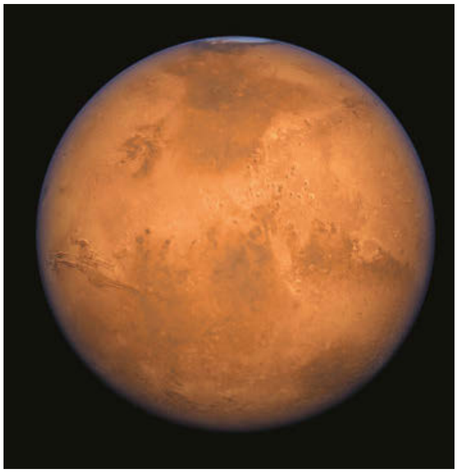


FIGURE 5.2.11 The gravitational field strength on the surface of Mars (shown here) is different from the gravitational field strength on the surface of Earth, which, in turn, is different from that on the Moon.

Worked example 5.2.4

GRAVITATIONAL FIELD STRENGTH ON ANOTHER PLANET OR MOON

Calculate the magnitude of the gravitational field on the surface of the Moon, given that the Moon's mass is 7.35×10^{22} kg and its radius is 1740 km.
Compare the answer with Earth's average gravitational field strength 9.8 N kg^{-1}.

Thinking	Working
Recall the formula for gravitational field strength.	$g = G\frac{M}{r^2}$
Convert the Moon's radius to m.	r = 1740 km = 1740 × 1000 m = 1.74×10^6 m
Substitute values into the formula.	$g = G\frac{M}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{7.35 \times 10^{22}}{(1.74 \times 10^6)^2}$ = 1.62 N kg^{-1}
Compare the field strength with Earth's average gravitational field strength by calculating the ratio $\frac{g_{Earth}}{g_{Moon}}$.	$\frac{g_{Earth}}{g_{Moon}} = \frac{9.8}{1.62}$ = 6.1 The gravitational field strength on the surface of Earth is six times stronger than on the Moon.

➤ Try yourself 5.2.4

GRAVITATIONAL FIELD STRENGTH ON ANOTHER PLANET OR MOON

Calculate the strength of the gravitational field on the surface of the distant exoplanet Kepler-10C, the largest known rocky planet, which is 17 times more massive than Earth.
$M_{Kepler\text{-}10C} = 1.0 \times 10^{26}$ kg
$r_{Kepler\text{-}10C}$ = 15 000 km
Compare the answer with Earth's average gravitational field strength 9.8 N kg^{-1}.

Introducing general relativity

Hold onto your hats. Here's a shock: Newtonian gravity is not the way the universe actually works! Newtonian gravity is a wonderfully useful approximation that works in all but the most extreme conditions. But in those extreme conditions, for example within black holes or very close to very massive objects such as stars, Newton's model of gravity stops working properly.

The system that really explains the way gravity functions was developed by Albert Einstein in 1915, and is known as *general relativity*.

When general relativity was first proposed, physicists struggled to accept that Newton's long-accepted laws were wrong.

However, the theory was accepted when Einstein's general relativity correctly explained the quirks in Mercury's orbit that Newtonian physics could not, and properly predicted the bending of light as it passed the Sun.

General relativity also predicted the existence of gravitational waves, which were detected by the LIGO facilities in late 2015, after a huge international scientific effort including many Australian researchers (see Science as a Human Endeavour).

There are two principles of general relativity that explain how mass and 'spacetime' (the fabric of the universe) affect each other:

1 Mass tells spacetime 'how to bend'.
2 The curvature of spacetime tells mass 'how to move'.

WS 3.1.7

You will learn more about special relativity in Chapter 10.

SCIENCE AS A HUMAN ENDEAVOUR

Gravitational waves and the Australian connection

The successful detection of gravitational waves in late 2015 was the culmination of a century of physics. When Albert Einstein predicted such waves in his 1915 theory of general relativity, he said they could never be detected, as the displacement would be too small to measure.

According to Einstein's theory of general relativity, objects with mass bend spacetime. Two massive objects, such as black holes, that had been orbiting each other, would cause ripples in spacetime if they collided. These ripples are gravitational waves.

Fast forward to 2015 and the instruments at LIGO (the Laser Interferometer Gravitational-Wave Observatory) are accurate enough to measure displacements as small as one-thousandth the width of a proton.

LIGO is made up of two large facilities: one in Washington state, in the northwest of the USA, and the other 3000 km southeast near New Orleans, Louisiana. Each facility comprises two 2 km long buildings at right angles, along which a laser is shone and reflected back. The two perpendicular beams should arrive simultaneously, with any tiny deviations indicating that the length of one building has increased or decreased.

And as a gravitational wave passes through the Earth, that is precisely what happens. Depending on the source of the wave, one building or the other becomes about one quadrillionth of a mm (10^{-18} m) longer than the other for a few milliseconds as the wave passes.

Australian physicists played a key part in the project, including working on the mirrors that position LIGO's lasers, the detectors that detect changes in path length, and software to interpret results. Australian gravitational waves research is coordinated by the ARC Centre of Excellence for Gravitational Waves Discovery (OzGrav).

The first gravitational waves were successfully detected in September 2015, and were calculated to be the result of a collision between two black holes: one of 36 solar masses (i.e. 36 times more massive than our Sun) and one of 29 solar masses.

Review

1 Explain how gravitational waves that pass through the Earth are detected by the LIGO observatory.

2 The first gravitational waves event to be measured, in September 2015, was found to be the result of a collision between two orbiting black holes: one 36 times more massive than our Sun (7.16×10^{31} kg) and another 29 times more massive than our Sun (5.77×10^{31} kg). Because black holes are so dense, at the moment they merged it is calculated their centres were only 350 km apart. Calculate the gravitational force between the two black holes at the moment they merged.

FIGURE 5.2.12 (a) Monash University (Australia) astrophysicist Chris Whittle in the optics vacuum chamber at LIGO, Washington USA, assisting with the replacement of an interferometer mirror. The cleanroom suit minimises dust, which can foul the equipment.
(b) LIGO's observatory in Washington state, USA, showing the two perpendicular arms of the facility.

5.2 Review

SUMMARY

- A gravitational field is a region in which a gravitational force is exerted on all matter within that region.
- A gravitational field can be represented by a gravitational field diagram.
  - The arrowheads indicate the direction of the gravitational force.
  - The spacing of the lines indicates the relative strength of the field. The closer the line spacing, the stronger the field.
- The strength of a gravitational field can be calculated using the following formulas: $g = \frac{F_g}{m}$ and $g = G\frac{M}{r^2}$.
- The gravitational field strength on Earth's surface is approximately 9.8 N kg^{-1}. This varies from location to location and with altitude.
- The gravitational field strength on the surface of any other planet depends on the mass and radius of the planet.

KEY QUESTIONS

Retrieval

1 State the units used to express acceleration due to gravity. State the average value for the acceleration due to gravity at the Earth's surface.

2 Name the person who proposed the new theory of gravity in 1915, which correctly explained even extreme gravitational fields.

Comprehension

3 Describe the direction in which gravitational field lines point within a classroom at the Earth's surface. Explain why we assume the field lines are parallel.

Analysis

4 Compare the magnitude of the gravitational field at a distance of 1200 km from the centre of a planet with that at a distance of 400 km.

5 Determine the gravitational field strength in the classroom of Imogen and Scott who use a spring balance to measure the weight of a 149 g set of slotted masses to be 1.45 N.

6 Calculate the magnitude of Earth's gravitational field for each different type of orbit listed in the table below.

r_{Earth} = 6370 km
$M_{Earth} = 5.97 \times 10^{24}$ kg

	Type of orbit	Altitude (km)
a	low-Earth orbit	2 000.0
b	medium-Earth orbit	10 000.0
c	semi-synchronous orbit	20 200
d	geosynchronous orbit	35 786

7 On 12 November 2014, after many attempts, the Rosetta spacecraft landed a probe on the comet 67P/Churyumov–Gerasimenko.

a Calculate the magnitude of the comet's gravitational field strength at its surface, assuming this comet is a roughly spherical object with a mass of 9.98×10^{12} kg and a diameter of 1.80 km.

b Compare this gravitational field strength with that at the Earth's surface, 9.8 m s^{-2}.

8 When a star dies, its atomic structure may collapse to form a very small, very dense body known as a neutron star. A typical neutron star may still have a mass larger than our Sun, but be smaller than a city.

a Compare the gravitational field strength on the surface of such a star with that on our own Sun.

b Calculate the gravitational field strength at the surface of a neutron star that has mass 3×10^{30} kg and radius 10 km.

c Compare this to the strength of the gravitational field at Earth's surface.
Use g_{Earth} = 9.8 m s^{-2}.

d Calculate the distance from the neutron star where the gravitational field strength is the same as the gravitational field strength at the surface of Earth.
Use g_{Earth} = 9.8 m s^{-2}.

9 A hypothetical planet in a distant solar system is distinctly non-spherical in shape. Its polar radius (5.0×10^3 km) is only half of its equatorial radius (1.00×10^4 km).

a Describe how different the gravitational field strength would be at the equator compared to the poles.

b Calculate the magnitude of the field at the equator, and confirm your answer from part **a**. The gravitational field strength at the poles is 8.10 N kg^{-1}.

10 Calculate the distance, in Earth radii, of an astronaut from the centre of Earth when the astronaut travels away from Earth to a region in space where the gravitational force due to Earth is only 1.0% of that at the Earth's surface.

Chapter review

05

KEY TERMS

altitude
apparent weight
field
gravimeter
gravitational constant
gravitational field
gravitational field strength
gravitational force
inverse square law
Newton's law of universal gravitation

KEY QUESTIONS

Retrieval

1 Newton's law of universal gravitation is used to calculate the gravitational force acting on a person standing on the surface of Earth. Assume the mass of Earth is 5.97×10^{24} kg and its radius is 6370 km.
  - **a** State the equation you would use to calculate gravitational force.
  - **b** Indicate what units your answer will be given in.

Comprehension

2 The planet Jupiter and the Sun exert gravitational forces on each other.
  - **a** Determine, qualitatively, the force exerted on Jupiter by the Sun and compare it to the force exerted on the Sun by Jupiter.
  - **b** Determine, qualitatively, the acceleration of Jupiter caused by the Sun and compare it to the acceleration of the Sun caused by Jupiter.

Analysis

3 A person standing on the surface of Earth experiences a gravitational force of 900 N. Determine which of the following gravitational forces this person will experience at a height of two Earth radii above Earth's surface.
  - **A** 900 N
  - **B** 450 N
  - **C** zero
  - **D** 100 N

4 During a tourist space mission, a wealthy astronaut of mass 100.0 kg initially accelerates at $30.0\,\text{m}\,\text{s}^{-2}$ upwards, then travels in a stable circular orbit at an altitude where the gravitational field strength is $8.20\,\text{N}\,\text{kg}^{-1}$.
  - **a** Determine the apparent weight of the astronaut during lift-off.
    - **A** zero
    - **B** 980 N
    - **C** 2020 N
    - **D** 3980 N
  - **b** Identify which of the following the astronaut will feel during the lift-off phase.
    - **A** lighter than usual
    - **B** heavier than usual
    - **C** the same as usual
  - **c** Identify the mass of the astronaut during the lift-off phase.
    - **A** lower than usual
    - **B** greater than usual
    - **C** the same as usual
  - **d** Determine the true weight of the astronaut during the orbit phase.
    - **A** zero
    - **B** 980 N
    - **C** 100.0 N
    - **D** 820 N

5 The gravitational force of attraction between Saturn and Dione, a moon of Saturn, is equal to 2.79×10^{20} N. Calculate the orbital radius of Dione. Use the following data:

mass of Dione = 1.05×10^{21} kg

mass of Saturn = 5.69×10^{26} kg

6 Of all the planets in the solar system, Jupiter exerts the largest force on the Sun: 4.16×10^{23} N. Calculate the acceleration of the Sun due to this force, using mass of the Sun = 1.99×10^{30} kg.

7 Calculate the acceleration due to gravity on the surface of Pluto if it has a mass of 1.31×10^{22} kg and a radius of 1190 km.

8 Calculate the apparent weight of a 50.0 kg person in a lift under the following circumstances. Use $g = 9.8\,\text{m}\,\text{s}^{-2}$.
  - **a** accelerating downwards at $0.600\,\text{m}\,\text{s}^{-2}$
  - **b** moving downwards at a constant speed of $2.00\,\text{m}\,\text{s}^{-1}$

9 A comet of mass 1100 kg is plummeting towards Jupiter. Jupiter has a mass of 1.90×10^{27} kg and a radius of 7.15×10^{7} m. The comet is about to crash into Jupiter.

- **a** Calculate the magnitude of the gravitational force that Jupiter and the comet exert on each other.
- **b** Calculate the acceleration of the comet towards Jupiter.
- **c** Calculate the acceleration of Jupiter towards the comet.

10 Calculate the distance from the Sun (which has a mass of 1.99×10^{30} kg), at which an astronaut would experience the same gravitational field strength as they experience at the Earth's surface (namely $9.8\,N\,kg^{-1}$).

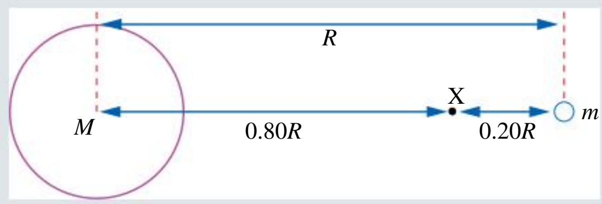
11 Determine what gravitational field strength has been assumed in the following setting. A set of bathroom scales is calibrated so that when the person standing on it has a weight of 6.00×10^{2} N, the scales read 61.5 kg.

12 Calculate the gravitational field strength at the surface of Neptune, which has a radius of 2.48×10^{7} m and a mass of 1.02×10^{26} kg.

13 Earth is a flattened sphere. Its radius at the poles is 6357 km, and at the equator the radius is 6378 km. Earth's mass is 5.97×10^{24} kg.

- **a** Calculate Earth's gravitational field strength at the equator.
- **b** Calculate how much stronger the gravitational field would be at the North Pole compared with the equator using the information in part **a**. Give your answer as a percentage of the strength at the equator to one significant figure.

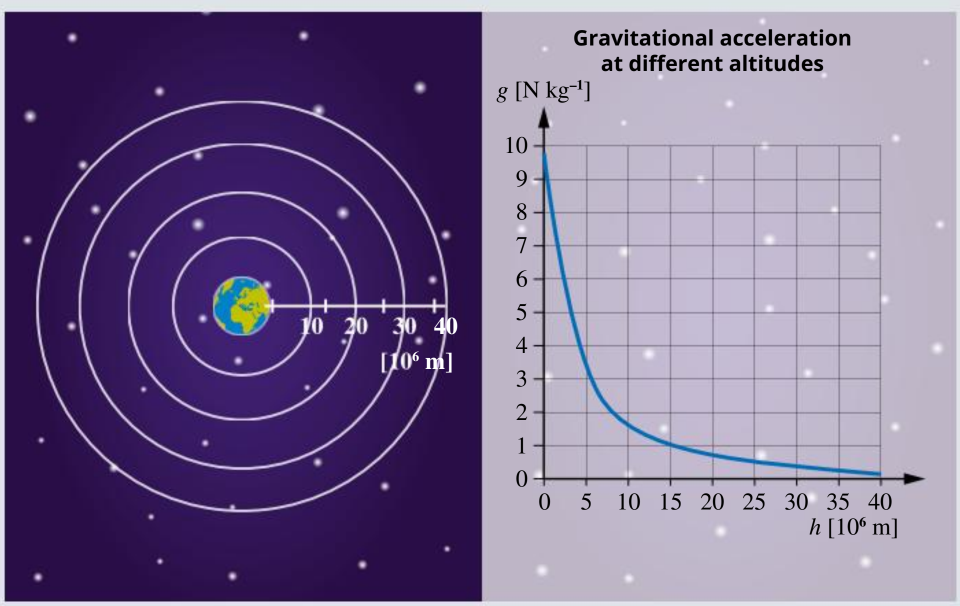
14 Two stars of masses M and m are in orbit around each other. As shown in the following diagram, they are a distance R apart. A spacecraft located at point X experiences zero net gravitational force from these stars. Calculate the value of the ratio $\frac{M}{m}$.



Knowledge utilisation

15 The value for gravitational acceleration g decreases according to the inverse square law with increasing altitude above Earth, as shown in the diagram and graph. The blue line on the graph gives the value of gravitational acceleration (g) at various altitudes (h).

- **a** Determine the approximate altitude at which the gravitational field strength will be $4\,N\,kg^{-1}$ using the graph.
- **b** Compare the strength of the gravitational field strength at ground level and at an altitude of 6500 km, using the graph. Predict what the difference will be.



CHAPTER

06 Orbits

Satellites are an integral part of our modern technological society. Our communications, including television, the internet, navigation, weather forecasting and space exploration all rely on our ability to place satellites into the correct orbits.

This chapter has two main themes.

The first looks at how our understanding of the universe developed over many millennia, beginning with a geocentric model and culminating in the heliocentric model of the solar system. The basic laws uncovered in that time are now used at the very frontiers of science to help us understand galaxies and discover worlds orbiting distant stars.

The second theme examines natural and artificial satellites and demonstrates how Kepler's and Newton's laws help us to know what they are and how they behave.

Syllabus subject matter

Topic 1 • Gravity and motion

ORBITS

- recall Kepler's laws of planetary motion
- solve problems involving Kepler's third law
- recall that Kepler's third law can be derived from the relationship between Newton's Law of Universal Gravitation and uniform circular motion.

SCIENCE AS A HUMAN ENDEAVOUR

- Artificial satellites

6.1 Kepler's laws of planetary motion

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

- recall all three of Kepler's laws
- show how Kepler's third law can be derived from the equations of uniform circular motion and Newton's law of universal gravitation
- use Kepler's third law to calculate the radii and period of planets and satellites.

MODELS OF THE UNIVERSE

From ancient times, people have always sought ways to explain their world and their place in it. They would have looked at the sky above and decided that the heavens were under the control of various gods and spiritual identities beyond their comprehension. They observed that the Sun and Moon, together with many other bodies only visible at night, moved in predictable paths from east to west across the sky. It was this repetitive pattern which soon led to a model in which the motion of those bodies could be understood in concrete terms.

FIGURE 6.1.1 Elaborate illustrations of the geocentric universe adorned many texts in the Middle Ages.

The earliest model was perhaps the most obvious one. The **geocentric** model (Figure 6.1.1) described the heavenly bodies as travelling around the Earth in circular orbits centred on the Earth (from the Greek *geos* for 'Earth'). Each body followed its own individual path against the backdrop of all the stars, which seemed not to move at all, but to be fixed on the celestial sphere—much like stars stuck on a bedroom ceiling. The Sun and Moon were closest to Earth, and the other members of the system—the wandering planets and comets—were at varying further distances. The immovable stars were the most distant of all.

From years of observations, Ptolemy, a Greco-Roman philosopher in Alexandria in the 2nd century, formulated a mathematical description of the geocentric system. Ptolemy's model could be used to accurately predict the positions of the Moon and planets, as well as eclipses. As such, it can be described as an 'empirical' model: one that fits the observations and can be used to make predictions. In order to describe the **retrograde motion** of the planets, his model had to incorporate various complications such as 'epicycles'. (A planet will generally seem to move in a steady direction across the background of distant stars. However, some planets occasionally move for a short time in the opposite, or retrograde, direction). Although all orbits were perfect circles centred on the Earth, the planets followed their own small orbits around centres that orbited Earth.

Ultimately, it was these complications that led to the demise of Ptolemy's geocentric model and the acceptance of the better, theoretical **heliocentric** or Sun-centred model. The heliocentric model had been proposed by Aristarchus (c. 310–230 BCE), but was not widely accepted because it seemed to contradict common sense.

It took some courage for Nicolaus Copernicus to publish his theory in 1543, as it contradicted the idea that Earth occupied the prime position in the universe, as implied by the Bible. While not abandoning circular orbits and epicycles altogether, Copernicus centred the planetary orbits on the Sun, and the Moon's orbit on the Earth. He also:

- placed Mercury, Venus, Earth/Moon, Mars, Jupiter and Saturn in order from the Sun
- described Earth's day–night rotation, its annual solar revolution and Earth's tilted axis to explain the seasons
- showed that planetary retrograde motion was explained by the Earth's motion around the Sun.

Although the Copernican model could better explain astronomical observations, it was still rather complicated and must be regarded as a stepping stone to the fuller theoretical model developed by Kepler and Newton.

KEPLER'S LAWS

Kepler, a German astronomer (Figure 6.1.2), published his three laws regarding the motion of planets in 1609. This was about 80 years before Newton published his law of universal gravitation. Kepler used extensive observations collected by Tycho Brahe to formulate his laws, which can be regarded as empirical as they had no immediate basis in theory. Kepler's laws related to the motion of the planets in orbit around the Sun, but these laws can be used for any **satellite** in orbit around any central mass. Kepler's essential contribution was the introduction of elliptical orbits, which did away with the need for the epicycles of Ptolemy and Copernicus.

Kepler's laws are as follows:

1 The planets move in elliptical orbits with the Sun at one **focus** (Figure 6.1.3). There is nothing at the other focus. Keep in mind that a circle is just a unique kind of **ellipse** in which both foci coincide at its centre.

2 The line connecting a planet to the Sun sweeps out equal areas in equal intervals of time (Figure 6.1.3).

3 For every planet, the ratio of the cube of the average orbital radius, r, to the square of the period, T, of revolution is the same for all planets: $\frac{r^3}{T^2}$ = a constant, k, known as Kepler's constant.

Kepler's first two laws proposed that planets moved in elliptical paths from furthest point (the **aphelion**) to closest point (the **perihelion**). The closer the planet was to the Sun, the faster it moved. It took Kepler many months of laborious calculations to arrive at his third law. Newton used Kepler's laws to justify the inverse square relationship. In fact, Kepler's third law can be deduced from Newton's law of universal gravitation.

HOW NEWTON DERIVED KEPLER'S THIRD LAW

Kepler made use of existing observations to derive his empirical rule relating the periods of the planets to their orbital radii. The formulation of his third law required many months of trial-and-error calculations.

However, Newton was able to derive the relationship $\frac{r^3}{T^2}$ = constant by combining his law of universal gravitation with the equations of circular motion.

Recall from Chapters 4 and 5 that the magnitude of the centripetal force acting on an object in circular motion is given by the equation $F_c = \frac{mv^2}{r} = \frac{4\pi^2 mr}{T^2}$ and that the law of universal gravitation is given by the equation $F_g = \frac{Gm_1m_2}{r^2}$. Newton equated these two expressions as shown below.

We denote the larger, central body as M and the smaller body in orbit around the larger one as m. The radius of the orbit is r. The force exerted on M by m is $F_{m \text{ on } M}$ and the force exerted on m by M is $F_{M \text{ on } m}$ (Figure 6.1.4).

$$F_{M \text{ on } m} = \frac{4\pi^2 mr}{T^2}$$

and $$F_{M \text{ on } m} = \frac{GMm}{r^2}$$

so $$\frac{4\pi^2 \cancel{m} r}{T^2} = \frac{GM\cancel{m}}{r^2}$$

and so $$\frac{r^3}{T^2} = \frac{GM}{4\pi^2} = \text{constant}$$

FIGURE 6.1.2 Johannes Kepler was the first to work out that the planets do not travel in circular paths, but rather in elliptical paths.

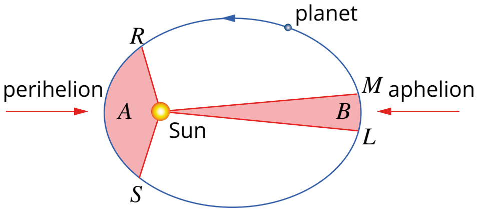


FIGURE 6.1.3 The planets, which are natural satellites of the Sun, orbit in elliptical paths with the Sun at one focus. Their speeds vary continually, and they are fastest when closest to the Sun. A line joining a planet to the Sun will sweep out equal areas in equal times. So, for example, the time it takes to move from R to S is equal to the time it takes to move from L to M, and so area A is the same as area B.

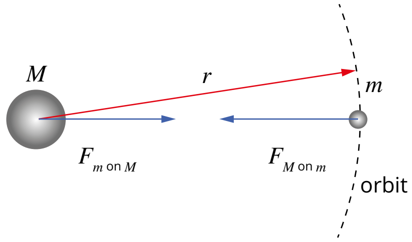


FIGURE 6.1.4 Diagram depicting the gravitational attraction between two bodies M and m, orbiting at a distance r.

Worked example 6.1.1

SATELLITES IN ORBIT

$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$ = constant

Determine the orbital speed of the Moon, assuming it is in a circular orbit of radius 384 000 km around Earth. Take the mass of Earth to be 5.97×10^{24} kg and use $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$r = 384\,000 \text{ km} = 3.84 \times 10^8 \text{ m}$
Choose the appropriate relationship between the orbital speed, v, and the data that has been provided. The centripetal force, $F_c = \frac{mv^2}{r}$, will be equal to the gravitational force, $F_g = \frac{Gm_1m_2}{r^2}$.	$\frac{mv^2}{r} = \frac{Gm_1m_2}{r^2}$ So, $\frac{v^2}{r} = \frac{GM}{r^2}$
Rearrange to make v the subject of the equation.	$v = \sqrt{\frac{GM}{r}}$
Substitute in values and solve for the orbital speed, v.	$v = \sqrt{\frac{(6.67 \times 10^{-11}) \times (5.97 \times 10^{24})}{3.84 \times 10^8}}$ $= 1.02 \times 10^3 \text{ m s}^{-1}$

➤ Try yourself 6.1.1

SATELLITES IN ORBIT

If you are using Kepler's third law as the ratio $\frac{r^3}{T^2}$ without the $\frac{GM}{4\pi^2}$ term, then you can use *any* suitable units for r and T.

If you are using Kepler's third law with the $\frac{GM}{4\pi^2}$ term, then you must use SI units for r (m) and T (s).

Determine the orbital speed of a satellite that is in a circular orbit of radius 42 100 km around Earth. Take the mass of Earth to be 5.97×10^{24} kg and use $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

For any central mass, M, the term $\frac{GM}{4\pi^2}$ is constant and equal to the ratio $\frac{r^3}{T^2}$ for all its satellites (Figure 6.1.5). So, for example, if you know the orbital radius, r, and period, T, of one of the moons of Saturn, you could calculate $\frac{r^3}{T^2}$ and use this as a constant value for all of Saturn's moons. If you knew the period, T, of a different satellite of Saturn, you could then calculate its orbital radius, r.

For example, Saturn's largest moon, Titan, has a period of 15.9 days and an orbital radius of 1.22×10^6 km. A smaller moon, Iapetus, has a period of 79 days. Its orbital radius can be found using Kepler's third law.

First calculate Kepler's constant for Titan.

$$k_{\text{Titan}} = \frac{r^3_{\text{Titan}}}{T^2_{\text{Titan}}} = \frac{(1.22 \times 10^6)^3}{15.9^2} = 7.183 \times 10^{15} \text{ km}^3 \text{ day}^{-2}$$

Iapetus will have the same Kepler constant as Titan, so to find the orbital radius of Iapetus, its period is substituted into the Kepler's constant equation.

$$k_{\text{Iapetus}} = \frac{r^3_{\text{Iapetus}}}{T^2_{\text{Iapetus}}} = \frac{r^3_{\text{Iapetus}}}{79^2} = 7.183 \times 10^{15}$$

$$r^3_{\text{Iapetus}} = 79^2 \times 7.183 \times 10^{15}$$

$$r_{\text{Iapetus}} = \sqrt[3]{79^2 \times 7.183 \times 10^{15}} = 3.6 \times 10^6 \text{ km}$$

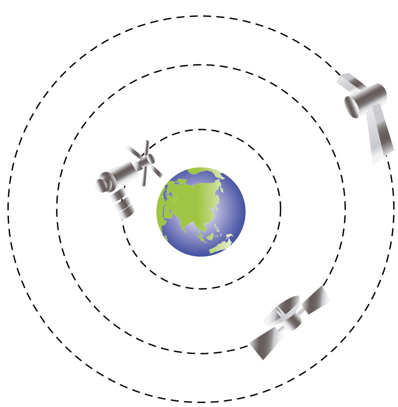


FIGURE 6.1.5 These three satellites are at different distances from Earth and hence, according to Kepler's third law, will have different orbital periods. For all three, the ratio of $\frac{r^3}{T^2}$ will equal the same constant value.

Worked example 6.1.2

WORKING WITH KEPLER'S LAWS

Ganymede is the largest of Jupiter's moons. It has a mass of 1.66×10^{23} kg, an orbital radius of 1.07×10^{6} km and an orbital period of 6.18×10^{5} s (7.15 days).

a Calculate the orbital radius (in km) of Europa, another moon of Jupiter, which has an orbital period of 3.55 days. Use Kepler's third law.

Thinking	Working
Note down the values for the known satellite. You can work in days and km as this question involves the ratio $\frac{r^3}{T^2}$ without using $\frac{GM}{4\pi^2}$.	Ganymede: $r = 1.07 \times 10^6$ km $T = 7.15$ days
For all satellites of a central mass, $\frac{r^3}{T^2}$ = constant. Work out this ratio for the known satellite.	$\frac{r^3}{T^2} = \text{constant}$ $= \frac{(1.07 \times 10^6)^3}{7.15^2}$ $= 2.40 \times 10^{16}$
Use this constant value with the ratio for the satellite in question. Make sure T is in days to match the ratio calculated in the previous step.	Europa: $T = 3.55$ days, $r = ?$ $\frac{r^3}{T^2} = \text{constant}$ $\frac{r^3}{3.55^2} = 2.40 \times 10^{16}$
Make r^3 the subject of the equation.	$r^3 = 2.40 \times 10^{16} \times 3.55^2$ $= 3.02 \times 10^{17}$
Solve for r. The unit for r is km as the original ratio was calculated using km.	$r = \sqrt[3]{3.02 \times 10^{17}}$ $= 6.71 \times 10^5$ km Note: Europa has a shorter period than Ganymede so you should expect Europa to have a smaller orbit than Ganymede.

b Calculate the mass of Jupiter using the orbital data for Ganymede.

Thinking	Working
Note down the values for the known satellite. You must work in SI units to find the mass value in kg.	$r_G = 1.07 \times 10^9$ m $T_G = 6.18 \times 10^5$ s $m = 1.66 \times 10^{23}$ kg $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2} $M = ?$
Select the expressions from the equation for centripetal acceleration that best suit your data. $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2} = \frac{GM}{r^2} = g$	Use the third and fourth terms of the expression. $\frac{4\pi^2 r}{T^2} = \frac{GM}{r^2}$ These two expressions use the given variables r and T, and the constant G, so that a solution may be found for M.
Transpose to make M the subject.	$M = \frac{4\pi^2 r^3}{GT^2}$
Substitute values and solve.	$M = \frac{4\pi^2 (1.07 \times 10^9)^3}{6.67 \times 10^{-11} \times (6.18 \times 10^5)^2}$ $= 1.90 \times 10^{27}$ kg

c Calculate the orbital speed of Ganymede in km s^{-1}.

Thinking	Working
Note the values you will need to use in the equation $v = \frac{2\pi r}{T}$.	$r = 1.07 \times 10^6$ km $T = 6.18 \times 10^5$ s $v = ?$
Substitute values and solve. The answer will be in km s^{-1} if r is expressed in km.	$v = \frac{2\pi r}{T}$ $= \frac{2\pi \times 1.07 \times 10^6}{6.18 \times 10^5}$ $= 10.9$ km s^{-1}

➤ Try yourself 6.1.2

WORKING WITH KEPLER'S LAWS

Callisto is the second largest of Jupiter's moons. It is about the same size as the planet Mercury. Callisto has a mass of 1.08×10^{23} kg, an orbital radius of 1.88×10^{6} km and an orbital period of 1.44×10^{6} s (16.7 days).

a Calculate the orbital radius (in km) of Europa, another moon of Jupiter, which has an orbital period of 3.55 days. Use Kepler's third law.

b Calculate the mass of Jupiter using the orbital data for Callisto.

c Calculate the orbital speed of Callisto in $km\,s^{-1}$.

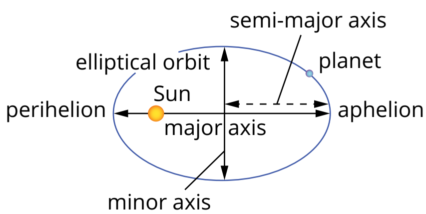


FIGURE 6.1.6 The semi-major axis is half the length of the major axis of the ellipse.

Recall that Kepler's first law stated that planets (and therefore satellites) travel in elliptical orbits with the Sun (or other central body) at one focus. So far, when looking at the third law, we have assumed that the orbits are highly circular and used the orbital radius. When the third law is applied more generally to elliptical orbits, the **semi-major axis** (Figure 6.1.6) is used instead of the radius. The semi-major axis is half the length of the **major axis**, which is the longest diameter of the ellipse.

The major axis is the longest distance between two points on an ellipse and the semi-major axis is half of that distance. In the case of a planet, the semi-major axis is given by the formula $a = \frac{1}{2}(d_{aphelion} + d_{perihelion})$.

The modification to Kepler's third law is minor, replacing the radius, r, with the semi-major axis, a, so it becomes $\frac{a^3}{T^2}$ = constant.

USING KEPLER'S LAWS

One interesting application of Kepler's third law is in determining the characteristics of exoplanets. When a planet crosses (transits) the line of sight between its star and Earth, the observed brightness of the star may decrease slightly for the time the planet is in front of the star. Such **transits** are observed from time to time in our own solar system with Mercury and Venus. (One of the important reasons for Captain Cook's voyage to the South Seas was to observe the transit of Venus in 1769 from Tahiti. Accurate measurements of the transit were hoped to lead to a more precise measurement of the scale of the solar system.)

If the star is observed for long enough, the orbital period of the planet can be calculated from the 'light curve' which will show the regular dips in intensity due to the planet's transits. Figure 6.1.7 shows how the light from the star is reduced when a planet moves in front of it. For stars within our neighbourhood of the galaxy, the mass of the star can be calculated in a number of ways. If we know the star's mass and the planet's period, its orbital radius can be determined from Kepler's third law and Newton's law of gravity.

$$r^3 = \frac{GM_{star}}{4\pi^2}T^2$$

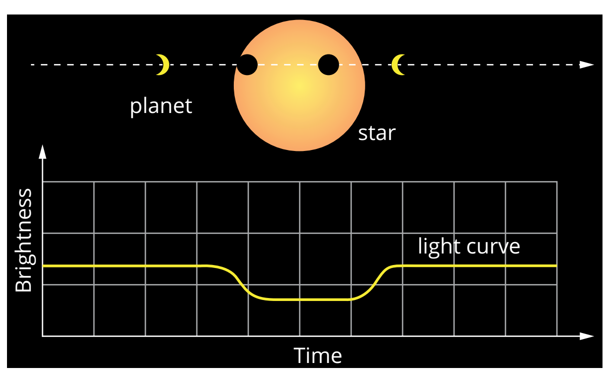


FIGURE 6.1.7 A light curve for an exoplanet

Note that this transit method only works if the orbit of the planet happens to be edge-on to Earth. It doesn't work as well for small Earth-like planets, which do not obscure the star's disc very much. A more generally applicable method is the 'radial velocity' method, also known as the 'wobble' method. (Refer to the Science as a Human Endeavour 'Hunting Exoplanets' in Chapter 5.)

This method relies on the fact that the orbit of a planet is not really centred on the centre of the central body, but on the centre of mass of the two bodies. This shows up in a 'wobble' in the motion of the star caused by the orbiting planet—sometimes it moves away from us and then towards us. These regular small variations in the star's velocity can be measured via the Doppler shift of the spectral lines in its spectrum. The period of the wobble is then used as the period of the planet, enabling an estimate of the orbital radius of the exoplanet.

6.1 Review

SUMMARY

- The geocentric model of the universe placed Earth at the centre with the Sun, Moon and planets moving in circular paths around it.
- Ptolemy's model was an empirical geocentric model in which the planets travel around Earth in circular orbits.
- Ptolemy needed to introduce epicycles to explain the retrograde motion of some planets.
- Copernicus described a heliocentric model with the Sun at the centre, while planets moved in circular orbits around it.
- Kepler formulated his three important laws:
  1 Planets travel around the sun in elliptical orbits.
  2 Each planet sweeps out equal areas in equal times.
  3 The ratio $\frac{r^3}{T^2}$ is a constant for all planets.
- Kepler's third law is useful in determining the radii and periods of planets and exoplanets.
- Newton's laws can be used to derive Kepler's laws from theory.

KEY QUESTIONS

Retrieval

1 State Kepler's three laws.

2 Define 'aphelion' and 'perihelion'.

Comprehension

3 Explain what Kepler's second law tells us about the speed of a comet as it approaches nearest to the Sun.

Analysis

4 Determine how Kepler's third law can be derived from the equations of circular motion and Newton's law of universal gravitation.

5 Calculate Jupiter's period in Earth years. Jupiter orbits the Sun at 5.20 AU. (An AU is an 'astronomical unit' and is equal to the average distance of Earth from the Sun or 150 million km.)

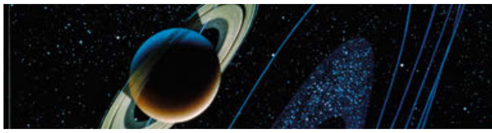
6 Determine Neptune's distance from the Sun in AU. It takes Neptune 165 years to orbit the Sun.

7 Determine the period in days of a satellite 6.90×10^6 m from Earth's centre. The period of the Moon is 27.3 days and its orbital radius is 3.82×10^8 m.

8 Galileo is credited with the discovery of four of Jupiter's many moons. One of the moons, Ganymede, is 10.7 AU from Jupiter's centre and orbits Jupiter in 7.15 Earth days. Another moon is called Io; it is 4.2 AU from Jupiter's centre. Calculate the period of Io in Earth days.

9 Calculate the mass of Mars given that the smaller of the two Martian moons, Deimos, has a period of 30.35 hours and the radius of its orbit is 23 460 km.

6.2 Satellites and their orbits



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

- differentiate between natural and artificial satellites.

Satellites are not propelled by rockets or engines. They orbit in freefall and the only force acting on them is the gravitational attraction between themselves and the body about which they orbit. This means that the satellites have centripetal acceleration that is equal to the gravitational field strength at their location (Figure 6.2.1).

Artificial satellites are often equipped with tanks of propellant that is squirted in the appropriate direction when the orbit of the satellite needs to be adjusted. The amount of fuel available for such adjustments is the major factor that determines the useful working life of the satellite.

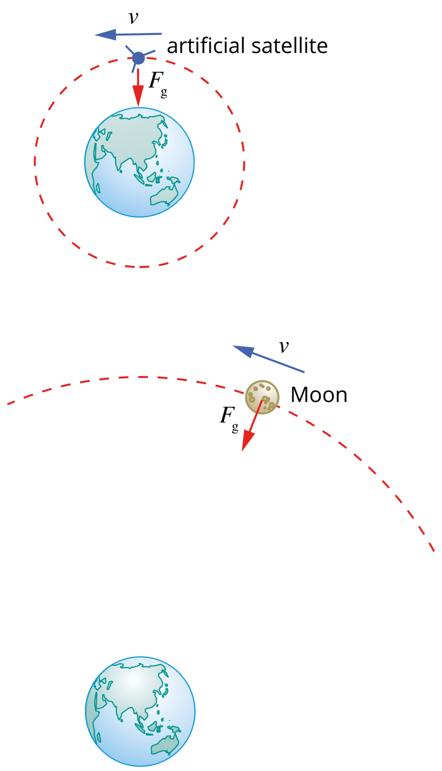


FIGURE 6.2.1 The only force acting on these artificial and natural satellites is the gravitational attraction of Earth. Both orbit with a centripetal acceleration equal to the gravitational field strength at their locations. Note that v and F_g are always perpendicular.

NATURAL SATELLITES

Natural satellites have existed throughout the universe for billions of years. The planets and asteroids of the solar system are natural satellites of the Sun (Figure 6.2.2).

Earth has one natural satellite: the Moon. The largest planets—Jupiter and Saturn—have more than sixty natural satellites each in orbit around them. Most of the stars in the Milky Way galaxy have planets and more of these exoplanets are being discovered each year.

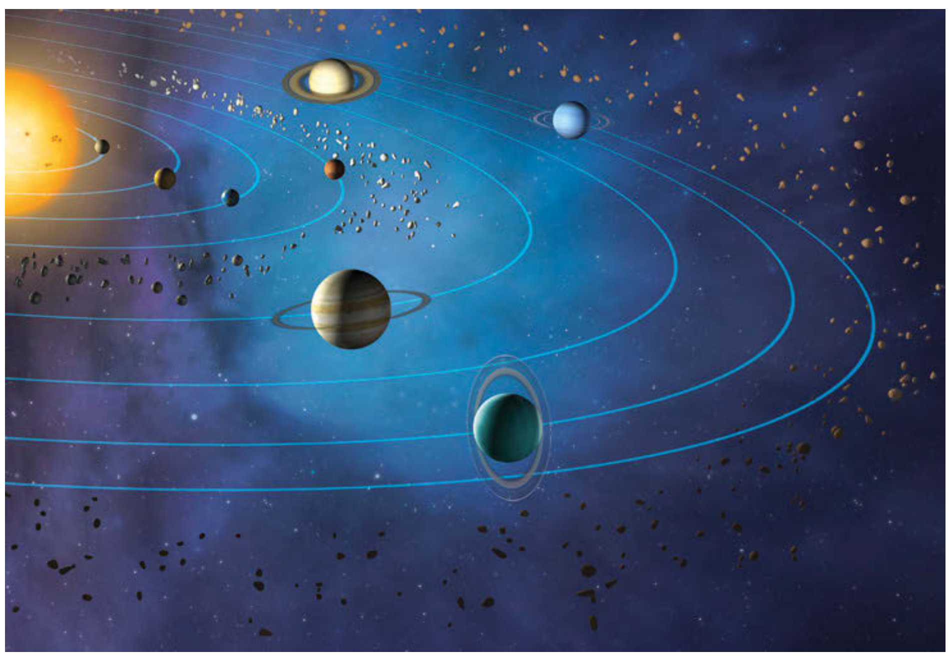


FIGURE 6.2.2 The planets are natural satellites of the Sun. The planets closer to the Sun have a shorter orbital period than the larger gas giants.

WS 3.1.6

SCIENCE AS A HUMAN ENDEAVOUR

Artificial satellites

In October 1957, the Soviet Union launched a satellite, Sputnik I, into an orbit that varied between 200 km and 1000 km above the surface of Earth. Sputnik I lasted for three months before it ran out of power and burnt up in the atmosphere. This was the first time human beings had successfully launched an object into space and have it circle Earth.

Australia became the seventh country to launch a satellite into space when the Defence Department launched WRESAT from the Woomera test range in northern South Australia in 1967.

Since then, more than 6500 satellites have been launched from all over the world from more than 40 countries. There are close to 5000 satellites currently orbiting Earth, and about 1800 of these are operational. Figure 6.2.3 shows what they would look like if they were bright enough to all be seen around the Earth.

FIGURE 6.2.3 An artist's impression of the thousands of satellites currently orbiting Earth. About half of them are very close to the Earth, only a few hundred kilometres above the ground, with the other half spread out in a ring approximately 36 000 km above the equator.

Initially, satellites were experimental and used mostly for military purposes. Today, the technology and miniaturisation of satellites allows them to take on a much wider range of tasks, including:

- communications (TV, radio, internet, telephone)
- climate and weather observations
- astronomy (Hubble Space Telescope, X-ray and gamma ray telescopes)
- military (spying, reconnaissance, 'killer' satellites)
- navigation (GPS, GLONASS, Galileo)
- Earth observing (remote sensing, mapping, biological surveys)
- habitation (ISS, the former Tiangong and Mir space stations)

Just like any object moving in a circle, a satellite will experience a centripetal force that keeps it moving around Earth. This force is solely due to the gravitational force it experiences from Earth. The higher a satellite is above Earth's surface the weaker the gravitational force, and thus the slower the satellite will move. The equation that relates the speed, v, of a satellite to its height above Earth's surface, h, is:

$$v = \sqrt{\frac{Gm_E}{(R_E + h)}}$$

where G is the gravitational constant $6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$, m_E is the mass of the Earth, 5.97×10^{24} kg, and R_E is the average radius of the Earth, 6378 km.

A satellite moving more slowly will have a greater period, T, around Earth as the radius increases:

$$T = 2\pi\sqrt{\frac{(R_E + h)^3}{Gm_E}}$$

Satellites in low-Earth orbits, where the height above Earth's surface ranges from just above most of the atmosphere (160 km) to 2000 km, typically have periods of between 90 minutes and 2 hours. Many spy and Earth-observing satellites are located in this type of orbit, as are the International Space Station and the Hubble Space Telescope.

Satellites in medium-Earth orbits, where the range of altitude is from 2000 km to 35 786 km, include many navigation satellites such as GPS and remote-sensing satellites. These are located here as they can cover the surface of Earth at least twice in one day.

A special orbit of height 35 786 km above the Earth's surface gives the satellite a period of 23 hours, 56 minutes and 4 seconds, which is the same as the period of Earth's rotation, hence the name geosynchronous orbits. A geosynchronous satellite will return to the same position in the sky each day and are thus very useful for TV, radio and internet communications.

Higher orbits with periods longer than one day and are generally used by the military, for weather monitoring and astronomical observations.

Review

1 Explain why 160 km is the lowest height limit above the Earth's surface for low-Earth orbits.

2 Explain why geosynchronous orbits are the optimal orbit for communications satellites.

3 The Iridium constellation is a privately owned system of communications satellites used by subscribers to access telephone networks anywhere on Earth. As of 2018, there are 66 individual satellites that orbit at an average height of 776 km above Earth's surface.
Calculate the average speed of the Iridium satellites as they move in their orbits (in km s^{-1}), and determine how long one orbit takes to complete.

4 The Bureau of Meteorology obtains weather imagery from the Japanese-owned Himawari-8 geostationary satellite. A geostationary satellite is a geosynchronous satellite that is at a point directly above the equator, and therefore will not appear to move in the sky at all.
Calculate the average speed in km s^{-1} of the Himawari-8 satellite as it moves in its orbit around the Earth.

SCIENCE AS A HUMAN ENDEAVOUR

Space junk

Rockets and satellites have been sent into space since the late 1950s. Objects with sufficient speed to attain orbit will remain in orbit forever, or at least until some external force is applied to them. So what has happened to all that stuff sent into space?

Today there are about 1800 satellites that are still in operation. There are also about 3000 satellites that have reached the end of their operational life or have malfunctioned but are still in orbit.

In 2007, a Chinese satellite was deliberately destroyed by a missile, creating thousands of pieces of debris. In 2009, a collision between the defunct Russian Cosmos 2251 and an operational US Iridium 33 created even more debris. This debris and the defunct satellites are classified as space junk (Figure 6.2.4).

The presence of this fast-moving space junk puts the other satellites and the International Space Station (ISS) at risk from collision. Currently about 22000 pieces of space junk are being tracked and monitored. There have been several occasions where satellites have been moved to avoid collisions with space junk. On one occasion, a piece of debris that is thought to have been a fleck of paint cracked the window of the ISS.

Even if concerted efforts are made to limit the lifetimes of satellites and to regulate the number of new satellites entering low-Earth orbits, the problem may well get worse by itself. Every time a substantial collision occurs, more debris is created. This, in turn, has the potential to cause further collisions, in a cascading effect.

The UN has passed a resolution to remove defunct satellites from low-Earth orbits by placing them in much higher orbits, or bringing them back to Earth and allowing them to burn up in the atmosphere.

Review

1 Even though some of the debris is very small, its speed relative to another satellite may be up to 50000 km h^{-1}. Calculate the kinetic energy of a 0.10 g fragment travelling at such a speed.

2 Figure 6.2.4 makes it look as if there is not much room in space. To obtain an idea of how much room on average is taken by each piece of junk:

- calculate the total volume above Earth's surface from an altitude of 100 km up to an altitude of 400 km
- divide it by 22000.

(Hint: Find the surface area of a sphere, using $4\pi r^2$ with the radius as r_{Earth} + 250 km. Then multiply that area by 300 km to get the total volume.)

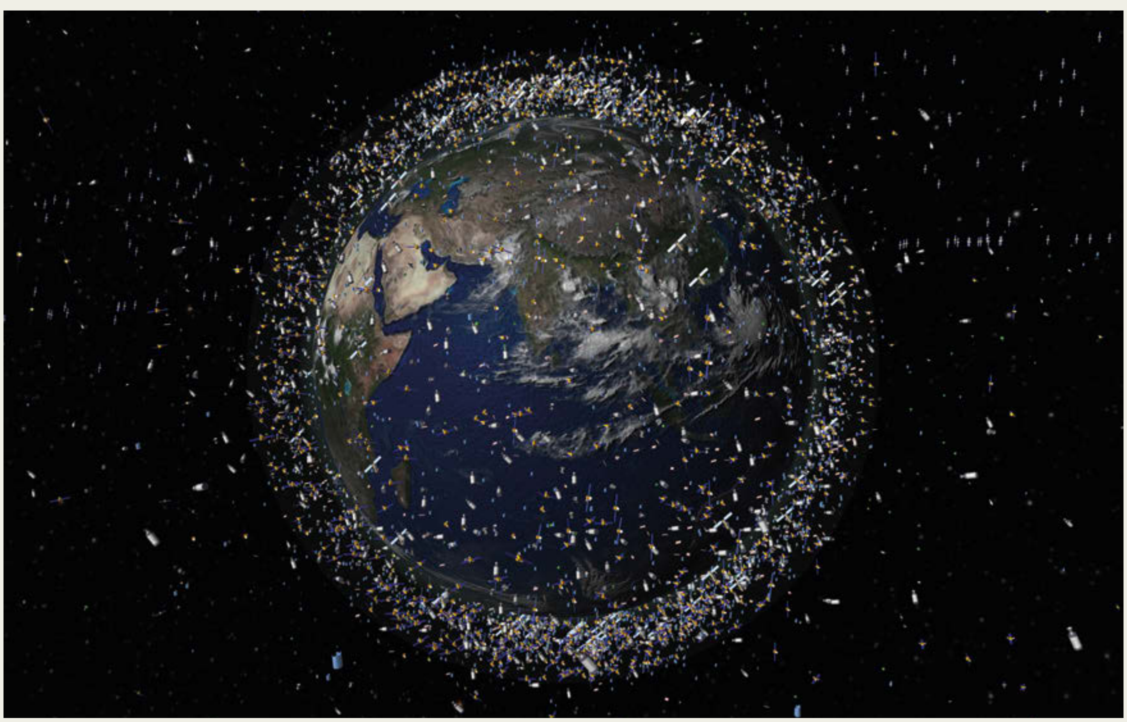


FIGURE 6.2.4 An artist's impression of the location of space debris and abandoned satellites in near-Earth orbits

6.2 Review

SUMMARY

- A satellite is an object that is in a stable orbit around a larger central mass.
- The only force acting on a satellite is the gravitational attraction between it and the central body.

KEY QUESTIONS

Retrieval

1 Define 'satellite'.

Comprehension

2 Describe the advantages gained by placing a TV broadcast satellite in a geostationary orbit rather than a low-Earth orbit.

3 A radio signal is sent from a ground station to a geostationary satellite 35 800 m directly overhead. Show how the minimum time for a reply is found. Determine the effect this time would have on a conversation between two people using this satellite.

Analysis

4 A Navstar GPS satellite has a period of 12 hours, compared with a geostationary satellite whose period is 24 hours. Determine the ratio of the geostationary orbital radius to the orbital radius of the Navstar satellite. Calculate the orbital radius of the Navstar satellite if the geostationary satellite has an orbital radius of 42 164 km.

Chapter review

WS 3.1.8

06

KEY TERMS

aphelion
artificial satellite
ellipse
focus
geocentric
heliocentric
major axis
natural satellite
perihelion
retrograde motion
satellite
semi-major axis
transit

KEY QUESTIONS

Retrieval

1 Identify the correct statement below.
A Earth is a satellite of Mars.
B The Moon is a satellite of the Sun.
C The Sun is a satellite of Earth.
D Earth is a satellite of the Sun.

2 Identify the largest planet in the solar system.
A Jupiter
B Venus
C Earth
D Sun

Comprehension

3 Select which is most likely to be the speed of a planet's moon when it is nearest the planet, if the moon has an elliptical orbit and its speed is $20\,km\,s^{-1}$ when it is at its average distance from the planet.
A $10\,km\,s^{-1}$
B $15\,km\,s^{-1}$
C $20\,km\,s^{-1}$
D $25\,km\,s^{-1}$

4 Select the option that correctly completes the sentence. In our solar system, the value of Kepler's constant is the same for all the:
A planets
B planets but not Pluto
C planets and all the moons
D planets and the moons, but not Earth satellites

5 One of the most massive and luminous known stars is called the Pistol Star. It has a mass of approximately 100 times that of our Sun. Determine how long it would take a planet to orbit the Pistol Star if the planet was orbiting the Pistol Star at the same distance that the Earth orbits our Sun.

6 In August 2017, the gravitational waves produced by a pair of colliding neutron stars were recorded at two different Laser Interferometer Gravitational-Wave Observatory (LIGO) installations in the United States. The two dense stars were orbiting each other around their common centre of mass and, as they approached each other under the influence of gravity, their frequency of rotation increased. Just before they collided and formed a black hole, the frequency of rotation exceeded 1 kHz. Determine the reasons for the increasing frequency, using Kepler's third law.

Analysis

7 The dwarf planet Ceres is the largest object in the asteroid belt.
a Calculate its period in Earth days if it orbits the Sun in a circular orbit of radius of 2.7675 AU.
b There are thousands of other objects in the asteroid belt, revolving around the Sun at different distances. Determine the range of the asteroid belt from the Sun in AU, if an asteroid year ranges from 1.2×10^3 days to 2.0×10^3 days.

8 The table below shows the period and orbital radius of the solar system's planets.

	Orbital radius (10^6 km)	**Orbital period (days)**
Mercury	57.9	88.0
Venus	108.2	224.7
Earth	149.6	365.2
Mars	227.9	687.0
Jupiter	778.6	4331
Saturn	1433.5	10 747
Uranus	2872.5	30 589
Neptune	4495.1	59 800

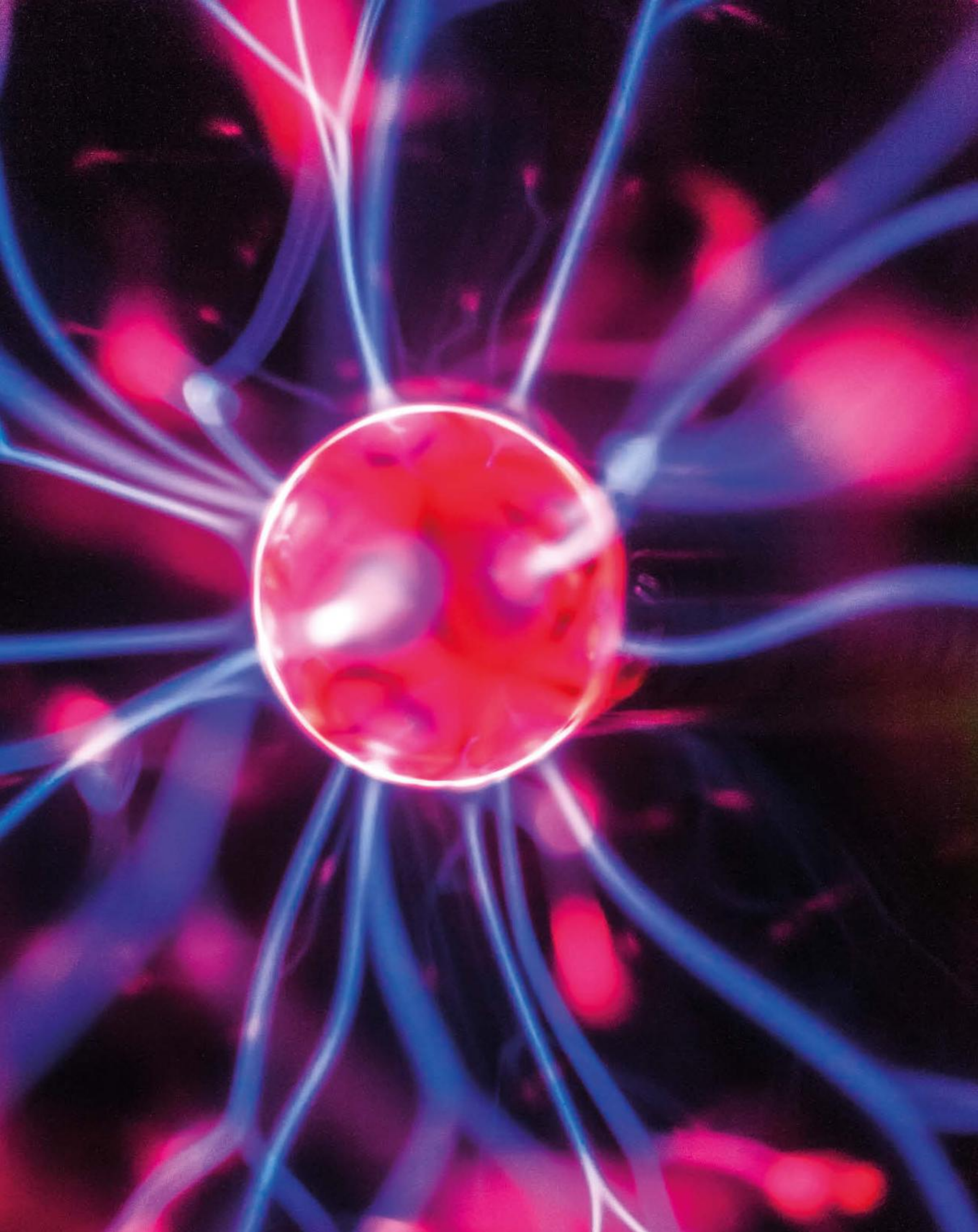
a Enter this data into a computer spreadsheet and produce a plot of r vs T.
b Explain why this graph is not a straight line.
c Identify the quantities of the linear relationship described by Kepler's third law.
d Represent the data above to produce a straight line graph. Plot the data on graph paper or plot it on a computer.
e Determine the gradient of the graph in each case.
f Determine the mass of the Sun, using the gradient.

9 Atlas, one of Saturn's moons, has an orbital radius of 1.37×10^5 km and a period of 0.60 days. The largest of Saturn's moons is Titan. It has an orbital radius of 1.20×10^6 km. Calculate the orbital period of Titan in days.

Knowledge utilisation

10 An AU is an 'astronomical unit' and is equal to the average distance of Earth from the Sun (or 150 million km). When using the units AU and year, the value of Kepler's constant for Earth is $1.0\,AU^3\,y^{-2}$. Halley's comet has a highly elliptical orbit with a period of approximately 75 years. Determine the greatest distance Halley's comet is from the Sun if, at its closest approach, it is 0.586 AU from the Sun.

11 Discuss the process of calculating the mass of a planet that has natural satellites. Assess why the masses of Venus and Mercury, which don't have natural satellites, were more difficult to calculate.



CHAPTER 07

Electric fields

The properties of electrostatics, such as the attraction of small objects when rubbed together, have been known since Thales of Miletus studied charged amber in Greece in 600 BCE. For centuries, the effects of charge build-up were just an intellectual curiosity to scientists and philosophers until the end of 17th century, when its properties were studied and formalised.

We now know that the behaviour of charges and electricity is due to the formation of and interaction with electric fields around charges. The study of electric fields and their manipulation has many applications in physics, chemistry and biology, and indeed has vastly shaped the modern world.

The work done by moving charges through electric fields is responsible for all the electrical technology you use, and the disturbance of electric fields with your fingers forms the basis of almost all touchscreen technology used in smartphones and tablets today.

In this chapter you will investigate electric fields, the concepts that apply to forces, charges and fields, and some of the interactions between these closely related phenomena.

Syllabus subject matter

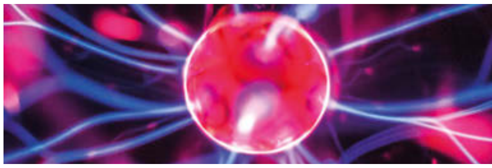
WS 3.2.1

Topic 2 • Electromagnetism

ELECTROSTATICS

- define Coulomb's Law and recognise that it describes the force exerted by electrostatically charged objects on other electrostatically charged objects
- solve problems involving Coulomb's Law
- define the terms *electric fields*, *electric field strength* and *electrical potential energy*
- solve problems involving electric field strength
- solve problems involving the work done when an electric charge is moved in an electric field.

7.1 Coulomb's law



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

- define Coulomb's law and use it to predict the force that charged particles exert on each other.

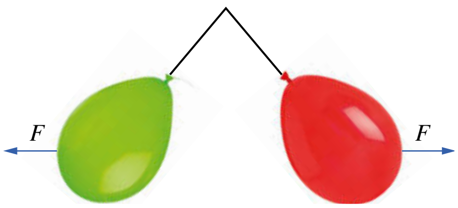


FIGURE 7.1.1 Two similarly charged balloons will repel each other by applying a force on each other.

Electricity is the set of physical phenomena associated with the presence and motion of electric charge. Recall from *Pearson Physics 11 Queensland*, Chapter 4, that a force acts between two charged particles: two like charges will repel each other, and two unlike charges will attract each other. Charles Coulomb first published the quantitative details of this force in 1785. The force between any combination of electrical charges can be understood in terms of the force between two 'point charges' separated by a certain distance (Figure 7.1.1). The effect of distance on the electric field strength from a single charge and the force created by that field between charges is explored in this section.

THE FORCE BETWEEN CHARGED PARTICLES

Coulomb found that the force between two point charges—Q and q—separated by a distance, r, was proportional to the product of the two charges, and inversely proportional to the square of the distance between them.

This is another example of an inverse square law, as discussed in Chapter 5 in relation to the gravitational force.

Coulomb's law can be expressed by the following equation:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$$

where

F is the force on each charged object (N)

Q is the charge on one point (C)

q is the charge on the other point (C)

r is distance between the charged points (m)

ε_0 is the permittivity of free space, which is equal to $8.8542 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$.

By including the sign of the charges in the calculation, a positive force value indicates repulsion and a negative force value indicates attraction.

The permittivity of free space (ε_0) has a value of $8.8542 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$ in air or a vacuum. As this value is constant for air or a vacuum, the expression at the front of Coulomb's law can be calculated. The result of the calculation is given the name Coulomb's law constant (k) and is equal to $8.9875 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$. For ease of calculation this is usually rounded to $8.99 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$. So, in Coulomb's law, if:

$$k = \frac{1}{4\pi\varepsilon_0}$$

then the equation becomes:

$$F = k\frac{Qq}{r^2}$$

where $k = 8.99 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$.

$F = k\frac{Qq}{r^2}$

where $k = 8.99 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$.

The forces between charges in Coulomb's law are treated in the same way as the forces in Newton's laws. The forces are vectors, and the forces between different charged particles will add as vectors. Vector addition and subtraction can be used to deal with more complex systems of particles and the effect of the **Coulomb force** between particles can be represented using vector diagrams (Figure 7.1.2).

For collections of more than two particles, Coulomb's law can be used to calculate the force for each individual particle and the resulting vectors can then be added up.

Factors affecting the electric force

The force between two charged points is proportional to the product of the two charges. Thus if the force between two charged points is 10 N and the charge on one of the points is doubled, then the force between the two points would double to 20 N. It is interesting to note that, regardless of the charge on each point, the force on each point in a pair will be equal to the other. For example, if Q is +10 μC and q is +10 μC, then the repulsive forces on each of these points would be equal in magnitude. The forces would also be equal on both points if Q is +100 μC and q is +1 μC.

The force is also inversely proportional to the square of the distance between the two charged points. This means that if the distance between Q and q is doubled, the force on each point charge will decrease to one quarter of the previous value.

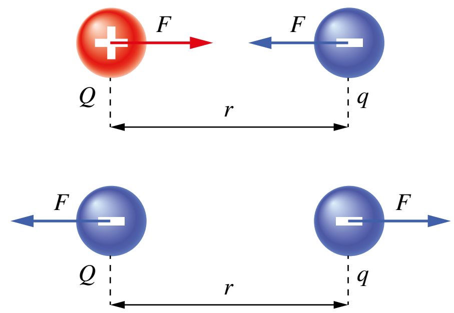


FIGURE 7.1.2 Forces acting between two point charges

One coulomb in perspective

Coulomb's law can be used to calculate the force between two charges of 1 C each, placed 1 m apart.

$$F = k\frac{Qq}{r^2} = 8.99 \times 10^9 \times \frac{1.0 \times 1.0}{1^2} = 8.99 \times 10^9\,\text{N}$$

The force is approximately 10^{10} N. This is equivalent to the weight provided by a mass of 918 000 tonnes (Figure 7.1.3).

FIGURE 7.1.3 Two 1 C charges 1 m apart would produce a force of 10^{10} N, which is almost twice the weight of the Sydney Harbour Bridge.

This demonstrates that a 1 C charge is a huge amount of charge. In reality, the amount of charge that can be placed on ordinary objects is a tiny fraction of a coulomb. Even a highly charged Van de Graaff generator will have only a few microcoulombs (1 μC = 10^{-6} C) of excess charge.

Another way to get a feel for the magnitude of electrical forces is to realise that all matter is held together by the electrical forces between atoms. For example, the mass of Mount Everest is supported by the electrostatic repulsion between the electrons around neighbouring atoms in the rock underneath it. The strength of the hardest steel is due to the electrical forces of attraction between its ions and the delocalised electrons between them. In comparison to the Earth's gravitational force on an atom, the electrical forces between atoms are about a billion, billion (1×10^{18}) times stronger. In fact, only in the last stages of the gravitational collapse of a giant star can the gravitational forces overwhelm the electrical forces between its atoms and cause the star to collapse into a super-dense neutron star.

Worked example 7.1.1

USING COULOMB'S LAW TO CALCULATE FORCE

Two small spheres A and B act as point charges separated by 10.0 cm in air. Calculate the force on each point charge if A has a charge of 3.00 μC and B has a charge of –45.0 nC.
Use $\varepsilon_0 = 8.8542 \times 10^{-12}\,C^2\,N^{-1}\,m^{-2}$.

Thinking	Working
Convert all values to SI units.	$Q = 3.00 \times 10^{-6}\,C$ $q = -45.0 \times 10^{-9} = -4.50 \times 10^{-8}\,C$ $r = 0.100\,m$
State Coulomb's law.	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$
Substitute the values for Q, q, r and ε_0 into the equation and calculate the answer.	$F = \frac{1}{4\pi \times 8.8542 \times 10^{-12}} \times \frac{3.00 \times 10^{-6} \times -4.50 \times 10^{-8}}{0.100^2}$ $= -0.121\,N$
Assign a direction based on a negative force being attraction and a positive force being repulsion.	$F = 0.121\,N$ attraction

➤ Try yourself 7.1.1

USING COULOMB'S LAW TO CALCULATE FORCE

Two small spheres A and B act as point charges separated by 75.0 mm in air. Calculate the force on each point charge if A has a charge of 475 nC and B has a charge of 833 pC.
Use $\varepsilon_0 = 8.8542 \times 10^{-12}\,C^2\,N^{-1}\,m^{-2}$.

Worked example 7.1.2

USING COULOMB'S LAW TO CALCULATE CHARGE

Two small positive point charges with equal charge are separated by 1.25 cm in air. Calculate the charge on each point charge if there is a repulsive force of 6.48 mN between them.
Use $k = 8.99 \times 10^9\,N\,m^2\,C^{-2}$.

Thinking	Working
Convert all values to SI units.	$F = 6.48 \times 10^{-3}\,N$ $r = 1.25 \times 10^{-2}\,m$
State Coulomb's law.	$F = k\frac{Qq}{r^2}$
Substitute the values for F, r and k into the equation and calculate the answer.	$Qq = \frac{Fr^2}{k}$ $= \frac{6.48 \times 10^{-3} \times (1.25 \times 10^{-2})^2}{8.99 \times 10^9}$ $= 1.126 \times 10^{-16}$ As $Q = q$: $Q^2 = 1.126 \times 10^{-16}$ $Q = \sqrt{1.126 \times 10^{-16}}$ $= +1.06 \times 10^{-8}\,C$ $q = +1.06 \times 10^{-8}\,C$

➤ Try yourself 7.1.2

USING COULOMB'S LAW TO CALCULATE CHARGE

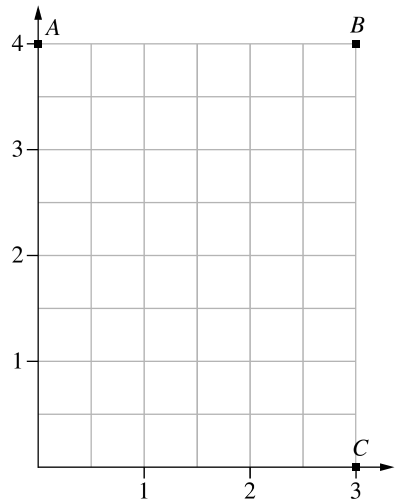
Two small point charges are charged by transferring a number of electrons from Q to q. The charges on the two points are equal and opposite, and the point charges are separated by 12.7 mm in air. Calculate the charge on Q and q if there is an attractive force of 22.5 μN between them.

Use $k = 8.99 \times 10^{9}\,\mathrm{N\,m^2\,C^{-2}}$.

Worked example 7.1.3

USING COULOMB'S LAW TO CALCULATE THE FORCE BETWEEN MULTIPLE CHARGES

Three point charges A, B and C are separated as shown in the diagram below.

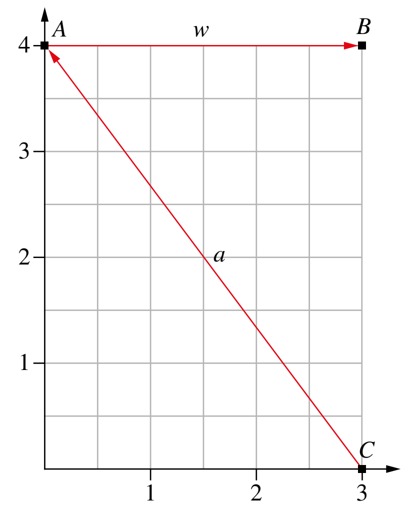


Calculate the magnitude and direction of the net force acting on charge A, given that $q_A = -1.6 \times 10^{-19}$ C, $q_B = +1.6 \times 10^{-19}$ C, and $q_C = -1.6 \times 10^{-19}$ C. The distance scale is in mm.

Use $k = 8.99 \times 10^{9}\,\mathrm{N\,m^2\,C^{-2}}$.

Thinking	Working
Write down the distance between A and B in SI units.	From the grid, AB = 3 mm = 3×10^{-3} m.
Write down the distance between A and C in SI units.	Using Pythagoras: $c^2 = a^2 + b^2$ $c = \sqrt{a^2 + b^2}$ $= \sqrt{9+16}$ $= 5 \times 10^{-3}$ m
Write out each of the charges in units of Coulomb.	$q_A = -1.6 \times 10^{-19}$ C $q_B = 1.6 \times 10^{-19}$ C $q_C = -1.6 \times 10^{-19}$ C
Calculate the force acting on A by B.	$F_{BA} = k\frac{Qq}{r^2}$ $= 8.99 \times 10^{9} \times \frac{-(1.6\times10^{-19})^2}{(3.0\times10^{-3})^2}$ $= -2.56 \times 10^{-23}$ N

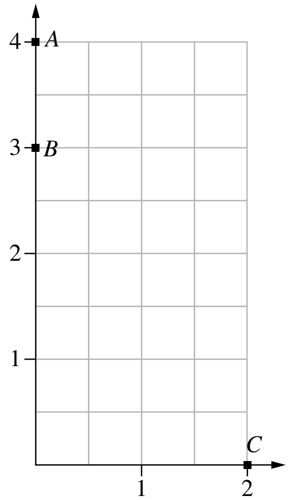
Worked example 7.1.3 *continued*

Calculate the force acting on A by C.	$F_{CA} = k\frac{Qq}{r^2}$ $= 8.99 \times 10^9 \times \frac{(-1.6\times10^{-19})^2}{(5.0\times10^{-3})^2}$ $= 9.2 \times 10^{-24}$ N
Draw arrows to designate the vectors of the two forces.	
Add the two-dimensional vectors to give the resultant force on A.	The vector CA is at an angle of $\theta = \tan^{-1}\left(\frac{4}{3}\right) = 53.1°$ above the horizontal, so its horizontal component is: $F_H = 9.2 \times 10^{-24} \times \cos 53.1°$ $= 5.52 \times 10^{-24}$ N Similarly, its vertical component is: $F_V = 9.2 \times 10^{-24} \times \sin 53.1°$ $= 7.36 \times 10^{-24}$ N There is only one force in the vertical direction, so this comprises the net vertical force. To get the net horizontal force, we add the horizontal components of the vectors: $F_{H\ net} = -5.52 \times 10^{-24} + 2.56 \times 10^{-23}$ $= 2.01 \times 10^{-23}$ N So the net force acting on A is 7.36×10^{-24} N in the positive vertical direction, and 2.01×10^{-23} N in the positive horizontal direction.
Use Pythagoras to calculate the final net force and its angle above the horizontal.	$F = \sqrt{F_H^{\ 2} + F_V^{\ 2}}$ $= \sqrt{(2.01\times10^{-23})^2 + (7.36\times10^{-24})^2}$ $= 2.1 \times 10^{-23}$ N $\theta = \tan^{-1}\left(\frac{7.36\times10^{-24}}{2.01\times10^{-23}}\right) = 20°$ $F_{net} = 2.1 \times 10^{-23}$ N at an angle of 20° above the positive horizontal line.

➤ Try yourself 7.1.3

USING COULOMB'S LAW TO CALCULATE THE FORCE BETWEEN MULTIPLE CHARGES

Three point charges A, B and C are separated as shown in the diagram below.



Calculate the magnitude and direction of the net force acting on charge A when $q_A = -1.0 \times 10^{-8}$ C, $q_B = +0.5 \times 10^{-8}$ C and $q_C = -2.5 \times 10^{-8}$ C. Length units are in mm.

Use $k = 8.99 \times 10^9$ N m^2 C^{-2}.

7.1 Review

SUMMARY

- Coulomb's law describes the force exerted by electrostatically charged objects on other electrostatically charged objects.
- Coulomb's law for the force between two charges q_1 and q_2 separated by a distance of r is:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$$

- The constant, ε_0, in Coulomb's law is the permittivity of free space, and has a value of $8.8542 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$.
- For air or a vacuum, the expression $\frac{1}{4\pi\varepsilon_0}$ at the front of Coulomb's law can be simplified to the value of k, called the Coulomb's law constant, which has a value of approximately $8.99 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$. So:

$$F = k\frac{Qq}{r^2}$$

- In more complex systems of more than two particles, Coulomb's law can be used to calculate the force for each individual particle and the resulting vectors are added up.

KEY QUESTIONS

Retrieval

1 Define 'Coulomb's law'.

Comprehension

2 **a** List the three quantities on which the force between two particles depends.

b Describe the relationships (e.g. linear, inverse etc.) for the force between two particles.

3 A charge of $+q$ is placed a distance r from another charge also of $+q$. A repulsive force of magnitude F is found to exist between them.

Describe the changes, if any, that will occur to the force in the following situations, by identifying the correct options from the text in bold.

a If one of the charges is doubled to $+2q$, the force will **halve/double/quadruple/quarter** and **repel/attract**.

b If both charges are doubled to $+2q$, the force will **halve/double/quadruple/quarter** and **repel/attract**.

c If one of the charges is changed to $-2q$, the force will **halve/double/quadruple/quarter** and **repel/attract**.

d If the distance between the charges is halved to $0.5r$, the force will **halve/double/quadruple/quarter** and **repel/attract**.

Analysis

4 Determine the net force acting on a positive unit charge with one negative unit charge 1 m to its left and one negative unit charge 1 m to its right.

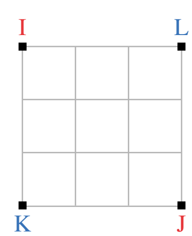
5 Assess what force you would expect to be exerted on a single negative elementary charge (i.e. an electron's charge) surrounded by four equidistant positive elementary charges.

6 A hydrogen atom consists of a proton and an electron separated by a distance of 53 pm (picometres). Calculate the magnitude and sign of the force applied to a proton carrying a charge of $+1.602 \times 10^{-19}$ C by an electron carrying a charge of -1.602×10^{-19} C.

7 Calculate the repulsive force on each proton in a helium nucleus separated in a vacuum by a distance of 2.50 fm.

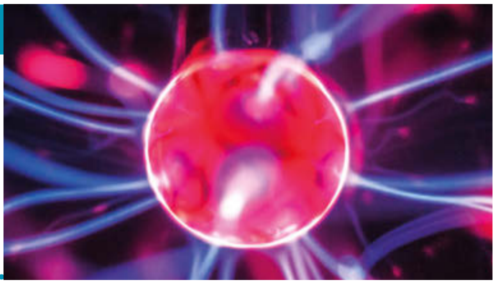
Use $k = 8.99 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$, 1 fm = 1×10^{-15} m and $q_p = +1.602 \times 10^{-19}$ C.

8 Two positive (red) and two negative (blue) elementary charges are fixed on the edges of a 1.0 m × 1.0 m square table as shown below.



Calculate the net force acting on charge I (with direction in terms of horizontal and vertical components).

7.2 Electric fields



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

- define what an electric field is
- calculate and explain how an electric field affects the behaviour of other charged particles
- predict how a charged particle will induce an electric field of its own
- draw field lines to represent the electric fields of various systems.

ELECTRIC FIELDS

There are four fundamental forces in nature that act at a distance; that is, they can exert a force on an object without making any physical contact with it. These are called non-contact forces, and include the strong nuclear force, the weak nuclear force, the electromagnetic force and the gravitational force.

In order to understand these forces, scientists use the idea of a field. A field is a region of space in which objects experience a force due to a physical property related to the field. Gravity, electricity and magnetism can all be described by fields. Chapter 5 described the direction, shape and strength of gravitational fields around a mass. In this section the electric field will be explained.

An **electric field** surrounds positive and negative charges, and exerts a force on other charges within the field.

FIGURE 7.2.1 Charged plasma follows lines of the electric field produced by a Van de Graaff generator.

ELECTRIC FIELD LINES

An electric field is a vector quantity—it has both direction and strength.

In order to visualise electric fields around charged objects you can use electric **field lines**. Some field lines are already visible. For example, the charged plasma in Figure 7.2.1 follows the lines of the electric field, and the girl's hair in Figure 7.2.2 is tracing out the path of the field lines. Diagrams of field lines can also be constructed.

Field lines are drawn with arrowheads indicating the direction of the force that a small positive test charge would experience if it were placed in the electric field. Therefore, field lines point away from positively charged objects and towards negatively charged objects. Usually, only a few representative lines are drawn.

FIGURE 7.2.2 The girl's hair follows the lines of the electric field produced when she became charged while sliding down the plastic slide.

> Remember: like charges repel and unlike (opposite) charges attract.

The density of field lines (how close they are together) is an indication of the relative strength of the electric field. This is explained in more detail later in this section.

Rules for drawing electric field lines

When drawing electric field lines (in two dimensions) around a charged object, there are a few rules that need to be followed.

- The space between field lines indicates the strength of the field. The closer the lines, the stronger the field.
- Electric field lines go from positively charged objects to negatively charged objects.

- Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.
- Field lines can never cross; if they did, it would indicate that the field is in two directions at that point, which can never happen.
- Around small charged spheres, called **point charges**, the field lines radiate like the spokes on a wheel.
- Around point charges you should draw at least eight field lines: top, bottom, left, right and another field line in between each of these.
- Between two point charges, the direction of the field at any point is the resultant field vector determined by adding the field vectors due to each of the two point charges.
- Between two oppositely charged parallel plates, the field lines between the plates are evenly spaced and are drawn straight from the positive plate to the negative plate.
- Always remember that these drawings are two-dimensional representations of a three-dimensional field.

Figures 7.2.3 and 7.2.4 show some examples of how to draw electric field lines. Figure 7.2.3a shows the electric fields around positive and negative point charges, Figure 7.2.3b shows the electric field of an electric dipole and Figure 7.2.4 shows the electric field of a parallel plate.

a

b

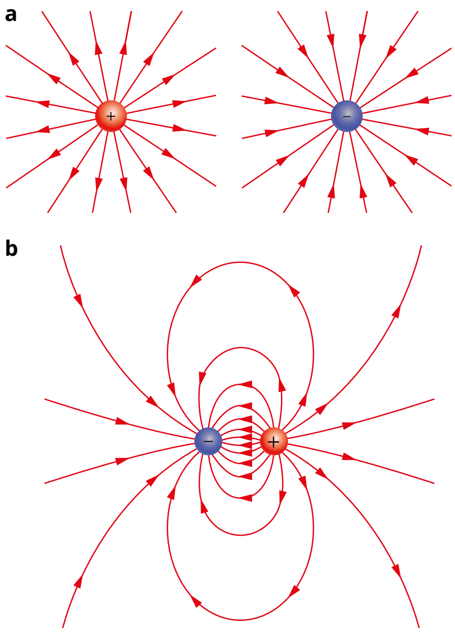


FIGURE 7.2.3 (a) Positive point charges have their electric field lines pointing radially outwards. Negative point charges have their electric field lines pointing radially inwards. (b) When positive and negative charges are placed together they form an electric dipole. Their field lines interact in a more complex fashion than in (a).

Strength of the electric field

The distance between adjacent field lines indicates the strength of the field. Around a point charge, the field lines are closer together near the charge and further apart away from the charge. You can see this in the field-line diagrams in (Figure 7.2.3). Therefore, the **electric field strength**, E, decreases as the distance from a point charge increases.

A uniform electric field is established between two parallel metal plates that are oppositely charged. The field strength is constant at all points within a uniform electric field, so the field lines are parallel (Figure 7.2.4).

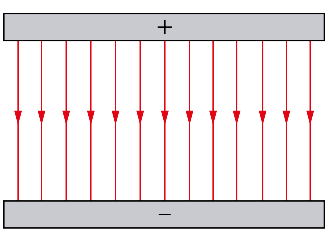


FIGURE 7.2.4 The field between a positive and a negative plate is entirely uniform and parallel.

FORCES ON FREE CHARGES IN ELECTRIC FIELDS

If a charged particle, such as an electron, is placed within an electric field, it experiences a force. The direction of the field and the sign of the charge allow you to determine the direction of the force.

Figure 7.2.5 shows a positive test charge (proton) and a negative test charge (electron), within a uniform electric field. Recall that the direction of an electric field is defined as the direction of the force that a positive charge would experience within the electric field. So, an electron will experience a force in the opposite direction to the electric field, while a proton will experience a force in the same direction as the field.

The magnitude of the force experienced by a charged particle due to an electric field can be determined using the equation $F = qE$.

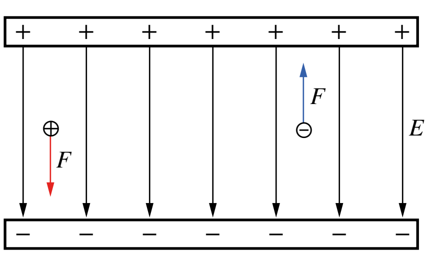


FIGURE 7.2.5 The direction of the electric field, E, indicates the direction in which a force would act on a positive charge. A negative charge would experience a force in the opposite direction to the field.

$F = qE$

where

F is the force on the charged particle (N)

q is the charge of the object experiencing the force (C)

E is the strength of the electric field ($N\,C^{-1}$).

This equation illustrates that the force experienced by a charge is proportional to the strength of the electric field, E, and the size of the charge, q. That is, the larger the electric charge of a particle, the more it is influenced by other charged particles. The force on the charged particle will cause the charged particle to accelerate in the field. This means that the particle could increase its velocity, decrease its velocity, or change its direction while in the field.

To calculate the acceleration due to the force experienced, you can use the equation from Newton's second law:

$$F = ma$$

where

m is the mass of the accelerating particle (kg)

a is the acceleration ($m\,s^{-2}$).

Worked example 7.2.1

USING $F = qE$

Calculate the magnitude of the uniform electric field that would cause a force of 5.00×10^{-21} N on an electron. ($q_e = -1.60 \times 10^{-19}$ C)	
Thinking	**Working**
Rearrange the relevant equation to make electric field strength the subject.	$F = qE$ $E = \frac{F}{q}$
Substitute the values for F and q into the rearranged equation and calculate the answer. (As only magnitude is required, q can be kept positive.)	$E = \frac{5.00 \times 10^{-21}}{1.60 \times 10^{-19}}$ $= 3.12 \times 10^{-2}\ N\,C^{-1}$

Electric field strength can be thought of as the force applied per coulomb of charge, which is expressed in the equation:

$$E = \frac{F}{q}$$

You will recognise this as the previous equation, $F = qE$, transposed to make E the subject.

➤ Try yourself 7.2.1

USING $F = qE$

Calculate the magnitude of the uniform electric field that creates a force of 9.00×10^{-23} N on a proton. ($q_p = +1.60 \times 10^{-19}$ C)

The electric field at a distance from a charge

In the previous section, the electric field, E, is defined as being proportional to the force exerted on a positive test charge and inversely proportional to the magnitude of that charge. It is measured in $N\,C^{-1}$. Defining the electric field in this way means that it is independent of the size of the charge placed into the field (i.e. the test charge) and is fully described by the charge *creating* the field at a particular point.

It is useful also to be able to determine the electric field at a distance from a single point charge.

The magnitude of the electric field at a distance from a single point charge is given by:

$$E = k\frac{q}{r^2}$$

or

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$$

where

E is the strength of the electric field around a point (N C^{-1})

q is the charge on the point creating the field (C)

r is the distance from the charge (m)

ε_0 is the permittivity of free space (8.8542×10^{-12} C^2 N^{-1} m^{-2})

$k = 8.99 \times 10^9$ (N m^2 C^{-2}).

Note that we define an electric field at each point by how a particle *would* interact with it at that position. That is, using $F = Eq$ and the above expression for E, we arrive back at $F = k\frac{Qq}{r^2}$, which is just Coulomb's law, the force that would be exerted on our test charge by the charge creating the field.

Worked example 7.2.2

ELECTRIC FIELD OF A SINGLE POINT CHARGE

Calculate the magnitude and direction of the electric field at a point P at a distance of 20.0 cm below a negative point charge, q, of 2.0×10^{-6} C.

Thinking	Working
Convert units to SI units as required.	$q = -2.0 \times 10^{-6}$ C $r = 20.0$ cm $= 0.200$ m
Substitute the known values to find the magnitude of E using $E = k\frac{q}{r^2}$.	$E = k\frac{q}{r^2}$ $= 8.99 \times 10^9 \times \frac{2.0 \times 10^{-6}}{0.20^2}$ $= 4.5 \times 10^5$ N C^{-1}
The direction of the field is defined as that acting on a positive test charge (see previous section). Point P is below the charge.	Since the charge is negative, the direction will be towards the charge q, or upwards.

➤ Try yourself 7.2.2

ELECTRIC FIELD OF A SINGLE POINT CHARGE

WS 3.2.2 WS 3.2.3 PA 3.2.1 PA 3.2.2

Calculate the magnitude and direction of the electric field at point P at a distance of 15 cm to the right of a positive point charge, q, of 2.0×10^{-6} C.

7.2 Review

SUMMARY

- An electric field is a region of space around a charged object in which another charged object will experience a force.
- Electric fields are represented using field lines.
- Electric field lines point in the direction of the force that a positive charge within the field would experience.
- A positive charge experiences a force in the direction of the electric field and a negative charge experiences a force in the opposite direction to the field.
- The spacing between the field lines indicates the strength of the field. The closer together the lines are, the stronger the field.
- A stronger electric field indicates that the field will exert a larger electrostatic force on a charged object.
- Electric field strength can be expressed as $E = \frac{F}{q}$.
- Around point charges the electric field radiates in all directions (three dimensionally).
- The magnitude of the electric field at a distance from a single point charge is given by $E = k\frac{q}{r^2}$, or $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$.
- Between two oppositely charged parallel plates, the field lines are parallel and therefore the field has a uniform strength.
- When charges are in an electric field, they accelerate in the direction of the force acting on them.
- The force on a charged particle can be determined using the equation $F = qE$.
- Force can be related to the acceleration of a particle using the equation $F = ma$.

KEY QUESTIONS

Retrieval

1 Recall whether the rules below for drawing electric field lines are true or false.

- **a** Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.
- **b** Field lines can cross; this indicates that the field is in two directions at that point.
- **c** Electric fields go from negatively charged objects to positively charged objects.
- **d** Around small charged spheres called point charges you should draw at least eight field lines: top, bottom, left, right and in between each of these.
- **e** Around point charges the field lines radiate like spokes on a wheel.
- **f** Between two point charges the direction of the field at any point is the field due to the closest of the two point charges.
- **g** Between two oppositely charged parallel plates the field between the plates is evenly spaced and is drawn straight from the negative plate to the positive plate.

Comprehension

2 Describe how the strength of an electric field changes with distance from a charge.

3 Describe the direction of the force acting on a negative charge with respect to the direction of the field.

4 Describe the two effects that an electric field may have on the motion of a charged particle.

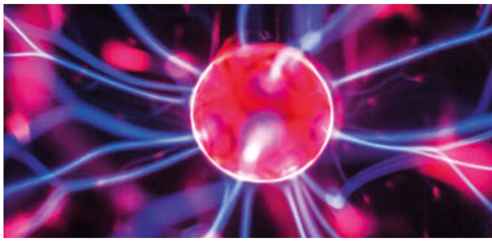
Analysis

5 Calculate the force applied to a balloon carrying a charge of 5.00 mC in a uniform electric field of 2.50 $N\,C^{-1}$.

6 Calculate the charge on a plastic disc if it experiences a force of 0.025 N in a uniform electric field of 18 $N\,C^{-1}$.

7 Calculate the acceleration of an electron in a uniform electric field of 3.25 $N\,C^{-1}$. The mass of an electron is 9.109×10^{-31} kg and its charge is -1.60×10^{-19} C.

7.3 Electrical potential energy



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

- describe the important quantities of electric potential and electrical potential energy
- calculate the work done on or by a charged particle as it moves through an electric field.

WORK DONE IN UNIFORM ELECTRIC FIELDS

We have discussed the force exhibited by an electric field on another charge. You know from your studies of Newton's laws that an unbalanced force on a charge will induce an acceleration, giving it kinetic energy. There is therefore some work being done by the electric field on the charge. This module studies how this energy transfer takes place, and what the consequences are on the charge.

A 'uniform' electric field is one that is constant at each point. It has parallel, equally spaced field lines.

Electric potential and electrical potential energy

In discussing work done by an electric field we introduce two related, but distinct, quantities: **electrical potential** and electrical potential energy.

Electrical potential energy is a form of energy that is stored in a field. Work is done *on* the field when a charged particle is forced to move in it. Conversely, work can be done *by* the field on the charged particle.

Electric potential (V) is defined as the work required per unit charge to move a positive point charge from infinity to a place in the electric field. It is the difference in potential energy stored in the field between a test charge at infinity and a test charge at a particular point.

$$V = \frac{\Delta U}{q}$$

where

ΔU is the difference in potential energy stored in the field between a test charge at infinity and a test charge at a particular point.

The electric potential at infinity is defined as zero. This definition leads to:

$$V = \frac{W}{q}$$

$$W = qV$$

where

W is the work done on a positive point charge or on the field (J)

q is the charge of the point charge (C)

V is the electrical potential (J C^{-1}) or volts (V).

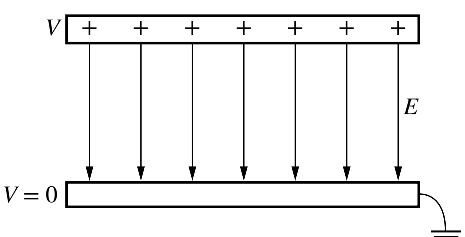


FIGURE 7.3.1 The potential of two plates when one has a positive potential and the other is earthed

Consider two parallel plates (Figure 7.3.1) in which the positive plate is at a potential (V) and the other plate is earthed, which is defined as zero potential. The difference in potential between these two plates is called the electrical **potential difference** (V).

Between any two points in an electric field, E, separated by a distance, d, that is parallel to the field, the potential difference, V, is then defined as the change in the electric potential between these two points (Figure 7.3.2).

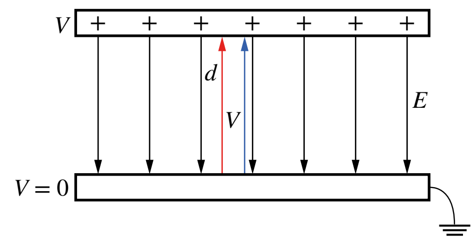


FIGURE 7.3.2 The potential difference between two points in a uniform electric field

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

$V = Ed$

where

V is the difference in electric potential (V)

E is the electrical field strength of the uniform electric field (V m^{-1})

d is the distance between points, parallel to the field (m).

Calculating work done

By combining the two equations mentioned so far, you can derive an equation for calculating the work done on a point test charge to move it a distance across a potential difference.

$$W = qV \quad \text{and} \quad V = Ed \quad \text{so} \quad W = qEd$$

where

W is the work done on the point charge or on the field (J)

q is the charge of the point charge (C)

E is the electrical field strength (V m^{-1} or N C^{-1})

d is the distance between points, parallel to the field (m).

Work done by or on an electric field

When calculating work done, which changes the electrical potential energy, remember that work can be done either:

- by the electric field on a charged object, or
- on the electric field by forcing the object to move.

You need to examine what is happening in a particular situation to know how the work is being done.

For example, if a charged object is moving in the direction it would naturally tend to go within an electric field, then work is done by the field. So, when a positive point charge is moved in the direction of the electric field, the electric field has done work on the point charge. (Refer to q_2 in Figure 7.3.3.)

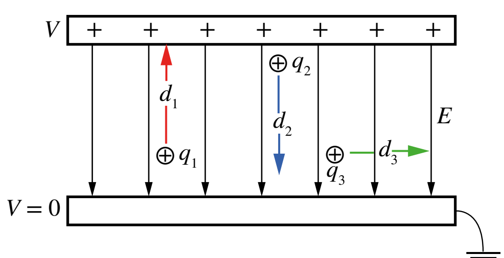


FIGURE 7.3.3 Work is being done on the field by moving q_1 and work is being done by the field on q_2. No work is done on q_3 since it is moving perpendicular to the field.

When work is done by a charged object on an electric field, the object is forced to move against the direction it would naturally go. Work has been done on the field by forcing the object to move. For example, if a force causes a positive charge to move towards the positive plate within a uniform electric field, work has been done on the electric field by forcing the object to move. (See q_1 in Figure 7.3.3.)

If a charge does not move any distance parallel to the field, then no work is done on or by the field. (See q_3 in Figure 7.3.3.)

Worked example 7.3.1

WORK DONE ON A CHARGE IN A UNIFORM ELECTRIC FIELD

Isabelle sets up a parallel plate arrangement so that one plate is at a potential of 12.0 V and the other earthed plate is positioned 0.50 m away. Calculate the work done to move a proton from the positive plate a distance of 10.0 cm towards the negative plate. ($q_p = +1.60 \times 10^{-19}$ C)

Identify what does the work and what the work is done on.

Thinking	Working
Identify the variables presented in the problem to calculate the electric field strength E.	$V_2 = 12.0$ V $V_1 = 0$ V $d = 0.50$ m
Use the equation $E = \frac{V}{d}$ to determine the electric field strength.	$E = \frac{V}{d}$ $= \frac{12.0 - 0}{0.50}$ $= 24.0\ \text{V m}^{-1}$
Use the equation $W = qEd$ to determine the work done. Note that d here is the distance that the proton moves.	$W = qEd$ $= 1.60 \times 10^{-19} \times 24.0 \times 0.100$ $= 3.8 \times 10^{-19}$ J
Determine if work is done on the charge by the field or if work is done on the field.	As the positively charged proton is moving naturally towards the negative plate, then work is done on the proton by the field.

➤ Try yourself 7.3.1

WORK DONE ON A CHARGE IN A UNIFORM ELECTRIC FIELD

Jack sets up a parallel plate arrangement so that one plate is at a potential of 36.0 V and the other earthed plate is positioned 2.00 m away. Calculate the work done to move an electron from the positive plate a distance of 75.0 cm towards the negative plate. ($q_e = -1.60 \times 10^{-19}$ C)

Identify what does the work and what the work is done on.

COMPARING GRAVITATIONAL AND ELECTRIC FIELDS

Gravitational force brings gas clouds together to form planets, stars and galaxies. It causes stars to collapse to black holes, generating gravitational fields strong enough that even light can't escape. Yet the gravitational force of attraction between two electrons is less than 8×10^{-37} N.

The relationships developed for gravitational and electric fields over this chapter and Chapter 5 reveal the parallels and differences between related field concepts for gravitational masses and point charges. They are summarised in Table 7.5.1.

TABLE 7.5.1 Comparison of gravitational and electric fields

Quantity or description	Gravitational fields	Electrical fields
how field strength varies with distance, r, from a mass or charge	$g = G\frac{M}{r^2}$	$E = k\frac{q}{r^2}$
force between masses or charges	$F_g = G\frac{m_1 m_2}{r^2}$	$F = k\frac{Qq}{r^2}$
potential energy changes in a uniform field	$E_g = mg\Delta h$	$W = qV$
force due to a uniform field	$F_g = mg$	$F = qE$

WS 3.2.4

7.3 Review

SUMMARY

- Electric field strength can be expressed as $E = \frac{F}{q}$ and $E = \frac{V}{d}$.
- Between two oppositely charged parallel plates, the field lines are parallel and therefore the field has uniform strength.
- When charges are in an electric field, they accelerate in the direction of the force acting on them.
- Electrical potential energy is the energy that is stored in an electric field when a charge is placed somewhere in that field.
- Electrical potential energy allows work to be done on a charged particle in a field.
- When a charged object is moved against the direction it would naturally move in an electric field, then work is done on the field.
- When a charged object is moved in the direction it would naturally tend to move in an electric field, then the field does work on the particle.
- The work done on or by an electric field can be calculated using the equations $W = qV$ or $W = qEd$.
- Electrical potential is defined as the work required per unit charge to move a positive point charge from infinity to a place in the electric field.

KEY QUESTIONS

Retrieval

1 Define 'electric potential'.

2 Define 'potential energy'.

Comprehension

3 Describe a situation in which work is done by a field on a charge, as well as one in which work is done by a charge on a field.

Analysis

4 Determine if work was done on the field or by the field or if no work is done, for each of the following charged objects in a uniform electric field.

- **a** An electron moves towards a positive plate.
- **b** A positively charged point remains stationary.
- **c** A proton moves towards a positive plate.
- **d** A lithium ion (Li^+) moves parallel to the plates.
- **e** An alpha particle moves away from the negative plate.
- **f** A positron moves away from the positive plate.

5 An alpha particle is located in a parallel plate arrangement that has a uniform electric field of $34.0\,V\,m^{-1}$.

- **a** Calculate the work done to move the alpha particle a distance of 1.00 cm from the earthed plate to the plate with a positive potential. ($q_a = +3.204 \times 10^{-19}\,C$)
- **b** Determine whether work was done on the field by the alpha particle, by the field on the particle or if no work was done.

6 Calculate the potential difference that exists between two points separated by 45.0 cm and parallel to the field lines in an electric field of strength $6.7 \times 10^2\,V\,m^{-1}$.

7 Calculate the potential difference that exists between two points separated by 30.0 cm, parallel to the field lines, in an electric field of strength $4.00 \times 10^3\,V\,m^{-1}$.

Chapter review

07

KEY TERMS

Coulomb force
Coulomb's law
electric field
electric field strength
electrical potential
field lines
point charge
potential difference

KEY QUESTIONS

Retrieval

1 Describe an electric field by selecting the best option below.
- **A** a region around an object that causes a force on other objects within that region
- **B** a region around a charged object that causes a charge on other objects within that region
- **C** a region around a charged object that causes a force on other objects within that region
- **D** a region around a charged object that causes a force on other charged objects in that region

2 Describe the direction of an electric field by selecting the best option below.
- **A** towards a positively charged object
- **B** away from a neutrally charged object
- **C** away from a positively charged object
- **D** away from a negatively charged object

3 Identify where the electrical field strength will be at a maximum between two plates forming a uniform electric field.
- **A** close to the positive plate
- **B** close to the earthed plate
- **C** at all points between the plates
- **D** at the mid-point between the plates

4 Identify the relationship between work done and potential difference by selecting the correct bold terms to complete the sentence.

When a positively charged particle moves across a potential difference from a positive plate towards an earthed plate, work is done by the **field/charged particle** on the **field/charged particle**.

Comprehension

5 Explain the difference between electric potential and potential difference.

6 A charge of $+q$ is placed a distance r from another charge also of $+q$. A repulsive force of magnitude F is found to exist between them.

Describe the changes, if any, which will occur to the force in the following situations, by choosing the correct bolded terms.
- **a** The distance between the charges is doubled to $2r$, so the force will **halve/double/quadruple/quarter** and **repel/attract**.
- **b** The distance between the charges is halved to $0.5r$, so the force will **halve/double/quadruple/quarter** and **repel/attract**.
- **c** The distance between the charges is doubled and one of the charges is changed to $-2q$, so the force will **halve/double/quadruple/quarter** and **repel/attract**.

Analysis

7 A test charge is placed at a point, P, 30 cm directly above a charge, q, of $+30 \times 10^{-6}$ C. Determine the magnitude and direction of the electric field at point P.
- **A** 300 N C^{-1} upwards
- **B** 300 N C^{-1} downwards
- **C** 3×10^{6} N C^{-1} upwards
- **D** 3×10^{6} N C^{-1} downwards

8 Calculate the force applied to an oil drop carrying a charge of 3.00 mC in a uniform electric field of 7.50 N C^{-1}.

9 Calculate the potential difference that exists between two points separated by 25.0 mm and parallel to the field lines in an electric field of strength 1.00×10^{3} V m^{-1}.

10 Calculate the magnitude of the force that would exist between two 1.00 C point charges separated by 1.00 km.

Use $k = 8.99 \times 10^{9}$ N m^{2} C^{-2}.

11 Calculate the work done to move a positively charged particle of 2.5×10^{-18} C a distance of 3.0 mm towards a positive plate in a uniform electric field of 556 N C^{-1}.

12 A particular electron gun accelerates an electron across a potential difference of 15 kV, a distance of 12 cm between a pair of charged plates. Determine the magnitude of the force acting on the electron.

Use $q_e = 1.60 \times 10^{-19}$ C.

13 A gold(III) ion is accelerated by the electric field created between two parallel plates separated by 0.020 m. The ion carries a charge of +3.0e and has a mass of 3.27×10^{-25} kg. A potential difference of 1.00×10^{3} V is applied across the plates. The work done to move the ion from one plate to the other results in an increase in the kinetic energy of the gold(III) ion. Calculate its final velocity If the ion starts from rest.

Use $q_e = -1.60 \times 10^{-19}$ C.

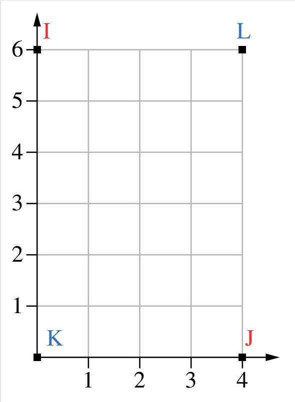
14 Calculate the magnitude of the force that would exist between two point charges of 5.00 mC and 4.00 nC separated by 2.00 m.

Use $k = 8.99 \times 10^{9}$ N m^{2} C^{-2}.

15 A point charge of 2.25 mC is positioned on top of an insulated rod on a table. Calculate the distance above the point charge at which a sphere of mass 3.00 kg containing a charge of 3.05 mC should be located so that it is suspended in the air.
Use $k = 8.99 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$.

16 Two point charges (30.0 cm apart in air) are charged by transferring electrons from one point to the other. Calculate how many electrons must be transferred so that an attractive force of 1.0 N exists. Consider only the magnitude of q_e in your calculations.
Use $k = 8.99 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$ and $q_e = -1.60 \times 10^{-19}$ C.

17 Two positive and two negative charges are fixed on the edges of a 4.0 mm × 6.0 mm table as shown below:
Point I has a charge of $+2.0_e$ (elementary charges), L has a charge of -4.0_e, K has a charge of -3.0_e, and J has a charge of $+5.0_e$.
Calculate the net force (magnitude and direction) acting on charge I.



18 A charged plastic ball of mass 5.00 g is placed in a uniform electric field pointing vertically upwards with strength of 300.0 N C^{-1}. Calculate the magnitude and sign of the charge required on the ball in order to create a force upwards that exactly equals the weight force of the ball.

19 Two metal spheres, one carrying a charge of −16.0 μC and the other a charge of +5.00 μC, are attracted to each other and touch. The charge distributes so the charge is equal on each sphere. A force of repulsion then exists between them and they move apart.
- **a** Calculate the force of attraction between them when they are 2.00 mm apart before they touch.
- **b** Determine the charge on each sphere after they touch.
- **c** Calculate the force between them after they touch and move 6.75 mm apart.

20 A beam of electrons, initially at rest, is accelerated in the electron gun of a linear accelerator to a velocity of $5.30 \times 10^7\ \mathrm{m\,s^{-1}}$.
- **a** Calculate how much work is done on each electron to achieve this velocity.
- **b** Determine the voltage they are accelerated through.

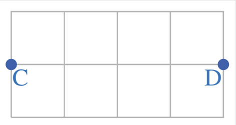
21 Two electrons approach each other. The charge on each the electron is -1.60×10^{-19} C. Determine the electrical force of repulsion between the two electrons when they are 5.4×10^{-12} m apart.
Use $k = 8.99 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$.

Knowledge utilisation

22 Zhoufan and Sylvia are experimenting with an unknown ion and wish to determine the charge that it carries. They decide to determine the magnitude and sign of this charge using their knowledge of Coulomb's law. They do not have equipment sensitive enough to measure the absolute value of a force between two particles, and can only determine ratios between relative forces (e.g. force A is three times stronger than force B).
In order to determine the charge on the unknown ion, they set up an experiment in which a maximum of two electrons and two ions can be laid down. Zhoufan and Sylvia are able to measure the distances between two charges with sufficient accuracy.
Design a setup for this experiment that will allow them to determine the charge on the ion, and explain why such a setup is necessary.

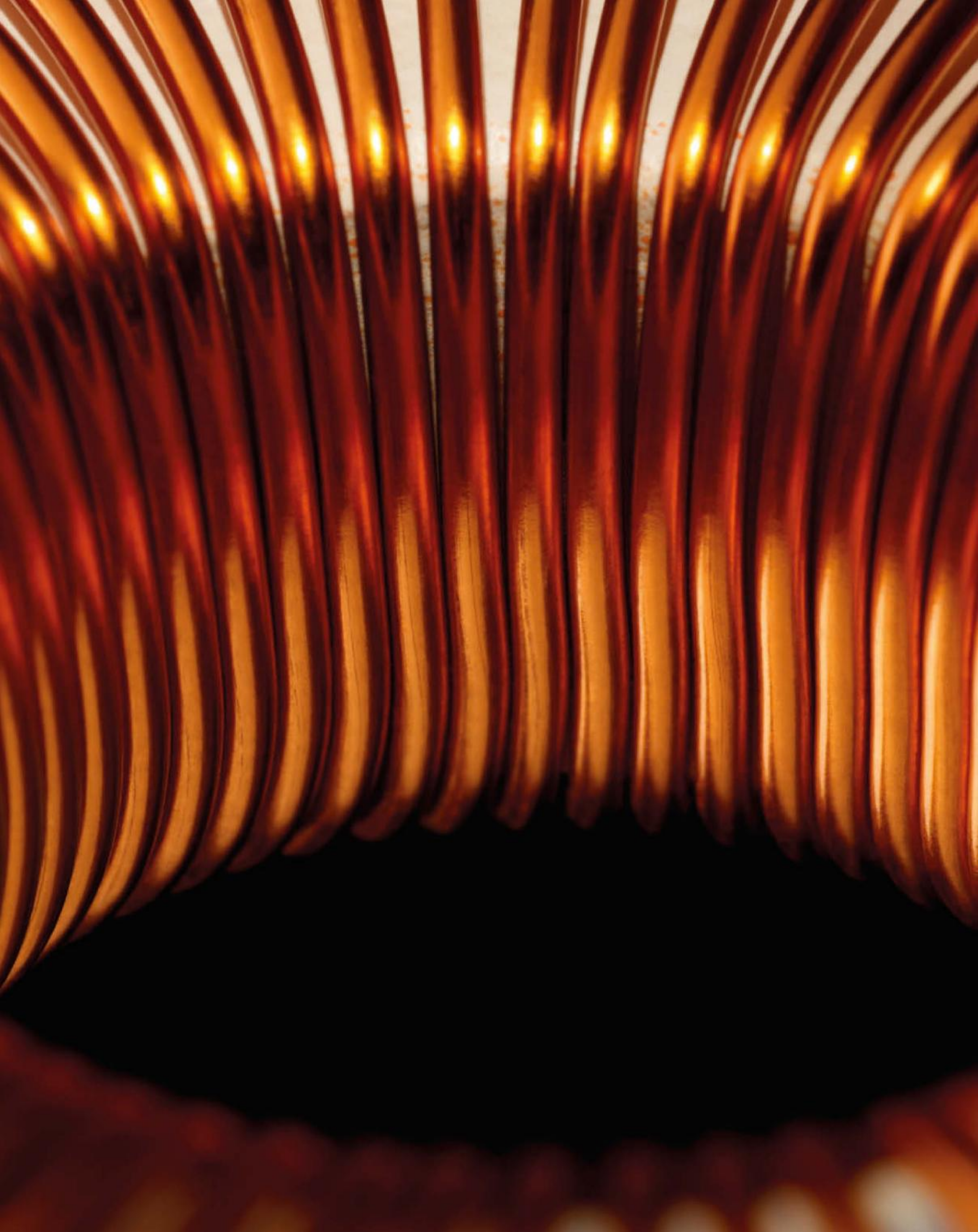
23 In an electrical circuit, a wire connects a region of high electric potential to a region of low electric potential in the form of a battery. Discuss how these concepts might be applied to an electric circuit, and explain how they could be applied to the lighting of a light globe.

24 Consider two fixed positive charges arranged as below 6.67×10^{-9} m apart. Charge C has a magnitude of -5.13×10^{-19} C and charge D has a magnitude of -2.83×10^{-19} C.



- **a** Draw an arrow to indicate the direction of the electric field created by C, and another arrow that indicates the electric field created by D, along the line that connects them.
- **b** Calculate the net electric field (i.e. the sum of the electric fields from C and D along the line connecting them) between the two charges at a point exactly halfway between them.
- **c** Determine how far from C is the net electric field zero.

25 A researcher sees a negatively charged oil drop with a mass of 1.161×10^{-14} kg hover stationary between two horizontal parallel plates. Between the plates there is an electric field of strength 3.55×10^4 N C^{-1}. The field is pointing vertically downwards.
Determine how many extra electrons are present in the oil drop. ($q_e = -1.60 \times 10^{-19}$ C and $g = 9.8\ \mathrm{N\,kg^{-1}}$)



CHAPTER 08
Magnetic fields

In 1820, Hans Christian Oersted discovered that an electric current could produce a magnetic field. His work established the initial ideas behind electromagnetism. Since then, our understanding and application of electromagnetism has developed to the extent that much of our modern way of living relies upon it.

In this chapter you will investigate the concept of magnetism, how materials become magnetised, how to describe magnetic fields through the use of field diagrams, and how to calculate magnetic fields in relation to electric current.

Syllabus subject matter

Topic 2 • Electromagnetism

MAGNETIC FIELDS

- define the term *magnetic field*
- recall how to represent magnetic field lines, including sketching magnetic field lines due to a moving electric charge, electric currents and magnets
- recall that a moving electric charge generates a magnetic field
- determine the magnitude and direction of a magnetic field around electric current-carrying wires and inside solenoids
- solve problems involving the magnitude and direction of magnetic fields around a straight electric current-carrying wire and inside a solenoid
- recall that electric current-carrying conductors and moving electric charges experience a force when placed in a magnetic field
- solve problems involving the magnetic force on an electric current-carrying wire and moving charge in a magnetic field.

SCIENCE AS A HUMAN ENDEAVOUR

- Medical imaging

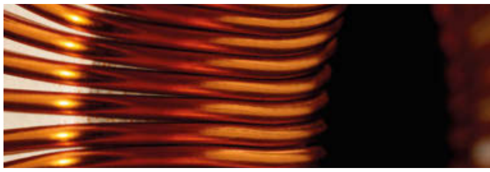
MANDATORY PRACTICAL 2

- Conduct an experiment to investigate the force acting on a conductor in a magnetic field.

MANDATORY PRACTICAL 3

- Conduct an experiment to investigate the strength of a magnetic field at various distances.

8.1 Magnets



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

- define 'magnetic field'
- describe the types of objects that produce magnetic fields.

FIGURE 8.1.1 In 1820, Hans Christian Oersted discovered the magnetic effect created by an electric current. Oersted is honoured by this statue in Oersted's Park, Copenhagen.

Although naturally-occurring magnets had been known for many centuries, by the early 19th century there was still no scientifically proven way of creating an artificial magnet. In 1820, the Danish physicist Hans Christian Oersted (whose statue is shown in Figure 8.1.1) developed a scientific explanation for the magnetic effect created by an electric current.

Oersted was a keen believer in the 'unity of nature', the concept that everything in the universe is somehow connected. He noticed that when he switched on a current from a voltaic pile (a simple early battery), a magnetic compass nearby moved. Intrigued by this observation, he carried out further experiments, which demonstrated that it was the current from the voltaic pile that was affecting the compass movement. His experiments showed that the stronger the current, and the closer the compass was to it, the greater the observed effect. These observations led him to conclude that the electric current was creating a **magnetic field**. This connection between electric and magnetic fields is fundamental to society today.

There are three types of magnets with which you may be familiar: permanent magnets, temporary magnets and electromagnets. **Permanent magnets** are materials that hold magnetic properties over a long period of time, or indefinitely. The magnets you keep on your refrigerator are permanent magnets. **Temporary magnets** are materials, such as soft iron, that will temporarily gain magnetic properties when exposed to a strong enough magnetic. Electromagnets, which will be explored in more detail in modules 8.4 and 8.5, are magnetic fields produced by passing an electric current through a coil of wire.

MAGNETISM

Before looking further into the connection between electric current and magnetic fields, it is necessary to review some fundamentals of **magnetism**. Magnetism is a physical phenomenon caused by magnets that results in a field that attracts or repels other magnetic materials.

The magnetic effect most people are familiar with is the attraction of iron or other **magnetic** materials to a magnet (Figure 8.1.2).

FIGURE 8.1.2 The bar magnet attracts drawing pins.

But, if you experiment with a magnet, you will find that each end of a magnet behaves differently, particularly when interacting with another magnet. One end will be attracted while the other is repelled. Each end of a magnet is referred to as a **magnetic pole**.

Like magnetic poles repel each other; unlike magnetic poles attract each other. These effects of attraction or repulsion of magnets are referred to as the **magnetic force**.

Ferromagnetic materials

Some materials experience magnetism more than other materials. For example, iron, cobalt and nickel experience magnetism more than aluminium. These materials are known as ferromagnetic materials. **Ferromagnetic materials** can easily be magnetised to become permanent magnets.

Ferromagnetic materials are used in many common applications for which magnetic materials are required. Common examples include the hard disk of a computer and the magnetic stripe on a bank, credit or EFTPOS card. Ferromagnetic materials are also used in many industrial applications, such as in motors and generators, and for electric power transmission and distribution.

MAGNETISATION OF MATERIALS

A piece of ferromagnetic material is divided into magnetic domains. A **magnetic domain** is a region in the material where the magnetic field is aligned.

Most often, ferromagnetic materials are found in an unmagnetised state. In the unmagnetised state, the magnetic fields in the separate magnetic domains point in different directions (Figure 8.1.3a). As a result, their magnetic fields cancel out.

Aligning all the magnetic domains in a ferromagnetic material creates a larger magnetic field (Figure 8.1.3b), resulting in a strongly magnetised material. By applying an external magnetic field to the unmagnetised material, the individual domains can be made to align with the external magnetic field. When the external magnetic field is removed, the individual magnetic domains remain fixed in their new orientation, and the new aligned domains produce a uniform resultant magnetic field. The ferromagnetic material is now magnetised.

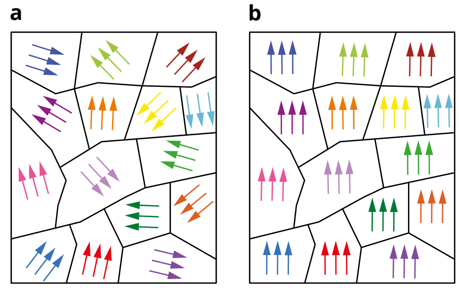


FIGURE 8.1.3 (a) The magnetic fields in separate magnetic domains point in different directions. As a result, their magnetic fields cancel out, resulting in an unmagnetised material. (b) The magnetic fields in separate magnetic domains point in the same direction (align), resulting in a magnetised material.

MAGNETIC FIELDS

In the previous chapter, you saw that point charges and charged objects produce an electric field in the space that surrounds them. For this reason, charged bodies within the field will experience a force. The direction of the electric field is determined by the direction of that force.

Magnets also create fields. If you do a simple test such as placing a pin near a magnet, you will observe that the pin will be pulled towards the magnet. This shows that the space around the magnet must therefore be affected by the magnet.

If you sprinkle iron filings on a piece of clear acetate that is held over a magnet, you will observe that the magnetic field will be clearly defined (Figure 8.1.4). The iron filings will line up with the field, showing clear field lines running from one end of the magnet to the other (Figure 8.1.4a).

Magnetic materials induce a magnetic field and any other magnetic materials will interact with that field and experience a force. For example, if you were to hold two magnets close together with the north pole of one close to the south pole of the other, they would both induce a magnetic field and interact with each other's fields. The resulting force of attraction between the north and south poles is a consequence of the interaction with these fields.

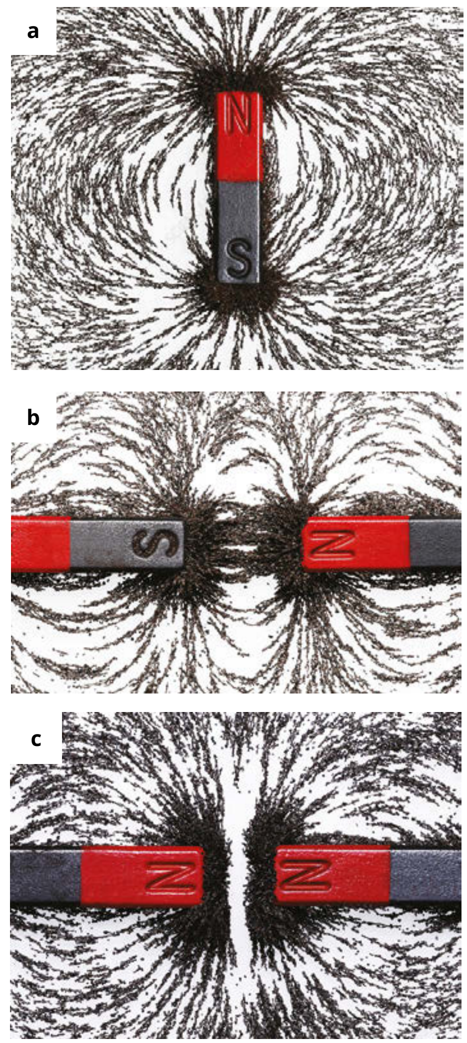


FIGURE 8.1.4 Iron fillings sprinkled around (a) a single bar magnet, and magnets with (b) unlike poles close together and (c) like poles close together. The patterns in the fields show the attraction and repulsion between poles.

Dipole fields

Try breaking a magnet in half. What you get is two smaller magnets, each with its own north and south poles. No matter how many times you break the magnet and how small the pieces are, each will be a separate little magnet with two poles. Because magnets always have two poles, they are said to be **dipolar**.

Magnets are dipolar and a magnetic field is said to be a **dipole field** (Figure 8.1.5). This is similar to electric charges where a positive and negative charge in close proximity to each other are said to form a **dipole**. A key difference is that you cannot have a single magnetic pole (or monopole), whether it be a south pole or a north pole; however, charges *can* exist on their own as either a positive or negative charge. Magnetic fields do not have monopole sources, only dipoles. Electric fields, however, are induced by single electric charges.

Like an electric field, a magnetic field decays the further you are away from its source. Unlike electric fields, however, magnetic fields do not have point sources—they must always be between a north and a south pole. As a result, the patterns of their field lines are more complicated than simple electric fields.

FIGURE 8.1.5 Magnets are always dipolar.

Earth's magnetic field

A suspended magnet that is free to move will always orientate itself in a north–south direction. That's essentially what the needle of a compass is—a freely suspended, small magnet. If allowed to swing vertically as well, then the magnet will tend to tilt vertically. The vertical direction (upwards/downwards) and the magnitude of the angle depend upon the direction of the magnet from either of the Earth's poles and the magnet's latitude.

Earth itself can be shown to have a giant magnetic field around it (Figure 8.1.6).

Earth's magnetic field is thought to come from electrical currents in the molten iron in Earth's outer core. The exact mechanism by which this field comes about is incredibly complex; however, scientists have been able to model some of its features. Earth's magnetic field extends well out into space and is responsible for deflecting much of the harmful, charged solar winds that fly towards us.

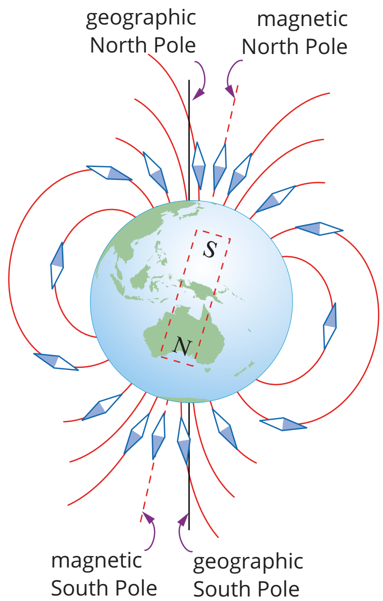


FIGURE 8.1.6 Earth acts somewhat like a huge bar magnet. The south pole of this imaginary magnet is near the geographic North Pole and is the point to which the north pole of a compass appears to point.

The names for the poles of a magnet derive from early observations of magnets orientating themselves with Earth's geographic poles. The magnets aligned themselves with Earth's magnetic field.

Initially, the end of the magnet pointing toward Earth's geographic north was denoted the north **pole** (short for north-seeking pole), and compasses are thus marked with this end as north. This meant that the actual magnetic North Pole of the Earth acted like the south pole of a simple bar magnet. It is now known that the geographic North Pole and the magnetic North Pole are slightly apart in distance. The same applies to the geographic South Pole and the magnetic South Pole, and the south-seeking pole of a magnet.

Earth's magnetic poles are not static like their geographic counterparts. For many years, the magnetic North Pole had been measured as moving at about 9 km per year (Figure 8.1.7). In recent years that has accelerated to an average of 52 km per year. Once every few hundred thousand years the magnetic poles flip in a phenomenon called 'geomagnetic reversal', so that a compass would point south instead of north. Earth is well overdue for the next flip, and recent measurements have shown that Earth's magnetic field is starting to weaken faster than in the past, so the magnetic poles may be getting close to a flip. While past studies have suggested such a flip is not instantaneous—it would take many hundreds if not a few thousands of years—some more recent studies have suggested that it could happen over a significantly shorter time period.

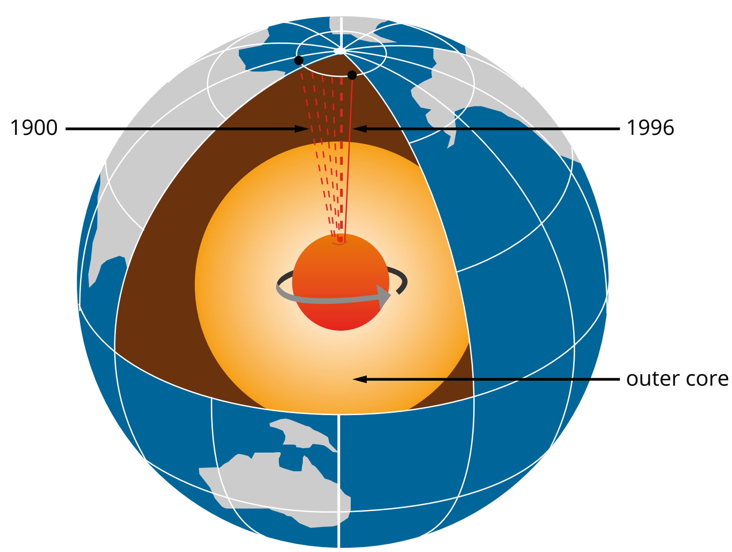


FIGURE 8.1.7 Diagram of Earth's interior and the movement of magnetic north from 1900 to 1996. Earth's outer core is believed to be the source of the geomagnetic field.

8.1 Review

SUMMARY

- Like magnetic poles repel, and unlike magnetic poles attract.
- Magnets are dipolar, having both north and south poles. A magnet with a single pole (monopole) is not known to exist.
- Earth has a dipolar magnetic field that acts like a huge bar magnet, with the south end near the geographic North Pole.

KEY QUESTIONS

Retrieval

1 List the three types of magnets and give a brief description of each one.

Comprehension

2 A magnetic material creates the magnetic field that, in turn, produces a magnetic force. This force is what causes magnetic materials to stick together, such as magnets to your refrigerator. Identify whether this force is a contact or non-contact force.

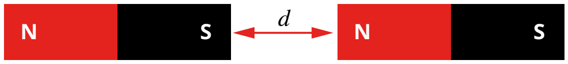
3 A magnet is suspended on a thin wire at its midpoint so that it is free to swing. Identify the approximate direction in which the north pole of the magnet will point, and explain your answer.

Analysis

4 Repeatedly cutting a magnet in half always produces magnets with two opposite poles. Determine the conclusion that can be reached in relation to the poles of a magnet, from this information.

5 Determine how you would test if an object was a magnet if you already had another magnet in your possession.

6 The following diagram shows two bar magnets separated by a distance *d*. At this separation, the magnitude of the magnetic force between the poles is equal to *F*.

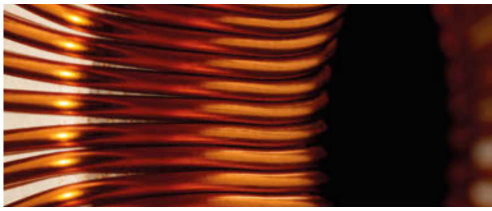


a Describe generally what will happen to the force between the poles if the distance, *d*, is increased.

b Determine what happens to the resulting accelerating motion between the two poles if *d* is increased.

c Determine how acceleration and force between the magnets change if the magnets are allowed to move together.

8.2 Magnetic field diagrams



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

- remember how to represent magnetic field lines
- draw magnetic fields surrounding objects in different scenarios
- relate magnetic field lines to your prior knowledge of vector diagrams.

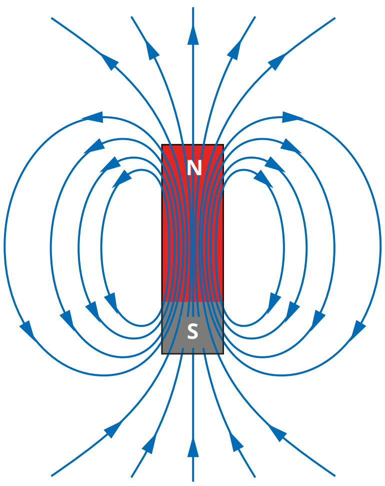


FIGURE 8.2.1 The field lines around and inside a bar magnet. The lines show the direction of the force on an (imaginary) single north pole.

> The magnetic field is a vector quantity, as it has both a magnitude and a direction.
>
> The strength, or vector magnitude, of the magnetic field is in units of tesla (T) and is denoted by the symbol *B*.

In physics it is often useful to represent abstract quantities with the aid of diagrams. In the same way that we can draw diagrams to represent electric field strength and direction at each point in space, we can present magnetic fields pictorially. Generally speaking, magnetic field diagrams indicate the amount of force that a magnetic material would experience in that region of space.

VECTOR FIELD MODEL FOR MAGNETIC FIELDS

Figure 8.2.1 shows the magnetic field associated with a simple bar magnet. The magnetic field around the bar magnet can be defined in vector terms by specifying both direction and magnitude.

The direction of the magnetic field at any point is the direction in which a compass would point if placed at that point; that is, towards the magnet's south pole. This is also the direction of the force the magnetic field would exert on an (imaginary) single north pole.

Denser (closer) lines indicate a relatively stronger magnetic field. As the distance from the magnet increases, the magnetic field is spread over a greater area and its strength at any point decreases. The strength and direction associated with the magnetic field at any point signifies that it is a vector quantity. The strength, or vector magnitude, of the magnetic field at a particular point is denoted by *B* and has units of tesla (T).

The field between two magnets is dependent on whether like or unlike poles are close together, the distance between the poles, and the relative strength of the magnetic field of each magnet. Iron filings or small plotting compasses can be used to visualise the field between and around the magnets (Figure 8.2.2).

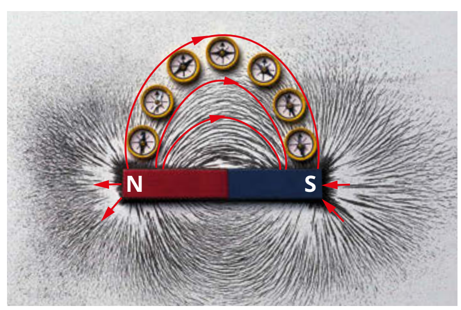


FIGURE 8.2.2 Field lines around a bar magnet can be visualised by placing small plotting compasses around the magnet. Field lines are drawn linking the direction in which each compass points, creating field lines that run from the north pole to the south pole of the magnet.

Because Earth has a giant magnetic field around it, you can also predict how compasses will orientate themselves around it—they will orientate themselves along the **magnetic field lines**. In Figure 8.2.2, note the direction of the magnetic field close to either pole, where the magnetic field lines run almost vertically. Magnets placed near Earth's magnetic poles will behave in the same way.

Different shaped magnets produce different shaped fields. Figure 8.2.3 shows the magnetic field plotted for a horseshoe magnet.

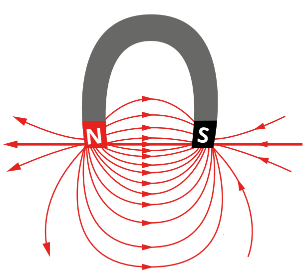


FIGURE 8.2.3 The horseshoe magnet has two unlike poles close to each other. This creates a very strong magnetic field.

The resultant direction of the magnetic field at a particular point will be the vector addition of each individual magnetic field acting at that point.

When two magnets are placed close together, two situations may arise. If the poles are unlike (Figure 8.2.4b), then attraction will occur between them, and a magnetic field will be created that extends between the two poles. If poles are alike (Figure 8.2.4c), repulsion will occur. In this situation, there will be a neutral point between the two poles where there is no magnetic field.

As the bar magnets in Figure 8.2.4 have a fixed strength and position, the associated magnetic fields will be static. Varying the magnetic field strength, by changing the magnets or varying the relative position of the magnets, would produce a changing magnetic field.

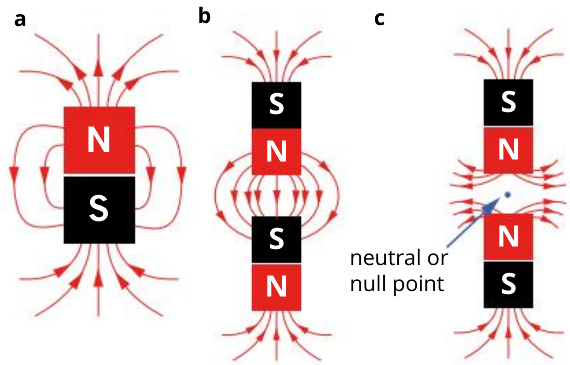


FIGURE 8.2.4 Magnetic field lines plotted for (a) a bar magnet, (b) opposite poles of magnets in close proximity and (c) like poles of magnets in close proximity.

8.2 Review

SUMMARY

- The direction of a magnetic field at a particular point is the same as that of the force on an imaginary single north pole.
- The magnetic field is a vector quantity, as it has both magnitude and direction. The magnitude of a magnetic field is measured in tesla (T).
- The resultant direction of interacting magnetic fields at any particular point will be the vector addition of each individual magnetic field acting at that point.

KEY QUESTIONS

Retrieval

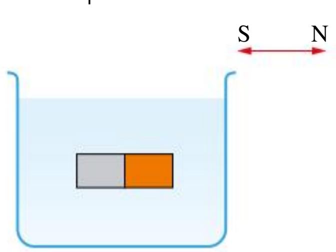
1 Describe the meaning of the direction of a magnetic field line at a particular point in space.

2 Recall the magnetic field around a single bar magnet by sketching it and indicating clearly the direction of the field, and the location of the north and south poles.

Comprehension

3 Explain how the strength of a magnetic field is indicated by the way field lines are drawn.

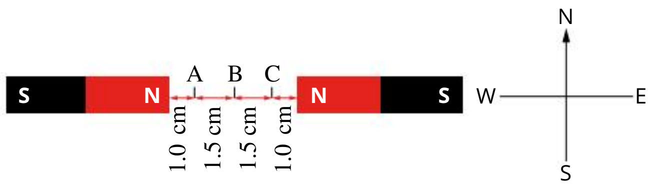
4 A student performs an experiment to test the properties of a bar magnet by observing how it aligns itself in Earth's magnetic field. She places the bar magnet in a container of water, and the magnet orientates itself according to the diagram below. Draw the field lines through the magnet and indicate its north and south poles.



Analysis

The following information applies to questions 5–7.

Two strong bar magnets which produce magnetic fields of equal strength are arranged as shown.

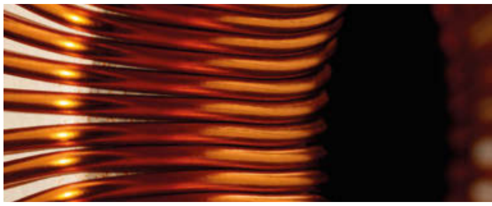


5 Determine the approximate direction of the resulting magnetic field at point A, ignoring the magnetic field of Earth.

6 Determine the approximate direction of the resulting magnetic field at point C, ignoring the magnetic field of Earth.

7 Predict the magnitude of the resulting magnetic field at point B, ignoring the magnetic field of Earth.

8.3 Creating magnetic fields



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

- describe how electric current can produce a magnetic field
- calculate the strength and direction of a magnetic field produced by a current-carrying wire.

In a general sense, magnetism arises from the movement of charged particles. This is the first hint that magnetic and electric fields are intertwined: charged particles induce an electric field, and it is only through the movement of these charged particles that we have an induced magnetic field. You know from your study of electronics that current is simply the flow of charge, and so current-carrying wires will have a magnetic field with some magnitude and direction.

MAGNETIC FIELDS AND CURRENT-CARRYING WIRES

In the introduction to this chapter the discovery of the connection between electric current and magnetic fields was noted. Oersted found that when he switched on the current from a voltaic pile, a nearby magnetic compass would move. It is thought that Earth's magnetic field is created by a similar effect by the circulating electric currents in its molten, metallic outer core.

A compass aligns itself at a tangent to the concentric circles around the wire (i.e. the magnetic field) so that the north-facing part of the compass points in the direction of the magnetic field. The stronger the current and the closer the compass is to the wire, the greater the force on the compass.

The magnetic field is perpendicular to the current-carrying wire, and the direction of the field will depend upon the current direction. There is a simple and easy way to determine the direction of the circular magnetic field, which is commonly referred to as the **right-hand grip rule**.

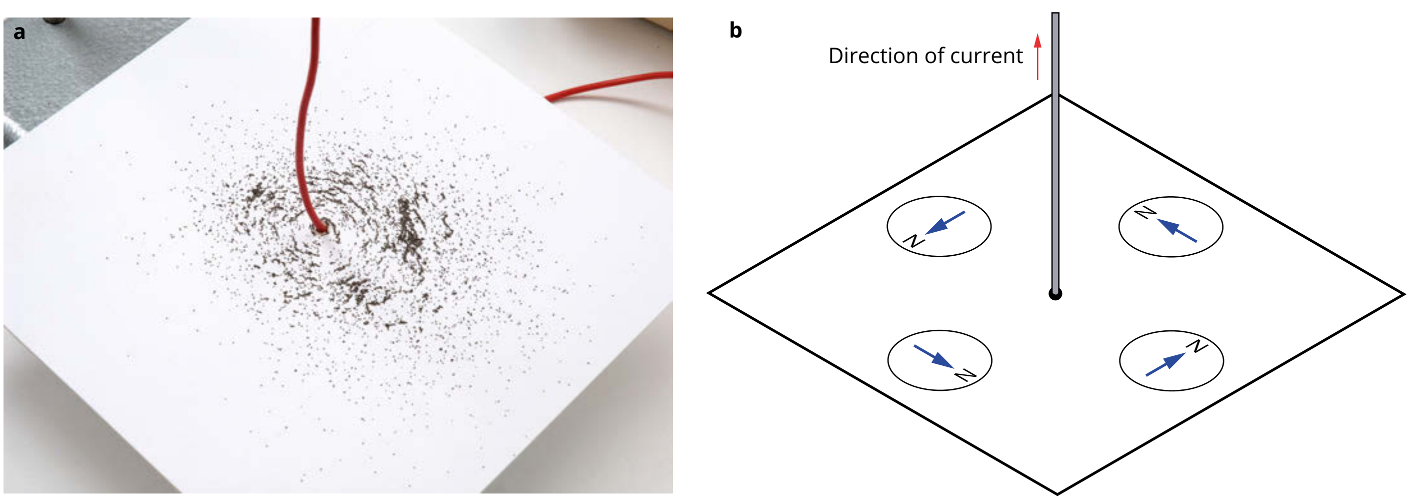
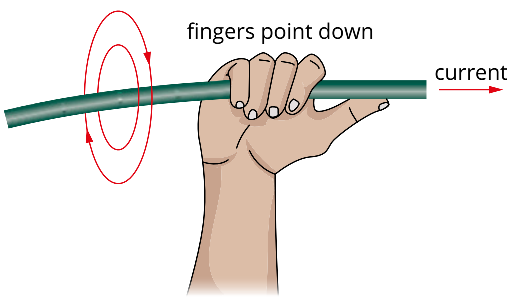


FIGURE 8.3.1 (a) The iron filings align with the magnetic field around a current-carrying wire and show the circular nature of the magnetic field. (b) Compasses indicate the direction of the field.

If safe, grasp the conducting wire with your right hand with your thumb pointing in the direction of the conventional electric current, I (positive to negative). (If it is not safe, imagine grasping the wire.) Observe the way your fingers are curled around the wire. The circular magnetic field will be perpendicular to the wire and in the direction your fingers are pointing (Figure 8.3.2).

Worked example 8.3.1

DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs horizontally across a table. The conventional current direction, *I*, is running from left to right. Determine the direction of the magnetic field created by the current.	
Thinking	**Working**
Recall that the right-hand grip rule indicates the direction of the magnetic field.	Hold your hand as if your fingers were gripping the wire. Point your thumb to the right in the direction of the current flow. 
Describe the direction of the field in relation to the wire in simple terms, so that the description can be readily understood.	The magnetic field direction is perpendicular to the wire and follows the direction in which your fingers are pointing.

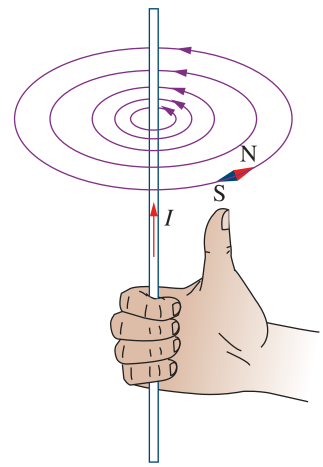


FIGURE 8.3.2 The right-hand grip rule can be used to find the direction of the magnetic field around a current-carrying wire, when the direction of the conventional current, *I*, is known.

➤ Try yourself 8.3.1

DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs along the length of a table. The conventional current direction, *I*, is running towards an observer standing at the near end. Determine the direction of the magnetic field created by the current as seen by the observer.

STRENGTH OF A MAGNETIC FIELD FROM A CURRENT-CARRYING WIRE

Straight, single-loop wires of a constant current have a field strength denoted by B (T). As you might expect, the magnetic field that comes from these wires is larger for greater currents, as there is more charge moving through the wire. For this reason, you would further expect that the magnetic field strength, B, is dependent on current, I.

The strength of the magnetic field generated by a single wire with current I at a distance r from the nearest point on the wire is given by:

$$B = \frac{\mu_0 I}{2\pi r}$$

where

B is the strength of the magnetic field (T)

μ_0 is the magnetic constant, also referred to as the **permeability of a vacuum**, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$

I is the current in the wire (A)

r is the distance from the wire (m).

Recall from Module 8.2 that the further away you are from a magnet, the further apart are its field lines and thus the weaker its magnetic field. Typically, this distance relation from a magnet is not easily defined; however, the magnetic field from a current-carrying wire presents a simpler system: the magnetic field decays radially in an outward direction from the wire, by the ratio $\frac{1}{r}$.

Worked example 8.3.2

STRENGTH OF THE MAGNETIC FIELD

A current-carrying wire is suspended in mid-air. A current of 2.0 mA is passed through it. Calculate the magnitude of the magnetic field at a distance of 150 cm from the wire. Ignore any effects from Earth's magnetic field.	
Thinking	**Working**
Recall the formula giving the strength of a magnetic field from a current-carrying wire. Identify each variable with the quantities given.	$B = \frac{\mu_0 I}{2\pi r}$ I = 2.0 mA r = 150 cm
Ensure that all units are in the appropriate form.	The SI unit for current is amps and for distance is metres. 2.0 mA = 0.0020 A = 2.0×10^{-3} A 150 cm = 1.50 m
Use the relevant quantities with their appropriate units in order to calculate the magnetic field. Give the final result in units of tesla.	$B = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \times 2.0 \times 10^{-3}}{2\pi \times 1.50}$ $= 2.7 \times 10^{-10}$ T

➤ Try yourself 8.3.2

STRENGTH OF THE MAGNETIC FIELD

A current-carrying wire is suspended in mid-air. A current of 4.0 mA is passed through it. Calculate the magnitude of the magnetic field at a distance of 43 mm from the wire. Ignore any effects from Earth's magnetic field.

MAGNETIC FIELDS BETWEEN PARALLEL WIRES

Two current-carrying wires arranged parallel to each other will each have their own magnetic field. The direction of the magnetic field around each wire is given by the right-hand grip rule. If the two wires are brought close together, their associated magnetic fields will interact, just as any two regular magnets would interact. The interaction could result in either an attraction or repulsion of the wires, depending on the direction of the magnetic fields between them (Figure 8.3.3). When the magnetic fields are in the opposite directions, this represents unlike poles, and so the wires attract. When the magnetic fields are in the same direction, the wires repel.

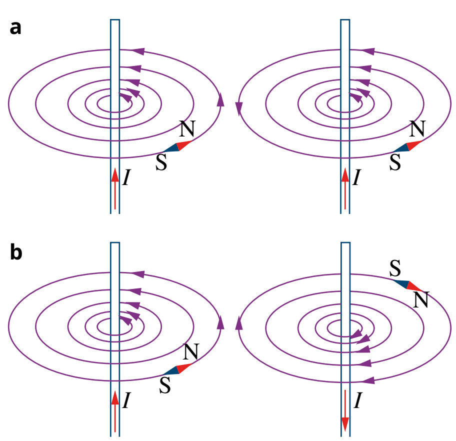


FIGURE 8.3.3 (a) Two current-carrying wires attract when current runs through them in the same direction. This is because the magnetic fields between the wires are in opposite directions, as you can see where the field lines are closest. (b) Two current-carrying wires repel when the current runs through them in opposite directions. This is because the magnetic fields are in the same direction.

Magnetism and relativity

Magnetism is not as straightforward as it seems! In fact, there are some subtle points that tie together the concepts of magnetism, electrostatics and special relativity. As discussed above, the magnetic fields around two parallel current-carrying wires will interact in the same way as the magnetic fields of two bar magnets. However, you might ask yourself what this magnetic force looks like from the viewpoint of an electron in one of the wires. The electron will assume it is stationary, as are the electrons in the second wire (assuming the same current flows). This leads to an apparent contradiction: magnetic fields are induced by moving charged particles, but we can find a point of view in which the charged particles are not moving. What, then, is the conclusion? A force occurs in all points of view, and according to Einstein, forces should not be measured from any one special point of view. At the beginning of the 20th century this was one of the unsolved mysteries of physics. The answer, as you will see in Chapter 10, comes from Einstein's special theory of relativity.

Consider two stationary charges, A and B, that are close to each other. They will each experience the electrostatic force discussed in Chapter 7. However, if we change points of view such that A and B are moving along a path, they will each carry an electric field *and* a magnetic field with which they interact. From this, physicists believe that the electric and magnetic fields are manifestations of a single electromagnetic field.

THREE-DIMENSIONAL FIELDS

Field lines can also be drawn for more-complex, three-dimensional fields such as that around the Earth or those around current-carrying loops and coils. Even for these more-complex fields, the right-hand grip rule can be used (Figures 8.3.4 and 8.3.5).

The direction of a magnetic field can be shown with a simple arrow on a field line when the field is travelling within the plane of a page (Figure 8.3.4), or a simple three-dimensional depiction (Figure 8.3.5).

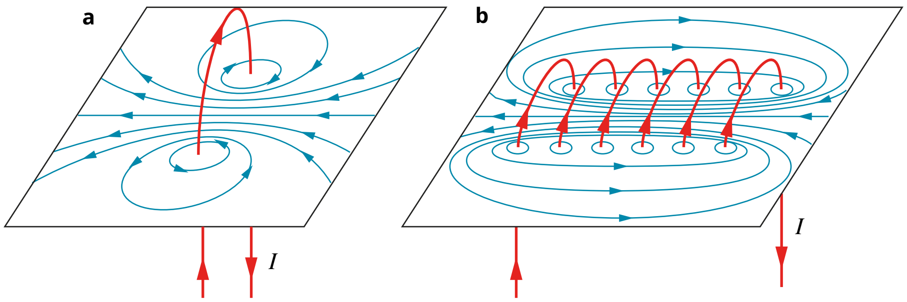


FIGURE 8.3.4 The magnetic field lines around (a) a single current loop and (b) a series of loops. The blue arrows indicate the direction of the magnetic field. The more concentrated the lines are inside the loops, the stronger the magnetic field is in this region.

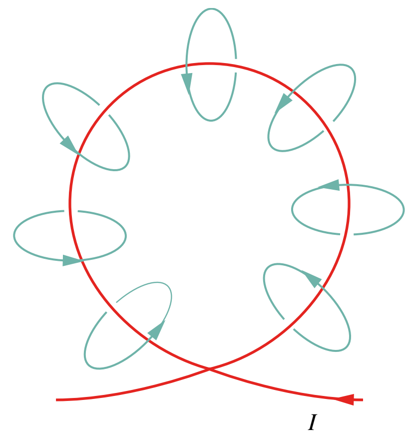


FIGURE 8.3.5 A three-dimensional representation of the magnetic field around a loop of wire in the plane of the page. The blue arrows show the direction of the magnetic field. Notice that the magnetic field is a circular shape, with no field lines crossing.

Figure 8.3.5 shows a three-dimensional representation of the magnetic field around a loop of wire. This same loop can also be represented in two dimensions using the following convention: when a field is running directly into or out of the plane of a page, dots are used to show a field coming out of the page and crosses are used to depict a field running directly into the page. This convention was adopted from the idea of viewing an arrow. The dot is the point of the arrow coming towards you, and the cross represents the tail feathers as the arrow travels away.

Figure 8.3.6 is a two-dimensional representation of the same magnetic field shown in Figure 8.3.5.

The strength of a field is depicted by varying the density of the dots and crosses. An increasing density indicates a strengthening of a field; decreasing density indicates a weakening of the field. More densely placed dots or crosses can also show a stronger area of the field. This is referred to as a non-uniform magnetic field.

As the magnetic field associated with a current-carrying coil is dependent upon the size of the current, the associated field may also be changing over time, either in magnitude, or, if the current is reversed, in direction.

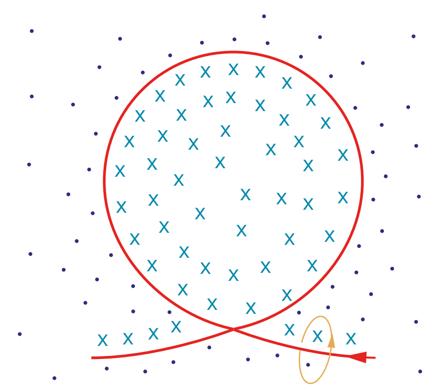


FIGURE 8.3.6 A two-dimensional representation of the same current-carrying loop depicted in Figure 8.3.5. Areas where the magnetic field is stronger are shown with a greater density of dots and crosses.

WS 3.2.5

Medical imaging

Many of the discoveries made by physicists about magnetic fields underpin the modern field of medical imaging. Human bodies contain many different, complex electric and magnetic fields that can be safely probed by strong electromagnets to obtain a medical image of the inside of the body.

You may be familiar with a magnetic resonance imaging (MRI) machine, frequently used in hospitals.

MRI machines

The exact physics behind MRI machines is somewhat more complicated than can thoroughly be described here; however, the idea stems from a phenomenon called **nuclear magnetic resonance (NMR)**. When certain atoms are placed in a strong magnetic field, their nuclei will enter what is called a **polarised** state, in which their intrinsic magnetic fields (termed their magnetic moments) will align with the external magnetic field. In this state, the nuclei of these atoms will absorb and re-emit electromagnetic radiation in the radio frequency range.

The frequency of the radiation absorbed and re-emitted is referred to as the **resonant frequency** of the nuclei and is dependent on the specific properties of the physical system. A type of resonance with which you will be familiar is to imagine pushing someone on a swing. When you push at a particular frequency that aligns with the person's motion through the air, you will get a positive feedback and they will start to swing faster and faster. Similarly, when scientists direct a particular frequency of radiation at these atomic nuclei—their resonant frequency—they will receive measurable feedback as the atoms absorb and re-emit the radiation.

The human body contains many atomic nuclei that are responsive to the applied magnetic fields, especially in regions containing ${}^{1}_{1}H$, such as in the water of soft tissue.

This particular resonant frequency depends on many factors, but, in particular, it is related to the strength of the magnetic field in which the atoms are placed. By varying the magnetic field applied to the body, the different responses of the different nuclei can be detected, and traced back to the strength of a magnetic field at a particular point. These highly complex techniques can be used to build up a picture of the structure and composition of tissue inside the body (Figure 8.3.7).

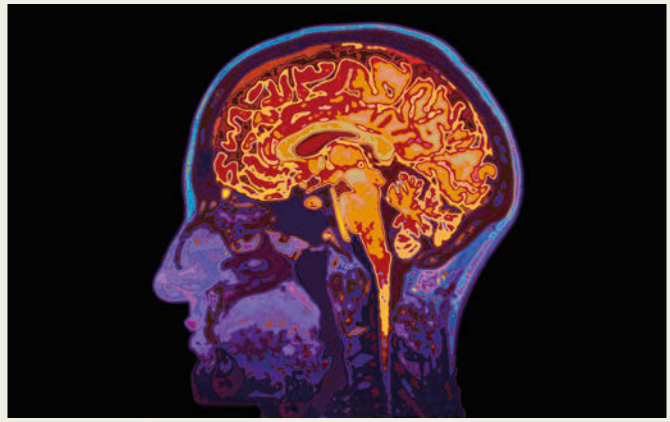


FIGURE 8.3.7 False-colour MRI scan of a patient's brain. The MRI provides a detailed look at the human brain without the use of any harmful or ionising radiation.

If you have ever undergone an MRI scan, you will have been instructed to remove all pieces of metal. The reason for this is a good one—MRI machines typically have magnetic fields of up to 1.5 T, about 50 000 times stronger than the Earth's magnetic field. If you were to stand near this machine with any magnetic materials on you, they would go flying dangerously towards the machine.

Prior to allowing a patient to undergo a scan, the patient will be checked for any metallic objects that could cause disruptions. Implants in a patient, such as pacemakers or prosthetic heart valves, can be dangerous, even fatal, in an MRI machine. Physicians need to exercise considerable caution when admitting patients for a scan. For this reason, many implants today are made with non-ferromagnetic materials, such as titanium, in order to be safe for use under MRIs.

Review

1. Explain why an MRI machine is more suited for imaging the brain than for imaging a broken arm.
2. Explain why an MRI could not be conducted with a uniform magnetic field.
3. Research other potential applications of MRI machines.

8.3 Review

SUMMARY

- A moving charge results in a magnetic field.
- An electrical current produces a magnetic field that is circular around a current-carrying conductor. The direction of the field is given by using the right-hand grip rule, when considering the direction of the conventional current.
- The magnetic field strength at a distance r from a current-carrying wire is given by $B = \frac{\mu_0 I}{2\pi r}$.
- A three-dimensional depiction of a magnetic field can be made by drawing dots to represent field lines coming out of the page, and crosses to represent field lines going into the page.

KEY QUESTIONS

Retrieval

1 Identify the direction of a magnetic field represented by crosses, and one represented by dots.

Comprehension

2 Describe how a magnetic field is induced by a charged particle, as well as the difference between an electric and a magnetic field.

3 Draw the direction of a magnetic field induced by a wire carrying current vertically upwards.

Analysis

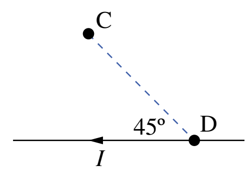
4 Christos measures the magnetic field strength, B, at a distance r away from the wire with a current I.

a Determine the field strength at a distance of $2r$ away from the wire.

The current in the wire is now changed to $3I$.

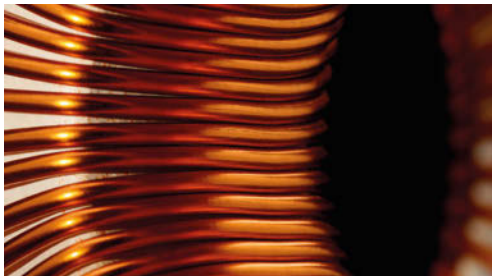
b Determine the field strength at the same distance from the wire.

5 Calculate the magnitude of the magnetic field strength at point C in the diagram below, given that C and D are 3.0 cm apart and make a 45° angle with the wire. The wire shown is carrying a current of 2.0 A.



6 If the strength of a magnetic field 20.0 cm away from a current-carrying wire is 3.0×10^{-6} T, calculate the current that passes through the wire.

8.4 Solenoids



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

- determine the magnitude and direction of magnetic fields inside different solenoids
- relate current-carrying coils to conventional bar magnets
- understand the relationship between the number of loops in a solenoid and its resulting magnetic field.

FIGURE 8.4.1 A large electromagnet is used to lift waste iron and steel at a scrapyard. Valuable metals such as these are separated and then recycled.

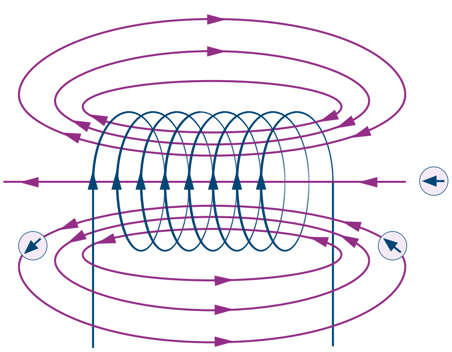


FIGURE 8.4.2 This solenoid has an effective 'north' end at the left and a 'south' end at the right. The compass, represented by arrows in circles, points in the direction of the field lines.

For magnetic fields to be truly useful, we need to understand how they behave and how they can be created. In this section, you will learn about the creation of specific magnetic fields through the different conformations of wires and wire coils.

CREATING AN ELECTROMAGNET

The earliest magnets were all naturally occurring. If you wanted a magnet, you needed to find one. They were regarded largely as curiosities. Hans Christian Oersted's discoveries made it possible to manufacture magnets, making the widescale use of magnets possible.

An **electromagnet**, as the name implies, runs on electricity. It works because an electric current produces a magnetic field around a current-carrying wire. If the conductor is looped into a series of coils, then the magnetic field can be concentrated within the coils. The more coils, the stronger the magnetic field and, therefore, the stronger the electromagnet.

The magnetic field can be strengthened further by wrapping the coils around a core. Normally, the atoms in materials like iron point in random directions and the individual magnetic fields tend to cancel each other out. However, the magnetic field produced by coils wrapped around an iron core can force the atoms within the core to point in one direction. Their individual magnetic fields add together, creating a stronger magnetic field.

The strength of an electromagnet can also be changed by varying the amount of electric current that flows through it.

The direction of the current creates poles in the electromagnet. The poles of an electromagnet can be reversed by reversing the direction of the electric current.

Today, electromagnets are used directly to lift heavy objects (Figure 8.4.1), as switches and relays, and as a way of creating new permanent magnets by aligning the atoms within magnetic materials.

THE MAGNETIC FIELD AROUND A SOLENOID

If many loops are placed side by side, their fields all add together and there is a much stronger effect. This can easily be achieved by winding many turns of wire into a coil termed a **solenoid**. The field around the solenoid is like the field around a normal bar magnet. The direction of the overall magnetic field can be determined by considering the field around each current-carrying wire making up the loop, and adding these together. The direction of the field of the solenoid depends on the direction of the current in the wire making up the solenoid (Figure 8.4.2).

A simple way to determine which end of a solenoid is which pole is to use a version of the right-hand grip rule from Module 8.3. Curl your right hand in the direction of the current coils (Figure 8.4.3); then the direction in which your thumb points is the direction of the magnetic field emerging from the middle of the solenoid. This end is the north pole (N), while the other end is the south pole (S). Note the difference between this and the right-hand grip rule used in Module 8.3. For a coiled wire we use our fingers to represent the current and thumb to represent the magnetic field, whereas for a straight wire the fingers represent the field and the thumb represents the direction of the current in the wire.

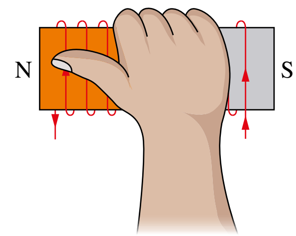


FIGURE 8.4.3 The right-hand grip rule for a solenoid.

The strength of a magnetic field inside a solenoid

Looking at the magnetic field in Figure 8.4.2 you will notice that the field lines flatten out somewhat inside the solenoid. If the solenoid were to get longer, the field lines would flatten out more and more until we had an essentially uniform, constant field inside the solenoid. It is with this approximation that we can discuss the strength of a magnetic field inside a solenoid.

In previous sections you learnt that the magnetic field at a point in space is the vector addition of all contributions to the magnetic field at this point. For this reason, it is not surprising that when two loops with current in the same direction are placed next to each other they will produce a magnetic field that is stronger than that produced by either loop alone. From this we can determine that the magnetic field inside a solenoid will depend on the number of loops. However, given that the magnetic field also decays with distance, the strength of the field in a solenoid also depends on the distance between the loops. The number of loops divided by the total length of the solenoid will give the number of loops per unit length of solenoid. It is this quantity that is used in our expression for the magnetic field inside a solenoid.

The magnetic field of a solenoid is given by $B = \mu_0 nI$

where

B is the strength of the magnetic field (T)

μ_0 is the magnetic constant, $\mu_0 = 4\pi \times 10^{-7}\,\text{T m A}^{-1}$

n is the number of loops per metre $= \frac{N}{L}$ for N loops in a solenoid of length L (m)

I is the current in the conductor (A).

This can also be expressed as $B = \frac{\mu_0 NI}{L}$, where L is the length of the magnetic field (m).

Worked example 8.4.1

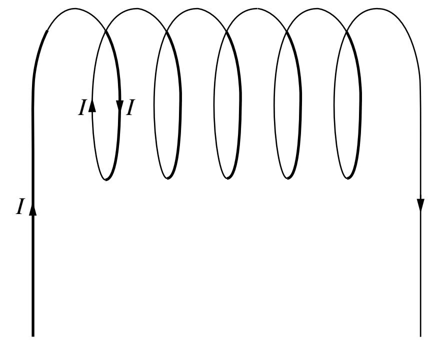
CALCULATING THE STRENGTH OF A MAGNETIC FIELD INSIDE A SOLENOID

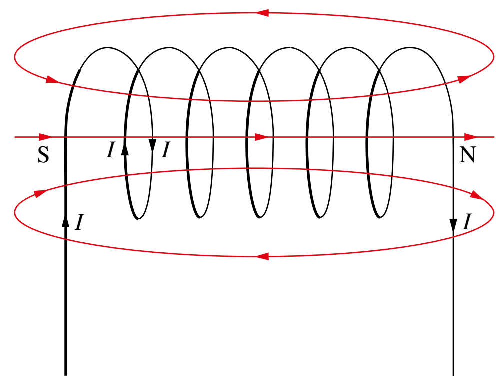
a Calculate the strength of the magnetic field inside a 60.0 cm long solenoid that has 80 loops and a current of 3.5 A flowing through it.

Thinking	Working
Ensure that the variables are in their standard units.	$L = 60\,\text{cm} = 0.60\,\text{m}$ $N = 80$ $I = 3.5\,\text{A}$
Apply the equation for magnetic field strength.	$B = \mu_0 nI = \frac{\mu_0 NI}{L}$
Substitute in the correct values to ascertain the strength of the magnetic field.	$B = \frac{4\pi \times 10^{-7} \times 80 \times 3.5}{0.60}$ $= 5.9 \times 10^{-4}\,\text{T}$

Worked example 8.4.1 *continued*

b Determine the direction of the magnetic field produced in the solenoid shown below, by sketching its field lines.



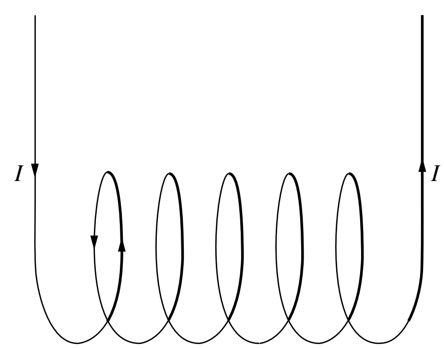
Thinking	Working
Align the fingers of your right hand in the same direction as the current running through the solenoid and stick your thumb out. Your thumb will be in the direction of the magnetic field from the solenoid.	

➤ Try yourself 8.4.1

CALCULATING THE STRENGTH OF A MAGNETIC FIELD INSIDE A SOLENOID

a Calculate the strength of the magnetic field inside a 20.0 mm long solenoid that has 120 loops and a current of 1.2 mA flowing through it.

b Determine the direction of the magnetic field produced in the solenoid shown below, by sketching its field lines.



8.4 Review

SUMMARY

- The direction of a magnetic field through a solenoid can be determined by applying the right-hand grip rule to the current-carrying loops.
- The magnetic field inside a solenoid is uniform, with magnitude given by $B = \frac{\mu_0 NI}{L}$.
- By expressing the number of loops per metre as $n = \frac{N}{L}$, we can re-write this equation as $B = \mu_0 nI$.

KEY QUESTIONS

Retrieval

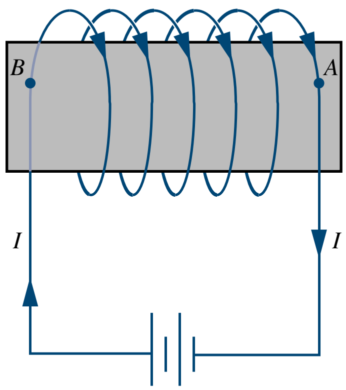
1 Define 'a solenoid'.

2 List three ways in which you could increase the strength of an electromagnet.

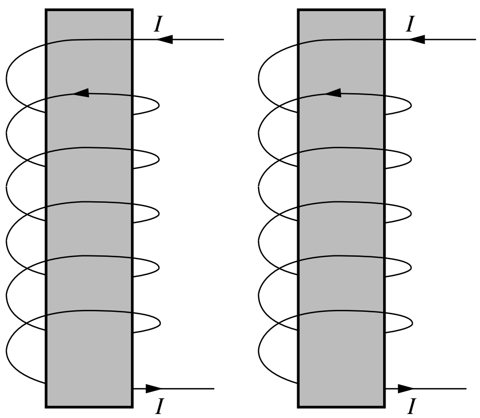
3 State the relationship between the number of coils in a solenoid and its magnetic field.

Comprehension

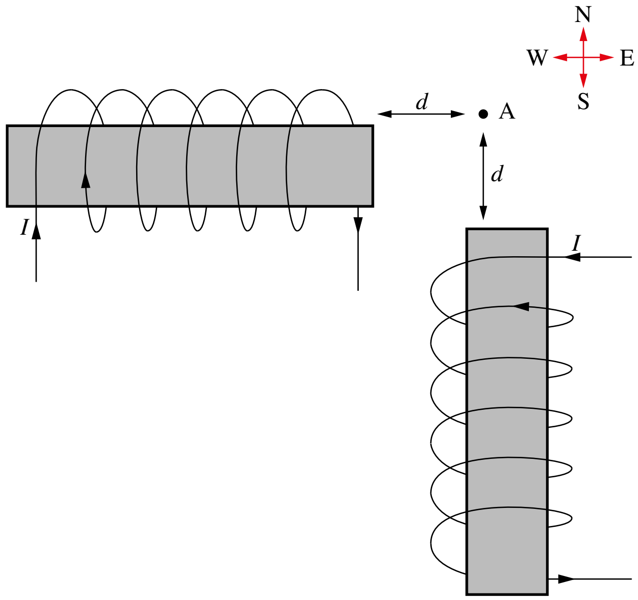
4 Identify which end, A or B, represents the north pole of the current-carrying solenoid shown below.



5 Describe what will happen to two solenoids that are arranged next to each other as shown. The solenoids are the same length, and have the same number of turns and current flowing through them. Carefully explaining your reasoning.



6 Determine the direction of the net magnetic field at point A when two identical solenoids are arranged as shown below.



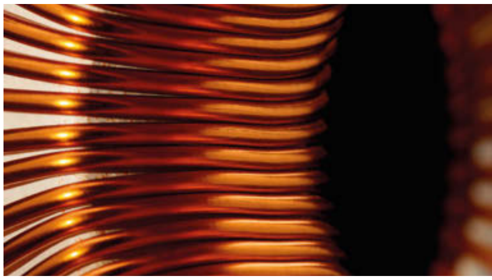
Analysis

7 Calculate the strength of the magnetic field inside a 3.00 cm long solenoid of 120 turns that has an electric current of 4.27 mA passing through it.

8 Jane wishes to determine the current running through a wire, but does not have an ammeter present. She arranges the wire into a 5.0 m coil with exactly 10 loops and measures the magnetic field within the solenoid to be 0.37 μT. Calculate the strength of the current running through the wire.

9 Calculate the number of turns a solenoid should have in order to produce a magnetic field of 1.0053 T inside it if it carries a current of 4.0 A and is 10.0 cm long.

8.5 Magnetic force on a current-carrying wire



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

- solve problems involving the magnetic force on a current-carrying wire
- determine the magnitude and direction of the magnetic force on a current-carrying wire
- calculate how the magnetic force on a current-carrying wire changes at different angles to the field.

THE FORCE ON A CURRENT-CARRYING WIRE

A current-carrying wire induces a magnetic field that can interact with other magnetic fields. You have learnt from your theory of magnetic and electric fields that interaction with these fields constitutes a force acting on an object. Hence it would be expected that current-carrying wires would experience a force in the presence of a magnetic field. This is the theory behind the operation of electric motors, which will be explained in Module 8.6.

The force acting on a wire in a magnetic field is related to the total amount of charge moving through the wire, which depends on its current and the total length of the wire. This relationship is expressed in the following formula:

$F = BIL$

where

F is the force on the wire perpendicular to the magnetic field (N)

B is the strength of the magnetic field (T)

I is the current in the wire (A)

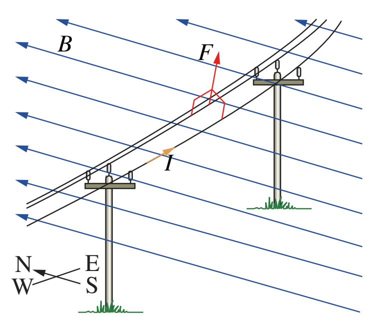
L is the length of the wire (m).

This formula is only useful when the wire is at right angles to the field; that is, when the force is at a maximum. The force is zero when the wire is parallel to the magnetic field. Furthermore, since (in general) the net force at a point is the sum of all the contributing forces, we add up all the contributions from different wires. If we happen to have a coil and there is more than one loop in the coil, then the total force is the number of loops multiplied by the magnetic force from each loop. That is, $F = nBIL$, where n is the number of turns of wire.

Worked example 8.5.1

MAGNITUDE OF THE FORCE ON A CURRENT-CARRYING WIRE

Determine the magnitude of the force due to Earth's magnetic field that acts on 1.0 m of a suspended power line running east-west near the equator at the moment it carries a current of 100.0 A from west to east. Assume that the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.

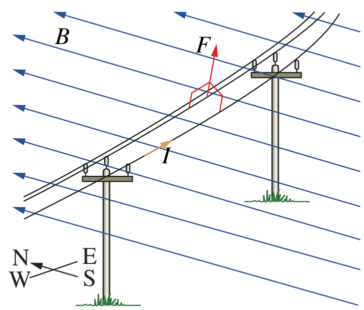


Thinking	Working
Check the direction of the power line and determine whether a force will apply. Forces only apply to the component of the line perpendicular to the magnetic field.	As the current is running west-east and the Earth's magnetic field runs south-north, the current and the field are at right angles and a force will exist.
Establish which quantities are known and which are required.	$F = ?$ $B = 5.0 \times 10^{-5}$ T $I = 100$ A $L = 1.0$ m
Substitute values into the force equation and simplify.	$F = BIL$ $= 5.0 \times 10^{-5} \times 100 \times 1.0$ $= 5.0 \times 10^{-3}$
Express the final answer in an appropriate form with a suitable number of significant figures. Note that only magnitude has been requested, so do not include direction.	$F = 5.0 \times 10^{-3}$ N

➤ Try yourself 8.5.1

MAGNITUDE OF THE FORCE ON A CURRENT-CARRYING WIRE

Determine the magnitude of the force due to Earth's magnetic field that acts on 1.0 m of a suspended power line running east-west near the equator at the moment it carries a current of 50.0 A from west to east. Assume that the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.



Determining the direction of the force

The direction of the force acting on the wire when the wire is at right angles to the magnetic field can be determined by a simple mnemonic called the **right-hand slap rule**. Open your palm out flat with your thumb perpendicular to your fingers (Figure 8.5.1). Point your thumb in the direction of the conventional current, and your outstretched fingers in the direction of the magnetic field. The direction of the resulting force on the current is the direction in which your palm is pointing.

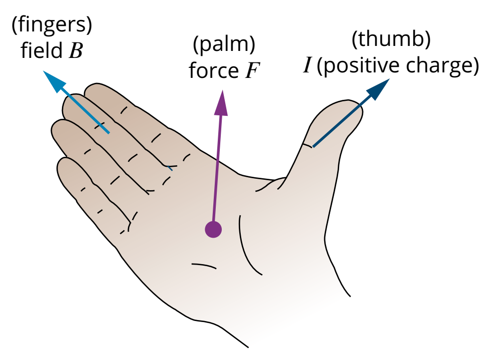
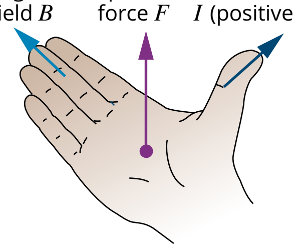


FIGURE 8.5.1 The right-hand slap rule: Point the thumb of your right hand in the direction of the conventional current and the fingers in the direction of the magnetic field. The force on the charge will be in the direction to which your palm points.

Worked example 8.5.2

DIRECTION OF THE FORCE ON A CURRENT-CARRYING WIRE

A current balance is used to measure the force from a magnetic field on a wire of length 5.0 cm running perpendicular to the magnetic field. The conventional current direction in the wire is from left to right. The magnetic field can be considered to be running into the page. Determine the direction of the force on the wire.	
Thinking	**Working**
The right-hand slap rule is used to determine the direction of the force. 	Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. into the page. Align your thumb so it is pointing right, in the direction of the current. Your palm should be facing upwards. That is the direction of the force applied by the magnetic field on the wire.
State the direction in terms of the other directions included in the question. Make the answer as clear as possible to avoid any misunderstanding.	The force on the wire is acting vertically upwards.

➤ Try yourself 8.5.2

DIRECTION OF THE FORCE ON A CURRENT-CARRYING WIRE

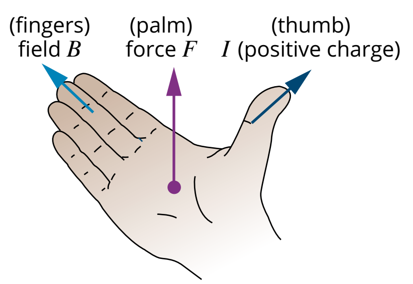
A current balance is used to measure the force from a magnetic field on a wire of length 5.0 cm running perpendicular to the magnetic field. The conventional current direction in the wire is from left to right. The magnetic field can be considered to be running out of the page. Determine the direction of the force on the wire.

Worked example 8.5.3

FORCE ON A CURRENT-CARRYING WIRE AND DIRECTION

The Amundsen–Scott South Pole Station sits at a point that can be considered to be at Earth's South Magnetic Pole (which behaves like the north pole of a magnet). Assume the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.	
a Determine the magnitude and direction of the magnetic force on a 2.0 m length of wire carrying a conventional current of 10.0 A vertically up the exterior wall of one of the buildings.	
Thinking	**Working**
Forces only apply to the components of the wire running perpendicular to the magnetic field. The direction of the magnetic field at the southern magnetic pole will be almost vertically upwards.	The section of the wire running up the wall of the building will be parallel to the magnetic field, *B*. Hence, no force will apply.
State your answer. A numeric value is required. Since there is no force, it is not necessary to state a direction.	$F = 0$ N

b Determine the magnitude and direction of the magnetic force on a 2.0 m length of wire carrying a conventional current of 10.0 A running horizontally right to left across the exterior of one of the buildings.

Thinking	Working
Forces only apply to the components of the wire running perpendicular to the magnetic field. The direction of the magnetic field at the southern magnetic pole will be almost vertically upwards (that is, out of the ground).	The section of the wire running horizontally across the building will be perpendicular to the magnetic field, *B*. A force, *F*, with a strength equivalent to *BIL* will apply.
Identify the known quantities.	$F = ?$ $B = 5.0 \times 10^{-5}$ T $I = 10.0$ A $L = 2.0$ m
Substitute into the appropriate equation and simplify.	$F = BIL$ $= 5.0 \times 10^{-5} \times 10.0 \times 2.0$ $= 1.0 \times 10^{-3}$ N
 The direction of the magnetic force is also required to fully specify the vector quantity. Determine the direction of the magnetic force using the right-hand slap rule.	Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. vertically up. Align your thumb so it is pointing left, in the direction of the current. Your palm should be facing outwards (towards the building). That is the direction of the force applied by the magnetic field on the wire.
State the magnetic force in an appropriate form with a suitable number of significant figures. Include the direction to fully specify the vector quantity.	$F = 1.0 \times 10^{-3}$ N outwards

➤ Try yourself 8.5.3

FORCE ON A CURRENT-CARRYING WIRE AND DIRECTION

Santa's house sits at a point that can be considered the Earth's Magnetic North Pole (which behaves like the south pole of a magnet).

Assume the strength of Earth's magnetic field at this point is 5.0×10^{-5} T.

a Calculate the magnetic force and its direction on a 2.0 m length of wire carrying a conventional current of 10.0 A vertically up the outside wall of Santa's house.

b Calculate the magnetic force and its direction on a 2.0 m length of wire carrying a conventional current of 10.0 A running horizontally right to left across the outside of Santa's house.

Conductors at an angle to a magnetic field

The force experienced by a current-carrying conductor is a vector quantity. The expression noted earlier, $F = BIL$, applies only to that component of the conductor that is perpendicular to the magnetic field, which is where the conductor experiences its maximum force. The conductor experiences zero magnetic force when it is parallel to the magnetic field. This gives us a clue that there is in fact some angular dependence to the force experienced by a current-carrying conductor in a magnetic field. To find the force acting on any conductor, or part of a conductor, moving at an angle, θ, to the magnetic field, use the equation:

$$F = BIL\sin\theta$$

This scenario is illustrated in Figure 8.5.2.

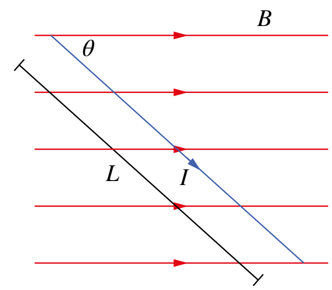


FIGURE 8.5.2 A current-carrying wire of length L is at an angle to a magnetic field.

Note that this is a calculation for the magnitude of the force. The direction stays the same as if the conductor were perpendicular to the field.

Worked example 8.5.4

FORCE ON A CURRENT-CARRYING WIRE AT AN ANGLE TO THE FIELD

Clint is investigating the force on a current-carrying wire in a magnetic field. He has a 3.0 m section of wire with current 0.200 A that is at an angle of 30.0° to a magnetic field of strength 1.3×10^{-3} T. Calculate the force he would expect to detect on the wire.	
Thinking	**Working**
Identify the correct formula to use.	Given that we are calculating the magnetic force acting on a conductor at an angle other than 90° to a field, we use the formula $F = BIL\sin\theta$.
Identify the known values.	$F = ?$ $B = 1.3 \times 10^{-3}$ T $I = 0.200$ A $L = 3.0$ m $\theta = 30°$
Use the above formula with the known values to calculate the force.	$F = BIL\sin\theta$ $= 1.3 \times 10^{-3} \times 0.200 \times 3.0 \sin 30°$ $= 3.9 \times 10^{-4}$ N

➤ Try yourself 8.5.4

SAT IA1

WS 3.2.6

FORCE ON A CURRENT-CARRYING WIRE AT AN ANGLE TO THE FIELD

Susie is investigating the force on a current-carrying wire in a magnetic field. She has a 0.15 m section of wire with current 0.0500 A at an angle of 45° to a magnetic field of strength 2.5×10^{-3} T. Calculate the force she would expect to detect on the wire.

8.5 Review

SUMMARY

- A current-carrying wire will experience a force when placed in a magnetic field.
  - The force is at a maximum when the wire is at right angles to the magnetic field.
  - The force is zero when the wire is placed parallel to the magnetic field.
  - The magnetic force on a current-carrying wire within a magnetic field is $F = BIL$.
  - The direction of the force is given by the right-hand slap rule in which the force travels out of the palm of the hand when the thumb and fingers are orientated in the direction of the (conventional) current and magnetic field respectively.
- The magnetic force on a current-carrying wire at an angle to a magnetic field is $F = BIL \sin \theta$.

KEY QUESTIONS

Retrieval

1 Identify the quantities used by the right-hand slap rule and how they describe the direction of the magnetic force.

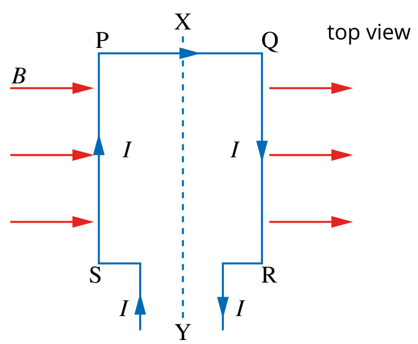
2 A current-carrying wire is at an angle, θ, to a magnetic field. State the values of θ at which the magnitude of the magnetic force acting on the wire is at:

a a minimum

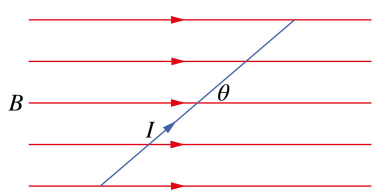
b a maximum.

Comprehension

3 Determine the direction of the force on the length of wire marked PQ in a rectangular loop of wire carrying a current, I, in a magnetic field, B, as shown below.



4 Determine the direction of the force acting on a current-carrying wire in a uniform magnetic field at an angle θ, as shown below.



5 Imogen places a current-carrying wire perpendicular to a uniform magnetic field and measures the magnetic force acting on it.

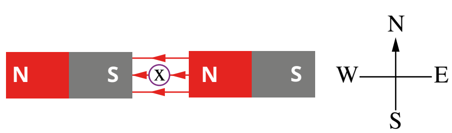
a Describe how the direction of the force would change if the angle of the wire is changed to 45°.

b Describe how the magnitude of the force would change if the current is doubled and the angle is reduced to 30°.

Analysis

6 An east–west power line of length 100 m is suspended between two towers. Assume that the strength of Earth's magnetic field in this region is 5.0×10^{-5} T. Calculate the magnetic force (including direction) on this power line at the moment it carries a current of 80 A from west to east.

7 The diagram below depicts a cross-sectional view of a long, straight, current-carrying conductor, located between the poles of a permanent magnet. The magnetic field, B, of the magnet, and the current, I, are perpendicular. Calculate the magnitude and direction of the magnetic force on a 5.0 cm section of the conductor when the current is 2.0 A into the page and B equals 2.0×10^{-3} T.



8 An east–west power line of length 8.00 m is suspended between two towers. Assume that the strength of the magnetic field of the Earth in this region equals 4.5×10^{-5} T from south to north.

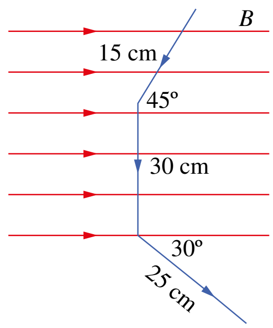
a Calculate the magnitude and direction of the magnetic force on this power line at the moment it carries a current of 50.0 A from east to west.

continued over page

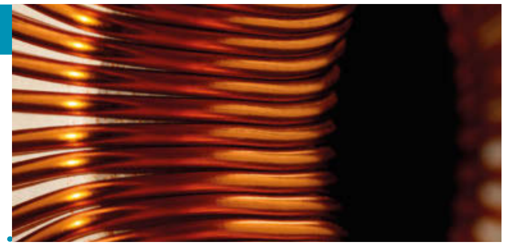
8.5 Review *continued*

b Over time, the ground underneath the eastern tower subsides, so that the power line is lower at that tower. Assess whether the magnitude of the magnetic force on the power line is greater than before, less than before or the same as before. Assume all other factors are the same.

9 Consider the wire below, which is set up in a shape of three of the four sides of a trapezium. The current running through the wire is 3.0 A. Calculate the total force acting on the wire and give the direction of this force if the magnetic field is 0.350 T.



8.6 Motors



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

- predict the behaviour of coils made to rotate in a magnetic field
- understand the basics of how electric currents can be used to create rotating motors
- understand the roles of the different components of a DC motor.

Physicists have always been interested in the relationship between electricity and magnetism because they wanted to understand the basic workings of the universe. For the world at large, however, this understanding provided a more practical form of excitement. It enabled the generation and use of electricity on a large scale. One of the most obvious applications of the understanding of electromagnetism gained in the 19th century is the electric motor.

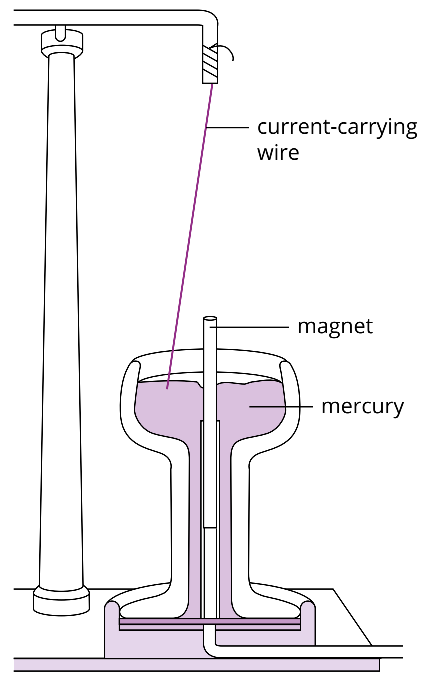


FIGURE 8.6.1 Michael Faraday's electric motor

DC MOTORS

The main components and the principles have been the same for all **direct current** (DC) motors since Michael Faraday built the first one in 1821 (Figure 8.6.1). In Faraday's motor, a magnet was mounted vertically in a pool of mercury. A wire carrying a current hung from a support above. (The mercury provided a path for the current.) The magnetic field of the magnet spread outwards from the top of the magnet and so there was a component of this field that was perpendicular to the wire. This produced a horizontal force on the wire that kept it rotating around the magnet. Use the right-hand slap rule from the previous module to convince yourself that if the current flows down and the magnetic field points out from the central magnet, the wire will rotate clockwise when viewed from above.

In modern DC motors, a current-carrying coil of wire in a magnetic field experiences a magnetic force. This magnetic force, as seen in Module 8.5, is equal to BIL and acts on two or more of its sides, (for example, AB and CD in Figure 8.6.2a). In practice, many turns of wire (N) are used and the magnetic field is provided by more than one permanent magnet or by an electromagnet.

Consider a single square coil of wire, with vertices ABCD, carrying a current, I, in a magnetic field, B (Figure 8.6.2).

Initially the wire coil is aligned horizontally with the magnetic field, B (Figure 8.6.2a). Sides AD and BC are parallel to the magnetic field, so no magnetic force will act on them. Sides AB and CD are perpendicular to the field, so both of these sides will experience a magnetic force. Using the right-hand slap rule, there is a downwards force on AB and an upwards force on CD. These two forces will act together on the coil and cause it to rotate anticlockwise. If the coil is free to turn it will move towards the position shown in Figure 8.6.2b.

In Figure 8.6.2b, there will be a magnetic force acting on every side of the coil. However, the forces acting on sides AD and BC will be equal and opposite in direction. They will tend to stretch the coil outwards but won't affect its rotation. The forces on sides AB and CD will remain and the coil will continue to rotate anticlockwise.

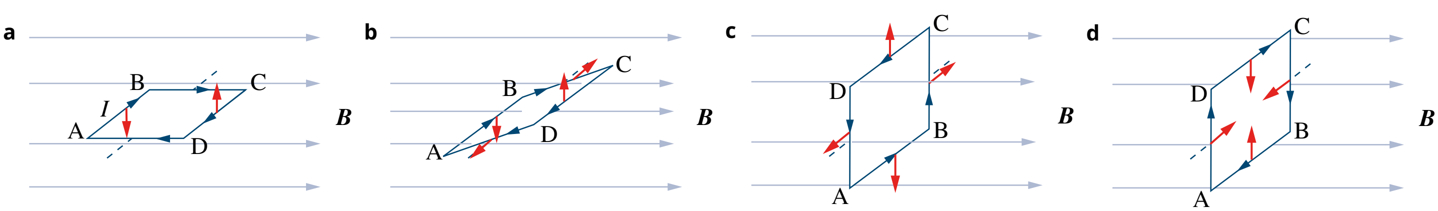


FIGURE 8.6.2 A magnetic force acts on each side of a current-carrying square wire coil in a magnetic field, B.

As the coil rotates to the position shown in Figure 8.6.2c, the forces acting on each side are such that they will tend to keep the coil in this position. The force on each side will act outwards from the coil. There are no turning forces at this point, but any further rotation will induce a force in the opposite direction causing the coil to rotate clockwise, back to this perpendicular position. For the coil to continue to rotate anticlockwise at this point, the current direction needs to be reversed. This is shown in Figure 8.6.2d. With the current reversed, all of the forces are reversed, and provided the coil has a little momentum to get it past the perpendicular position, it will continue to rotate anticlockwise. This ability to reverse the current direction at the point where the coil is perpendicular to the magnetic field is a key design feature in DC motors. It is a **commutator** that allows the current to be reversed.

PRACTICAL DC MOTORS

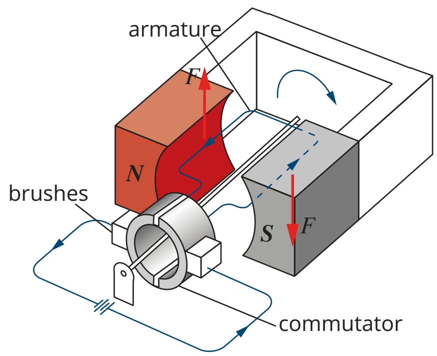


FIGURE 8.6.3 The main parts of a simple but practical single-coil DC electric motor.

A basic single-coil electric motor with a simple mechanism to reverse the current direction will work, but it won't turn very smoothly. That's because the maximum force will only apply each half turn or twice for every full turn. A number of enhancements have been developed over time to make DC motors highly practical.

The commutator is usually made from a split ring of copper or another good conductor on which conducting brushes (usually carbon blocks) rub. Each half is connected to one end of the coil of wire. This arrangement of brushes prevents the wire from becoming tangled as the coil rotates. The commutator reverses the current at the point where the coil is perpendicular to the magnetic field, which keeps the coil rotating (Figure 8.6.3).

Practical motors will have many sets of coils of many turns each, spaced at an angle to each other (Figure 8.6.4).

The coils are wound around a soft iron core to increase the magnetic field that passes through them. The whole arrangement of core and coils is called an armature (Figure 8.6.4). Permanent magnets are generally used to provide the magnetic field in small motors, but in larger motors electromagnets are used as they can produce larger and stronger fields. These magnets are usually stationary, as distinct from the rotating rotor or armature, and are often referred to as the stator. The commutator is arranged to feed current to the particular coil that is in the best position to provide the maximum turning force. The total turning force will be the sum of the turning forces on all the individual coils.

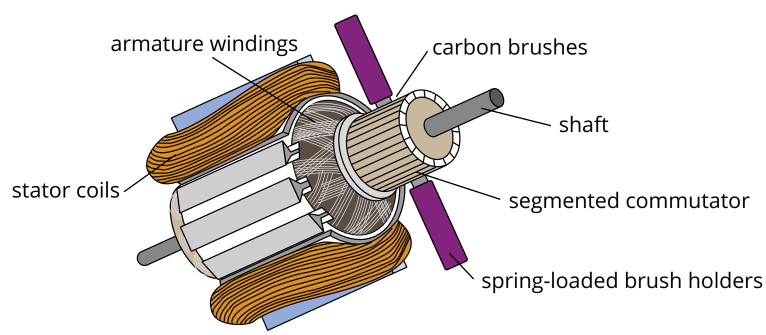


FIGURE 8.6.4 A typical multi-coil DC electric motor, showing the main components. Note that there are many sets of coils offset by an angle from each other. The stator coils produce an electromagnet that provides the magnetic field. The commutator feeds current to the armature coils in the position where maximum turning force will be experienced.

Generally speaking, the larger the turning force in an electric motor the better. This is achieved by the use of a strong magnetic field, a large number of turns of wire in each coil, a high current and a large area of coil. All this adds to the cost, so when designing an electric motor, each aspect may be compromised to some extent in light of its potential use.

8.6 Review

SUMMARY

- The wire coil of a simple DC motor keeps rotating because the direction of current, and hence the turning force, is reversed each half turn by the commutator.
- In the case of a single square or rectangular coil, the total turning force applied to the coil will be twice that acting on the one side.
- The armature of a practical motor consists of many coils that are fed current by the commutator when they are in the position of maximum turning force.
- The total turning force will be the sum of the turning forces on all the individual coils.

KEY QUESTIONS

Retrieval

1 Indicate the situation(s) where the magnitude of the turning force is at a maximum with respect to the axis of rotation.

Comprehension

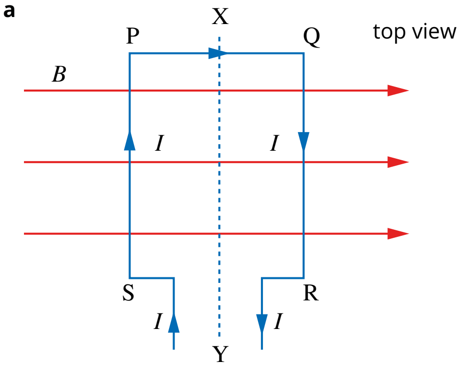
The information below applies to questions 2–6.

Part (a) of the diagram below depicts a top view of a single current-carrying coil in an external magnetic field *B*.

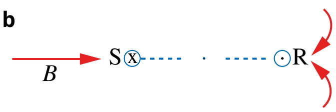
Part (b) of the diagram is the corresponding cross-sectional view as seen from point Y. The following data apply:

$B = 0.10\,T$, $PQ = 2.0\,cm$, $PS = QR = 5.0\,cm$, $I = 2.0\,A$.

a



b



2 Determine the magnitude and direction of the magnetic force acting on side PS.

3 Determine the magnitude and direction of the magnetic force acting on side QR.

4 Determine the magnitude of the force on side PQ.

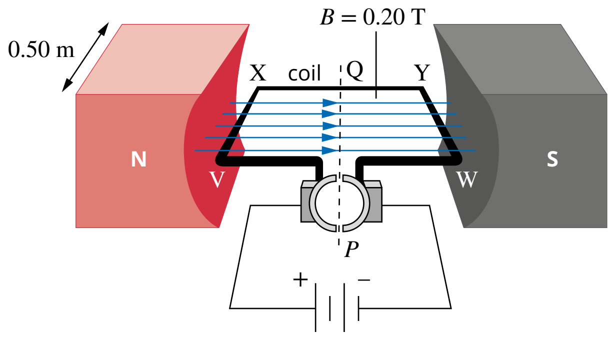
5 Determine the direction, as seen from Y, in which the coil rotates. The coil is free to rotate about an axis through XY.

6 Assess the behaviour of the torque magnitude with the changing of the current direction through the coil.

Analysis

The following information applies to questions 7–9.

The diagram shows a simplified version of a DC motor.

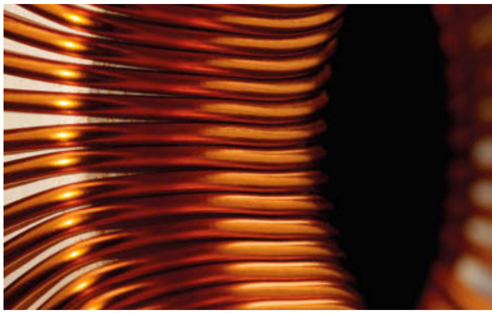


7 Calculate the magnitude of the force on segment WY when a current of 1.0 A flows through the coil.

8 Determine the direction in which the coil will begin to rotate. Explain your reasoning.

9 Determine whether or not each of the following actions would cause the coil to rotate faster: increasing the current, increasing the magnetic field strength, and increasing the length of the coil in the magnetic field.

8.7 Magnetic force on a single charge



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

- describe and predict the behaviour of a moving electric charge in a magnetic field
- calculate the magnitude and direction of the magnetic force acting on a moving charged particle
- understand how this physics can be put into action in building and using particle accelerators.

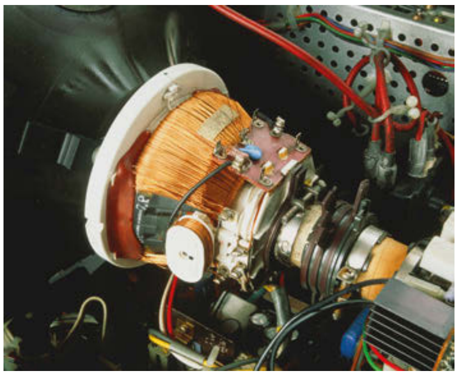


FIGURE 8.7.1 Electrons rushing down the length of a CRT (cathode ray tube) were the basis upon which old-style television sets worked. The electrons were deflected by the magnetic force they experienced as they passed through the 'yoke'—coils of copper wire at the back of the tube creating a strong variable magnetic field.

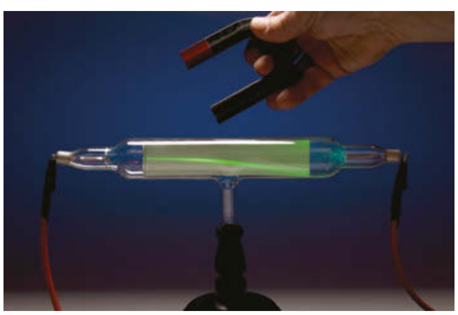


FIGURE 8.7.2 The electron beam of a cathode ray tube is deflected by a magnet.

An electric current is a flow of electric charges. These may be electrons in a metal wire, electrons and mercury ions in a fluorescent tube or cations and anions in an electrolytic cell. The nature of the flowing charge that makes up the current does not matter. A magnetic field is produced around the flow of charge, and a force is experienced within this field (Figure 8.7.1). In each case, it is the total rate of flow of charge, i.e. the current, that determines the field produced and the magnitude of the force.

MAGNETIC FORCE ON CHARGED PARTICLES

In Module 8.5 you learnt that a current-carrying wire in a magnetic field will experience a magnetic force. If we examine what constitutes a current (i.e. a flow of charge) then we can predict the force that an individual moving charged particle in a magnetic field will experience.

The principle behind a **cathode ray tube** (CRT) is that a charged particle moving within a magnetic field will experience a force. In Figure 8.7.2, a beam of electrons in a CRT is experiencing a force due to a magnetic field. The force causes the beam of electrons to bend. The magnitude of the force is proportional to the strength of the magnetic field, B, the component of the velocity of the charge that is perpendicular to the magnetic field and the charge on the particle. In Module 8.5 you investigated the manner in which a magnetic force acts on a current-carrying wire.

The formula $F = BIL$ is used to determine the force acting on the overall wire. The current in a given wire, however, is nothing more than the flow of charged particles. We can work backwards from the force on a charged current to investigate how this magnetic force behaves with free particles, that is:

$F = BIL$, where I is the flow of charge per second, $\frac{q}{t}$.

$\therefore F = B \times \frac{q}{t} \times L$. We can move the t to the right, and recognise that $\frac{L}{t}$ is the distance that a charged particle travels in a given amount of time, i.e. the speed (which we assign a direction with the current to give a velocity).

So $F = B \times q \times \frac{L}{t} = B \times q \times v$

Therefore, when v and B are perpendicular:

$F = qvB$

where

F is the force (N)

q is the electric charge on the particle (C)

v is the component of the velocity of the particle that is perpendicular to the magnetic field (m s^{-1})

B is the strength of the magnetic field (T).

This force is referred to as the **Lorentz force**. The force is at a maximum when the charged particle is moving at right angles to the field. There is no force acting when the charged particles are travelling parallel to the magnetic field or outside the magnetic field.

The direction of the force acting on a moving charged particle is given by the right-hand slap rule in the same way as for currents in Module 8.5. With your thumb in the direction of motion of a positive charge and your fingers in the direction of the magnetic field, your palm will face the direction of the force. This direction is the opposite for a negatively charged particle.

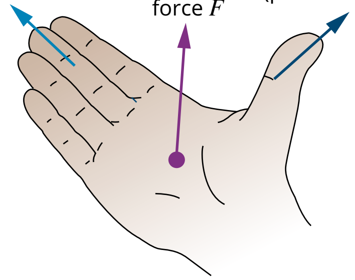
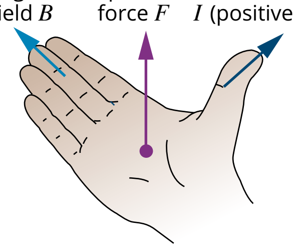


FIGURE 8.7.3 The right-hand slap rule: Point the thumb of the right hand in the direction of the movement of a positive charge (conventional current direction) and the fingers in the direction of the magnetic field. The force on the charge will point out from the palm.

Worked example 8.7.1

DIRECTION OF FORCE ON A NEGATIVELY CHARGED PARTICLE

<table>
<tr><td colspan="2">A single, negatively charged particle with a charge of -1.6×10^{-19} C is travelling horizontally out of a computer screen and perpendicular to a magnetic field, B, that runs horizontally from left to right across the screen. Describe the direction in which the force experienced by the charge will act.</td></tr>
<tr><th>Thinking</th><th>Working</th></tr>
<tr><td>The right-hand slap rule is used to determine the direction of the force on a positively charged particle.

</td><td>Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. left to right and horizontal.
If the negatively charged particle is travelling out of the screen, a positively charged particle would be moving in the opposite direction. Align your thumb so it is pointing into the screen, in the direction that a positive charge would travel.
Your palm should be facing downwards. That is the direction of the force applied by the magnetic field on the negative charge out of the screen.</td></tr>
</table>

➤ Try yourself 8.7.1

DIRECTION OF FORCE ON A NEGATIVELY CHARGED PARTICLE

A single, negatively charged particle with a charge of -1.6×10^{-19} C is travelling horizontally from left to right across a computer screen and perpendicular to a magnetic field, *B*, that runs vertically down the screen. Describe the direction in which the force experienced by the charge will act.

Worked example 8.7.2

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE

A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of $10.0\,\mathrm{m\,s^{-1}}$ perpendicular to a magnetic field, B, of strength 4.0×10^{-5} T.

Determine the magnitude of the force the particle will experience from the magnetic field.

Thinking	Working
Check the direction of the velocity and determine whether a force will apply. Forces only apply to the component of the velocity perpendicular to the magnetic field.	The particle is moving perpendicular to the field, so a force will apply: $F = qvB$.
Establish which quantities are known and which ones are required.	$F = ?$ $q = +1.6 \times 10^{-19}$ C $v = 10\,\mathrm{m\,s^{-1}}$ $B = 4.0 \times 10^{-5}$ T
Substitute values into the force equation.	$F = qvB$ $= 1.6 \times 10^{-19} \times 10 \times 4.0 \times 10^{-5}$
Express the final answer in an appropriate form. Note that only magnitude has been requested so do not include direction.	$F = 6.4 \times 10^{-23}$ N

➤ Try yourself 8.7.2

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE

A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of $50.0\,\mathrm{m\,s^{-1}}$ perpendicular to a magnetic field, B, of strength 6.0×10^{-5} T.

Determine the magnitude of the force the particle will experience from the magnetic field.

Objects moving at an angle to the magnetic field

The force experienced by a charge moving in a magnetic field is a vector quantity. The force equation noted on page 166 applies only to that component of the velocity of the charge perpendicular to the magnetic field. To find the force acting on an object moving at an angle θ to the magnetic field, use:

$$F = qvB\sin\theta$$

The $\sin\theta$ component of this equation comes from resolving a particle's velocity v into its parallel and perpendicular components. If you resolve the velocity of a positively charged particle, as in Figure 8.7.4, you will have two vector components. One of them will be perpendicular to the magnetic field, and one of them will be parallel to the field. The velocity component parallel to the field experiences no force, and so the entirety of the force acting on the particle is due to its velocity perpendicular to the field, $v\perp$.

Using trigonometry, this perpendicular velocity can be written as $v\sin\theta$ (Figure 8.7.4). Thus, the total force acting is $F = qv\perp B = qvB\sin\theta$. Using the right-hand slap rule with our thumb in the direction of the perpendicular velocity and fingers in the direction of the magnetic field, we see that the force on this charged particle is out of the page.

A charged particle travelling at a steady speed in a magnetic field experiences this force at an angle to its path and will be diverted.

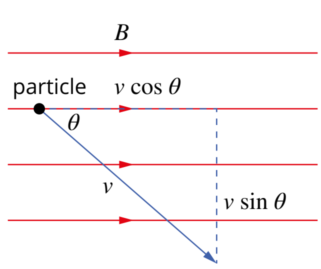


FIGURE 8.7.4 A particle travelling at an angle to a magnetic field can have its velocity vector resolved into parallel and perpendicular components.

This is the theory behind CRT screens. As the direction of the charged particle changes, so does the angle of the force acting on it. In a very large magnetic field the charged particles will move in a circular path. Mass spectrometers and particle accelerators both work on this principle.

When high-energy particles in the solar wind from the Sun meet the Earth's magnetic field, they also experience this type of force. As the particles approach the Earth, they encounter the magnetic field and are deflected in such a way that they spiral towards the poles, losing much of their energy and creating the auroras: the southern aurora, or aurora australis, and the northern aurora, or aurora borealis (Figure 8.7.5).

FIGURE 8.7.5 Charged particles from the Sun or deep space are trapped by Earth's magnetic field, causing them to spiral towards the poles. As they do this, they lose energy and emit light, creating the auroras.

Worked example 8.7.3

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE AT AN ANGLE TO THE FIELD

A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of 1.8×10^{6} m s^{-1} at an angle of 60.0° to a magnetic field, B, of strength 3.5×10^{-3} T.

Calculate the magnitude of the force the particle will experience from the magnetic field.

Thinking	Working
Establish which quantities are known and which ones are required.	$F = ?$ $q = +1.6 \times 10^{-19}$ C $v = 1.8 \times 10^{6}$ m s^{-1} $B = 3.5 \times 10^{-3}$ T $\theta = 60.0°$
Substitute values into the force at an angle equation.	$F = qvB\sin\theta$ $= 1.6 \times 10^{-19} \times 1.8 \times 10^{6} \times 3.5 \times 10^{-3} \times \sin 60.0°$
Express the final answer in an appropriate form. Note that only magnitude has been requested so do not include direction.	$F = 8.7 \times 10^{-16}$ N

➤ Try yourself 8.7.3

MAGNITUDE OF FORCE ON A POSITIVELY CHARGED PARTICLE AT AN ANGLE TO THE FIELD

A single, positively charged particle with a charge of 3.2×10^{-19} C travels at a velocity of 2.3×10^{4} m s^{-1} at an angle of 45° to a magnetic field, B, of strength 5.0 T.

Calculate the magnitude of the force the particle will experience from the magnetic field.

PARTICLE ACCELERATORS

Particle accelerators are machines that were originally designed to investigate the nature of matter by examining the structure of atoms and molecules. Charged particles, such as electrons, protons or atomic nuclei, are accelerated to speeds often close to that of light. These particles travel through an electric field, inside a hollow tube pumped to an ultra-high vacuum, with pressures comparable to those found in deep space. Strong magnets direct the particles to collide with a target or with another moving particle. Scientists obtain information about the make-up of the subatomic particles fired from the machine, or the target samples that are hit, by analysing the types of collisions that occur.

FIGURE 8.7.6 This tandem Van de Graaff accelerator uses two generators to produce beams of charged particles that are accelerated by potential differences of up to 10 million volts.

One of the first particle accelerators was the Van de Graaff accelerator, similar to the Van de Graaff generator (Figure 8.7.6). Developed in the 1930s, it can accelerate charged particles between metal electrodes to energies of about 15 MeV before they collide with a fixed target. Currently, the world's most powerful particle accelerator is the Large Hadron Collider. It is located at CERN on the France–Switzerland border. It can produce energies of 13 TeV. Two sets of particles can be accelerated in opposite directions around its central evacuated ring, to meet in a collision of mammoth energies.

Accelerating charged particles

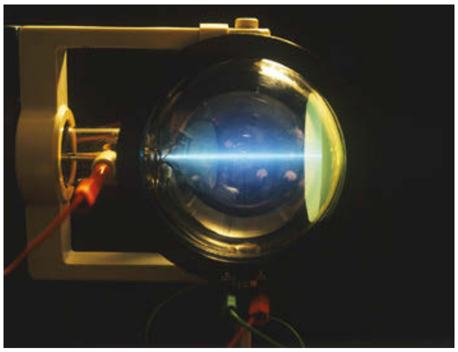


FIGURE 8.7.7 Cathode ray tube

A CRT is a useful type of particle accelerator. Electrons are released from a negative terminal, or hot cathode, in a vacuum, and accelerated towards a positive terminal, or anode. The beam of electrons is collimated (narrowed) as it passes through a slit, and releases light when it hits a fluorescent screen. A potential difference of about 2–3 kV exists between the cathode and the anode, which causes the charged particles to accelerate. Older style televisions (before plasma, LCD and LED screens were invented), some visual display units and cathode ray oscilloscopes (CRO) use a CRT (Figure 8.7.7).

An old computer monitor, cathode ray oscilloscope or larger-scale particle accelerator relies on a source of charged particles to be accelerated. The device used to provide these particles is called an **electron gun**.

In an electron gun, electrons are, in effect, boiled off a heated wire filament, or cathode, shown on the left in Figure 8.7.8. They are accelerated from rest across an evacuated chamber towards a positively charged plate, or anode, due to the electric field created between charged plates. Once the electrons pass through a gap in this positive plate, their motion can be further controlled by additional electric and magnetic fields. Focusing magnets are also used to control the width of the beam.

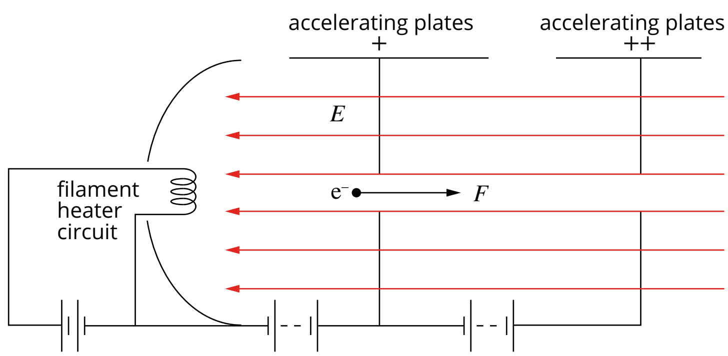


FIGURE 8.7.8 Electron-gun assembly

Consider an electric field acting on an electron as the result of a pair of oppositely charged parallel plates connected to a DC power supply. The electron is attracted to the positive plate and repelled from the negative plate. An electric field is acting upon any charged particle within this region. This electric field is a vector quantity and may be compared in some ways to the Earth's gravitational field. Recall from Chapter 7 that an electric field has units $N\,C^{-1}$ and is defined as:

$$E = \frac{F}{q}$$

where F is the force (N) experienced by a charged particle due to an electric field and q is the magnitude of the electric charge of a particle in the field, in this case an electron (1.6×10^{-19} C).

A charge will then experience a force equal to qE when placed within such an electric field.

Also recall from Chapter 7 that the magnitude of the electric field may also be expressed as:

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

where d is the separation of the plates (m) and V is the potential difference (V). Combining these two relationships produces an expression for the force on a charge within a pair of parallel charged plates:

$$\frac{F}{q} = \frac{V}{d}$$

$$F = \frac{qV}{d}$$

In addition, calculations of the energy gained by an electron as it is accelerated towards a charged plate by the electric field can be made. Recall from Module 7.3 that the work done in this case is equivalent to:

$$W = qV$$

This equation can be used to calculate the increase in kinetic energy as an electron accelerates from one plate to another.

If a charge is accelerated from rest from an electron gun, then:

$$E_k = W = qV$$

$$E_\text{k} = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

where v is the final velocity and u is the initial velocity of the charge. If the electron accelerates from rest ($u = 0$), then this can be simplified to:

$$E_\text{k} = \frac{1}{2}mv^2 = qV$$

$\frac{1}{2}mv^2 = qV$

This is often referred to as the electron-gun equation. Rearranging to make v the subject gives:

$v = \sqrt{\frac{2qV}{m}}$.

THE BEHAVIOUR OF A CHARGED PARTICLE IN A MAGNETIC FIELD

To explore the forces acting on a beam of electrons in a particle accelerator, the effect of a magnetic field on an individual charged particle needs to be considered. Recall from earlier in this module that the force on a charged particle moving perpendicularly through a magnetic field is $F = qvB$, with the direction given by the right-hand slap rule.

In the case of the magnetic force on an electron moving within the magnetic field of a particle accelerator, the magnitude of charge, q, is equal to 1.6×10^{-19} C. Note that as this is a negatively charged particle, the direction of the force will be reversed; the right-hand slap rule uses conventional current rather than electron flow.

If a moving charge experiences a force of constant magnitude that remains at right angles to its motion, its direction will be changed but not its speed. In this way, bending magnets within a particle accelerator act to alter the path of the electron beam, rather than to speed the electrons up. As a result, the electrons will follow a curved path of radius r (Figure 8.7.9).

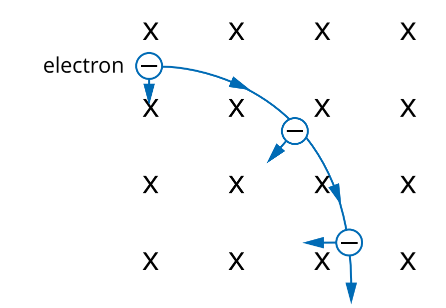


FIGURE 8.7.9 An electron moving in a magnetic field

In this case, the net force acting on the charge is:

$$F = ma$$

This is equivalent to the magnetic force on the charge, so that:

$$qvB = ma$$

The acceleration in this situation is centripetal (towards the centre of the circular path) and has magnitude:

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

Substituting this relationship into the previous equation gives:

$$qvB = \frac{mv^2}{r}$$

Rearranging this equation gives an expression that predicts the radius of the path of an electron travelling at right angles to a constant magnetic field:

$$r = \frac{mv}{qB}$$

where

r is the radius of the path (m)

m is the mass of the electron (9.109×10^{-31} kg)

v is the speed of the electron ($m\,s^{-1}$)

q is the charge on the electron (-1.60×10^{-19} C)

B is the strength of the magnetic field (T).

This relationship can be used to calculate the radius of the path followed by an electron travelling at right angles to any magnetic field. The electron could be a low-velocity electron or could be a high-velocity electron that has been accelerated by the powerful bending magnets within a particle accelerator. Further, the relationship can be used to calculate the radius of any charged particle—positive or negative—travelling at right angles to a magnetic field.

Worked example 8.7.4

CALCULATING SPEED AND PATH RADIUS OF ACCELERATED CHARGED PARTICLES

An electron gun releases electrons from its cathode which are then accelerated across a potential difference of 32 kV over a distance of 30.0 cm between a pair of charged parallel plates. Assume that the mass of an electron is 9.109×10^{-31} kg and the magnitude of the charge on an electron is 1.60×10^{-19} C.

a Calculate the strength of the electric field acting on the electron beam.

Thinking	Working
Ensure that the variables are in their standard units.	$32\,kV = 32 \times 10^3 = 3.2 \times 10^4\,V$ $30\,cm = 0.30\,m$
Apply the correct equation.	$E = \frac{V}{d}$
Solve for E.	$E = \frac{3.2 \times 10^4}{0.30}$ $= 1.1 \times 10^5\,V\,m^{-1}$

b Calculate the speed of the electrons as they exit the electron gun.

Thinking	Working
Apply the correct equation.	$\frac{1}{2}mv^2 = qV$
Rearrange the equation to make v the subject and solve for v.	$v = \sqrt{\frac{2qV}{m}}$ $= \sqrt{\frac{2 \times 1.60 \times 10^{-19} \times 3.2 \times 10^4}{9.109 \times 10^{-31}}}$ $= 1.06 \times 10^8\,m\,s^{-1}$

c The electrons then travel through a uniform magnetic field perpendicular to their motion. Given that the strength of this field is 0.20 T, calculate the expected radius of the path of the electron beam.

Thinking	Working
Apply the correct equation.	$r = \frac{mv}{qB}$
Solve for r.	$= \frac{9.109 \times 10^{-31} \times 1.06 \times 10^8}{1.60 \times 10^{-19} \times 0.2}$ $= 3.0 \times 10^{-3}\,m$

➤ Try yourself 8.7.4

CALCULATING SPEED AND PATH RADIUS OF ACCELERATED CHARGED PARTICLES

An electron gun releases electrons from its cathode which are accelerated across a potential difference of 25 kV over a distance of 20.0 cm between a pair of charged parallel plates. Assume that the mass of an electron is 9.109×10^{-31} kg and the magnitude of the charge on an electron is 1.60×10^{-19} C.

a Calculate the strength of the electric field acting on the electron beam.

b Calculate the speed of the electrons as they exit the electron gun.

c The electrons then travel through a uniform magnetic field perpendicular to their motion. Calculate the expected radius of the path of the electron beam given that the strength of this field is 0.30 T.

Deflection of alpha, beta and gamma radiation in a magnetic field

In Year 11 you learnt about different types of radiation: alpha particles, beta particles and gamma rays. Alpha particles, the strongly positively charged nuclei of helium atoms, will be deflected in a magnetic field. The right-hand slap rule is used to determine the direction. Beta particles can be positively or negatively charged and so the direction of this force depends on the charge that they carry. Gamma rays, the high-energy beams of light that are emitted in certain nuclear reactions, are uncharged and so will pass through a magnetic field without deflection.

We can calculate the difference in the effect on alpha and beta particles in a magnetic field by determining their path radii. Alpha particles have an approximate mass of 6.64×10^{-27} kg and a charge of $2 \times 1.602 \times 10^{-19}$ C. The path radius of alpha particles at a speed of $1.5 \times 10^{6}\,\text{m s}^{-1}$ in a magnetic field of 1.0 T is:

$$r_\alpha = \frac{mv}{qB} = \frac{6.64 \times 10^{-27} \times 1.5 \times 10^{6}}{2 \times 1.602 \times 10^{-19} \times 1.0} = 0.031\,\text{m}$$

Similarly, a beta particle has a mass of 9.11×10^{-31} kg and a charge magnitude of 1.602×10^{-19} C. At the same speed in the same field, its path radius is:

$$r_\beta = \frac{mv}{qB} = \frac{9.11 \times 10^{-31} \times 1.5 \times 10^{6}}{1.602 \times 10^{-19} \times 1.0} = 8.5 \times 10^{-6}\,\text{m}$$

It is clear that the lower mass of the beta particles results in a much smaller path radius for these particles. This is the reason why many early particle accelerators dealt with collisions of electrons rather than heavier particles like protons. It requires far less powerful magnets to keep beta particles at a high velocity within a given path radius. It was only in 1971 that CERN unveiled the world's first proton–proton collider, the Intersecting Storage Rings.

The different paths of alpha, beta and gamma radiation in a magnetic field are summarised in Figure 8.7.10.

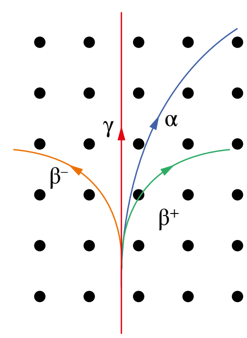


FIGURE 8.7.10 The paths of different types of radiation in a magnetic field. Using the right-hand slap rule, we see that positively charged particles are forced to the right. Alpha (α) particles are much heavier than beta particles, and so are deflected less. Beta minus (β^-) is deflected the same amount as beta plus (β^+), but in the opposite direction. Gamma (γ) rays are uncharged and so pass straight through.

WS 3.2.7 WS 3.2.8

8.7 Review

SUMMARY

- The magnitude of the force on a charged object within a magnetic field is proportional to the strength of the magnetic field, B, the component of the velocity of the charge that is perpendicular (at right angles) to the magnetic field, and the charge on the particle.
- This force is referred to as the Lorentz force.
- The force is at a maximum when the charged particle is moving perpendicular to the magnetic field: $F = qvB$.
- The force is zero when the charged particle is travelling parallel to the magnetic field.
- When the velocity is at an angle to the field, the force on a charged particle is $F = qvB\sin\theta$.
- The right-hand slap rule is used to determine the direction of the force on a positive charge moving in a magnetic field, B. The direction of the force on a negatively charged particle is in the opposite direction.
- Particle accelerators are machines that accelerate charged particles, such as electrons, protons and atomic nuclei, to speeds close to that of light.
- The radius of the path of a charged particle travelling at right angles to a uniform magnetic field is given by $r = \frac{mv}{qB}$.
- The velocity of a charged particle accelerated within a potential difference is given by $v = \sqrt{\frac{2qV}{m}}$.

KEY QUESTIONS

Retrieval

1 State the equation for the Lorentz force for a charged particle travelling perpendicularly to a magnetic field and what each quantity represents.

2 Identify the force acting on a particle if the velocity is parallel to the magnetic field.

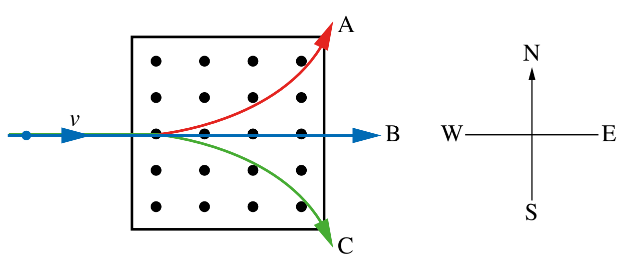
3 State how the radius of a curved path changes when the velocity of the particle is doubled.

Comprehension

4 State the direction in which a charged particle will move if there is no magnetic field present. Explain your reasoning.

5 When discussing the motion of a charged particle relative to a magnetic field, the symbol θ is used to designate the angle between the velocity vector of the particle and the magnetic field lines.
Explain why the force on a particle travelling at an angle θ to a magnetic field is $qvB\sin\theta$ rather than $qvB\cos\theta$.

6 The following diagram shows a particle, with initial velocity v, about to enter a uniform magnetic field, B, directed out of the page.



a State the direction of the force just as the particle enters the field if the particle is positively charged.
b Describe the path this particle will follow.
c Identify whether the kinetic energy of the particle increases, decreases or remains constant.
d Identify the path a negatively charged particle would follow.
e Determine the kind of particle that could follow path B.

7 Explain how particle accelerators are able to use electromagnetic fields to provide the centripetal acceleration to change the direction of a charged particle.

Analysis

8 A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C is travelling into a computer screen perpendicular to a magnetic field, B, that runs horizontally from left to right across the screen. Determine the direction in which the force experienced by the charge acts.

9 A single, positively charged particle with a charge of $+1.6 \times 10^{-19}$ C travels at a velocity of $0.500\,\text{m}\,\text{s}^{-1}$ from left to right perpendicular to a magnetic field, B, of strength 2.0×10^{-5} T, running vertically downwards. Calculate the magnitude of the force that the particle will experience from the magnetic field.

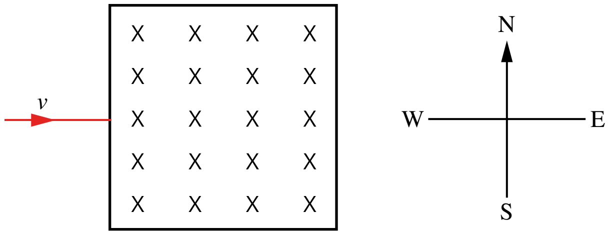
10 An electron with a charge of -1.60×10^{-19} C is moving eastwards into magnetic field of strength $B = 1.5 \times 10^{-5}$ T acting in a north-easterly direction. Calculate the magnitude and direction of the force it initially experiences as it enters the magnetic field if the magnitude of the initial velocity is $1.0\,\text{m}\,\text{s}^{-1}$.

11 A single, negatively charged particle with a charge of -1.6×10^{-19} travels at a velocity of $1.0 \times 10^5\,\text{m}\,\text{s}^{-1}$ from right to left parallel to a magnetic field, B, of strength 3.0×10^{-5} T.

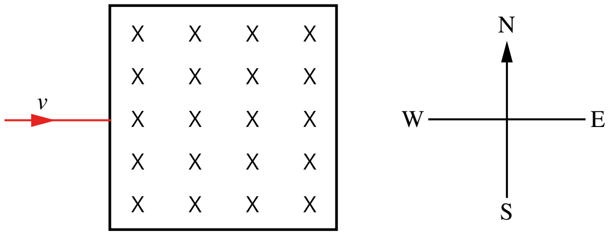
Calculate the magnitude of the force the particle will experience from the magnetic field.

12 An electron with speed $7.6 \times 10^6\,\text{m}\,\text{s}^{-1}$ travels through a uniform magnetic field and follows a circular path of diameter 9.2×10^{-2} m. Calculate the magnetic field strength through which the electron travels.

13 An electron with a charge of -1.60×10^{-19} C is moving eastwards into a magnetic field of strength 1.5×10^{-5} T acting into the page, as shown below. Determine the magnitude and direction of the force the electron initially experiences as it enters the magnetic field if the magnitude of the initial velocity is $2.0 \times 10^7\,\text{m}\,\text{s}^{-1}$.



14 An alpha particle with a charge of $+3.2 \times 10^{-19}$ C is moving eastwards into a magnetic field acting into the page, as shown below. The force it experiences is F. Determine the magnitude and direction of the magnetic force it would experience in terms of F if the velocity, v, of the particle is doubled.



15 Tristen is studying the tracks left by an unknown particle travelling in a magnetic field. Using a variety of techniques, he calculates the mass to be 2.3×10^{-26} kg. He then sends the particle at a velocity of $1.80 \times 10^8\,\text{m}\,\text{s}^{-1}$ through a 2.0 T magnetic field at an angle of 35°. Determine the charge of the particle if the acceleration of the particle is detected to be $4.88 \times 10^{15}\,\text{m}\,\text{s}^{-1}$.

Investigating the force on a conductor in a magnetic field

Conduct an experiment to investigate the force acting on a conductor in a magnetic field.

- 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 investigate the force acting on a conductor in a magnetic field.

Rationale (scientific background to the experiment)

A current-carrying wire will experience a force when placed perpendicular to a magnetic field.

The force, F, experienced by the wire is given by $F = BIL$, where I is the current in the wire (A), L is the length of the wire (m) and B is the strength of the magnetic field (T), as shown on page 166.

By varying the current through a wire placed in a magnetic field of known constant strength and measuring the force experienced by the wire using a balance, a relationship between current and force can be found.

Timing

30 minutes

Materials

- commercial current balance or copper wire (at least 4.00 m) to construct same
- electronic balance (0.1 g resolution or better)
- variable DC power supply
- ammeter or current sensor
- permanent magnets (preferably a strong horseshoe magnet)

Safety

- Make sure the ammeter is set up correctly (in series) in your circuit.
- Do not allow current to flow through the wires for any longer than a few seconds. The wires (and possibly the power supply) can become hot and cause burns and damage equipment. Do not exceed 1 A.

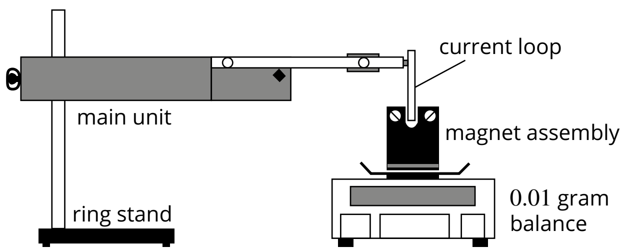
Method

Risk assessment

Assessment of risks includes chemical hazards and physical hazards. 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. Set up the commercial current balance following the manufacturer's instructions. The diagram below shows a typical arrangement of current balance and electronic balance. Consult your manufacturer's instructions for the appropriate arrangement for your apparatus.

   A similar balance can be made if a commercial balance is not available. Wind copper wire into a square of 5.0 cm by 5.0 cm at least 10 times. Place the horseshoe magnet on the electronic balance with the north and south poles facing up. Stand the 10 loops of copper wire on a retort stand so that it hangs with one edge exactly parallel to and between the N and S poles of the horseshoe magnet. Zero/tare the balance.



2. Change the current flowing through the wire, I, by varying the voltage, V. Measure the reading on the balance for five different values of I. Be careful to keep the current below 1 A or at least within the range of your ammeter or sensor.
3. The force acting on the wire is due to the interaction between the magnetic field of the horseshoe magnet and the magnetic field generated by the current flowing through the wire. The balance will read either a positive or negative value, depending on the direction of the current. The value displayed on the balance is the equivalent of how much the 'mass' of the wire has changed, i.e. the force recorded in the table opposite will be equal to the mass displayed multiplied by 9.8 (the acceleration due to gravity).

4 Note the results in a table for current through the wire and force exerted on the current balance, with the uncertainty for each measurement. The uncertainty in the measurement for the current is likely to be ±0.1 A (but please determine this for your apparatus); and the uncertainty in the measurement for the change in mass exerted on the current balance is always ± 1 of the smallest decimal displayed. Refer to Chapter 1 for a reminder of how to determine the uncertainties in a measurement.

5 Repeat the same measurements at least two more times in order to obtain an average.

6 Change the value of the current through the wire by changing the voltage and repeat steps 3–5 for a total of at least five different values of current.

Variables

i Independent: the current, I, flowing through the wire

ii Dependent: the force, F, experienced by the wire in the magnetic field

iii Controlled: magnetic field, length of wire

Analysing

Raw and processed data

TABLE 1 Measured force experienced by a wire in a magnetic field

Measured current, I (± ____ A)				Measured change in mass, m (± ____ kg)				Calculated force, F (± ______ N)			
Trial 1	Trial 2	Trial 3	Average	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 on a graph, with the independent variable I on the x-axis and the dependent variable F on the y-axis. Include error bars for each point plotted.

2 Draw a line of best fit. Use your error bars to draw minimum and maximum lines.

3 Calculate the uncertainty in the gradient.

4 Identify any points on your graph that do not fit the trend. Explain why this may be the case.

5 Determine the gradient of the line of best fit. Using $F = BIL$, the gradient is equal to BL.

6 Measure the value of L, which is the *total* length of wire that passes through the gap between the north and south poles of the horseshoe magnet. Determine the uncertainty in L.

7 Use the gradient and value of L to determine the value of B, which is the strength of the horseshoe magnet. Also calculate the uncertainty in B using the uncertainties in the gradient and L.

8 Compare your graph with the graphs drawn by other groups who used different values for current, and magnets of different size and strength. Describe what you notice about the shapes of the graphs.

9 Explain whether you expected the graphs to be to same or different.

10 Compare the value, and uncertainty, of the strength of the horseshoe magnet with other groups. Discuss any consistency in the results.

➤ 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 investigate the force acting on a wire in a magnetic field. State whether you were able to find a linear relationship between the current flowing through the wire and the force experienced. Discuss whether your results confirmed the formula $F = BIL$.

2 State your final value of the strength of the magnetic field of the horseshoe magnet and the value's uncertainty.

Evaluation

3 Considering your analysis and conclusion, discuss whether the experiment provided an effective method of measuring the force experienced by the current-carrying wire.

4 Consider whether the level of uncertainty that you calculated in step 9 of Analysis was reasonable.

Improvements

5 If you were to repeat the experiment, propose what you would 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

1 Determine whether this experiment would work using any magnet.

2 Identify any limitations to using this method for other magnets.

3 Outline how this method could be used to determine the strength and direction of Earth's magnetic field.

4 For this experiment, the current-carrying wire is placed parallel to the poles of the magnet. Explain the change in the force of placing the current-carrying wire at an angle to the magnet.

➤ 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.

Investigating the strength of a magnetic field at various distances

Conduct an experiment to investigate the strength of a magnet at various distances.

- 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 investigate the strength of a magnetic field at various distances from a current-carrying wire.

Rationale (scientific background to the experiment)

The strength of the magnetic field around a current-carrying wire varies with the distance from the wire according to:

$$B = \frac{{}_0 I}{2\pi r}$$

where B is the magnetic field strength, μ_0 is the magnetic constant, I is the current flowing through the wire and r is the distance from the wire.

Timing

30 minutes

Materials

- copper wire
- ammeter or current sensor
- variable DC power supply
- 30 cm ruler
- resistor
- magnetic field sensor or magnetic field app for a smartphone
- clamp stand and clamp

Safety

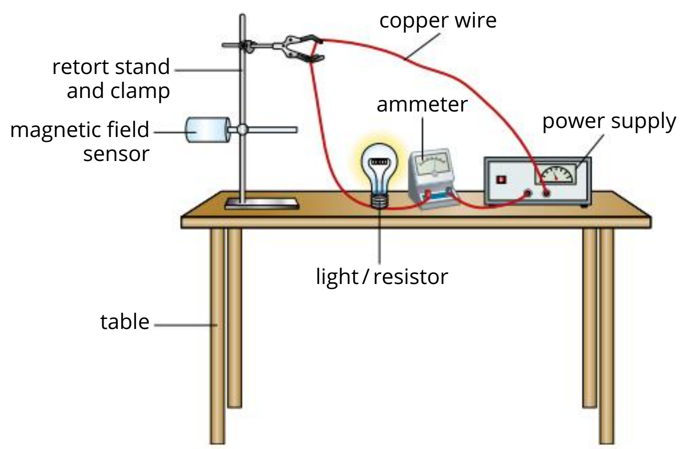
- Make sure the ammeter is set up in series in your circuit.
- Do not allow current to flow through the wires any longer than a few seconds. The wires (and possibly the power supply) can become hot and cause burns and damage equipment. Keep the current below 1 A.

Method

Risk assessment

Assessment of risks includes chemical hazards and physical hazards. Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment Book or download from your eBook.

1 Set up a circuit using the variable power supply, the copper wire, the resistor and the ammeter. Attach the copper wire to the clamp on a retort stand placed at the end of a table so that one end of the wire hangs down to the table but at an angle to the table. Connect the other end of the wire to the power supply. The circuit is completed by connecting the two ends of the wire via a resistor and power supply.



2 Turn on the power supply. Note down the value of I on the ammeter or current sensor. Measure the magnetic field at five perpendicular distances from the wire using the magnetic field sensor.

3 Note the results in a table for distance from the copper wire and magnetic field strength, with the uncertainty for each measurement. The uncertainty in the measurement for the distance is likely to be ±0.5 cm, and the uncertainty in the measurement for magnetic field strength is determined by the instrument you are using. Refer to Chapter 1 for a reminder of how to determine uncertainties in a measurement.

4 Repeat the measurements twice in order to obtain an average.

Variables

i Independent: the distance, r, from the conductor

ii Dependent: the magnetic field strength, B

iii Controlled: the current, I, flowing through the wire

Analysing

Raw and processed data

TABLE 1 Measured magnetic field strength at different distances from a current-carrying wire

Measured distance, r (± _____ m)				Measured magnetic field strength, B (± ______ T)			
Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
			±				±
			±				±
			±				±
			±				±
			±				±

TABLE 2 Measured magnetic field strength and the reciprocal of the distance

Reciprocal of measured distance, $\frac{1}{r}$ (± _____ m^{-1})				Measured magnetic field strength, B (± ______ T)			
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 on a graph, with the independent variable r on the x-axis and the dependent variable B on the y-axis. Include error bars for each point plotted.
2. Describe the shape of this graph.
3. Plot the results from Table 2 on a graph, with the reciprocal of the independent variable, $\frac{1}{r}$, on the x-axis and the dependent variable B on the y-axis. Include error bars for each point plotted.
4. Draw a line of best fit. Use the error bars to draw a minimum and maximum line.
5. Identify any points on your graph that do not fit the trend. Explain why this might have been the case.
6. Calculate the gradient of the line of best fit. Using $B = \frac{\mu_0 I}{2\pi r}$, the gradient is equal to $\frac{\mu_0 I}{2\pi}$. Use the measured value for I and the value of π to calculate the value of μ_0.
7. Use the uncertainty in the gradient and the uncertainty in I to calculate the uncertainty in μ_0.
8. Compare your graph to the graphs drawn by other groups who used different values for current. Describe what you notice about the shape of the graphs.
9. Compare your value of μ_0 with other groups.
10. Discuss whether you would expect your results to be to same or different.

➤ 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 investigate the strength of the magnetic field from a current-carrying wire at various distances. State the relationship you found between the distance from the conductor and the magnetic field strength. Consider whether your results fit the formula $B = \frac{\mu_0 I}{2\pi r}$. State your value for μ_0 with its uncertainty.

Evaluation

2 Considering your analysis and conclusion, discuss whether the experiment provided an effective method of measuring the magnetic field strength at various distances.

3 Consider whether the level of uncertainty that you calculated in step 9 of Analysis was reasonable.

Improvements

4 If you were to repeat the experiment, propose what you would 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 Consider if this experiment would work if you measured the distance from the wire in any direction, other than perpendicular to the wire.

6 Identify any limitations to using this method for other distances from the wire.

➤ 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 respects 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

SAT IA2

08

KEY TERMS

cathode ray tube (CRT)
commutator
dipolar
dipole
direct current
electromagnet
electron gun
ferromagnetic materials
Lorentz force
magnetic
magnetic domain
magnetic field
magnetic field lines
magnetic force
magnetic pole
magnetism
nuclear magnetic resonance (NMR)
permanent magnet
permeability of a vacuum
polarised
pole
resonant frequency
right-hand grip rule
right-hand slap rule
solenoid
temporary magnet

KEY QUESTIONS

Retrieval

1 Select the correct statement relating to magnetic poles.

A Opposite poles attract, like poles repel.
B Opposite poles repel, like poles attract.

2 Identify the best option to complete the sentence.

The magnitude of the magnetic force on a conductor aligned so that the current is running parallel to a magnetic field is:

A zero
B a maximum
C dependent on the size of the current
D dependent on the length of the conductor
E dependent on the size of the magnetic field

3 Define ‘magnetic dipole’.

4 The right-hand slap rule is used to determine the force on a current-carrying conductor perpendicular to a magnetic field. Recall what part of the hand corresponds to the following physical quantities:

a magnetic force
b magnetic field
c current in the conductor.

Comprehension

5 Identify the correct statement about the magnetic field strength in a solenoid:

A The magnetic field at a point well inside a solenoid is uniform and dependent on the radius of the solenoid.
B The magnetic field at a point well inside a solenoid is uniform and independent on the radius of the solenoid.
C The magnetic field at a point well inside a solenoid is non-uniform and dependent on the radius of the solenoid.
D The magnetic field at a point well inside a solenoid is non-uniform and independent on the radius of the solenoid.

6 Elizabeth constructs a simple DC electric motor consisting of *N* loops of wire wound around a wooden armature, and a permanent horseshoe-shaped magnetic of strength *B*. The student connects the motor to a 9 V battery but is not happy with the speed of rotation of the armature. Identify which one or more of the following modifications will most likely increase the speed of rotation of the armature.

A increase the number of turns *N*
B use a 12 V battery instead of a 9 V battery
C replace the wooden armature with one of soft iron
D connect a 100 Ω resistor in series with the armature windings

7 Explain why ferromagnetic materials make for stronger permanent magnets.

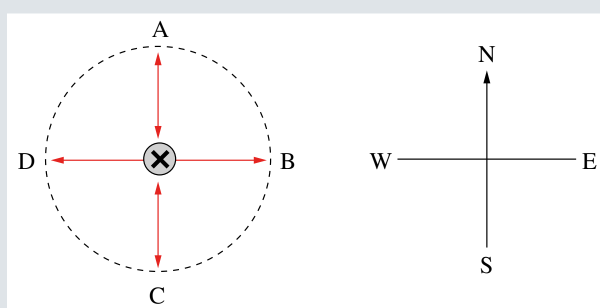
8 Discuss how a non-magnetised ferromagnetic material becomes magnetised.

9 Draw the magnetic field lines between two like poles and two opposite poles.

10 Describe how the magnetic fields of two current-carrying wires parallel to each other interact when the current in both wires is running in the same direction.

The following diagrams relates to questions 11–13.

The figure below shows a cross-sectional view of a long, straight, current-carrying conductor, with its axis perpendicular to the plane of the page. The conductor carries an electric current into the page.

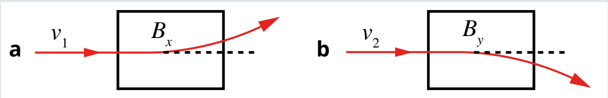


11 Determine the direction of the magnetic field produced by this conductor at point B.

12 Describe the direction of the magnetic field produced at point D if the current through the conductor is doubled.

13 Describe the direction of the magnetic field produced at point A if the direction of the current is reversed and halved.

14 The following diagrams show two different electron beams being bent as they pass through two different regions of a uniform magnetic field of equal magnitudes B_x and B_y. The initial velocities of the electrons in the respective beams are v_1 and v_2. Select the correct term from those in **bold**, to complete the sentence.



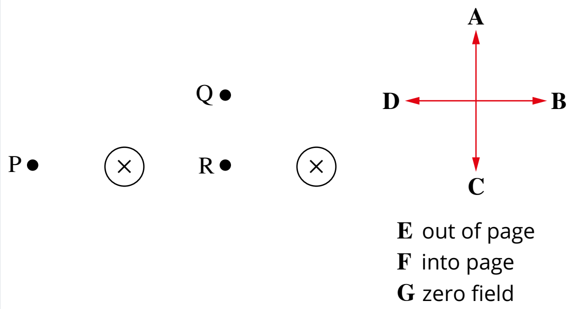
For the electron beams to behave as shown in **a**, v_1 is **equal to/less than** v_2 and the region of the magnetic field, B_y, must be acting **out of/into** the page.

15 A horseshoe magnet is held vertically with the north pole of the magnet on the left and the south pole of the magnet on the right.

Describe the direction of the magnetic force acting on a wire passing between the poles.

16 Power lines carry an electric current in Earth's magnetic field. Determine whether a north–south power line or an east–west power line would experience the greater magnetic force. Explain your answer.

17 The left diagram below represents two conductors, both perpendicular to the page and both carrying equal currents into the page (shown by the crosses in the circles). Ignore any contribution from Earth's magnetic field. Choose the correct options from the arrows A–D and letters E–G.



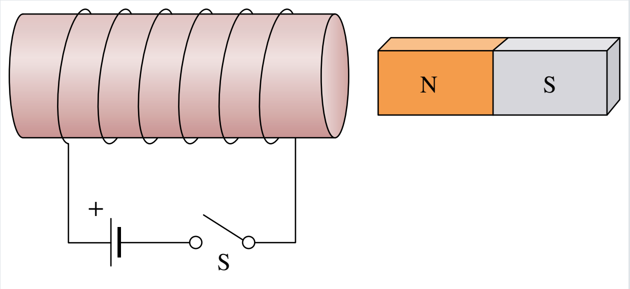
Determine the direction of the magnetic field due to the two currents at each of the following points.

a point P

b point Q

c point R

18 An electromagnet with a soft iron core is set up as shown in the diagram below. A small bar magnet with its north end towards the electromagnet is placed to the right of it. The switch S is initially open. The following questions refer to the force between the electromagnet and the bar magnet under different conditions.

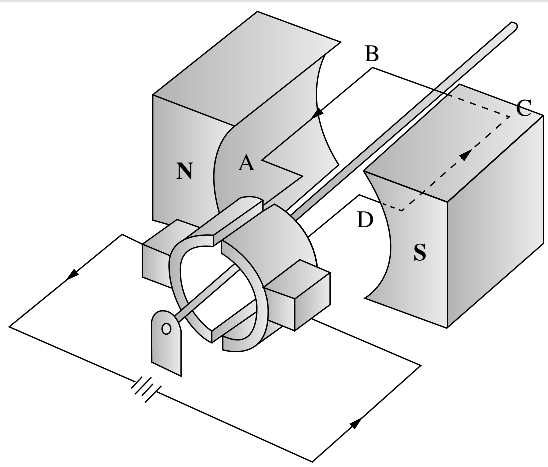


a Describe the force on the bar magnet while the switch remains open.

b Describe the force on the bar magnet when the switch is closed and a large current flows.

c The battery is removed and then replaced so that the current flows in the opposite direction. Describe the force on the bar magnet now when the switch is closed.

19 Consider the electric motor shown.



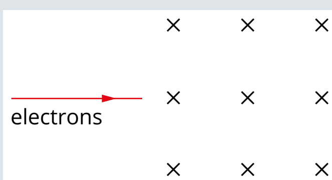
a The direction of the current in the coil is from D anticlockwise to A, as shown. Describe the direction of the force on sides AB and CD.

b Identify in which position of the coil the turning effect of the forces is greatest.

c At one point in the rotation of the coil the turning effect becomes zero. Explain where this occurs and why the motor actually continues to rotate.

20 Explain the function of the commutator in a DC electric motor.

21 This diagram shows a stream of electrons entering a magnetic field. Draw the diagram and show the subsequent path of the electrons through the magnetic field.



Analysis

22 Calculate the strength of the magnetic field a distance of 0.750 m away from a wire if the current running through the wire is 0.200 A.

The following information relates to questions 23–25.

A solenoid carrying a current of 10.0 A produces a magnetic field of 6.0×10^{-4} T.

23 Determine the resulting magnetic field strength if the current is increased to 40.0 A and the number of turns per unit length is reduced by a factor of two.

24 Determine the resulting magnetic field strength if the current is decreased to 5.0 A and the number of turns per unit length is reduced by a factor of two.

25 Calculate by how much the current required to generate the magnetic field would be reduced if the magnetic field remains the same and the number of turns was increased by a factor of 10.

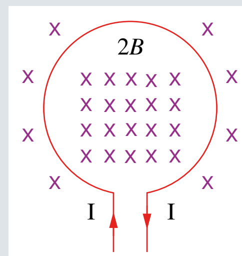
26 A current-carrying wire runs horizontally across a table. The conventional current direction, *I*, is running from right to left. The wire produces a magnetic field of 2.0×10^{-6} T measured 10.0 cm from the wire.

a Calculate the current the wire must be carrying to produce that field.

b Draw a diagram showing the direction of the magnetic field around the wire.

The following information relates to questions 27–29.

The diagram below shows a loop carrying a current *I* that produces a magnetic field of magnitude *B* in the centre of the loop. Its direction is not shown in the diagram. The loop is placed into a region where there is already a steady field of magnitude *B* (the same magnitude as that due to *I*) directed into the page. The resultant magnetic field inside the loop has a magnitude of 2*B*.



27 Calculate the magnitude and direction of the resultant field be at the centre of the loop if the current in the loop is switched off.

28 Calculate the magnitude and direction of the resultant field at the centre of the loop if the current in the loop is doubled.

29 Calculate the magnitude and direction of the resultant field at the centre of the loop if the current in the loop is reversed but maintained at the same magnitude.

30 Determine the current, *I*, flowing in a wire 3.2 m long if the maximum force on it is 0.800 N when it is placed in a uniform magnetic field of 0.0900 T.

31 Calculate the magnitude and direction of the magnetic force on conductors with the following sets of data.

a $B = 1.0$ mT left, $L = 5.0$ mm, $I = 1.0$ mA up

b $B = 0.10$ T down, $L = 1.0$ cm, $I = 2.0$ A into the page

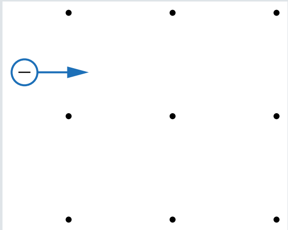
32 Calculate the force exerted on an electron ($q = 1.60 \times 10^{-19}$ C) travelling at a speed of 7.0×10^{6} m s^{-1} at a 45° angle to a uniform magnetic field of strength 8.6×10^{-3} T. Given that the mass of an electron is 9.109×10^{-31} kg, calculate the resulting acceleration that the electron experiences.

33 An electron with speed of 4.3×10^{6} m s^{-1} travels through a uniform magnetic field and follows a circular path of diameter 8.4×10^{-2} m. Calculate the magnetic field strength through which the electron travels.

34 a Calculate the magnitude of the force exerted on a proton (mass = 1.673×10^{-27} kg) travelling at speed of $6.4 \times 10^6\,m\,s^{-1}$ at right angles to a uniform magnetic field of strength 9.1×10^{-3} T.

b Calculate the radius of its orbit, given that this force directs the electron in a circular path.

35 The diagram below represents an electron being fired at right angles towards a uniform magnetic field acting out of the page.

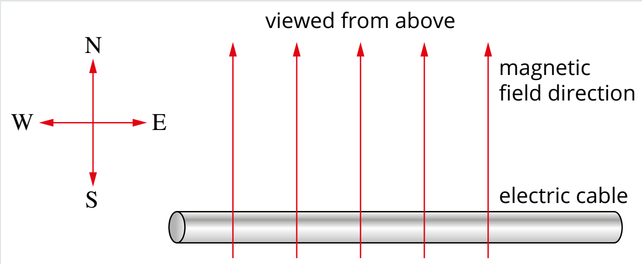


a Show the continued path of the electron on a copy of the diagram.

b Consider the factors that would alter the path radius of the electron as it travels.

The following information applies to questions 36–40.

The diagram below shows a horizontal, east–west electric cable located in a region where Earth's magnetic field is horizontal and has a magnitude of 1.0×10^{-5} T. The cable has a mass of $0.050\,kg\,m^{-1}$.



36 Determine the magnitude of the magnetic force on a 1.0 m section of this cable if a 100.0 A current is flowing through it.

37 Determine the direction of the current that will produce a force on this cable out of the page.

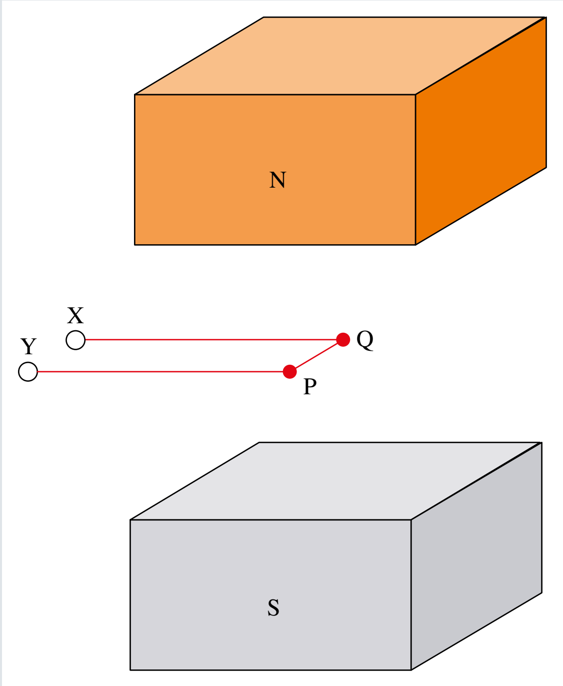
38 Calculate the magnitude of current required to produce zero resultant vertical force on a 1.0 m section of this cable. Use $g = 9.8\,m\,s^{-2}$.

39 Determine the change in magnetic force per metre on this cable if the direction of this current is reversed. Assume that a 100.0 A current is flowing through this cable from west to east.

40 The cable now makes an angle of 30.0° with the direction of Earth's magnetic field. Calculate the force that a 100.0 A current passing through this cable would produce.

The following information relates to questions 41–43.

The following diagram shows a section of a conducting loop XQPY, part of which is placed between the poles of a magnet whose uniform field strength is 1.0 T. The side PQ has length 5.0 cm. X is connected to the positive terminal of a battery while Y is connected to the negative terminal. A current of 1.0 A then flows through this loop.

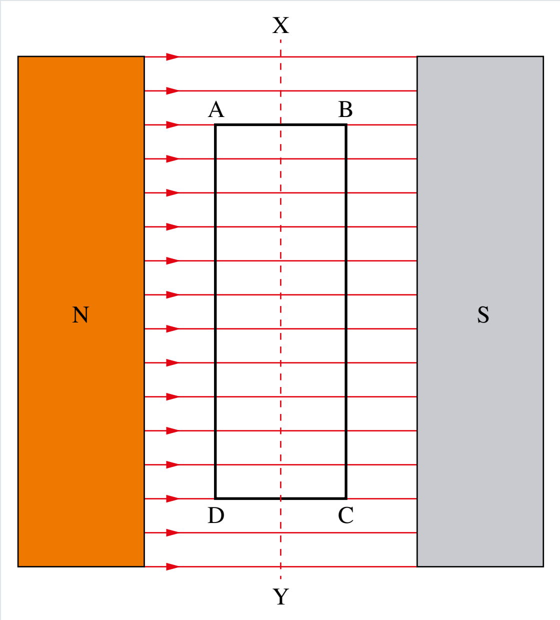


41 Calculate the magnitude of the force on side PQ.

42 Determine the direction of the force on side PQ.

43 Determine the magnitude of the force on a 1.0 cm section of side XQ that is located in the magnetic field.

The following information relates to questions 44–45.
A rectangular coil containing exactly 100 turns and of dimensions 10.0 cm × 5.0 cm is located in a magnetic field $B = 0.25$ T, as shown. It is free to rotate about the axis XY. The coil carries a constant current $I = 200.0$ mA flowing in the direction ADCB.



44 Determine the magnitude and direction of the magnetic force on sides:

a AB

b DC

45 Determine the magnitude and direction of the magnetic force on sides:

a AD

b BC

46 A rectangular loop of exactly 100 turns is suspended in a magnetic field $B = 0.50$ T. The plane of the loop is parallel to the direction of the field. The dimensions of the loop are 20.0 cm perpendicular to the field lines and 10.0 cm parallel to them.

a It is found that there is a force of 40.0 N on each of the sides perpendicular to the field. Calculate the current in each turn of the loop.

b This loop is then replaced by a square loop of side length 10.0 cm, with twice the current and half the number of turns. Determine the force on each of the perpendicular sides now.

c The original rectangular loop with the original current is returned but a new magnet is used that provides a field strength of 0.80 T. Determine the force on the 20.0 cm side now.

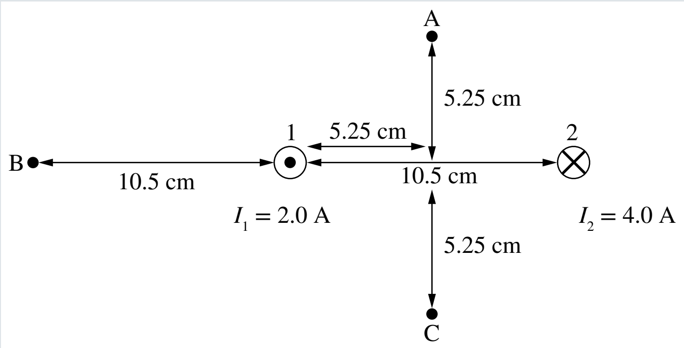
47 Calculate the radius of the path an electron will follow if the electron travels through a magnetic field of strength 1.2 T with a speed of 4.2×10^6 m s^{-1}.

48 An electron beam travelling through a cathode ray tube is subjected to simultaneous electric and magnetic fields. The electrons emerge with no deflection. Calculate the distance between plates X and Y given that the potential difference across the parallel plates X and Y is 3.0 kV and that the applied magnetic field is of strength 1.6×10^{-3} T.

Knowledge utilisation

49 Assume you were making an electromagnet and wanted to create a strong magnet that uses the least amount of power. Propose the most appropriate method to increase the magnetic strength while using the least amount of power.

50 Consider the two wires set up as shown below.

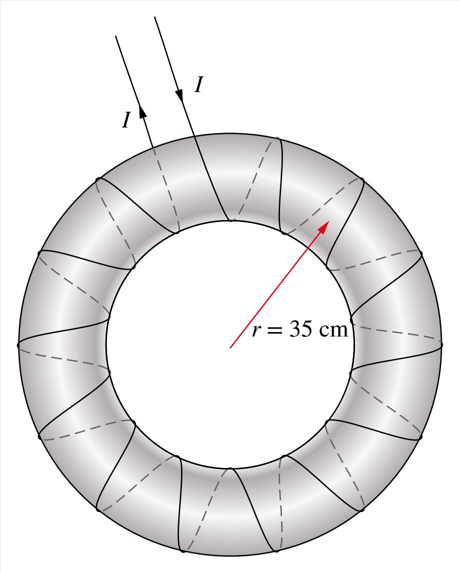


a Determine the direction of the magnetic field due to wire 1 at points A, B and C.

b Determine the direction of the magnetic field due to wire 2 at points A, B and C.

c Calculate the net magnetic field strength and direction at points A, B and C.

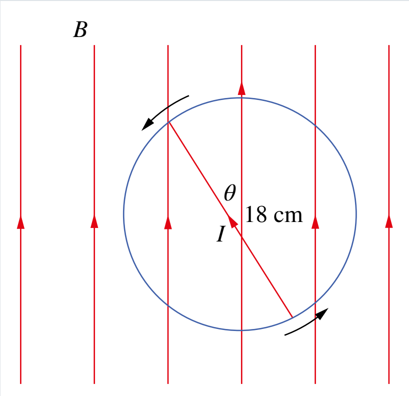
51 This question deals with a slightly different type of solenoid, one arranged in a shape called a *toroid*, as shown below. The solenoid has exactly 60 turns, a central radius of 35 cm, and a current of 4.3 A.

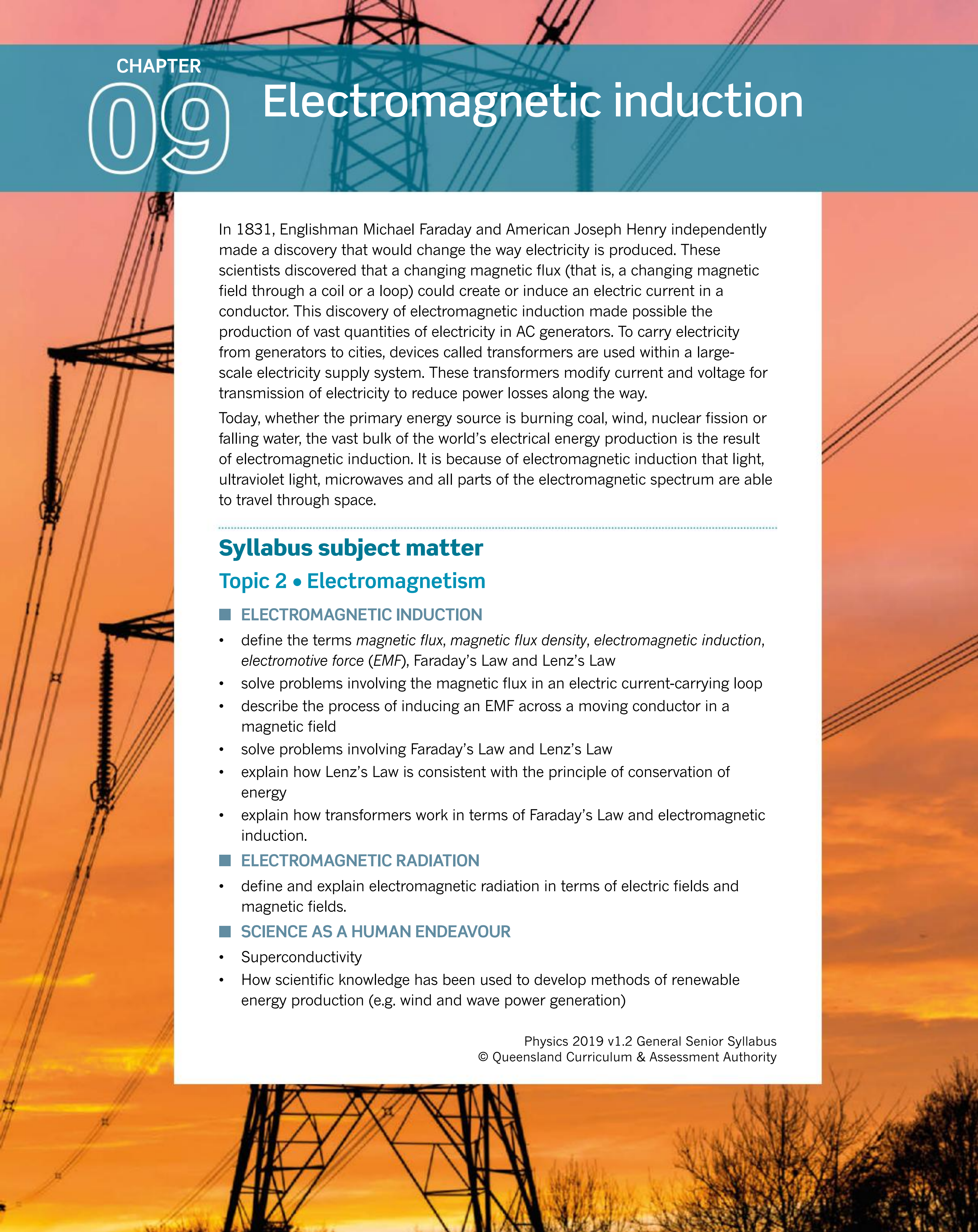


a Determine the direction of the magnetic field that runs through this solenoid, using your knowledge of magnetic fields of coils.

b Calculate the strength of the magnetic field inside the toroid.

52 Natalie decides to set up an experiment to test the angular dependence of the force on a current-carrying wire in a magnetic field. To this end, she sets up a wire on a wheel as shown below. Consider the rest of the wire to be directed into the table and unaffected by the magnetic field. She takes measurements of the force acting on the wire as it rotates from 0 to 360°. The wire is carrying a current of 4.0 A and is 18 cm long. Generate a sketch of the force versus angle graph for a magnetic field of 0.500 mT, taking the initial force direction to be positive.





CHAPTER 09

Electromagnetic induction

In 1831, Englishman Michael Faraday and American Joseph Henry independently made a discovery that would change the way electricity is produced. These scientists discovered that a changing magnetic flux (that is, a changing magnetic field through a coil or a loop) could create or induce an electric current in a conductor. This discovery of electromagnetic induction made possible the production of vast quantities of electricity in AC generators. To carry electricity from generators to cities, devices called transformers are used within a large-scale electricity supply system. These transformers modify current and voltage for transmission of electricity to reduce power losses along the way.

Today, whether the primary energy source is burning coal, wind, nuclear fission or falling water, the vast bulk of the world's electrical energy production is the result of electromagnetic induction. It is because of electromagnetic induction that light, ultraviolet light, microwaves and all parts of the electromagnetic spectrum are able to travel through space.

Syllabus subject matter

Topic 2 • Electromagnetism

ELECTROMAGNETIC INDUCTION

- define the terms *magnetic flux*, *magnetic flux density*, *electromagnetic induction*, *electromotive force* (*EMF*), Faraday's Law and Lenz's Law
- solve problems involving the magnetic flux in an electric current-carrying loop
- describe the process of inducing an EMF across a moving conductor in a magnetic field
- solve problems involving Faraday's Law and Lenz's Law
- explain how Lenz's Law is consistent with the principle of conservation of energy
- explain how transformers work in terms of Faraday's Law and electromagnetic induction.

ELECTROMAGNETIC RADIATION

- define and explain electromagnetic radiation in terms of electric fields and magnetic fields.

SCIENCE AS A HUMAN ENDEAVOUR

- Superconductivity
- How scientific knowledge has been used to develop methods of renewable energy production (e.g. wind and wave power generation)

9.1 Magnetic flux

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

- define the terms 'magnetic flux' and 'magnetic flux density'
- calculate the magnetic flux threading a coil of area, A, when the coil is positioned:
  - parallel to
  - at an angle θ to
  - perpendicular to a magnetic field of strength, B.

FIGURE 9.1.1 Michael Faraday's original induction coil. Passing a current through one coil induces a voltage in the second coil. This voltage is only present when the current through the first coil is changing. This coil is now on display at the Royal Institution in London.

INDUCING AN EMF

After Oersted's discovery that an electric current produces a magnetic field (Module 8.3), Michael Faraday, an English scientist, was convinced that the reverse should also be true—a magnetic field should be able to produce an electric current.

Faraday wound two coils of wire onto an iron ring (Figure 9.1.1). By connecting a battery to one of the coils he created a strong current through it which therefore created a strong magnetic field. He expected to detect the creation of an electric current in the second coil. No matter how strong the magnetic field, he could not detect an electric current in the other coil.

One day he noticed that the galvanometer (a type of sensitive ammeter) attached to the second coil flickered when he turned on the current that created the magnetic field. It gave another flicker, in the opposite direction, when he turned the current off. It was the change in the magnetic field that mattered, not the strength of the magnetic field.

MAGNETIC FLUX

To be able to develop ideas about the change in a magnetic field, it is useful to be able to describe the 'amount of magnetic field'. This amount of magnetic field is referred to as the **magnetic flux**, a scalar quantity, denoted by the symbol Φ. Faraday pictured a magnetic field as consisting of many lines of force. The density of the lines represents the strength of the magnetic field. Magnetic flux can be related to the total number of these lines that pass within a particular area. (This can be referred to as the amount of magnetic flux that threads the coil or area, like thread going through the eye of a needle.) A strong magnetic field acting over a small area can produce the same amount of magnetic flux as a weaker field acting over a larger area (Figure 9.1.2). For this reason, magnetic field strength, B, is also referred to as **magnetic flux density**. B can be thought of as being proportional to the number of magnetic field lines per unit area perpendicular to the magnetic field. The magnetic flux will be at a maximum when the area examined is perpendicular to the magnetic field and zero when the area being examined is parallel to the magnetic field.

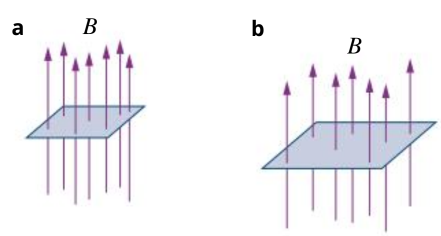


FIGURE 9.1.2 A strong magnetic field acting over a small area (a) will have the same magnetic flux as a weaker magnetic field acting over a larger area (b).

Based on this, magnetic flux is defined as the product of the strength of the magnetic field, B, and the area of the field perpendicular to the field lines:

$\Phi = B_{\perp} A$

where

Φ is the magnetic flux. The unit for magnetic flux is the weber, abbreviated to Wb (1 Wb = 1 T m^{-2})

B is the strength of the magnetic field in tesla (T)

A is the area perpendicular to the magnetic field in square metres (m^2).

The subscript $\perp$ is included in the formula to indicate that the area referred to is perpendicular to the magnetic field.

Since it is the area perpendicular to the magnetic field that contributes to magnetic flux, the angle between the magnetic field and the area through which the field passes will affect the amount of magnetic flux. As the angle increases or decreases from 90°, the amount of magnetic flux will decrease until it is zero when the area under consideration is parallel to the magnetic field. Referring to Figure 9.1.3, the relationship between the amount of magnetic flux and the angle θ to the field is $\Phi = BA\cos\theta$.

It is important to note that θ is not the angle between the plane of the area and the magnetic field. Rather, it is the angle between a normal to the area and the direction of the magnetic field; hence the use of $\cos\theta$. When the area is at right angles to the magnetic field, the angle θ between the normal and the field is 0° and $\cos 0° = 1$ (Figure 9.1.3a). When the area is parallel to the magnetic field, the angle θ between the normal and the field is 90° and $\cos 90° = 0$ (Figure 9.1.3c).

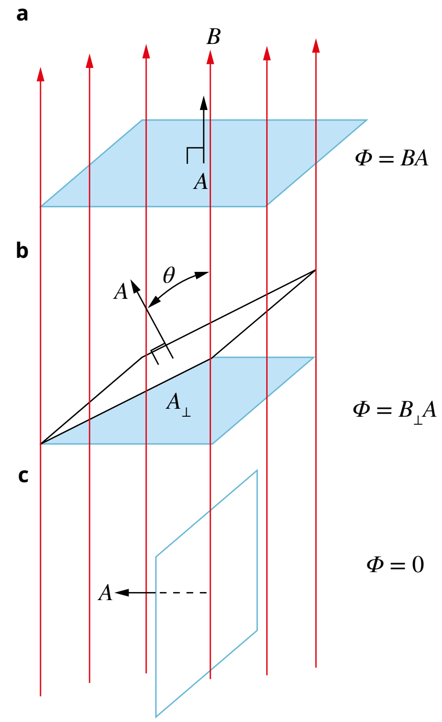


FIGURE 9.1.3 The magnetic flux is the strength of the magnetic field, B, multiplied by the area perpendicular to the magnetic field, given by $A\cos\theta$ and shown as the shaded areas in the above diagrams.

Worked example 9.1.1

MAGNETIC FLUX WITH AREA PERPENDICULAR TO A MAGNETIC FIELD

A student places a horizontal square coil of wire of side length 5.0 cm into a uniform vertical magnetic field of 0.10 T. Calculate how much magnetic flux threads the coil.

Thinking	Working
Calculate the area of the coil perpendicular to the magnetic field.	side length = 5.0 cm = 0.05 m area of the square = (0.05 m)^2 = 0.0025 m^2
Calculate the magnetic flux.	$\Phi = B_{\perp}A$ = 0.1 × 0.0025 = 0.000 25 Wb
State the answer in an appropriate form.	$\Phi = 2.5 \times 10^{-4}$ Wb or 0.25 mWb

➤ Try yourself 9.1.1

MAGNETIC FLUX WITH AREA PERPENDICULAR TO A MAGNETIC FIELD

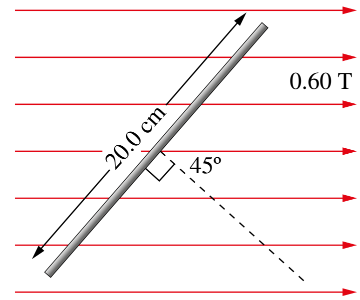
Aksh places a horizontal square coil of wire of side length 4.0 cm into a uniform vertical magnetic field of 0.050 T. Calculate how much magnetic flux threads the coil.

Worked example 9.1.2

MAGNETIC FLUX WITH AREA AT AN ANGLE TO A MAGNETIC FIELD

Isabelle places a horizontal square coil of wire of side length 20.0 cm into a uniform horizontal magnetic field of 0.60 T. The normal to the coil makes an angle of 45° to the magnetic field.

Determine the amount of magnetic flux that threads the coil.



Thinking	Working
Calculate the area of the coil.	side length = 20.0 cm = 0.20 m area of the square = $(0.20\ \text{m})^2$ = $0.04\ \text{m}^2$
Calculate the component of the magnetic flux density that is acting perpendicular to the coil.	$\Phi = BA\cos\theta$ $= 0.6 \times 0.04 \times \cos 45°$ $= 0.01697$ Wb
State the answer in an appropriate form.	$\Phi = 1.7 \times 10^{-2}$ Wb or 17 mWb

➤ Try yourself 9.1.2

MAGNETIC FLUX WITH AREA AT AN ANGLE TO A MAGNETIC FIELD

Isabelle now replaces the original square coil of wire with one that has a side length of 35.5 cm. She rotates the coil of wire so the normal to the coil makes an angle of 65° to the original horizontal magnetic field. Determine the amount of magnetic flux that threads the coil.

9.1 Review

SUMMARY

- Magnetic flux is defined as the product of the strength of the magnetic field, B, and the area of the field perpendicular to the field lines, i.e. $\Phi = B_{\perp}A$.
- The amount of magnetic flux varies with the angle of the field to the area under investigation. It is at maximum when the area is perpendicular (i.e. $\theta = 0°$ to the normal) to the field and zero when the area is parallel (i.e. $\theta = 90°$ to the normal) to the field, i.e. $\Phi = BA\cos\theta$.
- The unit for magnetic flux is the weber, Wb; $1\,\text{Wb} = 1\,\text{T}\,\text{m}^{-2}$.

KEY QUESTIONS

Retrieval

1 Recall what the density of magnetic field lines shows.

2 Indicate the orientation of a coil in a magnetic field that produces the maximum flux through the coil.

3 For a loop of area A placed inside a magnetic field of strength B, the magnetic flux cutting through the loop is defined as $\Phi = BA\cos\theta$. Describe where the angle θ is measured to complete the calculation.

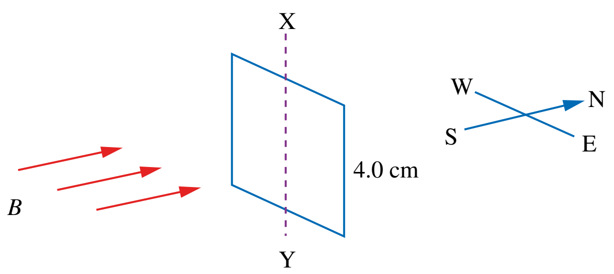
Comprehension

4 Describe how much magnetic flux 'threads' a 4.0 cm square coil of wire parallel to a uniform vertical magnetic field of 0.050 T.

5 A circular wire coil of radius 5.0 cm is perpendicular to a region of uniform magnetic field, $B = 1.6$ mT. Determine the magnetic flux passing through the loop.

Analysis

6 A square loop of wire of side 4.0 cm is in a region of uniform magnetic field, $B = 2.0 \times 10^{-3}$ T north, as in the diagram below. The loop is free to rotate about a vertical axis XY. When the loop is in its initial position, its plane is perpendicular to the direction of the magnetic field.

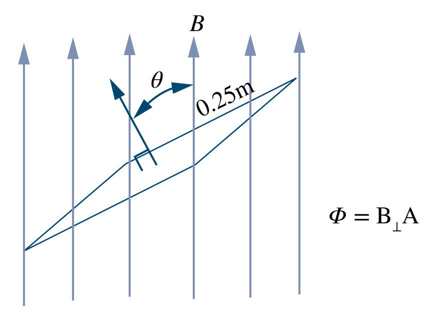


a Calculate the magnetic flux passing through the loop.

b Describe what happens to the amount of magnetic flux passing through the loop as the loop is rotated through one complete revolution.

c The loop now remains stationary but the source of the magnetic field rotates in a 180° arc around the loop. Determine if flux changes in the same way as it did when the loop was rotated. Explain your response.

7 The amount of flux threading the 0.25 m square loop shown in the diagram below is 4.2×10^{-2} Wb. The loop is placed at an angle θ inside a uniform magnetic field of strength 0.82 T.



a Calculate the angle between the normal to the loop and the magnetic field.

b Determine the size of the angle between the loop itself and the magnetic field.

9.2 Electromotive force

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

- define *electromagnetic induction*
- recognise that an electromotive force (EMF) is induced in a conductor when there is a change in magnetic flux
- explain why there is a separation of charges on opposite ends of a conductor that is moving perpendicular to a magnetic field.

CREATING AN ELECTRIC CURRENT

Michael Faraday conducted a simple experiment to see if it was possible to produce an electric current from a magnetic field. Figure 9.2.1 shows a simplified version of this experiment. Imagine that a strong electric current is fed into the coil on the left-hand side of Figure 9.2.1. Faraday knew that this would create a magnetic field around this coil. He expected that this magnetic field would produce a current in the coil on the right side of the iron ring. But as mentioned in Module 9.1, the galvanometer only flickered when the current in the first loop was turned on or off. This observation confirmed that it is possible for an electric current to be created due to a magnetic field. However, a steady magnetic field alone will not produce an electric current. The needle on the galvanometer scale only moved when the magnetic field was changing. When the current in the first loop stayed on, the reading on the galvanometer dropped to zero.

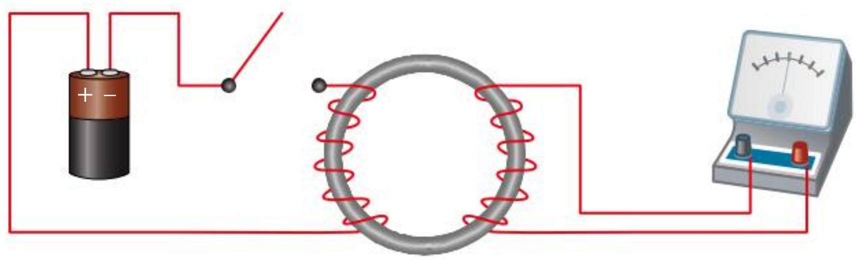


FIGURE 9.2.1 Michael Faraday fed an electric current into a coil wrapped around an iron ring like the one shown in this diagram. He expected the magnetic field created by this current to induce an electric current in the coil on the right-hand side. The galvanometer only produced a flicker when the current was switched on or off. This showed that a changing flux induces electric current.

The effect Faraday noticed is readily seen when a bar magnet is moved quickly into a number of coils of wire that are connected to a galvanometer (Figure 9.2.2). The creation of an electric current in a conductor due to a change in the magnetic field acting on that conductor is called **electromagnetic induction**. In fact, any change in magnetic flux through a conductor creates or induces an electric current. This change in flux may result from a change in the area, a change in magnetic field strength or a change in the angle of flux through the conductor. The discovery of electromagnetic induction has changed the world, enabling us to generate electricity. Michael Faraday was not alone in the discovery of electromagnetic induction. Joseph Henry (1797–1878), an American physicist, independently discovered the phenomenon of electromagnetic induction a little ahead of Michael Faraday, but Faraday was the first to publish his results.

INDUCED EMF

An electric current is created in a conductor whenever there is a change in magnetic flux. This current is produced by an induced EMF, ε. Although the term 'EMF' is derived from the name **electromotive force**, it is a voltage, or potential difference, rather than a force. Figure 9.2.3 indicates the induction of an EMF, and therefore current, caused by the perpendicular movement of a conducting wire relative to a magnetic field.

Electromotive force can be abbreviated to EMF or emf.

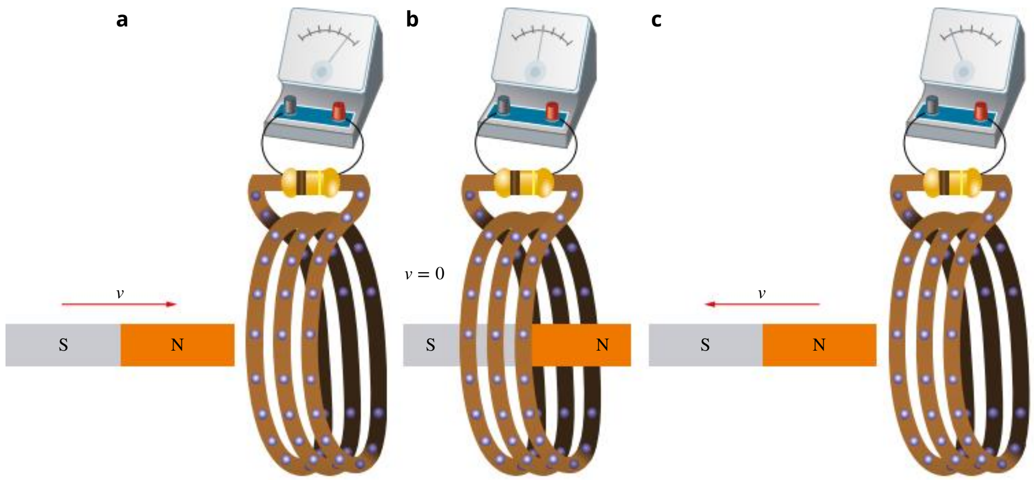


FIGURE 9.2.2 (a) If a magnet is quickly inserted into a number of coils that are connected to a galvanometer, there will be a flicker on the scale as the magnet is inserted. (b) When the magnet becomes stationary, there is no change in magnetic flux, and hence no current is induced. (c) As the magnet is removed from the coils, the galvanometer will flicker in the opposite direction.

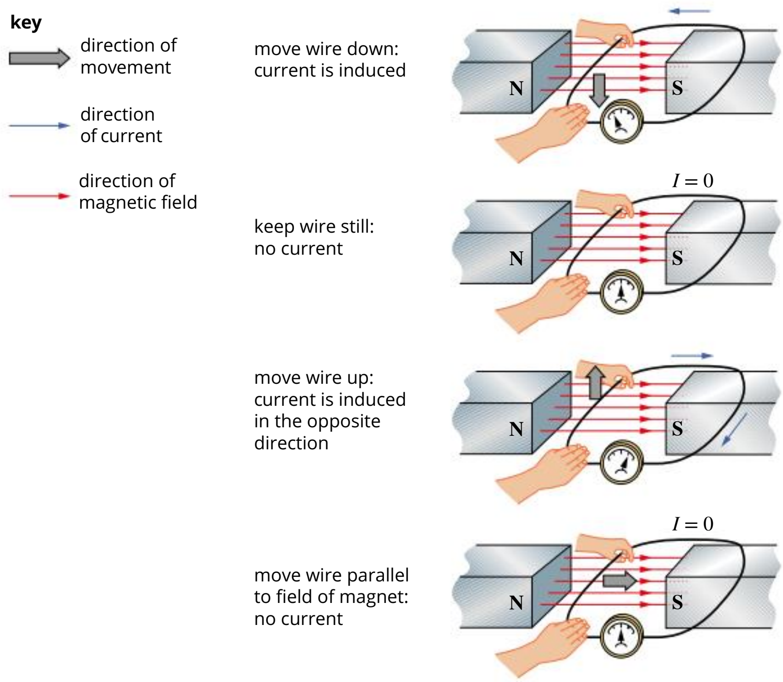


FIGURE 9.2.3 An EMF is induced in a wire when it moves perpendicular to a magnetic field.

Faraday largely based his investigations on **induced currents** in coils, but another way of inducing an EMF is by moving a straight conductor in a magnetic field. It is not hard to understand why this is the case, when you know that charges moving in a magnetic field will experience a force.

In Chapter 8, it was established that when a charge, q, moves at a speed, v, perpendicular to a magnetic field, B, the charge experiences a force, F, and $F = qvB$.

Considering the direction of movement shown in Figure 9.2.4, and applying the right-hand slap rule with your thumb pointing to the left in the direction of the movement of positive charge, and the magnetic field acting downwards, these positive charges experience a force along the conductor and out of the page. The force on the negative charges within the conductor would be along the conductor but into the page.

As the charges in Figure 9.2.4 move apart due to the force they are experiencing from the magnetic field, one end of the conductor will become more positive and the other more negative, and a potential difference, ΔV, or EMF will be induced between the ends of the conductor.

Consider now an electron moving along the conductor. The force from the magnetic field will do work on the electron as it moves along a length, l. To calculate the work done:

$$W = \text{force} \times \text{distance} = qvB \times l$$

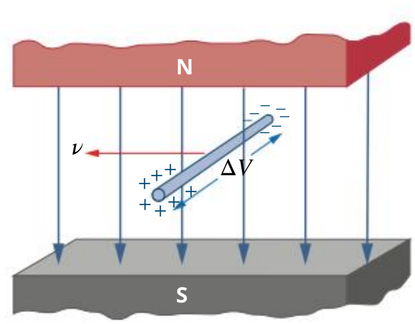


FIGURE 9.2.4 A potential difference, ΔV, will be produced across a straight wire moving to the left in a downwards-pointing magnetic field.

The EMF is equal to the work done per unit charge, so:

$$\varepsilon = \frac{W}{q} = \frac{qlvB}{q}$$

and thus:

> $\varepsilon = lvB$
>
> where
>
> ε is the induced EMF in volts (V)
>
> l is the length of the conductor in metres (m)
>
> v is the speed of the conductor perpendicular to the magnetic field in metres per second ($m\,s^{-1}$)
>
> B is the strength of the magnetic field in tesla (T).

The size of the induced current increases as the speed of the conductor increases. Note that if the conductor were to move parallel to the magnetic field, then there would be no current induced.

Worked example 9.2.1

ELECTROMOTIVE FORCE ACROSS AN AIRCRAFT'S WINGS

An aircraft with a wingspan of 64 m is flying at a speed of 990 $km\,h^{-1}$ at right angles to Earth's magnetic field of 5.0×10^{-5} T.

Determine whether the aircraft will develop a dangerous EMF between its wingtips solely from Earth's magnetic field.

Thinking	Working
Identify the quantities required in the correct units.	$\varepsilon = ?$ $l = 64\,m$ $B = 5.0 \times 10^{-5}\,T$ $v = 990\,km\,h^{-1} = 990 \times \frac{1000}{3600} = 275\,m\,s^{-1}$
Substitute into the appropriate formula and simplify.	$\varepsilon = lvB$ $= 64 \times 275 \times 5.0 \times 10^{-5}$ $= 0.88\,V$
State your answer as a response to the question.	$\varepsilon = 0.88\,V$ This is a very small EMF and would not be dangerous.

➤ Try yourself 9.2.1

ELECTROMOTIVE FORCE ACROSS AN AIRCRAFT'S WINGS

A fighter jet with a wingspan of 25 m is flying at a speed of 2000.0 $km\,h^{-1}$ at right angles to Earth's magnetic field of 5.0×10^{-5} T.

Determine whether the jet will develop a dangerous EMF between its wingtips solely from Earth's magnetic field.

9.2 Review

SUMMARY

- An induced EMF, ε, is produced by a changing magnetic flux in a process called electromagnetic induction.
- The induced EMF in a straight conductor moving in a magnetic field, B, is given by $\varepsilon = lvB$, where v is perpendicular to B.
- The direction of the induced EMF can be found using the right-hand slap rule.

KEY QUESTIONS

Retrieval

1 Refer to Figure 9.2.2a on page 195, which shows a simple version of the experiment Michael Faraday conducted when investigating electromagnetic induction. Identify the change that had to occur in the first coil in order for a current in the second coil to be detected.

Comprehension

2 When the current to the first coil shown in Figure 9.2.1 on page 194 is left on, there is no induced current recorded on the galvanometer. Explain why this is the case from what you understand about electromagnetic induction.

3 Imagine that a bar magnet is dropped through a large number of coils wound together as a cylinder. Explain what you would expect to see on the galvanometer as the magnet:

a falls into the coils from above

b moves through the inside of the coil cylinder

c falls out of the coils.

4 Explain whether an EMF would be induced in a wire when a coil of the wire is brought towards a stationary bar magnet.

5 A rod 12 cm long is being moved at a speed of 0.150 m s^{-1} perpendicular to a magnetic field B. The strength of the magnetic field is 0.800 T. Calculate the induced EMF in the rod.

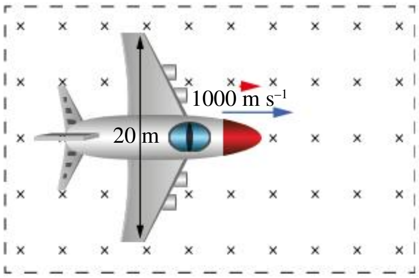
6 A metal rod is 13.2 cm long. It generates an EMF of 100.0 mV while moving perpendicular to a magnetic field of strength 0.90 T. Determine the speed at which it is moving.

7 A metal rod generates an EMF of 80.0 mV while moving at a speed of 1.6 m s^{-1} perpendicular to a magnetic field of strength 0.50 T. Determine the length of the metal rod.

Analysis

8 A rod of length 10.0 cm and of very small diameter is held vertically and dropped downwards through a magnetic field of strength 0.80 T directed vertically upwards. The rod's initial speed was zero. Determine the induced EMF in the rod at an instant 5.0 s after it was dropped.

9 The aircraft shown to the right has a wingspan of 20.0 m and is moving at a speed of 1000.0 m s^{-1} in the magnetic field of Earth in a plane perpendicular to the lines of the field, where the flux density is 2.5×10^{-5} T.

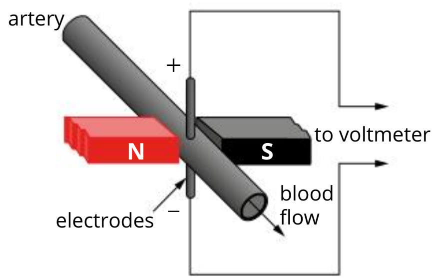


a Calculate the magnitude of the induced EMF between the wingtips of the aircraft.

b Predict how this EMF would change in magnitude if the aircraft was to complete a 90° turn downwards so that it was flying parallel to Earth's magnetic field.

10 The rate of fluid flow within a vessel can be measured using the induced EMF when the fluid contains charged ions. A small magnet and a sensitive voltmeter calibrated to measure speed are used. This can be applied to measure the flow of blood (which contains iron in solution) in the human body.

The diameter of a particular artery is 2.00 mm, the strength of the magnetic field applied is 0.10 T and the measured EMF is 0.10 mV. Determine the speed of the flow of the blood within the artery.



11 Consider the conductor shown in Figure 9.2.4 on page 194, which is moving inside a vertical magnetic field. In the instant shown in the diagram, the conductor is moving to the left and positive charges are pushed along the conductor out of the page. Predict what will happen to the charge separation if the conductor:

a moves to the right

b continuously oscillates horizontally back and forth inside the magnetic field.

9.3 Faraday's law

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

- describe Faraday's law of induction
- use Faraday's law to calculate the EMF induced by a changing magnetic flux.

FACTORS AFFECTING INDUCED EMF

Faraday's early experiments largely centred on investigating electromagnetic induction in coils or multiple loops of wire. Faraday found that if a magnet is moved quickly into a coil, an EMF is induced, which causes a current to flow in the coil. If the magnet is removed, then a current flows in the coil in the opposite direction. Alternatively, if the magnet is held steady and the coil is moved in a way that changes the magnetic flux, then once again an EMF is induced and an electric current flows. It doesn't matter whether the coil or the magnet is moved—it is a *change* in flux that is required to induce the EMF.

Faraday quantitatively investigated the factors affecting the size of the EMF induced in a coil. First, an EMF will be induced by a change in the magnetic field. A simple example of this is to witness the EMF induced when a magnet is brought towards or moved away from a wire coil. The greater the change, the greater the EMF.

However, Faraday found that it is not only a change in the strength of a magnetic field, B, that induces an EMF. An EMF can also be induced by changing the area perpendicular to the magnetic field through which the magnetic field lines pass, A, while keeping B constant. Alternatively, an EMF is induced when the angle through which the magnetic field lines pass through a perpendicular area is changed. An example of this is to witness the EMF induced when a wire coil is rotated in the presence of a fixed magnetic field. This discovery indicates that the requirement for an induced EMF is to have a *changing magnetic flux*, Φ.

Finally, Faraday discovered that the faster the change in magnetic flux, the greater the induced EMF.

FARADAY'S LAW OF INDUCTION

In the previous module, it was shown that the EMF generated as a straight conductor of length l moves with speed v through a perpendicular magnetic field of strength B is:

$$\varepsilon = lvB$$

Consider a wire of length l moving through a perpendicular magnetic field as shown in Figure 9.3.1. As the wire moves with speed v, it sweeps across lines of magnetic flux. In time Δt the wire moves a distance of $v\Delta t$ and sweeps through an area of $lv\Delta t$. The amount of flux that is swept through is then

$$\Delta\Phi = B\Delta A = Blv\Delta t$$

This can be written as:

$$Blv = \frac{\Delta\Phi}{\Delta t}$$

But $\varepsilon = lvB$, so $\varepsilon = \frac{\Delta\Phi}{\Delta t}$.

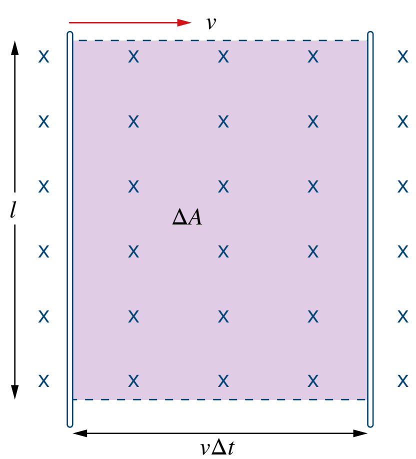


FIGURE 9.3.1 The area, ΔA (shaded), swept out by the wire in the field, B in time, Δt is equal to $lv\Delta t$.

The magnitude of the EMF generated in the wire is equal to the rate at which the wire is sweeping through the flux. Although this derivation was for a straight wire moving across a magnetic field, it is also true whenever a change in flux gives rise to an EMF.

This is now known as **Faraday's law** of induction and is one of the basic laws of electromagnetism.

Magnetic flux is defined as $\Phi = B_{\perp}A$.

If the flux through n turns (or loops) of a coil changes from Φ_1 to Φ_2 during a time t, then the average induced EMF during this time will be:

$$\varepsilon = -n\frac{(\Phi_2 - \Phi_1)}{t}$$

and if the change in magnetic flux $\Phi_2 - \Phi_1 = \Delta\Phi$, then:

$$\varepsilon = -\frac{n\Delta(BA_{\perp})}{\Delta t}$$

This can also be written as

$$\varepsilon = -n\frac{\Delta\Phi}{\Delta t}$$

The negative sign is placed there as a reminder of the direction of the induced EMF. This is discussed further in Module 9.4. In general you will be concerned only with the magnitude of the EMF, which means you don't consider the negative sign or any negative quantities in a calculation.

If the ends of the coil are connected to an external circuit, then a current, I, will flow. The magnitude of the current is found using Ohm's law:

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

where

R is the resistance

V is the EMF of the coil.

A coil not connected to a circuit will act like a battery not connected to a circuit. There will still be an induced EMF but no current will flow.

It is important to note that any change in magnetic flux will, by Faraday's law, produce an EMF. The magnetic flux could change in a number of ways, or in a combination of a number of factors, such as a change in the:

- area of coil
- magnetic field strength
- angle of flux threading a loop.

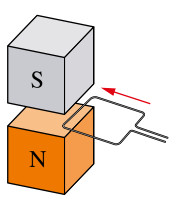
When using Faraday's Law, n is the number of loops of a coil that the magnet flux is cutting.

Don't confuse this with the magnetic field of a solenoid where n is the number of loops per metre.

Worked example 9.3.1

INDUCED EMF IN A COIL

A student winds a coil of area 40.0 cm^2 and places it horizontally in a vertical uniform magnetic field of 0.10 T, as shown below.



a Calculate the magnetic flux perpendicular to the coil.

Thinking	Working
Identify the quantities to calculate the magnetic flux through the coil and convert to SI units where required.	$B = 0.10\,\text{T}$ $A = 40\,\text{cm}^2 = 40 \times 10^{-4}\,\text{m}^2$
Calculate the magnetic flux and give your answer with appropriate units.	$\Phi = B_{\perp}A$ $= 0.10 \times 40 \times 10^{-4}$ $= 4.0 \times 10^{-4}\,\text{Wb}$

Worked example 9.3.1 *continued*

b Calculate the magnitude of the average induced EMF in the coil when the coil is removed from the magnetic field in a time of 0.5 s.	
Identify the quantities for determining the induced EMF. Ignore the negative sign.	$\Delta\Phi = \Phi_2 - \Phi_1$ $= 0 - 4.0 \times 10^{-4}$ $= 4.0 \times 10^{-4}$ Wb $\Delta t = 0.5$ s
Calculate the magnitude of the average induced EMF, ignoring the negative sign that indicates the direction.	$\varepsilon = -n\frac{\Delta\Phi}{\Delta t}$ $= \frac{4.0 \times 10^{-4}}{0.5}$ $= 0.0008$ V or 8.0×10^{-4} V

➤ Try yourself 9.3.1

INDUCED EMF IN A COIL

Laura winds a coil of area 50.0 cm^2 with exactly 10 turns. She places it horizontally in a vertical uniform magnetic field of 0.10 T.

a Calculate the magnetic flux perpendicular to the coil.

b Calculate the magnitude of the average induced EMF in the coil when the coil is removed from the magnetic field in a time of 1.0 s.

Worked example 9.3.2

NUMBER OF TURNS IN A COIL

A coil of cross-sectional area 1.0×10^{-3} m^2 is placed next to an electromagnet that is initially turned off. When it is switched on, the magnetic field strength increases from zero to 0.20 T in 0.50 s. The magnitude of the average induced EMF is measured as 0.10 V. Determine the number of turns that must be on the coil.	
Thinking	**Working**
Identify the quantities needed to calculate the magnetic flux through the coil when in the presence of the magnetic field and convert to SI units where required.	$B = 0.20$ T $A = 1.0 \times 10^{-3}$ m^2
Calculate the magnetic flux when in the presence of the magnetic field.	$\Phi = B_{\perp}A$ $= 0.20 \times 1.0 \times 10^{-3}$ $= 2.0 \times 10^{-4}$ Wb
List the known quantities and those required to complete Faraday's law.	$n = ?$ $\Delta\Phi = \Phi_2 - \Phi_1$ $= 2.0 \times 10^{-4} - 0$ $= 2.0 \times 10^{-4}$ Wb $\Delta t = 0.50$ s $\varepsilon = 0.10$ V
Rearrange Faraday's law and solve for the number of turns on the coil, *n*. Ignore the negative sign.	$\varepsilon = -n\frac{\Delta\Phi}{\Delta t}$ $n = \frac{\varepsilon\Delta t}{-\Delta\Phi}$ $= \frac{0.10 \times 0.50}{2.0 \times 10^{-4}}$ $= 250$ turns

➤ Try yourself 9.3.2

NUMBER OF TURNS IN A COIL

A coil of cross-sectional area $2.0 \times 10^{-3}\,m^2$ is placed next to an electromagnet that is initially turned off. When it is switched on, the magnetic field strength increases from zero to 0.20 T in 1.00 s. The magnitude of the average induced EMF is measured as 0.40 V. Determine the number of turns that must be on the coil.

PA 3.2.4

9.3 Review

SUMMARY

- The EMF induced in a conducting loop in which there is a changing magnetic flux is proportional to the negative rate of change of flux.
- $\varepsilon = -n\frac{\Delta\Phi}{\Delta t}$, which is Faraday's law of induction. This can also be written as $\varepsilon = -\frac{n\Delta(BA_\perp)}{\Delta t}$
- n is the number of loops or coils of wire that the magnetic flux is cutting.
- According to Faraday's law, an EMF can be induced by a change in:
  - the area of a coil
  - the number of coils inside a magnetic field
  - magnetic field strength
  - angle of flux threading a loop
  - timeframe in which flux is being altered.
- The negative sign in Faraday's law indicates direction. For questions involving only magnitudes, you should not use the negative sign or any negative quantities.

KEY QUESTIONS

Retrieval

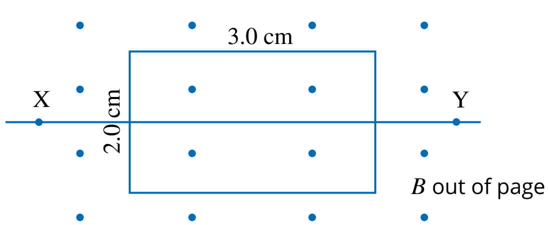
1 Faraday's law states that a changing magnetic flux will produce an EMF. Recall the units of EMF.

2 State three ways in which the magnetic flux through a loop in a magnetic field may change.

Comprehension

The following information relates to questions 3–5.

A single rectangular wire loop is placed with its plane perpendicular to a uniform magnetic field of 2.0 mT directed out of the page, as shown below. The loop is free to rotate about a horizontal axis XY.

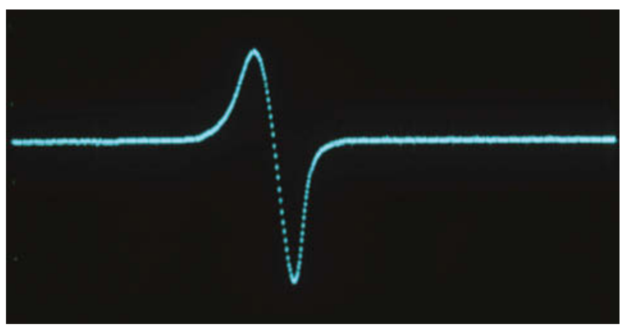


3 Determine how much magnetic flux is threading the loop in this position.

4 The loop is rotated about the axis XY through an angle of 90° so that its plane is now parallel to the magnetic field. Describe how much flux is threading the loop in this new position.

5 Determine the average induced EMF in the loop if the loop completes one-quarter of a rotation in 40.0 ms.

6 When a magnet is dropped through a coil, a voltage sensor will detect an induced voltage in the coil as shown below.



a Explain, in terms of Faraday's law and induced EMF, why the pulse shown changes from a positive to a negative.

b Explain why the pulse magnitude is larger on the negative side than the positive side.

continued over page

9.3 Review *continued*

Analysis

7 A wire coil consisting of a single turn is placed perpendicular to a magnetic field that experiences a decrease in strength of 0.10 T in 0.050 s. Calculate the area of the coil if the EMF induced in the coil is 0.020 V.

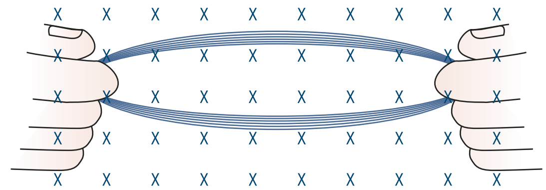
The following information relates to questions 8 and 9.

A coil of exactly 500 turns, each of area 10.0 cm^2, is wound around a square frame. The plane of the coil is initially parallel to a uniform magnetic field of 80.0 mT. The coil is then rotated through an angle of 90.0° so that the coil is now perpendicular to the field. The rotation is completed in 20.0 ms.

8 Calculate the magnitude of the average EMF induced in each turn of the coil during this time.

9 Calculate the total average EMF induced in the coil during the time the coil rotated.

10 Gayathri stretches a flexible wire coil of exactly 30 turns and places it in a uniform magnetic field of strength 5.0 mT that is directed into the page, as shown in the diagram to the right. While it is in the field, she allows the coil to regain its original shape. In doing so, the area of the coil changes at a constant rate from 250 cm^2 to 50.0 cm^2 in 0.50 s. Determine the average EMF induced in the coil during this time.



11 Abigail has a flexible wire coil of variable area of exactly 100 turns and a strong bar magnet, which has been measured to produce a magnetic field of strength B = 100.0 mT a short distance from it. Abigail has been instructed to demonstrate electromagnetic induction by using this equipment to light up an LED rated at 1.0 V. Consider one method by which she could complete this task. Include appropriate calculations in the explanation.

9.4 Lenz's law and its applications

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

- describe how to find the direction of the induced current in a conductor according to Lenz's law
- explain that Lenz's law is predicted by the law of conservation of energy.

In the previous section Faraday's law of induction was introduced.

$$\varepsilon = -\frac{n\Delta(BA_{\perp})}{\Delta t}$$

This can also be written as

$$\varepsilon = -n\frac{\Delta\Phi}{\Delta t}$$

The negative sign is there to remind you of the direction in which the induced EMF acts—that is, in which direction current flows as a result of the induced EMF.

Lenz's law, which is the focus of this section, is a common way of understanding how electromagnetic induction obeys the principle of conservation of energy and explains the direction of the induced EMF. It is named after Heinrich Lenz, whose research put a definite direction to the current created by the induced EMF resulting from a changing magnetic flux.

Understanding the direction of the current resulting from an induced EMF and how it is produced has allowed electromagnetic induction to be used in a vast array of devices that have transformed modern society, in particular in electrical generators. A metal detector is one example of a device that uses Lenz's law (Figure 9.4.1).

FIGURE 9.4.1 A diver uses a metal detector. If a metal object is found underneath the coil of the detector, an EMF will be induced which creates a current that will affect the original current. The direction of the induced current is predicted by using Lenz's law.

THE DIRECTION OF AN INDUCED EMF

Lenz's law states that the direction of an induced current is such that it will always oppose the *change in flux* that created it.

Figure 9.4.2 applies Lenz's law to the relative motion between a magnet and a single coil of wire. Moving the magnet towards or away from the coil will induce an EMF in the coil, as there is a change in flux. The induced EMF will produce a current in the coil. This induced current will then produce its own magnetic field. It is worth noting that Lenz's law is a necessary consequence of the law of conservation of energy: if Lenz's law were not true then the new magnetic field created by a changing flux would increase the original changing flux, which in turn would create more current, and so on. This violates the law of conservation of energy.

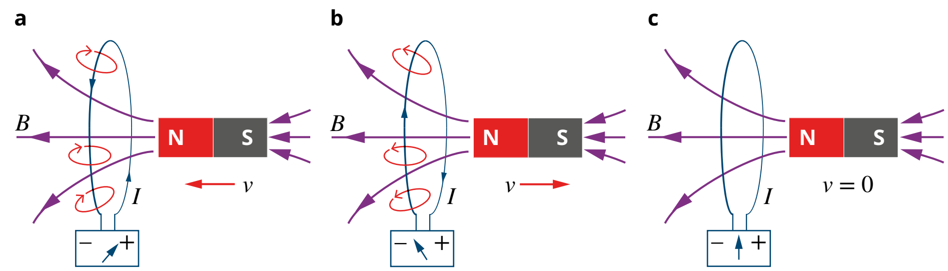


FIGURE 9.4.2 (a) The north end of a magnet is brought towards a coil from right to left, inducing a current that flows anticlockwise. (b) Pulling the north end of the magnet away from the coil from left to right induces a current in a clockwise direction. (c) Holding the magnet still creates no change in flux and hence no induced current.

Applying Lenz's law, the magnetic field created by the induced current will oppose the change in flux caused by the movement of the magnet. When the north end of a magnet is brought towards the loop from the right (Figure 9.4.2a), there is an increase in the magnetic flux from right to left through the loop. The induced EMF produces a current that flows anticlockwise around the loop when viewed from the right. The magnetic field created by this current, shown by the little circles around the wire, is directed from left to right through the loop. It opposes the magnetic field of the approaching magnet.

If the magnet is moved away from the loop (Figure 9.4.2b), the magnetic flux from right to left through the loop decreases. The induced EMF produces a clockwise current when viewed from the right. This creates a magnetic field that is directed from right to left through the loop. This field is in the same direction as the original magnetic field of the retreating magnet. However, note that it is opposing the change in the magnet's flux through the loop by attempting to replace the declining flux.

When the magnet is held stationary (Figure 9.4.2c) there is no change in flux to oppose and so no current is induced.

THE RIGHT-HAND GRIP RULE AND INDUCED CURRENT DIRECTION

The right-hand grip rule (see Chapter 8) can be used to find the direction of the induced current. Keep in mind that the current must create a magnetic field that opposes the change in flux due to the relative motion of the magnet and conductor. Point your fingers through the loop in the direction of the field that is *opposing* the change and your thumb will then indicate the direction of the conventional current (Figure 9.4.3).

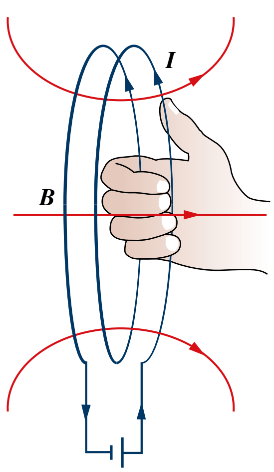


FIGURE 9.4.3 The right-hand grip rule can be used to determine the direction of a magnetic field from a current or vice versa. Your thumb points in the direction of the conventional current in the wire and your curled fingers indicate the direction of the magnetic field through the coil.

There are three distinct steps to determine the induced current direction according to Lenz's law:

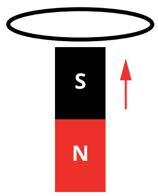
1 What is the change in flux that is happening?
2 What will *oppose* this change in flux?
3 What must be the direction of the current that would match this opposition?

The three steps to determine the induced current direction according to Lenz's law are further examined in Worked example 9.4.1.

Worked example 9.4.1

INDUCED CURRENT IN A COIL FROM A PERMANENT MAGNET

The south pole of a magnet is brought upwards towards a horizontal coil held above it. Determine the direction of the induced current flow in the coil.

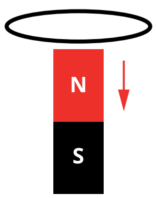


Thinking	Working
Consider the direction of the change in magnetic flux.	The magnetic field direction from the magnet will be downwards towards the north pole. The downwards flux from the magnet will increase as the magnet is brought closer to the coil. So the change in flux is increasing downwards.
What will oppose the change in flux?	The induced magnetic field that opposes the change would act upwards.
Determine the direction of the induced current required to oppose the change.	In order to oppose the change, the current direction would be anticlockwise when viewed from above (using the right-hand grip rule).

➤ Try yourself 9.4.1

INDUCED CURRENT IN A COIL FROM A PERMANENT MAGNET

The north pole of a magnet is moved downwards away from a horizontal coil held above it. Determine the direction of the induced current flow in the coil.



Worked example 9.4.2

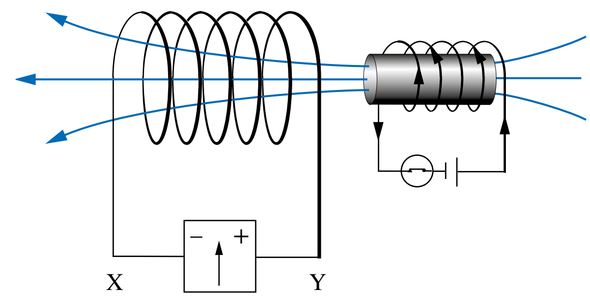
INDUCED CURRENT IN A COIL FROM AN ELECTROMAGNET

Instead of using a permanent magnet to change the flux in the loop as in Worked example 9.4.1, an electromagnet (on the right in the diagram below) could be used. Determine the direction of the current induced in the solenoid when the electromagnet is:

i switched on

ii left on

iii switched off.



Thinking	**Working**
Consider the direction of the change in magnetic flux for each case.	**i** Initially there is no magnetic flux through the solenoid. When the electromagnet is switched on, the electromagnet creates a magnetic field directed to the left. So the change in flux through the solenoid is increasing to the left. **ii** While the current in the electromagnet is steady, the magnetic flux through the solenoid is constant. **iii** In this case, initially there is a magnetic flux through the solenoid from the electromagnet directed to the left. When the electromagnet is switched off, there is no longer a magnetic flux through the solenoid. So the change in flux through the solenoid is decreasing to the left.
Identify what will oppose the change in flux for each case.	**i** The magnetic field that opposes the change in flux through the solenoid is directed to the right. **ii** There is no change in flux and so there will be no opposition needed and no magnetic field created by the solenoid. **iii** The magnetic field that opposes the change in flux through the solenoid is directed to the left.
Determine the direction of the induced current required to oppose the change for each case.	**i** In order to oppose the change, the current will flow through the solenoid in the direction from X to Y (or through the meter from Y to X), using the right-hand grip rule. **ii** There will be no induced EMF or current in the solenoid. **iii** In order to oppose the change, the current will flow through the solenoid in the direction from Y to X (or through the meter from X to Y), using the right-hand grip rule.

➤ Try yourself 9.4.2

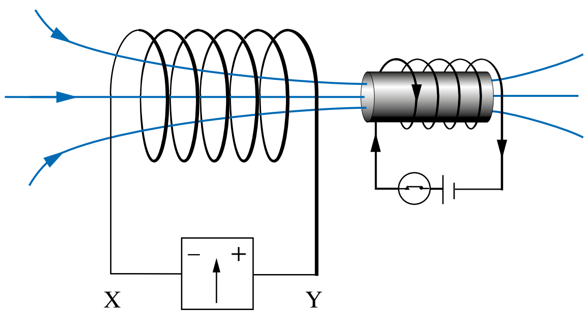
INDUCED CURRENT IN A COIL FROM AN ELECTROMAGNET

Refer to the diagram below. Determine the direction of the current induced in the solenoid when the electromagnet is:

i switched on

ii left on

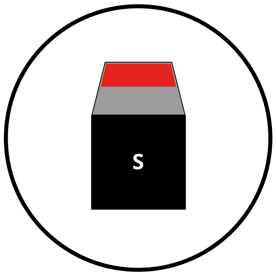
iii switched off.



Worked example 9.4.3

FURTHER PRACTICE WITH LENZ'S LAW

The north pole of a magnet is moving towards a coil, into the page. The south pole is shown at the top looking down in the diagram below. Determine the direction of the induced current flow in the coil while the magnet is moving towards the coil.

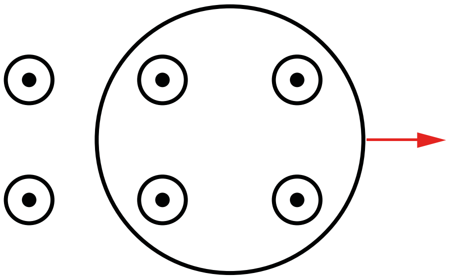


Thinking	Working
Consider the direction of the change in magnetic flux.	The magnetic field direction from the magnet will be away from the north pole, into the page. The flux from the magnet will increase as the magnet is brought closer to the coil. So the change in flux is increasing into the page.
Identify what will oppose the change in flux.	The magnetic field that opposes the change would act out of the page.
Determine the direction of the induced current required to oppose the change.	In order to oppose the change, the current direction would be anticlockwise when viewed from above (using the right-hand grip rule).

➤ Try yourself 9.4.3

FURTHER PRACTICE WITH LENZ'S LAW

A coil is moved to the right and out of a magnetic field that is directed out of the page. Determine the direction of the induced current flow in the coil while the magnet is moving.



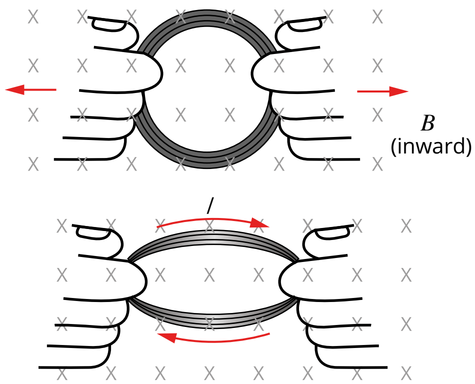


FIGURE 9.4.4 A current is induced by changing the area of a coil. The amount of flux (the number of field lines) through the coil is reduced and an EMF is therefore induced during the time that the change is taking place. The current flows in a direction that creates a field to oppose the reduction in flux into the page.

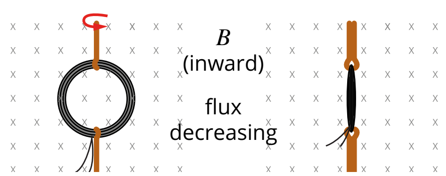


FIGURE 9.4.5 Changing the orientation of a coil within a magnetic field by rotating it reduces the amount of flux through the coil and so induces an EMF in the coil while it is being rotated.

DIFFERENT WAYS TO INDUCE CURRENT

It's important to note that an induced EMF is created while there is a change in flux, no matter how that change is created. As magnetic flux $\Phi = B_{\perp}A$, a change can be created by any method that causes a relative change in the strength of the magnetic field, B, and/or the area of the coil perpendicular to the magnetic field. So an induced EMF can be created in three ways:

- by changing the strength of the magnetic field
- by changing the area of the coil within the magnetic field
- by changing the orientation of the coil with respect to the direction of the magnetic field.

Figure 9.4.4 illustrates an example of the direction of an induced current that results during a decrease in the area of a coil.

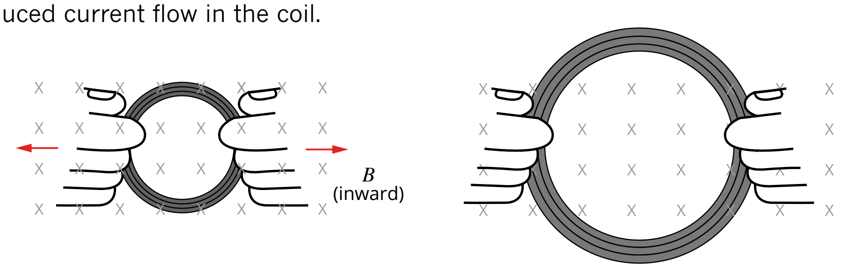
As the area of the coil decreases due to its changing shape, the flux through the coil (which is directed into the page) also decreases. Applying Lenz's law, the direction of the induced current would oppose this change and will be such that it acts to increase the magnetic flux through the coil into the page. Using the right-hand grip rule, a current would therefore flow in a clockwise direction while the area is changing.

In Figure 9.4.5, the coil is being rotated within the magnetic field. The effect is the same as reducing the area. The amount of flux flowing through the coil is reduced as the coil changes from being perpendicular to the field to being parallel to the field. An induced EMF would be created while the coil is being rotated. This becomes particularly important in determining the current direction in a generator.

Worked example 9.4.4

INDUCING AN EMF BY CHANGING THE AREA OF A COIL

A coil lies within a magnetic field that points into the page, as shown in the diagram. Initially the coil has a circular shape of radius 2.0 cm. Over a short time, the coil is stretched uniformly to double in radius. Determine the direction of the induced current flow in the coil.



Thinking	Working
Consider the direction of the change in magnetic flux.	The flux threading through the coil increases into the page as the area of the coil increases.
Identify what will oppose the change in flux.	The magnetic field that opposes the change would act out of the page.
Determine the direction of the induced current required to oppose the change.	In order to oppose the change, the current direction would be anticlockwise when viewed from above (using the right-hand grip rule).

➤ Try yourself 9.4.4

INDUCING AN EMF BY CHANGING THE AREA OF A COIL

A flexible square loop of wire lies within a magnetic field that points out of the page. Initially the coil is has been stretched so that its sides measure 5 cm. Over a short time, the coil is released and shrinks to its original size of 1 cm^2. Determine the direction of the induced current flow in the coil as it shrinks back to its original size.

APPLICATIONS OF LENZ'S LAW

If a conducting material such as metal plate encounters a changing magnetic field, then a circular current is induced within the conductor. These induced currents are called eddy currents.

Applying Lenz's law, an eddy current will be in a direction that creates a magnetic field that opposes the change in magnetic flux that created it. Thus, eddy currents can be used to apply a force that opposes the source of the motion of an external magnetic field. For example, if a metal plate is dragged out of a magnetic field, the magnetic flux directed into the plate decreases (Figure 9.4.6). An eddy current is induced inside the plate that opposes this change in flux. The eddy current moves in a clockwise direction and produces more flux through the plate. However, this eddy current within a magnetic field also experiences a magnetic force F, according to $F = BIL$. By the right-hand rule, this magnetic force acts to the left, opposing the motion of the plate and slowing it down.

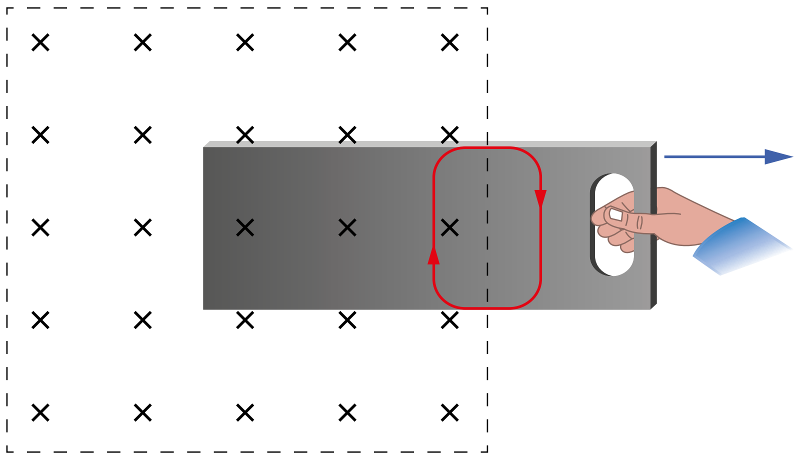


FIGURE 9.4.6 As the metal plate is moved to the right, out of the magnetic field that is directed into the page, an eddy current forms in a clockwise direction. This eddy current would resist the motion of the plate.

This is the basis of regenerative braking, by which the drag of the opposing magnetic field is utilised as a braking force.

Induction stoves also use eddy currents to operate. In contrast to a conventional gas or electric stove that heats via radiant heat from a hot source, an induction stove heats via the metal pot in which the food is being cooked. A coil of copper wire is placed within the cooktop (Figure 9.4.7). The **alternating current (AC)** electricity supply produces a changing magnetic field in the coil. This induces an eddy current in the conductive metal pot. The resistance of the metal in the pot, in which the eddy current flows, transforms electrical energy into heat and cooks the food.

While induction cooktops have only reached the domestic market in relatively recent times, the first patents for induction cookers where issued in the early 1900s. They have significant advantages over traditional electric cooktops in that they allow instant control of cooking power (similar to gas burners), they lose less energy through ambient heat loss and heating time, and they have a lower risk of burn injuries. Overall, the heating efficiency of an induction cooktop is about 12% better than traditional electric cooktops and twice that of gas.

While the heating effect of eddy currents is useful in an induction stovetop, it is a potentially major source of energy loss within an AC generator, motor or transformer. Laminated cores with insulating material between the thin layers of iron are used in these applications to reduce the overall conductivity and suppress eddy currents. However, if an eddy current was produced in a conductor that had very little, or no resistance (a superconductor), then the eddy current would not die away. How this property could be used is discussed in the Science as a Human Endeavour feature on the next page.

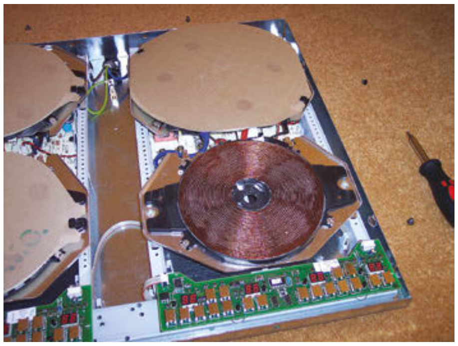


FIGURE 9.4.7 The coil of an induction zone within an induction cooktop. The large copper coil creates an alternating magnetic field.

WS 3.2.9

PA 3.2.3

SCIENCE AS A HUMAN ENDEAVOUR

Superconductivity

Superconductors are materials that have no resistance to the flow of electric current. Materials that act as superconductors open up a world of exciting applications in physics. The history of the discovery of superconductors has its beginnings in the early 1900s in the Netherlands, but the theories of producing and utilising these materials are constantly being revised and restructured.

Technological breakthroughs have often led to advances in physics. This was the case in 1908 when Kamerlingh Onnes, at the University of Leiden in the Netherlands, succeeded in liquefying helium. Helium liquefies at 4.2 K (–268.9°C). It was known that the electrical resistance of metals decreases as they cool, so one of the first things that Onnes and his assistant did was to measure the resistance of some metals at these very low temperatures.

Onnes was hoping to find that as the temperature of mercury dropped towards absolute zero its resistance would also gradually drop towards zero. What they found, however, was a complete surprise. At 4.2 K its resistance vanished completely!

Onnes coined the word ‘superconductivity’ to describe this phenomenon. Soon he found that some other metals also became superconducting at extremely low temperatures: lead at 7.2 K and tin at 3.7 K, for example. Curiously, metals such as copper and gold, which are very good conductors at normal temperatures, do not become superconducting at all. Onnes was awarded the 1913 Nobel Prize in Physics for his work in low-temperature physics.

Unfortunately, the superconducting metals lost their superconductivity in magnetic fields of about 0.1 T, which is quite a moderate field. However, in the 1940s it was found that some alloys of elements such as niobium had higher ‘critical temperatures’ and, more particularly, retained their properties in stronger magnetic fields. By 1973 the niobium–germanium alloy Nb_3Ge held the record with a critical temperature of 23.2 K in a critical field of 38 T, an extremely strong field.

In 1986 an entirely new and exciting class of superconductors was discovered. Georg Bednorz and Karl Müller, working in Switzerland, found that compounds of some rare earth elements and copper oxide had considerably higher critical temperatures. They received the 1987 Nobel Prize in Physics for their work.

These new high-temperature superconductors are ceramic materials made by powdering and baking the metal compounds. Most ceramics are insulators; it was a combination of good science and inspired guesswork that led Müller to try such unlikely candidates for superconductivity. So far, the record is held by solid hydrogen sulfide under very high pressure with a critical temperature, T_c of about 203 K—still rather cold, but significantly above the temperature of readily available liquid nitrogen (77 K). The abundance of nitrogen gas in the atmosphere (78%) makes liquid nitrogen a much cheaper alternative than liquid helium to use to cool superconducting materials. In the years since the discovery of high temperature conductors, there have been many breakthroughs in the discovery of both low- and high-temperature superconductors (Figure 9.4.9).

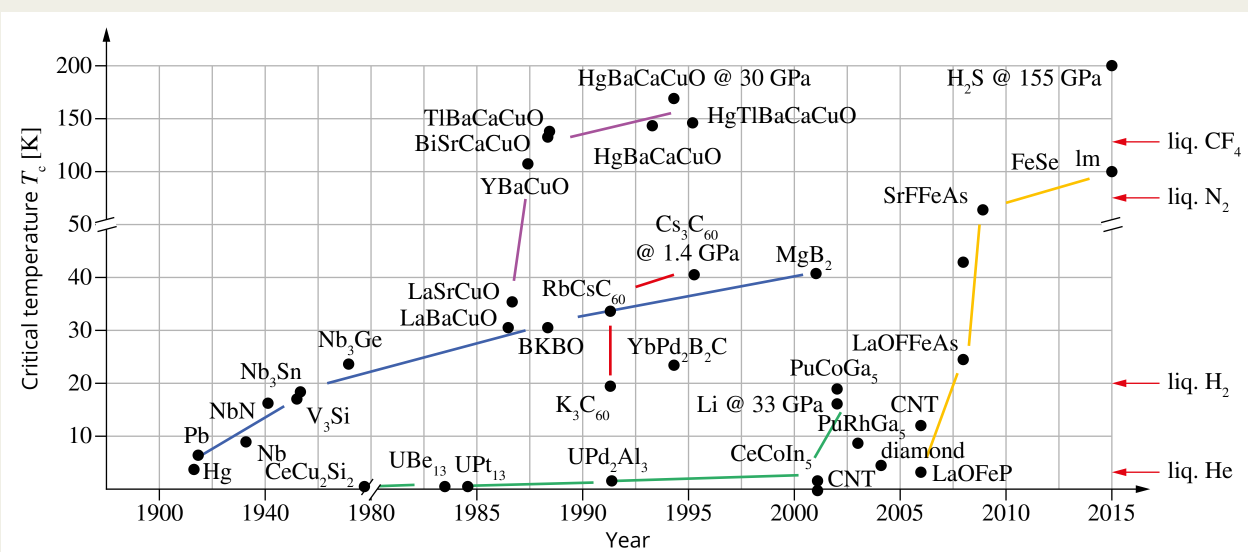


FIGURE 9.4.9 Since its beginnings in the early 1900s, enormous advances have been made in the increase of the critical temperature of superconducting materials.

Superconductivity, particularly in the newer materials, is still not fully understood. It can really only be discussed in terms of quantum physics, but one rather picturesque way of thinking about it is that electrons pair up and 'surf' electrical waves set up by each other in the crystal lattice of the material.

Much of the great promise of superconductivity has to do with the magnetic properties of superconductors. If an eddy current was produced in a conductor that had very little or no resistance, then the eddy current would not die away. If a magnet is brought near a superconductor, the induced current will create a flux within the superconductor that opposes the field of the magnet and repels the magnet. This results in magnetic levitation (Figure 9.4.8) and this phenomenon is called the Meissner effect.

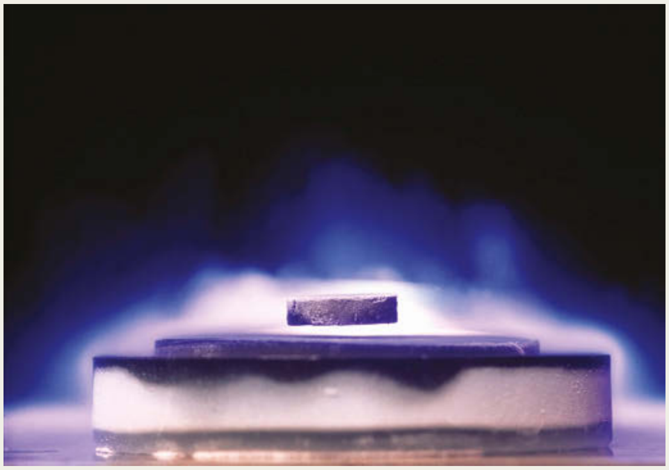


FIGURE 9.4.8 A disc magnet is repelled by a superconductor because the magnet induces a permanent current into the superconductor, which results in an opposing field.

The promise of superconductivity is enormous: low friction transport, no-loss transmission of electricity, and smaller and more powerful electric motors and generators. Superconducting magnets might be used to contain the extremely hot plasma needed to bring about hydrogen fusion, producing almost pollution-free energy in much the same way that the Sun does. There are, however, many difficulties to be overcome before these promises can be realised.

Review

1 **a** Describe one of the first experiments that Kamerlingh Onnes and his assistant completed after they had successfully liquefied helium.

b Explain why these scientists carried out this experiment.

2 Describe the Meissner effect and how this effect is useful.

3 Despite the advances in superconductor technology, these materials have not yet replaced electric circuits commonly in use today. Furthermore, there are many theories and heated debates about how superconductivity works. Conduct some research to outline what cuprates and pnictides are and how these materials are used as superconductors.

9.4 Review

SUMMARY

- Lenz's law states that the direction of an induced current is such that it will always oppose the *change in flux* that created it.
- There are three distinct steps to determine the induced current direction according to Lenz's law:
  1 What is the change in flux that is happening?
  2 What will oppose this change in flux?
  3 What must be the direction of the current that would match this opposition?
- Regenerative braking, metal detectors and induction stoves are examples of devices that utilise eddy currents produced in conducting materials due to Lenz's law.

9.4 Review *continued*

KEY QUESTIONS

Retrieval

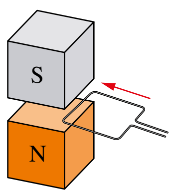
1 Recall the meaning of the negative sign in Faraday's law.

2 The north pole of a magnet moves left towards a loop. Identify whether the magnetic flux to the left increases or decreases.

3 State the rule used to find the direction of induced current.

Comprehension

4 Imagine that a wire coil is inserted into a magnetic field as shown below.



a Describe the direction of the initial flux threading the square loop.

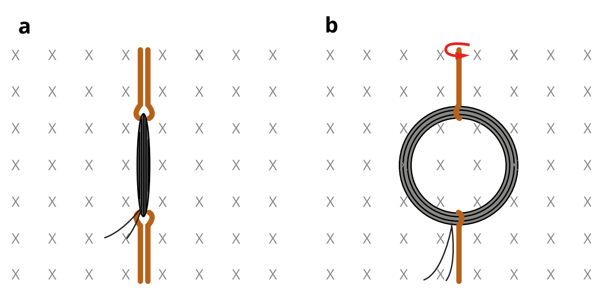
b Describe the direction of the flux threading the loop once it has been inserted into the field.

c Determine the direction of the change in magnetic flux through the loop.

d Determine the direction of the flux created by the induced EMF.

e Determine the direction of the induced current in the loop.

5 Consider a coil rotating in a magnetic field, as in the diagram below. The coil is rotating anticlockwise when viewed from above, from a position of minimum (a) to maximum (b) flux.



a Determine the direction of the initial flux threading the loop.

b Determine the direction of the flux threading the loop in its final position.

c Determine the direction of the change in magnetic flux through the loop.

d Determine the direction of the induced current in the loop.

6 A conducting loop is located at right angles to an external magnetic field. The magnetic field strength is constantly increasing in size and acts from left to right. A current is induced in the loop. Determine the direction of the current.

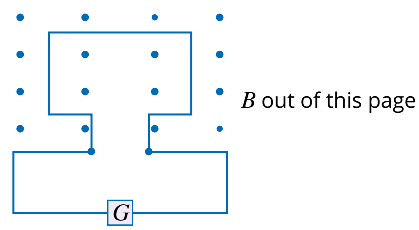
7 Explain when an eddy current is produced and discuss how an eddy current can be used in magnetic braking applications.

Analysis

8 A rectangular conducting loop forms the circuit shown below. The plane of the loop is perpendicular to an external magnetic field whose magnitude and direction can be varied. The initial direction of the field is out of the page.

a Deduce the direction of the magnetic field due to the induced current when the magnetic field is switched off.

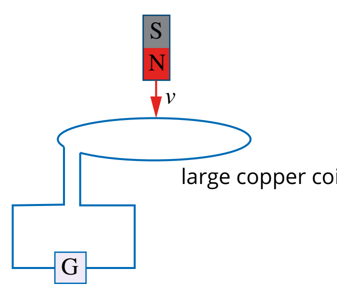
b Determine the direction of the magnetic field due to the induced current when the direction of the magnetic field is reversed.



9 A bar magnet is falling towards the centre of a horizontal copper coil, as shown below.

a Determine the direction (as seen from above) of the induced current in the coil when the magnet is in the position shown in the diagram.

b List four factors that would influence the magnitude of the induced current in the copper coil.



9.5 Electric power generators

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

- outline how a magnetic flux varies in an AC generator and how an EMF is induced
- describe how carbon brushes and slip rings enable an AC generator to operate.

Today we take the supply of electric power to our homes, schools and businesses for granted, but electric lighting has only existed for about 150 years.

The electric **generator** is probably the most important practical application of Faraday's discovery of electromagnetic induction. The principle of electric power generators is the same whether the result is alternating current (AC) or direct current (DC). Relative motion between a coil and a magnetic field induces an EMF in the coil. In small generators, the coil is rotated within a magnetic field, but in large power stations, car alternators and other industrial-level production, the coils are stationary and an electromagnet rotates inside them.

This might all sound quite similar to the way electric motors work (see Module 8.6). In fact, it is—a generator is basically just the inverse of a motor.

INDUCED EMF IN AN ALTERNATOR OR GENERATOR

A basic electric generator, or **alternator**, consists of many coils of wire wound on an iron core framework. This is called an **armature** and it is made to rotate in a magnetic field. The axle is turned by some mechanical means—mechanical energy is being converted to electrical energy—and an EMF is induced in the rotating coil.

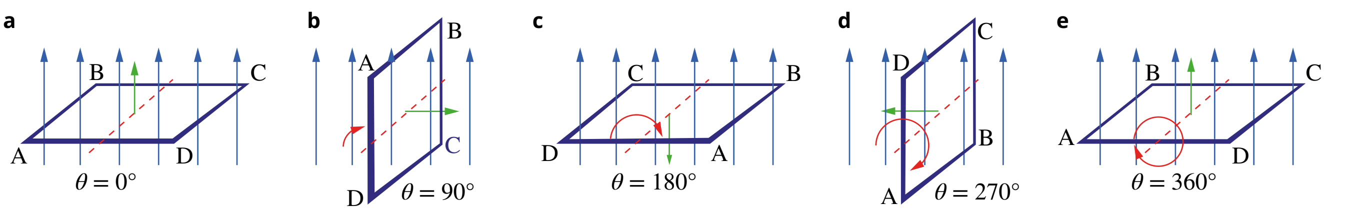


FIGURE 9.5.1 A single loop of a generator rotating in a magnetic field. (a) The plane of the area of the loop is perpendicular to the field B and the amount of flux $\Phi = BA$ is at a maximum. (b) The loop has turned one quarter of a turn and is parallel to the field; $\Phi = 0$. (c) As the loop continues to turn, the flux increases to a maximum but in the opposite sense relative to the loop in (a); $\Phi = -BA$. (d) The flux then decreases to zero again as the loop is parallel to the field before repeating the cycle again from (e) onwards.

Consider a single loop of wire in a generator (Figure 9.5.1). The loop is rotated clockwise, at constant speed, in a uniform magnetic field, B. The amount of flux threading through the loop will vary as it rotates. It is this change in flux that induces the EMF.

Lenz's law tells you that as the flux in the loop decreases from position (a) to (b) in Figure 9.5.1, the induced current will be in a direction such as to restore a magnetic field in the same direction, relative to the loop, as the external field. The right-hand grip rule can be used to show that the direction of the induced current will be D → C → B → A.

The direction of the induced current will reverse every time the plane of the loop reaches a point perpendicular to the field. The magnitude of the induced EMF will be determined by the rate at which the loop is rotating, according to Faraday's law. It will be a maximum when the rate of change of flux is a maximum. This is when the loop has moved to a position parallel to the magnetic field and the flux through the loop is zero, i.e. the gradient of the graph of flux versus angle shown in Figure 9.5.2 is a maximum. Note that this graph can also be construed as flux versus time, as the speed of rotation is constant.

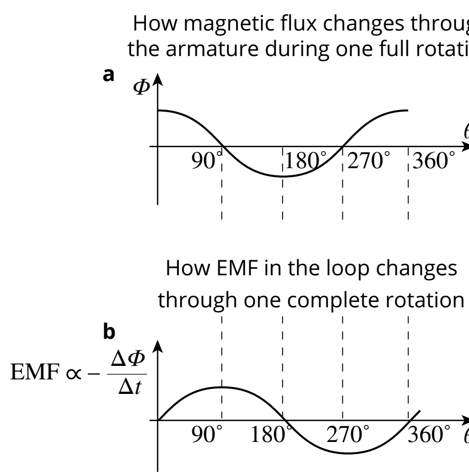


FIGURE 9.5.2 (a) The flux, Φ, through the loop of Figure 9.5.1 as a function of the angle between the field and the normal to the plane of the area, θ. (b) The rate of change of flux and hence EMF through the loop as a function of the angle between the field and the normal to the plane of the loop, θ. The loop is rotating at a constant speed.

An alternative way to think about how the EMF changes as the loop rotates is to remember that the EMF is actually created as the wires AB and CD cut across the magnetic field lines. Maximum EMF occurs when these wires cut the magnetic field lines perpendicularly, when θ is 90° or 270°, and zero EMF occurs when the motion of these wires is parallel to the field lines, i.e. when θ is 0°, 180° or 360°.

AC GENERATORS AND ALTERNATORS

A generator's construction is basically the same as a motor. The main components of an AC generator are shown in Figure 9.5.3.

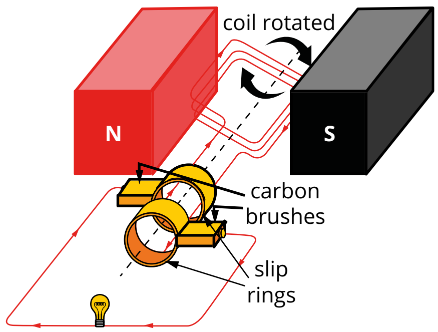


FIGURE 9.5.3 A schematic of an AC generator showing the main features.

Consider a coil, or armature, with a number of turns being rotated in a magnetic field and inducing an EMF (Figure 9.5.1). The resultant EMF alternates in direction, as shown by the graph going above and below the zero EMF line in Figure 9.5.2. This type of EMF or voltage produces an alternating current in the coil. How this alternating current is harnessed determines if the device is an AC alternator or a DC generator.

If the output from the coils is transferred to a circuit via continuous **slip rings**, the alternating current in the coil will be maintained at the output. The slip rings also allow the coil to rotate without tangling. Carbon **brushes** press against the slip rings to allow a constant output to be transferred to a circuit without a fixed point of connection.

ALTERNATING VOLTAGE AND CURRENT

An AC generator produces an alternating current that varies sinusoidally over time with the change in magnetic flux. The maximum EMF is only achieved at particular points in time. In Australia, mains power oscillates at 50 Hz and reaches a peak voltage of ±340 V each cycle, or a peak-to-peak voltage of 680 V (Figure 9.5.4). The average value of Australian AC voltage is 240 V.

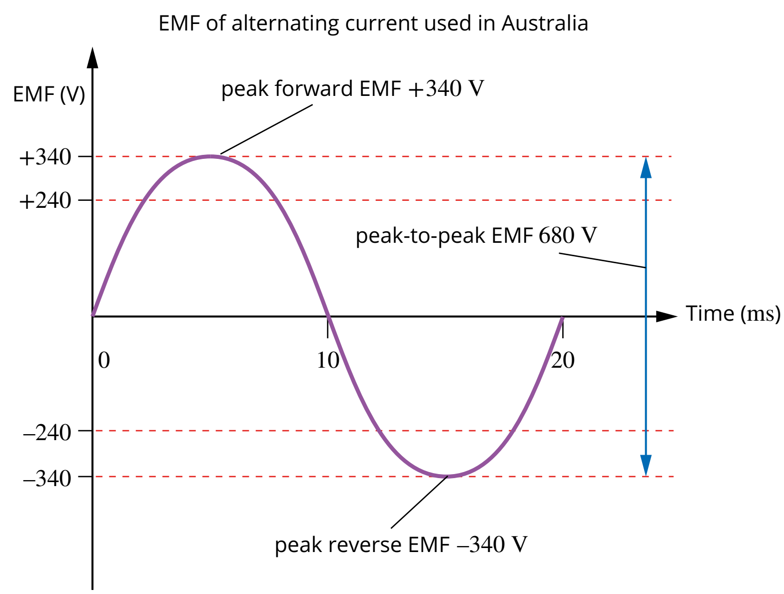


FIGURE 9.5.4 The voltage for Australian power points oscillates between +340 V and –340 V, 50 times each second. The value of a DC supply that would supply the same average power is 240 V.

9.5 Review

SUMMARY

- The principle of electric power generators is very similar to that of electric motors: relative motion between a coil and a magnetic field induces an EMF in the coil.
- The construction of a generator, or alternator, is very similar to that of an electric motor.
- A coil rotated in a magnetic field will produce an alternating induced current in the coil, with voltage and current varying as a sine wave.
- An AC alternator has slip rings that transfer the alternating current in the coil to the output.

KEY QUESTIONS

Retrieval

1 State the key principle of the operation of electric power generators.

2 Indicate whether the magnitude of the induced EMF will be at maximum or minimum when the rate of change of flux is a maximum.

Comprehension

3 According to Lenz's law, the magnitude of induced EMF is a maximum when the rate of change of magnetic flux is a maximum. This corresponds to the points of maximum gradient on a flux–time graph. Identify from Figure 9.5.2 on page 213 the angles of rotation for which this gradient is a maximum.

4 Assume that an anticlockwise rotation of a coil starting from $\theta = 0°$ perpendicular to a constant magnetic field initially produces a positive current. Draw a graph that best illustrates the variation in the induced EMF as a function of time for one full revolution of the coil.

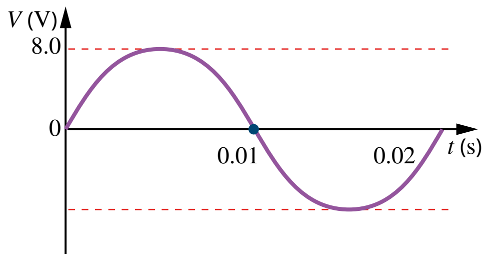
5 Describe the key components of a generator and their function, by completing the following table.

Component	Description	Function
armature		
carbon brushes		
slip rings		

Analysis

6 A simple generator consists of a coil of $n = 1000$ turns, each of radius 10 cm, mounted on an axis in a uniform magnetic field of strength, B. The following graph shows the voltage output as a function of time when the coil is rotated at a frequency of 50 Hz.

Voltage output over 0.02 s

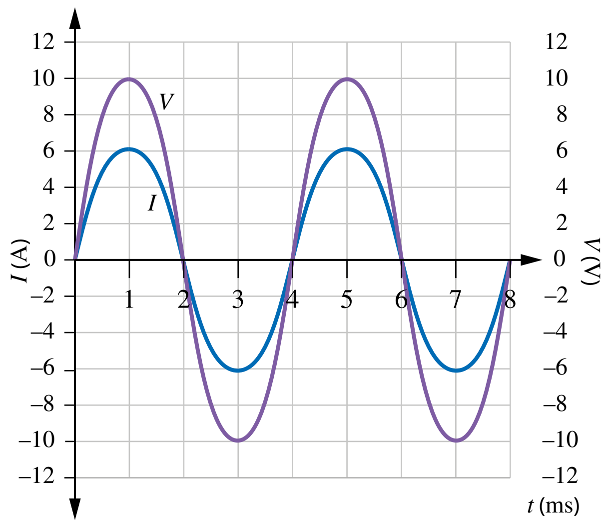


a Determine the value of the peak voltage.

b The generator is modified so that the magnetic field strength is doubled and the frequency of rotation is increased to 100 Hz. The radius of the coil is halved to 5.0 cm. Determine the peak output voltage of the generator now.

7 An AC supply of frequency 50 Hz is connected to a circuit, resulting in a peak current of 1.4 A being observed. Draw a graph that shows one full period of the variation of current with time for this circuit.

8 Arjun decides to test the output power of a new amplifier by using a voltage sensor to capture and display the alternating current I and voltage V that it produces. The result is shown in the graph below. Calculate the peak power rating possible for the amplifier.



9.6 Transformers

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

- explain how transformers work in terms of Faraday's law and electromagnetic induction.

When Faraday first discovered electromagnetic induction, he had effectively invented the transformer. A transformer is a device for increasing and decreasing an AC voltage. Transformers can be found in just about any electrical device and are an essential part of any electrical distribution system (Figure 9.6.1). They are the focus of this section.

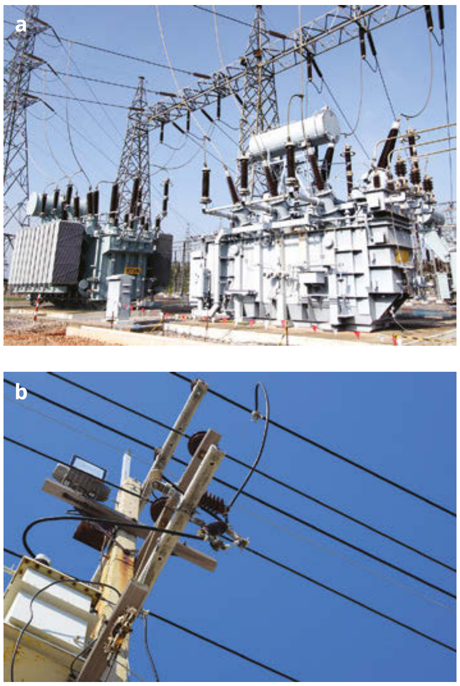


FIGURE 9.6.1 (a) View of transformers at an electrical substation. The substation takes electricity from the distribution grid and converts it to the lower voltages used by industrial or residential equipment. More common are the smaller distribution transformers, found on every suburban street (b). See if you can locate at least one on your street.

THE WORKINGS OF A TRANSFORMER

A **transformer** works on the principle of a changing magnetic flux inducing an EMF. No matter what the size or application, a transformer will consist of two coils known as the *primary* and *secondary* coils. The changing flux originates with the alternating current supplied to the primary coil. The changing magnetic flux is directed to the secondary coil where it will induce an EMF in that coil (Figure 9.6.2).

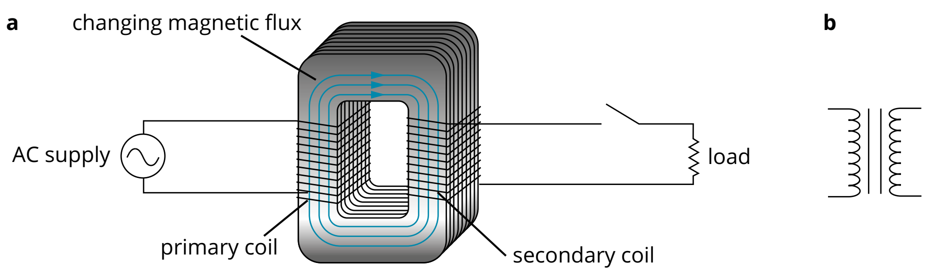


FIGURE 9.6.2 (a) In an ideal transformer, the iron core ensures that all the flux generated in the primary coil also passes through the secondary coil. (b) The symbol used in circuit diagrams for an iron-core transformer

The two coils can be interwoven using insulated wire, or they can be linked by a soft iron core. As discussed in Module 9.4, eddy currents are set up in the conducting iron core of transformers that experience a changing magnetic field. Eddy currents generate a considerable amount of heat, which reduces the efficiency of the transformer and could make the device a fire hazard. To reduce losses due to eddy currents, the core is made of laminations, which are thin plates of iron electrically insulated from each other and placed so that the insulation between the laminations interrupts the eddy currents. Transformers are designed so that nearly all of the magnetic flux produced by the primary coil will pass through the secondary coil. In an **ideal transformer**, the assumption is that this will be 100% efficient and energy losses can be ignored. In a real transformer, this assumption remains a good approximation. Transformers are one of the most efficient devices around, with practical efficiencies often being better than 99%.

AC VERSUS DC

A power distribution system works on alternating current. That may seem odd when many devices run on direct current, but one of the primary reasons is the ease with which alternating current can be transformed from one voltage to another.

A transformer works on the basis of a changing current in the primary coil inducing a changing magnetic flux. This in turn induces a current in the secondary coil. For this to work, the original current must be constantly changing, as it does in an AC supply.

A DC voltage has a constant, unchanging current. With no change in the size of the current, no changing magnetic flux will be created by the primary coil and, hence, no current is induced in the secondary coil. Transformers do not work with the constant current of a DC electrical supply. There will be a very brief induced current when a DC supply is turned on, and a change occurs from zero current to the supply level. There is a similar spike if the DC supply is switched off, but while the DC supply is constant there is no change in magnetic flux to induce a current in the secondary coil.

THE TRANSFORMER EQUATION

When an AC voltage is connected to the primary coil of a transformer, the changing magnetic field will induce an AC voltage of the same frequency as the original supply in the secondary coil. The voltage in the secondary coil will be different and depends upon the number of turns in each coil.

From Faraday's law, the average voltage in the primary coil, V_p, will affect the rate at which the magnetic flux changes:

$$V_p = n_p \frac{\Delta\Phi}{\Delta t}$$

or

$$\frac{\Delta\Phi}{\Delta t} = \frac{V_p}{n_p}$$

where n_p is the number of turns in the primary coil.

The induced voltage in the secondary coil, V_s, will be

$$V_s = n_s \frac{\Delta\Phi}{\Delta t}$$

and

$$\frac{\Delta\Phi}{\Delta t} = \frac{V_s}{n_s}$$

where n_s is the number of turns in the secondary coil.

Assuming that there is little or no loss of flux between the primary and secondary coil, then the flux in each will be the same and

$$\frac{V_p}{n_p} = \frac{V_s}{n_s}$$

or

$$\frac{V_s}{V_p} = \frac{n_s}{n_p}$$

The transformer equation, relating a voltage and number of turns in each coil, is:

$\frac{V_p}{V_s} = \frac{n_p}{n_s}$ or $\frac{V_s}{V_p} = \frac{n_s}{n_p}$ or $\frac{V_p}{n_p} = \frac{V_s}{n_s}$

where the subscript 'p' refers to the primary or first coil, and the subscript 's' refers to the secondary coil.

The transformer equation explains how the secondary (output) voltage is related to the primary (input) voltage. A **step-up transformer** increases the secondary voltage compared with the primary voltage. The secondary voltage is greater than the primary voltage and this is because the number of turns in the secondary coil is greater than the number of turns in the primary coil, i.e. if $n_s > n_p$ then $V_s > V_p$.

A **step-down transformer** decreases the secondary voltage compared with the primary voltage. The secondary voltage is less than the primary voltage because the number of turns in the secondary coil is less than the number of turns in the primary coil, i.e. if $n_s < n_p$ then $V_s < V_p$.

When using the transformer equation, *n* is the number of turns in each coil of the transformer.

Don't confuse this with the magnetic field of a solenoid where *n* is the number of loops per metre.

Worked example 9.6.1

TRANSFORMER EQUATION—VOLTAGE

A transformer is built into a portable radio to reduce the 240 V supply voltage to the required 12 V for the radio. Calculate the number of turns required in the primary coil if the number of turns in the secondary coil is exactly 100.

Thinking	Working
State the relevant quantities given in the question. Choose a form of the transformer equation that will be easy to rearrange and solve for the unknown variable.	$V_s = 12\,V$ $V_p = 240\,V$ $n_s = 100$ turns $n_p = ?$ $\frac{n_p}{n_s} = \frac{V_p}{V_s}$
Substitute the quantities into the equation, rearrange and solve for N_1.	$\frac{n_p}{100} = \frac{240}{12}$ $n_p = \frac{100 \times 240}{12}$ = exactly 2000 turns

➤ Try yourself 9.6.1

TRANSFORMER EQUATION—VOLTAGE

A transformer is built into a phone charger to reduce the 240 V supply voltage to the required 6.0 V. Calculate the number of turns required in the primary coil if the number of turns in the secondary coil is 100.

POWER OUTPUT

Although a transformer very effectively increases or decreases an AC voltage, energy conservation means that the output power cannot be any greater than the input power. Since a well-designed transformer with a laminated core can be more than 99% efficient, the power input can be considered equal to the power output, making it an 'ideal' transformer.

As power supplied is $P = VI$, then:

$$V_pI_p = V_sI_s$$

The transformer equation can then be written in terms of current, I.

ℹ The transformer equation relates current and the number of turns in each coil:

$\frac{I_p}{I_s} = \frac{n_s}{n_p}$ or $\frac{I_s}{I_p} = \frac{n_p}{n_s}$ or $\frac{I_p}{n_s} = \frac{I_s}{n_p}$

Note that the number-of-turns ratio for currents is the *inverse* of that for the transformer equation written in terms of voltage.

Worked example 9.6.2

TRANSFORMER EQUATION—CURRENT

The secondary coil of the transformer of a radio with 2000 turns in the primary coil and 100 turns in its secondary coil draws a current of 4.0 A. Calculate the current in the primary coil.	
Thinking	**Working**
State the relevant quantities given in the question. Choose a form of the transformer equation that will be easy to rearrange and solve for the unknown variable.	$I_s = 4.0\,A$ $n_s = 100$ turns $n_p = 2000$ turns $I_p = ?$ $\frac{I_p}{I_s} = \frac{n_s}{n_p}$
Substitute the quantities into the equation, rearrange and solve for I_p.	$\frac{I_p}{4.0} = \frac{100}{2000}$ $I_p = \frac{4.0 \times 100}{2000}$ $= 0.20\,A$

➤ Try yourself 9.6.2

TRANSFORMER EQUATION—CURRENT

A phone charger with 4000 turns in its primary coil and 100 turns in its secondary coil draws a current of 0.50 A. Calculate the current in the primary coil.

Worked example 9.6.3

TRANSFORMERS—POWER

The power drawn from the secondary coil of the transformer by a portable radio is 48 W. Determine what power is drawn from the mains supply if the transformer is an ideal transformer.	
Thinking	**Working**
The energy efficiency of a transformer can be assumed to be 100%. The power in the secondary coil will be the same as that in the primary coil.	The power drawn from the mains supply is the power in the primary coil, which will be the same as the power in the secondary coil: $P = 48\,W$.

➤ Try yourself 9.6.3

TRANSFORMERS—POWER

The power drawn from the secondary coil of the transformer in a phone charger is 3 W. Determine the power drawn from the mains supply if the transformer is an ideal transformer.

POWER FOR CITIES: LARGE-SCALE AC SUPPLY

In your school experiments using electrical circuits, it is likely that you have ignored the resistance of the connecting wires because the wires (generally made from copper) are good conductors, and so the resistance is very small over short distances. However, over large distances, even relatively good electrical conductors such as copper have a significant resistance.

Modern cities use huge amounts of electrical energy, most of which is supplied from power stations built at a considerable distance from metropolitan areas. Queensland has almost 14 000 km of high-voltage transmission network.

This network supplies power from the generators to the distribution systems. These distribution systems consist of more than 150 000 km of power lines, which connect power to consumers over large distances. The efficient transmission of the electrical energy with the least amount of power loss over that distance is therefore a very important consideration for electrical engineers, particularly given the vast distances between population centres in Australia.

The power lost in an electrical circuit is given by $P_{loss} = VI$, where V is the voltage drop across the load. Recalling Ohm's law, $V = IR$, and substituting, the power can be expressed in terms of either current and load resistance or voltage drop and load resistance:

$$P_{loss} = VI = I^2R = \frac{V^2}{R}$$

By considering the form of the equation that includes the current carried by the circuit and its electrical resistance ($P_{loss} = I^2R$), it is clear that transmitting large amounts of power using a large current will create very large power losses. If the current in the power lines can be reduced, it will significantly reduce the power loss. Since the power loss is proportional to the square of the current, then if the current is reduced by a factor of 3, for example, the power loss will be reduced by a factor of 3^2 or 9.

The challenge, then, is to transmit the large amounts of power being produced at power stations using a very low current. Transformers are the most common solution to this problem. Using a step-up transformer near the power station, the voltage is increased by a certain factor and, importantly, the current is decreased by the same factor. Due to the $P_{loss} = I^2R$ equation, the power lost during transmission is reduced by the square of that factor.

At this point you might be confused by the alternative equation for power loss: $P_{loss} = \frac{V^2}{R}$. A simple misunderstanding could make you think that increasing the voltage by using a step-up transformer would actually lead to greater power loss, if you use this equation to calculate power loss. However, V represents the voltage drop in a circuit. You must be careful not to confuse the voltage being *transmitted along* the wires with the voltage *drop across* the wires. So, even though the voltage being transmitted is increased by using a step-up transformer, the voltage drop across the wires would be reduced since $V = IR$, and thus the power loss would also be reduced.

The AC power from the generator is readily stepped up by a transformer to somewhere between 240 kV and 500 kV prior to transmission. Once the electrical lines reach the city, the voltage is stepped down in stages at electrical substations for distribution. The power lines in streets will have a voltage of about 2400 V, before being stepped down via small distribution transformers to 240 V for home use.

Worked example 9.6.4

TRANSMISSION LINE POWER LOSS

300.0 MW is to be transmitted from the Kogan Creek power station to Brisbane along a transmission line with a total resistance of 1.0 Ω. Calculate the total transmission power loss if the initial voltage along the line was 250 kV.	
Thinking	**Working**
Convert the values to SI units.	$P = 300\text{ MW} = 300 \times 10^6\text{ W}$ $V = 250\text{ kV} = 250 \times 10^3\text{ V}$
Determine the current in the line based on the required voltage.	$P = VI$ $\therefore I = \frac{P}{V}$ $I = \frac{300 \times 10^6}{250 \times 10^3}$ $= 1200\text{ A}$
Determine the corresponding power loss.	$P_{loss} = I^2R$ $= 1200^2 \times 1$ $= 1.4 \times 10^6\text{ W}$ or 1.4 MW

➤ Try yourself 9.6.4

TRANSMISSION LINE POWER LOSS

300.0 MW is to be transmitted from the Kogan Creek power station to Brisbane along a transmission line with a total resistance of 1.0 Ω. Calculate the total transmission power loss if the voltage along the line is now to be 500.0 kV.

LARGE-SCALE ELECTRICAL DISTRIBUTION SYSTEMS

Large-scale energy transmission is done through an interconnected grid between the power stations and the population centres where the bulk of the electrical energy is used. A wide-area synchronous grid, also known as an interconnection, directly connects a number of generators, and delivers AC power with the same relative phase to a large number of consumers.

No matter the source, the path the electrical power takes to the final consumer is very similar (Figure 9.6.3). Step-up transformers in a large substation near the power station will raise the voltage from that initially generated to 240 000 V (240 kV) or more. The electrical power will then be carried via high-voltage transmission lines to a number of substations near key centres of demand. Substations with step-down transformers then reduce the voltage to safer levels for distribution underground or via the standard 'electricity pole' you would be familiar with around city and country areas. Each group of 10–15 houses will be supplied by a smaller distribution transformer, mounted on the poles. This transformer reduces the voltage down to the 240 V AC, voltage that home and business installations are designed to run on.

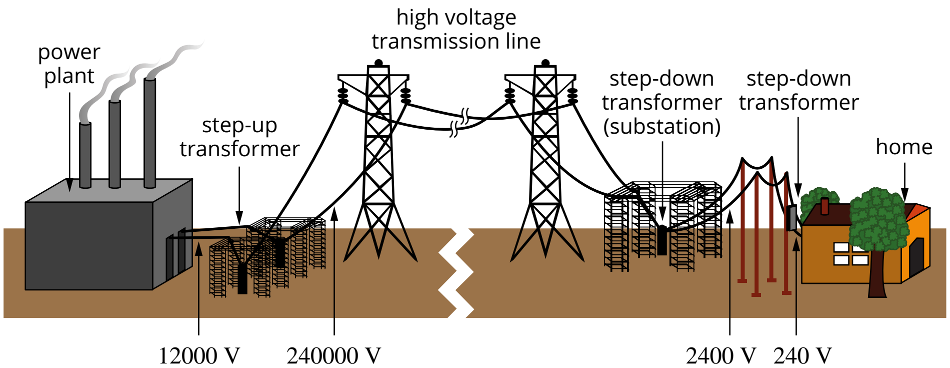


FIGURE 9.6.3 Transmitting electric power from generator to home uses AC power, so transformers can be used to minimise power losses through the system.

The use of AC as the standard for distribution allows highly efficient and relatively cheap transformers to convert the initial voltages created at the power station to much higher levels. The same power transmitted at a higher voltage requires less current and therefore has less loss of power. If it were not for this, the resistance of the transmission wires would need to be significantly reduced, which would require more copper in order to increase their cross-sectional area. This is both expensive and heavy. Using less copper means that cables can be lighter and thinner, and the supporting towers themselves can be comparatively shorter, cheaper and lighter to build.

PA 3.2.5

SCIENCE AS A HUMAN ENDEAVOUR

Renewable energy production

FIGURE 9.6.4 The generation of electricity through renewable resources such as wind power is crucial to limit the effects of global warming.

The greatest challenge of this generation is that of global warming and the changes to climate systems that result from the enhanced greenhouse effect. Now that the effects of the increased proportion of greenhouse gases such as carbon dioxide in our atmosphere are known, it is vital to use scientific knowledge to produce a range of renewable methods of energy production.

Oil, coal and gas are energy sources that cannot be replaced and are said to be non-renewable. When burnt, these fossil fuels release vast amount of energy, but also large amounts of the greenhouse gas carbon dioxide. The increased concentration of carbon dioxide in the atmosphere contributes to climate change.

As has been shown in this chapter, electric current is generated in a conductor when the magnetic flux cutting through a conductor changes. The energy released from the burning of fossil fuels is used to turn turbines consisting of coils of wire in a magnetic field.

The burning of fossil fuels has provided cities with a relatively cheap and accessible source of energy. Now, knowing the consequences on the world's climate and weather patterns, it is clear that scientific knowledge must be utilised to develop clean methods of generating electricity. If an alternative or renewable source of energy is used to turn these turbines, then it is possible to generate electricity without the production of greenhouse gases.

The key difficulty of harnessing renewable energy as the key solution of energy production is that it is not as reliable as burning fossil fuels. Renewable sources of energy, such as solar power, wind power (Figure 9.6.4), hydroelectric, geothermal, wave or tidal energy, and biomass and biogas, and energy harvested from organic waste vary in their generating power when the sun sets, the wind ceases or the waves flatten. This variation causes fluctuations in the amount of electrical energy that can be supplied. For a city, this can mean power blackouts.

A solution is to rely on not one energy source, but to use a many-pronged approach and to invest in new generations of battery technology. The development of battery storage banks allows excess energy to be stored for later use. Households using rooftop solar panels and solar hot water systems can reduce their demand on the electricity grid and even feed surplus electricity back into the system for later use. Many scientists advocate the benefits of nuclear energy. Although not renewable, nuclear energy produces vast amounts of energy without emitting greenhouse gases. Statistically, nuclear plants have an excellent safety record and present far fewer health risks than the burning of fossil fuels, which, aside from the challenges of global warming, adds particulates to the atmosphere, lowers air quality and presents respiratory risks to the community.

Figure 9.6.5a shows the spread of existing power stations, by type, throughout Queensland. The largest capacity power stations have been coal-fired power stations for many generations. Figure 9.6.5b shows the proposed power stations expected to be developed in Queensland over coming years. Several of these are large-scale power plants sourced from renewables. It is only by investing in energy sources apart from those relying on fossil fuels that the current trends of climate change will be contained.

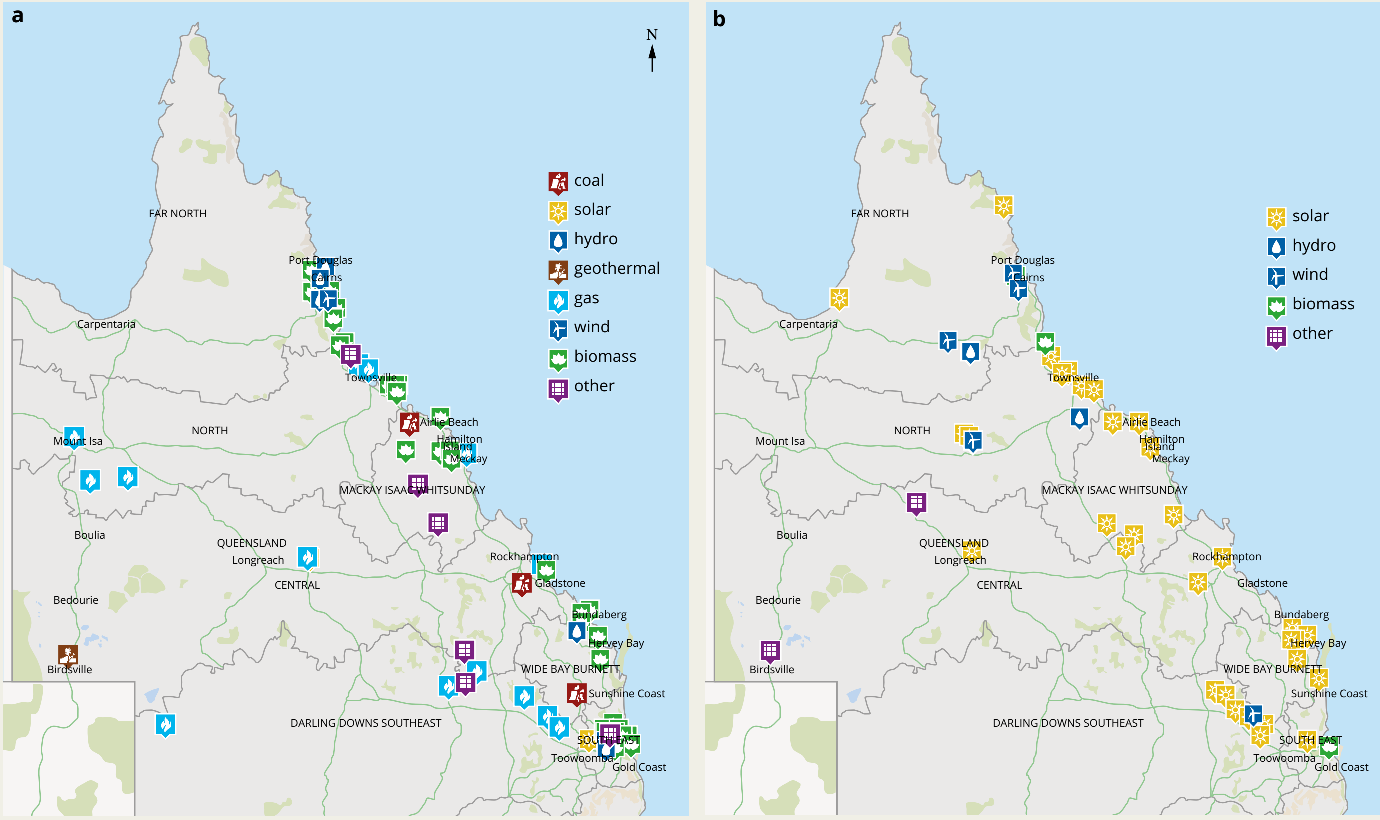


FIGURE 9.6.5 (a) This map shows the distribution of existing different sources of power stations of capacity over 1 MW in Queensland in 2017. (b) This map shows proposed power stations that are expected to be built over the next few years.

Review

1 Explain why fossil fuels such as coal, oil and gas have been used so widely for generations to produce electricity.

2 Explain why sources of power other than fossil fuels have been developed.

3 Discuss the main reason why renewables have not already replaced the use of fossil fuels.

4 The Tesla company is promoting the use of the Powerwall. Use the internet to research this device and answer the following.

- **a** Explain the purpose of the Powerwall.
- **b** Describe where it is mounted in a home.
- **c** Explain the benefits of a device such as this.

9.6 Review

SUMMARY

- A transformer works on the principle that a changing magnetic flux induces an EMF. No matter what the size or application, it will consist of two coils, known as the primary and secondary coils.
- Ideal transformers are 100% efficient; real transformers are often more than 99% efficient, and for this reason power losses within the transformer can be ignored in calculations.
- The transformer equation can be written in different versions, but is based on:
$$\frac{V_s}{V_p} = \frac{n_s}{n_p}$$
- n is the number of turns in each coil of the transformer.
- A *step-up* transformer *increases* the secondary voltage compared with the primary voltage.
- A *step-down* transformer *decreases* the secondary voltage compared with the primary voltage.
- The transformer equation can also be written in terms of current:
$$\frac{I_p}{I_s} = \frac{n_s}{n_p}$$
- The power lost in an electrical circuit is given by $P_{loss} = I^2R$.
- Transformers will not work with a DC voltage since it has a constant, unchanging current that creates no change in magnetic flux.
- The AC electrical supply from a generator is readily stepped up or down by transformers, hence AC is the preferred form of electrical energy in large-scale transmission systems.

KEY QUESTIONS

Retrieval

1 Define 'transformer'.

2 Identify what connects the primary and secondary coils of a transformer.

3 Identify the percentage efficiency of an ideal transformer.

4 State the transformer equation linking primary and secondary voltages to the number of turns on the primary and secondary coils.

Comprehension

5 Describe how a transformer works.

6 **a** Identify where eddy currents are created in a transformer.

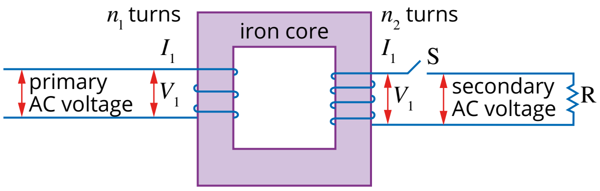
b Explain how the part of the transformer identified in part **a** is constructed in order to minimise the production of eddy currents.

7 Explain why a transformer will only operate using AC voltage and not DC voltage.

8 Identify whether the combinations of numbers of coils in the table below produce a step-up or step-down transformer.

n_1	n_2	Step-up or step-down transformer
1	50	
10	200	
20	1	
1000	25	

9 The figure below depicts an iron core transformer. An alternating voltage applied to the primary coil produces a changing magnetic flux. The secondary circuit contains a switch, S, in series with a resistor, R. The number of turns in the primary coil is n_1 and in the secondary n_2. The power in the first coil is P_1 and that in the second coil P_2. Assume that this is an ideal transformer.



a Represent the relationship between the power in the primary coil, P_1, and the power in the secondary coil, P_2, with an equation.

b Represent the relationship between the current in the secondary coil, I_2, and the current in the primary coil, I_1, in terms of the number of turns in each coil, with an equation.

Analysis

10 The primary windings of a transformer consist of exactly 20 turns and the secondary of exactly 200 turns. The primary voltage input is 8.0 V and a primary current of 2.0 A is flowing.

- **a** Determine the voltage across the load attached to the secondary coil.
- **b** Calculate how much power is being supplied to the load attached to the secondary coil.
- **c** Calculate the current in the secondary coil.

11 A security light is connected to a mains voltage of 240.0 V. It runs on a voltage of 12.0 V and a current of 2.0 A. A step-down transformer with exactly 800 turns on the primary winding is used to reduce the voltage from the mains level to the required operating voltage. Assume that the light is operating normally and that there is no power loss in the transformer.

- **a** Calculate the number of turns, to the nearest whole number, in the secondary coil.
- **b** Calculate the value of the current in the primary coil.
- **c** Calculate the power input to the primary coil of the transformer.
- **d** During some routine maintenance work, the primary coil of the transformer for the security light is unplugged from the AC mains supply and plugged into a DC supply of 240.0 V instead. Determine the new output (secondary) voltage.

12 A 100.0 km transmission line made from aluminium cable has a total resistance of 10.0 Ω. The line carries the electrical power from a 500.0 MW power station to a substation. Determine the power loss in the line if the line is operating at 250.0 kV.

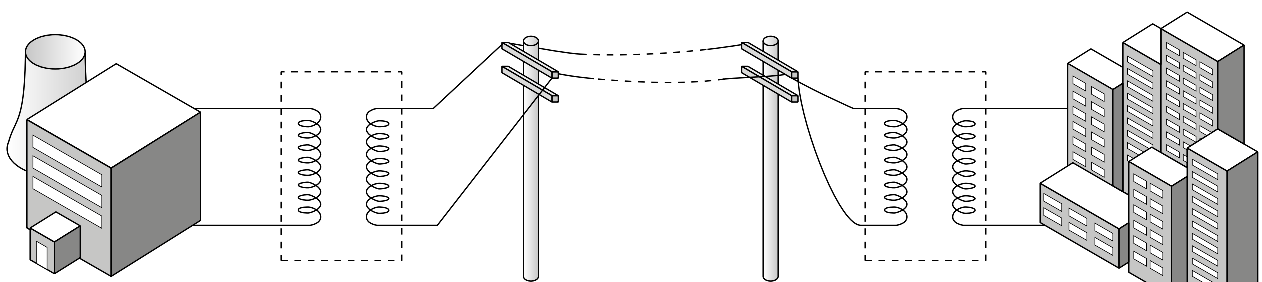
13 Power loss can be expressed by the formula:

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

Assess which of these two statements is true, and justify why the other response is incorrect.

- **A** The greater the voltage being transmitted in a transmission line, the greater the power loss.
- **B** The greater the current in the transmission line, the greater the power loss.

14 An electricity transfer system is shown below. The generator operates at 60.0 MW, the supply voltage from the generator is 12.0 kV and the total resistance in the transmission lines is 15.0 Ω. Calculate the voltage delivered to the city if the step-up transformer has its primary and secondary coils in the ratio of 1.00 : 10.0 and the step-down transformer has its coils in the ratio of 20.0 : 1.00.



9.7 Electromagnetic radiation

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

- understand that light is an electromagnetic wave and can travel through a vacuum
- use the wave equation to find the frequency or wavelength of light
- organise the electromagnetic spectrum into seven parts: radio waves, microwaves, infrared, visible light (red, orange, yellow, green, blue, violet), ultraviolet, X-rays and gamma rays
- describe properties of different types of electromagnetic radiation, such as their wavelength and energy.

FIGURE 9.7.1 Scientists had long puzzled and argued over the type of wave that is light. Light cannot be a simple mechanical wave because it can travel through empty space, unlike sound waves which can only travel through a medium.

In this chapter it has been shown that electric current can be used to produce a magnetic field and a changing magnetic field can be used to generate an electromotive force (EMF) or voltage. In the middle of the 19th century, the Scottish physicist James Clerk Maxwell used this knowledge to gain a key insight into the nature of light waves. In his mathematical study of electric and magnetic effects, he realised that some of the constants in his equations closely matched the current estimates of the speed of light. Maxwell went on to develop a comprehensive theory of electromagnetism in which light is a form of **electromagnetic radiation** (EMR) (Figure 9.7.1).

James Clerk Maxwell proposed that if a changing electric field is produced, for example by a charged particle moving backwards and forwards, then this changing electric field will produce a changing magnetic field at right angles to the electric field (Figure 9.7.2).

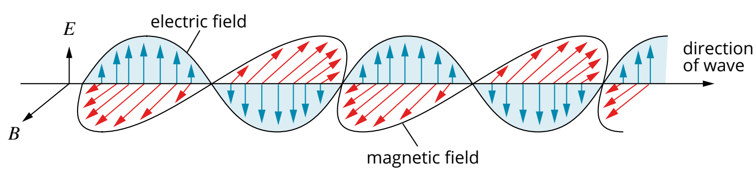


FIGURE 9.7.2 The electric and magnetic fields in electromagnetic radiation are perpendicular to each other and both are perpendicular to the direction of propagation of the radiation.

The changing magnetic field would, in turn, produce a changing electric field and the cycle would be repeated. In effect, this would produce two mutually propagating fields and the electromagnetic radiation would be self-propagating, i.e. it could extend outwards into space. Both the electric and magnetic fields would oscillate at the same frequency: the frequency of the light wave.

Maxwell's theoretical calculations provided a value for the speed at which EMR should propagate through empty space. This matched the experimental value for the speed of light measured by the French physicist Hippolyte Fizeau in 1849. The accepted defined value for the speed of light today is $299\,792\,458\,\mathrm{m\,s^{-1}}$. This is such an important constant that it is designated its own symbol, c. In calculations, the speed of light is usually approximated as $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$.

For light and other forms of EMR, the familiar wave equation that you studied in Unit 2 Physics, $v = f\lambda$, is usually written as:

$$c = f\lambda$$

where

f is the frequency of the wave in hertz (Hz)

λ is the wavelength of the wave in metres (m).

Maxwell's work represents a pivotal moment in the history of physics. Not only did he provide an explanation of the nature of light, he also brought together a number of formerly distinct areas of study—optics (the study of light), electricity and magnetism.

Worked example 9.7.1

USING THE WAVE EQUATION FOR LIGHT

Calculate the frequency of violet light with a wavelength of 400.0 nm (i.e. 400.0×10^{-9} m).	
Thinking	**Working**
Recall the wave equation for light.	$c = f\lambda$
Transpose the equation to make frequency the subject.	$f = \frac{c}{\lambda}$
Substitute in values to determine the frequency of this wavelength of light.	$f = \frac{3 \times 10^8}{400 \times 10^{-9}}$ $= 7.50 \times 10^{14}$ Hz

➤ Try yourself 9.7.1

USING THE WAVE EQUATION FOR LIGHT

A particular colour of red light has a wavelength of 600.0 nm. Calculate the frequency of this light.

SEARCHING FOR THE AETHER

As you will recall from your studies on light in Unit 2, one of the characteristics of mechanical waves is that they require a physical **medium** through which to propagate. For example, sound waves usually propagate through air and water waves propagate through water. For many years, scientists searched for a physical medium through which electromagnetic waves propagate. They even went so far as to give this medium a name: the 'luminiferous aether' or 'aether'.

However, all attempts to measure the presence or properties of the aether were unsuccessful. Eventually, scientists were forced to conclude that electromagnetic waves are able to propagate through a vacuum. This is examined in more detail in Chapter 10.

THE ELECTROMAGNETIC SPECTRUM

The wavelengths of all the different colours of visible light fall between 390 nm and 780 nm. Naturally, physicists were bound to inquire about other wavelengths of electromagnetic radiation. It is now understood that the visible spectrum is just one small part of a much broader set of possible wavelengths known as the **electromagnetic (EM) spectrum** (Figure 9.7.3).

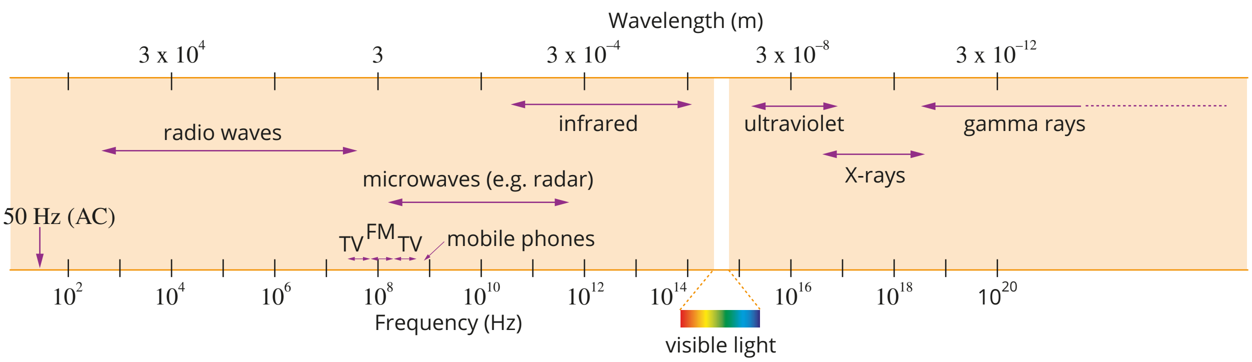


FIGURE 9.7.3 The electromagnetic spectrum

Changing the frequency and wavelength of the waves changes the properties of the electromagnetic radiation, and so the electromagnetic spectrum is divided into 'bands' according to how the particular types of EMR are used. The shorter the wavelength of the EM wave, the greater its penetrating power. This means that waves with extremely short wavelengths, such as X-rays, can pass through some materials (e.g. skin), revealing the structures inside (e.g. bone).

Long wavelength waves, such as AM radio waves, have such low penetrating power that they cannot even escape Earth's atmosphere, and can be used to 'bounce' radio signals around to the other side of the world. Table 9.7.1 compares the characteristics of different waves in the EM spectrum.

TABLE 9.7.1 Comparison of the different waves in the electromagnetic spectrum

Type of wave	Typical wavelength (m)	Typical frequency (Hz)	Object with comparable wavelength
AM radio wave	100	3×10^{6}	sports oval
FM radio or TV wave	3	1×10^{8}	small car
microwaves	0.03	1×10^{10}	50c coin
infrared	10^{-5}	3×10^{13}	white blood cell
visible light	10^{-7}	3×10^{15}	small cell
ultraviolet	10^{-8}	3×10^{16}	large molecule
X-ray	10^{-10}	3×10^{18}	atom
gamma ray	10^{-15}	3×10^{23}	atomic nucleus

Radio waves

One of the most revolutionary applications of EMR is the use of **radio waves** to transmit information from one point to another over long distances. Radio waves are the longest type of electromagnetic radiation, with wavelengths ranging from 1 mm to hundreds of kilometres. The principle of radio transmission is relatively simple and neatly illustrates the nature of electromagnetic waves.

A radio transmitter converts the signal (e.g. radio announcer's voice, music or stream of data) into an alternating current. When this alternating current flows in the transmission antenna, the electrons in the antenna oscillate backwards and forwards. This oscillation of charges in the antenna produces a corresponding electromagnetic wave that radiates outwards in all directions from the antenna.

When the radio wave hits the antenna of a radio receiver, the electrons in the receiver's antenna start to oscillate in exactly the same way as in the transmitting antenna. The radio receiver then reverses the process of the transmitter, converting the alternating current from the reception antenna back into the original signal (Figure 9.7.4).

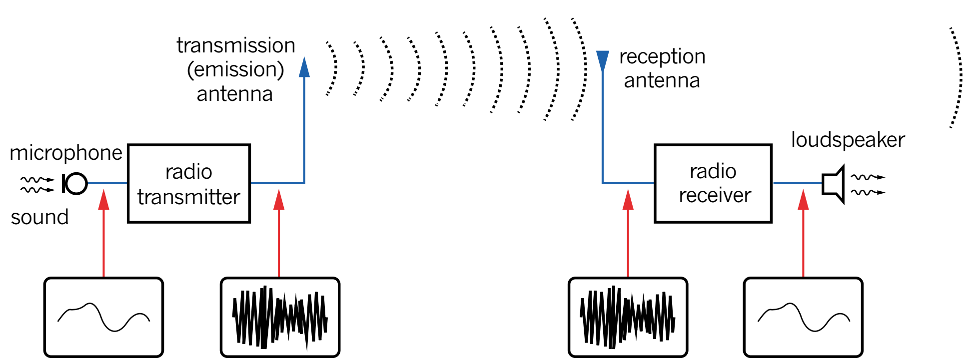


FIGURE 9.7.4 A typical radio transmission system

A radio wave pattern is produced using a 'carrier wave' of fixed frequency. This frequency is the 'channel' that the radio 'tunes into'. Many radio stations use the carrier wave frequency as part of their name. For example, Nova 106.9 transmits using a 106.9 MHz carrier wave.

The carrier wave is altered or 'modulated' by the signal containing the information to be transmitted. An AM radio system uses 'amplitude modulation', which means that the amplitude of the carrier wave is modulated to match the signal. In comparison, in FM or 'frequency modulation' it is the frequency of the carrier wave that is changed to represent the signal. In terms of circuitry, AM systems are much simpler than FM systems, although FM radio waves tend to transmit signals more clearly.

Microwaves

Microwaves have shorter wavelengths and therefore greater penetrating power than radio waves. They can be produced by devices with short antennas and hence are useful in personal communication applications such as mobile phones and wireless internet transmission. They also particularly useful in heating and cooking food (Figure 9.7.5).

A microwave oven is 'tuned' to produce a particular frequency of electromagnetic radiation: 2.45 GHz (i.e. 2.45×10^9 Hz). This is the resonant frequency of water molecules.

All solid objects have a frequency at which they will naturally vibrate. For example, you might recall from your study of waves in Chapter 10 of *Pearson Physics 11 Queensland* that musical instruments such as guitars and violins make use of the resonant frequencies of strings under tension.

When water molecules are bombarded with radiation with a frequency of 2.45 GHz, they start to vibrate quickly. This increases the average kinetic energy of the water molecules and therefore the temperature of the water in the substance increases. Effectively, the microwaves cause the water to heat up.

This heat then transfers by conduction and convection to the rest of the food. This is why food sometimes becomes soggy when heated in the microwave: the water molecules heat up faster than the food molecules around them. It also explains why recipes that do not contain much water cannot be cooked well in a microwave oven.

FIGURE 9.7.5 Microwave ovens produce electromagnetic radiation with a frequency of 2.45 GHz, which is the resonant frequency of water molecules.

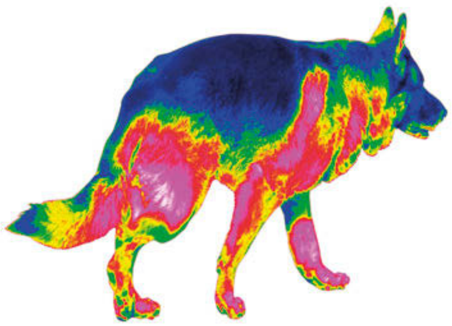


FIGURE 9.7.6 A thermal image shows the variation in infrared radiation emitted from this German Shepherd dog. The white and red regions seen in this false colour image correspond to the warmest parts of the dog.

Infrared radiation

The **infrared** section of the electromagnetic spectrum lies between microwaves and visible light. Infrared waves are longer than the red waves of the visible spectrum, hence their name.

Infrared light waves become useful because they are emitted by objects, to varying degrees, due to their temperature. Figure 9.7.6 shows the thermal image of a dog walking. Variations in intensity of infrared radiation are converted into a false colour image with each colour representing a different temperature.

The warmth that you feel when standing next an electric bar heater or a fire is due to infrared radiation (Figure 9.7.7). The radiant heat Earth receives from the Sun is transmitted in the form of infrared waves; life on Earth would not be possible without this important form of electromagnetic radiation.

FIGURE 9.7.7 The coals of a fire appear red because they release red light along with infrared radiation, which you experience as heat.

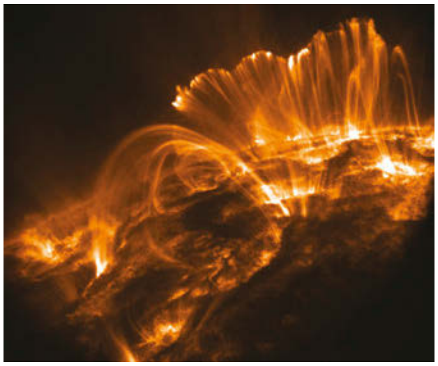


FIGURE 9.7.8 Re-coloured UV image of the surface of the Sun. The white areas reveal the hottest parts.

FIGURE 9.7.9 This X-ray image of a child's hips can be formed because X-rays can pass through human tissue.

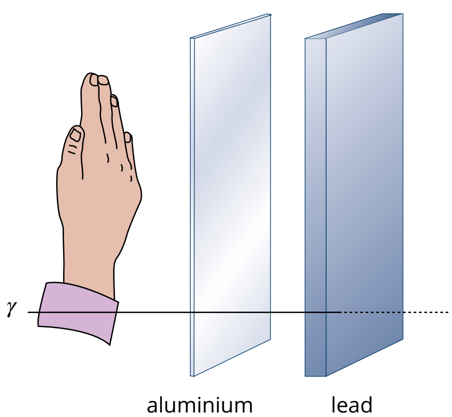


FIGURE 9.7.10 Gamma rays can travel through a human hand, a sheet of aluminium, a few centimetres of lead and even through up to 1 metre of concrete before being fully absorbed.

Visible light

The term '**visible light**' refers to a small portion of the electromagnetic spectrum that is visible to the human eye. Visible light has wavelengths between 3.90×10^{-7} to 7.80×10^{-7} m. The specialised cells called cones in the eye act as receivers. At the longer wavelength end of the electromagnetic spectrum, light is seen as red. In the middle of the spectrum light is seen as green and at the shorter wavelength end of the spectrum, light is seen as violet. All the colours we see are mixtures of the colours of the visible spectrum. Magenta, for example, is a mixture of red and blue. White light is a mix of all colours, a discovery made by Isaac Newton in 1666. Black is an absence of light.

Temperature changes may result in objects changing colour: as objects get hotter their wavelengths get shorter. For example, a flame changes from red to 'white' hot to blue. Scientists working in the field of astronomy use colour to help them determine the temperatures of hot objects such as stars. For example, the pale yellow parts of the surface of the Sun have a wavelength of about 550 nm and are determined to be 5800 K or 5527°C. The cooler red star Betelgeuse is estimated to have a temperature of 3000°C.

Ultraviolet light

As their name suggests, **ultraviolet** (UV) waves have wavelengths that are shorter than those of violet light and therefore cannot be detected by the human eye. Their shorter wavelengths give UV rays stronger penetrating power than visible light. In fact, UV rays can actually penetrate human skin and damage the DNA of skin cells, producing harmful skin cancers.

Scientists can make use of UV light to take images. Figure 9.7.8 is a UV image of the surface of the Sun taken after a solar flare has occurred. The image has been re-coloured so that it highlights areas of different temperature. Here, areas that are coloured white are the hottest. Images like these help scientists to learn about the temperatures of very hot objects. Taking an image of the Sun using visible light would not allow this same distinction.

X-rays

X-rays have much shorter wavelengths than visible light. This means that these forms of electromagnetic radiation have very high penetrating powers. For example, some X-rays can pass through different types of human tissues and so are very useful in medical imaging (Figure 9.7.9).

Unfortunately, this useful penetrating property of X-rays comes with inherent dangers. In Unit 1 Physics, ionising radiation such as X-rays and gamma rays were investigated. As X-rays pass through a human cell, they can damage the tissue, sometimes killing the cells or damaging the DNA in the cell nucleus, leading to harmful cancers. For this reason, our exposure to X-rays has to be carefully monitored to avoid harmful side effects.

Gamma rays

Gamma rays have wavelengths even shorter than those of X-rays. As a result, exposure to gamma rays can be very dangerous to human beings. Gamma rays are high-energy EMR. Gamma rays have no charge and are a very penetrating form of radiation (Figure 9.7.10). The main natural sources of gamma radiation exposure are the Sun and radioactive isotopes. Fortunately, Earth's atmosphere protects people from most of the Sun's harmful gamma rays, and radioactive isotopes are not commonly found in sufficient quantities to produce harmful doses of radiation.

9.7 Review

SUMMARY

- Although light exhibits many wave properties, it cannot solely be modelled as a mechanical wave because it can travel through a vacuum.
- Light is a form of electromagnetic radiation.
- Electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.
- Electromagnetic radiation can be used for a variety of purposes, determined by their frequency.
- Oscillating charges produce electromagnetic waves of the same frequency as the oscillation. Electromagnetic waves cause charges to oscillate at the frequency of the wave.
- Light (i.e. all electromagnetic radiation) travels through a vacuum at approximately $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.
- The wave equation $c = f\lambda$ can be used to calculate the frequency and wavelength of electromagnetic waves.
- Electromagnetic radiation can be organised into seven bands according to its wavelength. From longest to shortest, these are radio waves, microwaves, infrared radiation, visible light (red, orange, yellow, green, blue, violet), ultraviolet radiation, X-rays and gamma rays.

KEY QUESTIONS

Retrieval

1 Recall the two type of fields that oscillate to produce an electromagnetic wave.

2 State a key difference between light waves and mechanical waves.

3 State the angle of orientation between the changing electric and magnetic fields in an electromagnetic wave.

4 Identify the type of electromagnetic radiation with a wavelength of $3.0 \times 10^{-8}\,\text{m}$.

5 List the types of electromagnetic radiation below in order of increasing wavelength.
FM radio waves / visible light / infrared radiation / X-rays

6 Recall the range of wavelengths of visible light measured in nanometres.

Comprehension

7 Explain how it is possible for an electromagnetic wave to be self-propagating.

8 Discuss why scientists proposed the existence of an aether.

9 Determine whether visible light waves have a longer or shorter wavelength than microwaves.

10 Determine whether the penetrating ability of an electromagnetic wave increases or decreases with frequency.

11 Determine the type of electromagnetic radiation whose wavelength most closely matches the width of your little finger.

12 To transmit a radio signal, a radio wave is produced from an antenna.
- **a** Identify what oscillates inside the antenna to produce this radio wave.
- **b** Explain why these particles oscillate.

13 Explain how the carrier wave of an FM radio signal is modulated.

14 Explain why foods with a high water content cook effectively in a microwave oven.

15 Determine the frequencies of the following wavelengths of light.
- **a** red light of wavelength 656 nm
- **b** yellow light of wavelength 589 nm
- **c** blue light of wavelength 486 nm
- **d** violet light of wavelength 397 nm

Analysis

16 Although the currently defined value for the speed of light is $299\,792\,458\,\text{m}\,\text{s}^{-1}$, this is often approximated as $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$. Determine the percentage error introduced by this approximation.

17 Calculate the wavelength (in nm) of light with a frequency of $6.0 \times 10^{14}\,\text{Hz}$.

18 Calculate the wavelength of a UHF (ultra-high frequency) television signal with a frequency of $7.0 \times 10^7\,\text{Hz}$.

19 Calculate the frequency of an X-ray with a wavelength of 200.0 pm.

20 Calculate the wavelength of the electromagnetic waves produced by a microwave oven with a frequency of 2.45 GHz.

Chapter review

WS 3.2.10 WS 3.2.11

09

KEY TERMS

alternating current (AC)
alternator
armature
brushes
electromagnetic induction
electromagnetic radiation
electromagnetic (EM) spectrum
electromotive force
Faraday's law
gamma ray
generator
ideal transformer
induced current
infrared
Lenz's law
magnetic flux
magnetic flux density
medium
microwave
radio wave
slip rings
step-down transformer
step-up transformer
transformer
ultraviolet
visible light
X-ray

KEY QUESTIONS

Retrieval

1 Identify which of the following options correctly completes the sentence. The magnetic field generated near a section of horizontal wire in which current flows to the left is:

A in a straight line pointing upwards from the wire
B in a straight line pointing downwards from the wire
C in a clockwise loop around the wire when viewed from the left
D in an anticlockwise loop around the wire when viewed from the left

2 Identify the scenario that will *not* induce an EMF in a long, straight conductor.

A A magnet is brought near the conductor.
B The conductor is brought into a magnetic field.
C A magnet is stationary alongside the conductor.
D The conductor is rotated within a magnetic field.

3 A conducting loop is located in an external magnetic field whose direction (but not necessarily magnitude) remains constant. A current is induced in the loop. Identify the best description of the direction of the magnetic field due to the induced current.

A The direction can't be determined from the information supplied.
B It will always be in the same direction as the external magnetic field.
C It will always be in the opposite direction to the external magnetic field.
D It will be in the same direction as the external magnetic field if the external magnetic field gets weaker, and it will be in the opposite direction to the external magnetic field if the external magnetic field gets stronger.

4 Identify the best description of how a transformer transfers electrical energy from the primary windings to the secondary windings.

A The current through the primary windings produces no magnetic field in the secondary windings.
B The current through the primary windings produces a constant electric field in the secondary windings.
C The current through the primary windings produces a steady magnetic field in the secondary windings.
D The current through the primary windings produces a changing magnetic field in the secondary windings.

5 Identify the key difference between light waves and mechanical waves.

A Light waves do not undergo diffraction.
B Light waves can travel through a vacuum.
C Light waves do not have a measurable wavelength.
D The speed of light is too fast to be accurately measured.

6 Identify the orientation of the changing electric and magnetic fields in an electromagnetic wave.

A They are at 45° to each other.
B They are parallel to each other.
C They are perpendicular to each other.
D They are parallel but in opposite directions.

7 Identify the component of a transformer that directs the change in magnetic flux created in the primary coil towards the secondary coil.

8 Name a device that uses slip rings and state what slip rings do.

Comprehension

9 A magnetic field threads through a rectangular coil. Determine when the flux is at a maximum angle between the normal to the coil and the field.

A 0°
B 45°
C 90°
D 180°

10 A square loop of side length 10 cm is placed inside a magnetic field of strength 0.2 T. The coil is positioned at right angles to the field. Determine the flux threading of the coil.

A 0 Wb
B 2.0 Wb
C 0.02 Wb
D 0.002 Wb

11 Charlie and Tomin are investigating how current is generated by quickly inserting a magnet inside a coil of wire. Assume all conditions are kept the same except the variable being changed. Select which modification would not increase the EMF generated.

A Use a stronger magnet.
B Insert the magnet more slowly.
C Increase the diameter of the coils.
D Double the number of turns in the coil.

12 A small amount of EMF is generated in a DC motor in response to the rotation of the armature in the motor in the presence of an external magnetic field. Select the correct comparison of the net EMF generated by the DC motor to the supplied voltage.

A It is less than the supplied voltage.
B It is the same as the supplied voltage.
C It is greater than the supplied voltage.
D It is greater or less than the supplied voltage, depending on the speed of the motor.

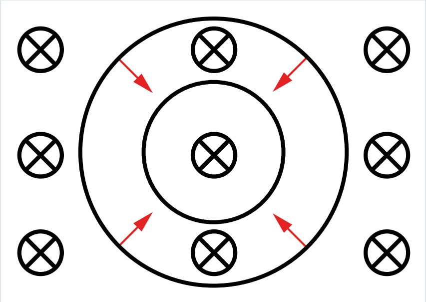
13 The power output from the secondary coil of a non-ideal transformer is a slightly less than the input to the primary coil. The voltage and current in the primary coil are denoted V_1 and I_1 respectively. The voltage and current in the secondary coil are denoted V_2 and I_2 respectively. Select the power output in the secondary coil.

A V_1I_1
B V_2I_2
C V_1I_2
D I_2^2R

14 When a transformer is plugged into the 240 V mains but there is nothing connected to the secondary coil, very little power is used. Explain the reason for this by selecting the best option below.

A The magnetic flux generated by the secondary coil almost balances out that due to the primary coil.
B There can be no magnetic flux generated in the transformer if the secondary coil has no current in it.
C The magnetic flux generated by the current in the primary coil produces an EMF that opposes the applied voltage.
D The primary and secondary coils are in series and so no current can flow in either if the secondary coil is open.

15 A coil in a magnetic field directed into the page is reduced in size as shown below. Determine the direction of the induced current flow in the coil while the coil is being reduced.



16 Show the correct order of steps X, Y and Z for the operation of a transformer.

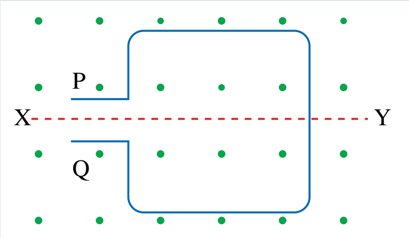
X: A changing magnetic flux in the secondary coil induces a changing EMF.

Y: An iron core transmits the changing magnetic field from the primary coil to the secondary coil.

Z: An alternating current in the primary coil creates a changing magnetic field in the primary coil.

Analysis

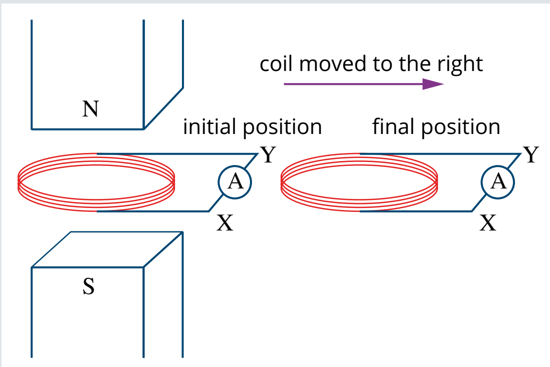
17 A rectangular coil of area 40.0 cm^2 and resistance 1.0 Ω is located in a uniform magnetic field $B = 8.0 \times 10^{-4}$ T that is directed out of the page. The plane of the coil is initially perpendicular to the field, as depicted in the diagram below.



a Calculate the magnitude of the EMF induced in the coil when the strength of the magnetic field is doubled in a time of 1.0 ms.

b Determine the direction of the current caused by the induced EMF in the coil when the strength of the magnetic field is doubled in a time of 1.0 ms.

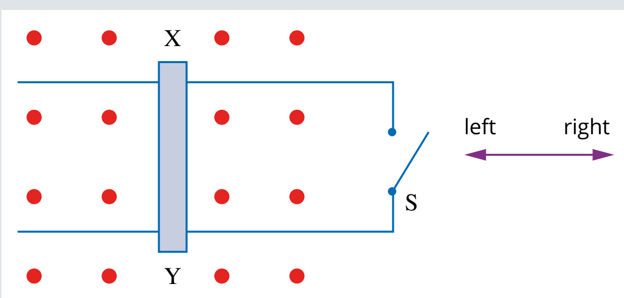
18 During a physics experiment Rhiannon pulls a horizontal circular coil from between the poles of two magnets in 0.10 s. The initial position of the coil is entirely in the field while its final position is free of the field. The coil has exactly 40 turns, each of radius 4.0 cm. The field strength between the magnets is 20.0 mT.



a Calculate the magnitude of the average EMF induced in the coil as it is moved from its initial position to its final position.

b Determine the direction of the current in the coil caused by the induced EMF.

19 A copper rod, XY, of length 20.0 cm is free to move along a set of parallel conducting rails as shown in the following diagram. These rails are connected to a switch, S, which completes a circuit when it is closed. A uniform magnetic field of strength 10.0 mT, directed out of the page, is established perpendicular to the circuit. S is closed and the rod is moved to the right with a constant speed of 2.0 m s^{-1}.

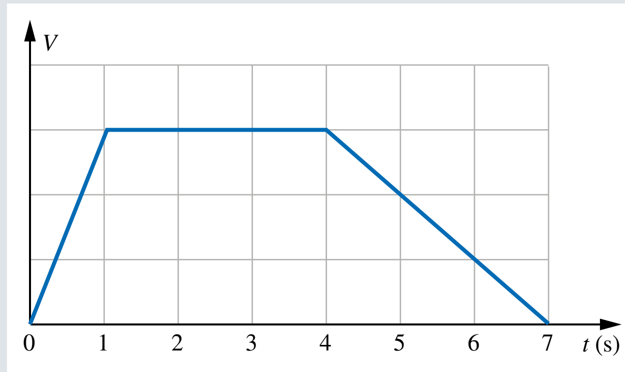


a Calculate the magnitude of the induced EMF in the rod in mV.

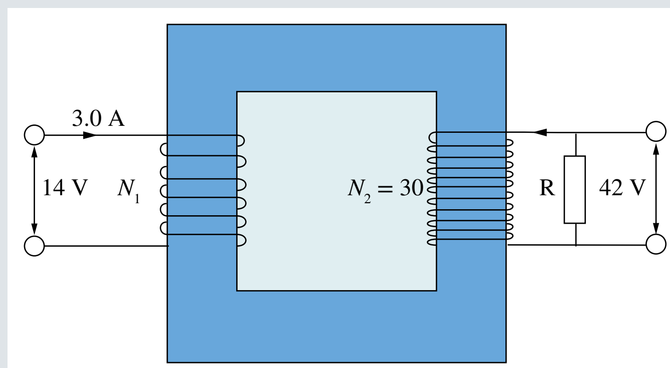
b Determine the direction of the current through the rod caused by the induced EMF.

20 A ship with a vertical steel mast of length 8.0 m is travelling due west at 4.0 m s^{-1} in a region where Earth's magnetic field is horizontal and is equal to 5.0×10^{-5} T north. Calculate the average EMF, in mV, that would be induced between the top and bottom of the mast.

21 Coils S_1 and S_2 are close together and linked by a soft iron core. The EMF in S_1 varies as shown in the graph below. Determine the shape of the variation of the current in S_2 by drawing a line graph. No calculations are required for this question.



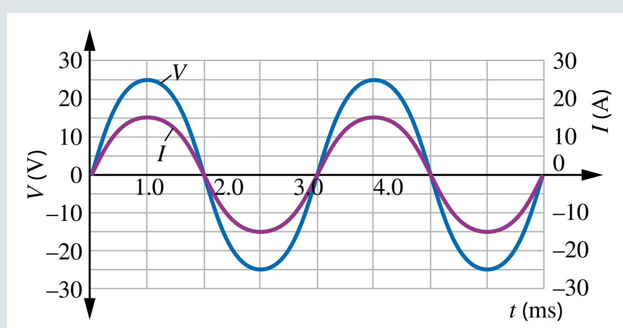
The following information relates to questions 22 and 23. An ideal transformer is operating with an input voltage of 14 V and primary current of 3.0 A. The output voltage is 42 V. There are exactly 30 turns in the secondary winding.



22 Determine the output current.

23 Determine the number of turns in the primary coil.

24 A student uses a voltage/current sensor to display the current, *I*, through, and the voltage, *V*, across, the output terminals of a small generator. The graph obtained from the display is shown below.
Calculate the peak power output of the generator.



25 Nhu decides to test the power output of her new stereo amplifier. The maximum power output guaranteed by the manufacturer (assumed accurate) is 60.0 W.

Assess the sets of specifications below and determine which one is consistent with this power output.

	Peak–peak voltage (V)	Peak–peak current (A)
A	20	3.0
B	40	6.0
C	40	12.0
D	20	6.0

The following information refers to questions 26 and 27.

Vani builds a simple alternator consisting of a coil containing exactly 500 turns, each of area 10.0 cm^2, mounted on an axis that can rotate between the poles of a permanent magnet of strength 80.0 mT. The alternator is rotated at a frequency of 50.0 Hz.

26 Calculate the EMF generated by the alternator.

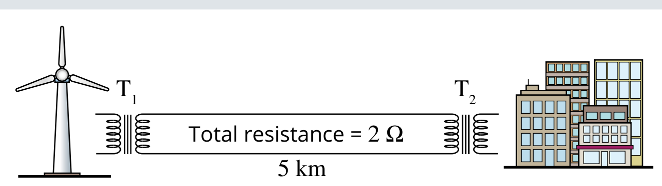
27 Assess the effect on the average EMF when the frequency is doubled to 100 Hz.

28 A generator is to be installed in a farm shed to provide 240 V power for the farmhouse. A twin-conductor power line with total resistance 8.0 Ω already exists between the shed and house. The farmer has seen a cheap 240 V DC generator advertised and is tempted to buy it.

Consider and explain two significant problems that you foresee with using the 240 V DC generator.

The following information relates to questions 29–32.

A wind turbine runs a 150 kW generator with an output voltage of 1000.0 V. The voltage is increased by a transformer T_1 to 10 000.0 V for transmission to a town 5.0 km away through power lines with a total resistance of 2.0 Ω. Another transformer, T_2, at the town reduces the voltage to 250 V. Assume that there is no power loss in the transformers (i.e. they are 'ideal').



29 Determine the current in the power lines.

30 Calculate the voltage at the input to the town transformer T_2.

31 Determine how much power is lost in the power lines.

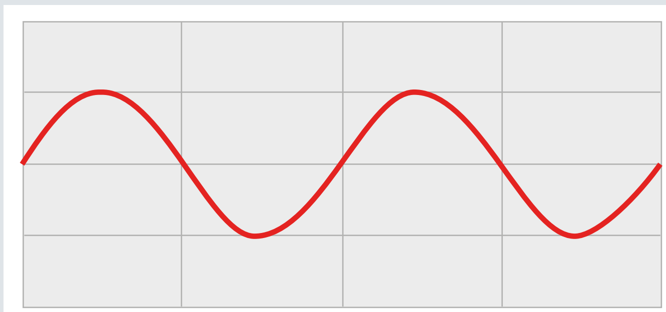
32 It is suggested that some money could be saved from the scheme by removing the first transformer. Assess whether this is a good plan. Use appropriate calculations and include an explanation.

33 An AM radio station has a frequency of 612 kHz. Calculate the wavelength of these waves to the nearest metre if the speed of light is 3×10^8 m s^{-1}.

34 Consider why a microwave oven is tuned to produce electromagnetic waves of a particular frequency.

Knowledge utilisation

35 Two students, Mia and Zane, are investigating the output of a generator. They initially have the generator rotating at a rate of 3000.0 revolutions per minute. The magnetic field within the generator is 0.50 T. The total number of turns in the armature coils is n = exactly 200, each of area A = 100.0 cm^2. Mia and Zane see the following trace on a digital display connected to the generator.



a Calculate the initial frequency of rotation of the generator.

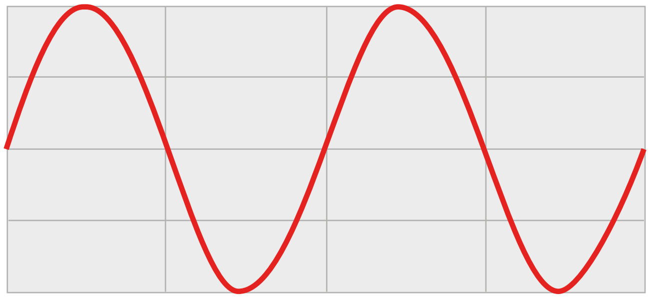
b Determine the average EMF generated during a quarter revolution of the generator coil.

c Study the table of data shown below. Evaluate the specifications in the table and determine which could produce, in the same period, the display described by diagram A in part **d** on the next page.

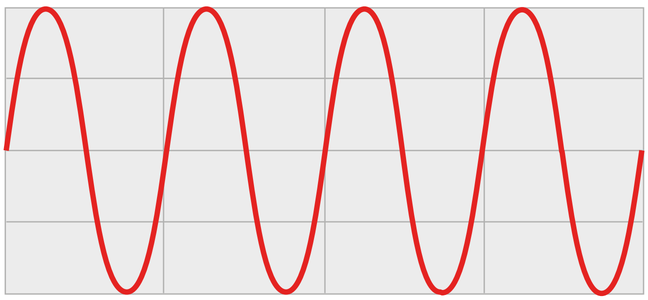
	f (Hz)	B (T)	n	A (cm^2)
A	50	0.50	200	100
B	100	0.50	200	100
C	100	1.00	50	100
D	50	0.50	400	100

d Determine which of the diagrams A–D best describes the trace on the digital display when the generator is operating at a frequency of 100 Hz.

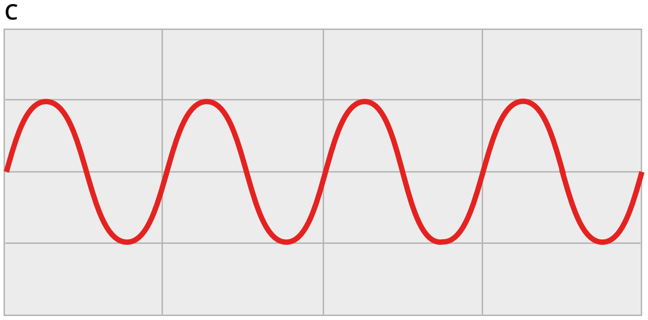
A



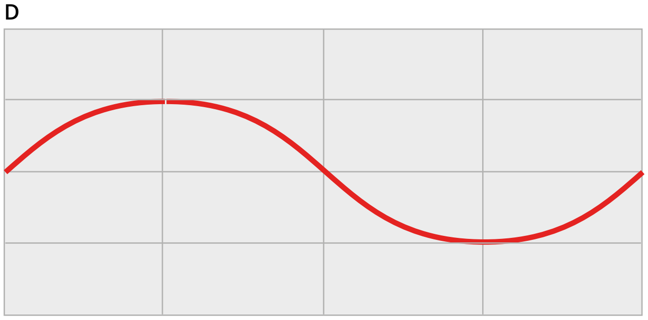
B



C

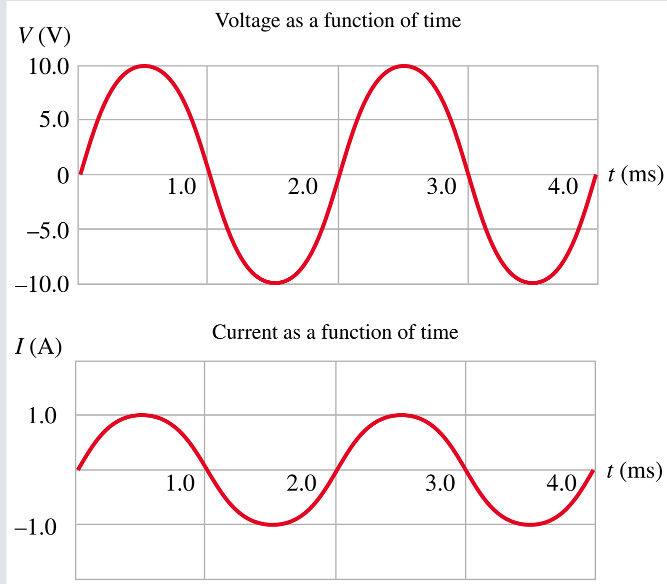


D



e Evaluate the specifications in the table and determine which could produce the display illustrated by diagram C.

36 The following diagram shows the voltage versus time graph and corresponding current versus time graph for an alternator that was built by Nikolay as part of a research project.



a Calculate the frequency of the voltage produced by the alternator.

b Determine the peak output voltage of this alternator.

c Calculate the maximum output power of the alternator.

d The students realised that they wanted the output of the generator to produce a peak current of 2 A. Propose three ways in which they could modify their experiment to allow this change to occur.

37 Lenz's law states that an induced EMF always produces a current whose magnetic field will oppose the original change in magnetic flux. Design an experiment to test Lenz's law.

UNIT 3 • REVIEW

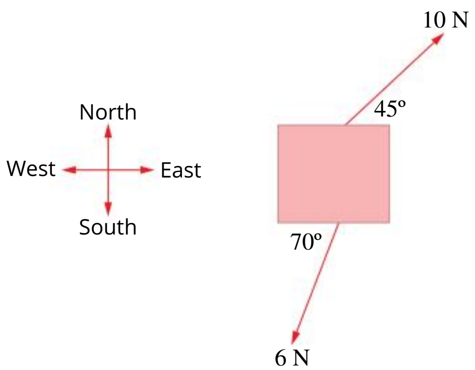
REVIEW QUESTIONS

TR 3.1 TR 3.2

Topic 1: Gravity and motion

Multiple choice

1 Two ropes are attached to a block on a frictionless plane as shown below, viewed from above. Identify the net force acting on the block.



A 5.3 N east
B 5.22 N N74°E
C 10.86 N north
D 5.15 N N52°E

2 A book is stationary on an inclined plane and three forces act on it: weight, friction and a normal reaction force. Identify the best description of the normal force.

A the net force in the vertical direction
B the force due to the gravitational field of Earth
C the support force acting perpendicular to the surface
D the net force in the direction perpendicular to the surface

3 A ball has been kicked at an angle of 30° from the surface at an initial velocity of $25\,m\,s^{-1}$. Identify the magnitude of the velocity of the ball at the highest point, assuming negligible air resistance.

A $25\,m\,s^{-1}$
B $12.5\,m\,s^{-1}$
C $21.7\,m\,s^{-1}$
D $10.0\,m\,s^{-1}$

4 A ball is being swung around on a string that provides a constant tension force. Initially the ball is travelling in a circular path of radius 20.0 cm with a period of 0.30 s. The string is adjusted so the ball travels in a circular path with a radius of 15.0 cm. Determine the average velocity of the ball in the new path.

A $4.12\,m\,s^{-1}$
B $2.05\,m\,s^{-1}$
C $3.95\,m\,s^{-1}$
D $2.51\,m\,s^{-1}$

5 A child on a piece of cardboard is sliding down a sand dune. The combined mass is 32 kg. The sand dune is at an angle of 35°. There is a constant frictional force of 60 N once the child starts moving. Identify the net force acting on the child.

A 257 N
B 197 N
C 180 N
D 120 N

6 Two students are playing on a merry-go-round. One student sits on the floor of the merry-go-round while the other student stands at the edge and pushes the merry-go-round in a circle. Identify the force(s) causing the sitting student to travel in a circle.

A the standing student pushing tangential to the circle
B the standing student pushing towards the centre of the circle
C friction between the sitting student and the floor of the merry-go-round towards the centre of the circle
D friction between the sitting student and the floor of the merry-go-round away from the centre of the circle

7 A desk fan has three blades, each 25 cm long. When on the lowest speed setting, the tips of the blades travel with a period of 0.8 s. Identify the velocity of the blade tips.

A $1.96\,m\,s^{-1}$
B $19.6\,m\,s^{-1}$
C $0.49\,m\,s^{-1}$
D $0.25\,m\,s^{-1}$

8 Select the option that correctly states Kepler's first law of planetary motion.

A The orbit of a planet is circular in shape with the Sun off centre.
B The orbit of a planet is circular in shape with the Sun in the centre.
C The orbit of a planet is elliptical in shape with the Sun in the centre.
D The orbit of a planet is elliptical in shape with the Sun at one of the foci.

9 A student designed an experiment to find the relationship between the launch angle and the horizontal distance travelled by a projectile. Identify which of the following lists of variables must be held constant in this experiment.

A launch velocity, horizontal distance, lab conditions
B launch angle, object being launched, lab conditions
C object being launched, time of flight, lab conditions
D object being launched, launch velocity, lab conditions

10 The Cassini space probe is orbiting Jupiter. Determine a possible orbital radius and period combination. (Jupiter's mass is 1.9×10^{27} kg, Cassini's mass is 2.2×10^{3} kg.)

A $r = 6.1 \times 10^{9}$ m, $T = 107.6$ s
B $r = 6.1 \times 10^{9}$ m, $T = 8.4 \times 10^{5}$ s
C $r = 1.5 \times 10^{8}$ m, $T = 3.2 \times 10^{4}$ s
D $r = 2.3 \times 10^{9}$ m, $T = 1.9 \times 10^{5}$ s

Short answer

1 At the Australia Day celebration fireworks, a rocket is launched at an angle of 85° to the horizontal.
a Calculate the initial velocity of the rocket given that it reaches a maximum height of 750 m and it starts from the ground.
b Determine the time at which the fireworks technician has set the timer so that the explosion happens at the maximum height.

2 A javelin is thrown from the hand of the athlete at an initial angle of 37° elevation, 1.7 m from the ground. It lands 3.51 s after it is let go. Calculate the initial velocity of the javelin and the horizontal distance travelled.

3 Draw a free-body diagram and calculate the magnitude of the normal force of a 200 g ball rolling down a smooth hill with an inclination of 20°.

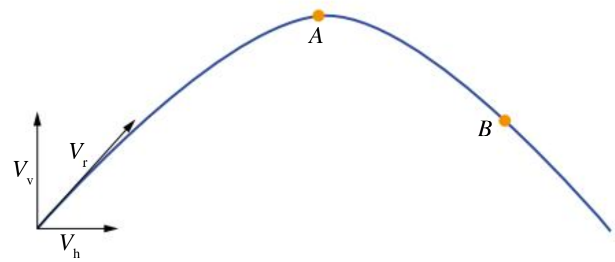
4 Describe gravitational fields, and provide an example.

5 A student conducting an experiment in an aeroplane uses a set of scales to measure the force of the gravitational field on a 7.500 kg object. The scales give a reading of 73.47 N.
a Calculate the strength of the gravitational field acting on the object.
b Determine the height at which the aeroplane is flying in order to provide the measurement taken.

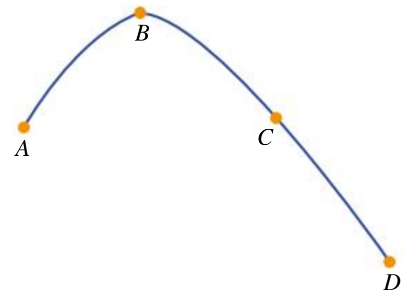
6 Astronomers investigating a newly observed planet and its moon determine the period of the moon's orbit to be 78.6 days and its orbital radius to be 5.86×10^{8} m.
a Calculate an estimate for the mass of the planet.
b Determine the magnitude of the average velocity with which the moon orbits the planet.

7 Chiron is a dwarf planet that orbits the Sun between Saturn and Uranus. It has an average orbital radius of 2.09×10^{12} m. Calculate the period of its orbit to the nearest year.

8 **a** The diagram below shows the path travelled by a soccer ball kicked from rest on the ground. Draw the vectors that represent the vertical, horizontal and resultant velocity at points A and B. The initial vectors are shown for reference.



b The diagram below shows the path travelled by a shot-put, from A to D, after it has been thrown by a competitor from a height of 1.92 m.



Draw the vertical component of velocity against time as the shot-put travels from the competitor's hand until it strikes the ground. Label the points A, B, C and D that correspond to these points on the curve on your graph. Other labels can be used to assist if needed.

9 A skier of mass 90 kg skis down a slope inclined at 15°. Assume the slope has negligible friction.
a Draw a free-body diagram of the skier, labelling all the forces acting on them and the appropriate angles.
b Calculate the magnitude of the normal force the skier will experience.
c Calculate the acceleration of the skier down the slope.
d Describe how the acceleration of the skier will change if they carry a pack of mass 10 kg as they travel down the same slope. Justify your answer.

10 A bucket is tied on the end of a rope of length 0.8 m that is held by a student. The student spins around, holding the end of the rope against their body, and allowing the bucket to swing out.
a Draw a free-body diagram of the forces acting on the bucket.
b Define 'centripetal acceleration' and describe the force that causes the acceleration.
c Calculate the tension force in the rope if the bucket of water weighs 1 kg, and the rope creates an angle of 20° between the student and the rope.
d Calculate the velocity of the bucket at this angle.
e Calculate the velocity and period of rotation of the bucket when the student changes the speed of the bucket so that it creates an angle of 40° to the vertical.

f The student drills a hole in the bucket so the water begins to drain. Describe how the motion of the bucket changes while the water is draining if the velocity is maintained.

11 A student conducted a practical investigation into the effect of launch angle on the horizontal distance (range) travelled by a projectile. The following results were obtained.

Angle (°)	Range (m)
10	0.61
20	0.92
30	1.1
40	1.16
45	1.17
50	1.15
60	1.05
70	0.8
80	0.35

a Draw a graph of the results of the investigation.

b Draw a trendline on your graph and describe the relationship found.

c The student measured the distance travelled by a projectile launched at an angle of 55° and recorded the distance as 0.9 m. Determine the predicted range at 55° and evaluate if 0.9 m is a valid range for this angle, from your graph.

d Predict the range of the projectile if the launch angle is increased to 90°. Justify your answer.

12 a Calculate the force of attraction that a 250 kg satellite orbiting Earth at a height of 36 000 km experiences from Earth's gravitational field.

b Discuss the extent to which the gravitational field of the Sun might influence the orbit of this satellite when it is between Earth and the Sun. Justify your answer with appropriate working.

Topic 2: Electromagnetism

Multiple choice

1 Select the sentence below that is not true of magnetic field lines.

A Magnetic field lines do not cross.

B Magnetic field lines must be continuous, only ending at a pole.

C Magnetic field lines go from the south pole to the north pole outside of a magnet.

D Areas where the magnetic field is stronger have field lines that are closer together.

2 Two charges are held apart and exert a force of 0.1 N on each other. The charges are measured as 4.0 μC and 9.0 μC. Determine the distance between the two charges.

A 18 m

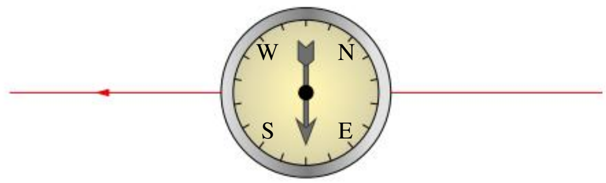
B 1.8 m

C 0.57 m

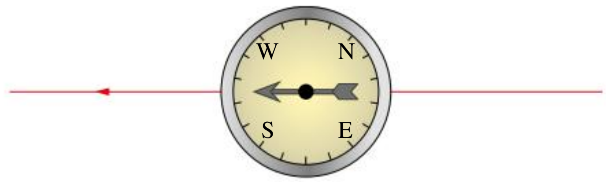
D 3.24 m

3 A compass is placed on top of a current-carrying wire. The current is in the direction from the right to the left of the page. Identify the direction in which the compass will point.

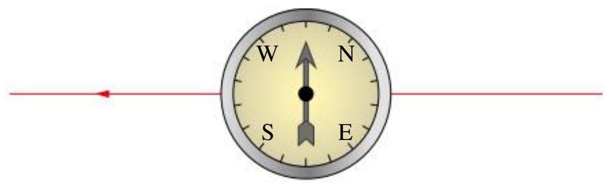
A



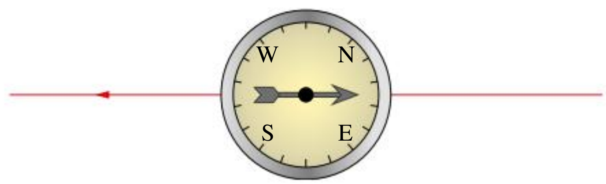
B



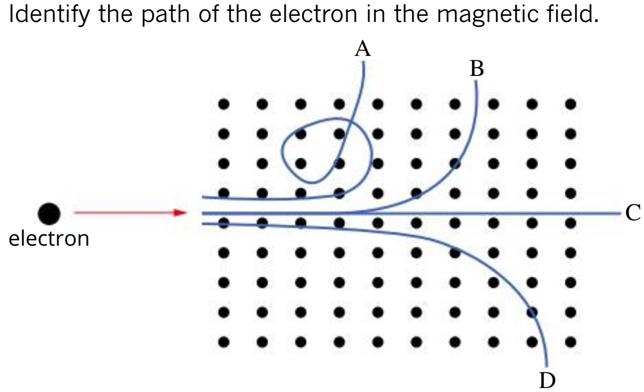
C



D



4 An electron is fired into a magnetic field as shown below. Identify the path of the electron in the magnetic field.



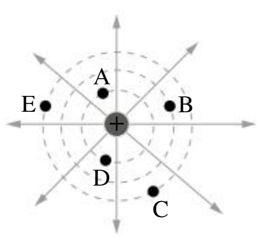
5 Identify the correct definition of magnetic flux.
- **A** a region of space where a force acts on an object due to its electric charge
- **B** the force acting per unit current per unit length on a wire placed at right angles to the magnetic field
- **C** a region in which a moving charge or a current-carrying conductor will experience a force when it is placed in it
- **D** a measure of the total magnetic field passing through an area calculated by multiplying the field strength by the perpendicular area

6 Choose the best description of electromagnetic radiation from the options given.
- **A** gamma rays from nuclear decay
- **B** an electric and magnetic field travelling as a longitudinal wave
- **C** parallel electric and magnetic fields travelling as a transverse wave
- **D** perpendicular electric and magnetic fields travelling as a transverse wave

7 Identify where an alternating current is produced in a transformer.
- **A** wire
- **B** iron core
- **C** primary coil
- **D** secondary coil

8 Select the correct description of Lenz's law.
- **A** An induced current will be created in the direction that opposes the original current.
- **B** An induced EMF will be created that is directly proportional to the rate of change of magnetic flux.
- **C** An induced current will be created that is directly proportional to the rate of change of magnetic flux.
- **D** An induced EMF will be created in the direction such that the current that it causes will be in the opposite direction to the current that is causing it.

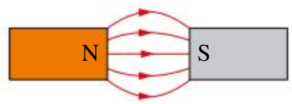
9 An electric field is created by a positive charge. The distribution of the electric field lines and equipotential lines is shown below. A test charge $+q$ is moved from point to point in the electric field. Identify which statement about work done by the electric field on charge $+q$ is true.



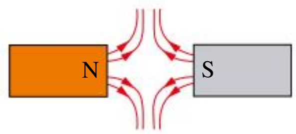
- **A** Work done moving the charge from point A to B is zero.
- **B** Work done moving the charge from point A to point D is zero.
- **C** Work done moving from point A to point B is the same as the work done moving from point C to point B.
- **D** Work done moving from point A to point B is greater than the work done moving from point A to point E.

10 Two bar magnets of equal strength are placed with the north and south poles towards each other. Identify the correct representation of the magnetic field lines that result.

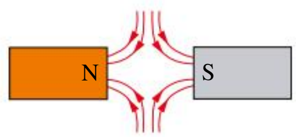
A



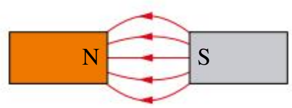
B



C



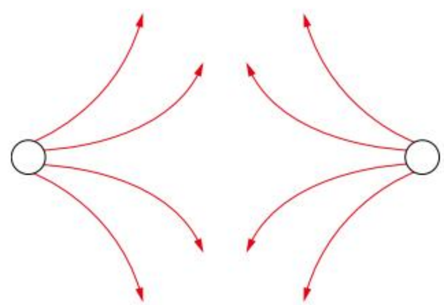
D



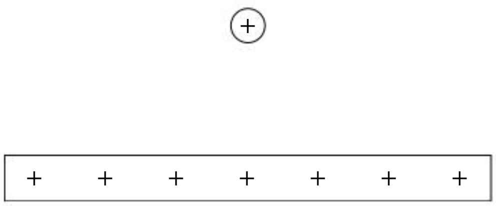
Short answer

1 An experiment is set up to measure how the strength of the magnetic field produced by a bar magnet varies with distance. List three things the experimenters must do to reduce the effect of the environment on the experiment.

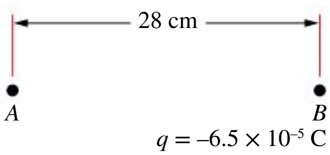
2 **a** Label the diagram below with the charges that would result in the field lines shown.



b Draw the field lines coming from the charge and the plate below. Draw field lines all around the circular object and at least eight field lines around the plate.



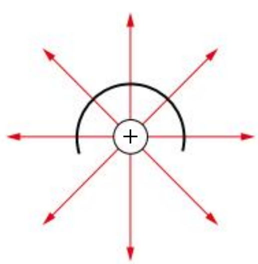
3 **a** Calculate the strength and direction of the electric field at point A 28 cm from point B, which has a charge $q = -6.5 \times 10^{-5}$ C, as indicated in the diagram below.



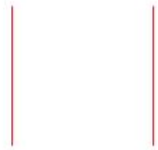
b A charged particle with $q = 2.4 \times 10^{-6}$ C is placed at point A. Calculate the force on the particle at point A.

4 **a** A positively charged plate is 5.00 cm above a negatively charged plate, and the electric field strength between the plates is 3.45×10^{2} N C^{-1}. Calculate how much work is done by the electric field to move a proton from the negative to the positive plate.

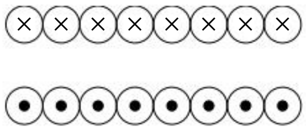
b An electron travels 3.50 mm in a circular arc around a positive point charge that generates an electric field of 7000 N C^{-1}. The electron's path is represented below. State what work is done by the electron in moving along this arc. Explain your answer.



5 **a** Two wire conductors run parallel to each other as shown below. Draw the direction of conventional current through the wires that will result in a force of attraction between them.



b Draw field lines around the solenoid below to represent the direction of the magnetic field that is created when a current flows through the solenoid coil. Label the north and south poles of the solenoid.



6 A motor is constructed by placing a single wire coil in a magnetic field. Consider one part of the coil with length 50 cm running perpendicular to a magnetic field of strength 2 mT.

a Calculate the force that will act on the length of coil when a current of 1.5 A flows through it.

b The length of coil is arranged so that the current runs from north to south in the coil and the magnetic field runs from east to west. State the direction of the force that acts on the length of coil.

7 A drone helicopter with metal rotor blades of length 15 cm from axis to tip is flying in Australia, where the vertical component of Earth's magnetic field is approximately 5×10^{-5} T upwards.

a Calculate the magnetic flux due to Earth's magnetic field that passes through the circular area swept out by the rotor blades.

b Assume the rotor spins at 10 revolutions per second. Calculate the magnitude of the average EMF induced between the axis and the tip of the rotor blade due to its rotation in Earth's magnetic field.

8 Two light sources emit different colours of light. Select the source with the higher energy.

Source A: Wavelength = 480 nm

Source B: Frequency = 6.38×10^{14} Hz

9 A charged Styrofoam™ ball of mass 0.32 g hovers 2.0 cm above a plate carrying a charge of -4.72×10^{-7} C. (The Styrofoam ball maintains its position due to a force between itself and the plate below.)

a State the law that can be used to calculate the force exerted between two charged objects.

b Identify whether the charge on the Styrofoam ball is positive or negative.

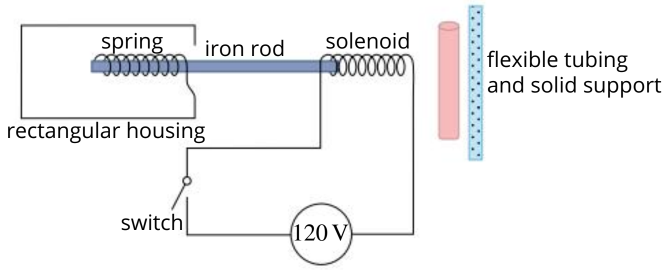
c Calculate the magnitude of the charge on the ball.

d The ball has developed its charge by accumulating electrons on its surface. Calculate how many electrons it needs to accumulate to gain the charge calculated in part **c**.

10 A model village has 15 electrical components, each rated as 6 V and 0.5 A, connected in series. The model's circuit is connected to the secondary coil of an iron core transformer that has a 1000-turn primary coil. The primary coil is connected to the 240 V 50 Hz mains supply.

- **a** Calculate the total voltage the circuit will need to supply to operate the 15 components.
- **b** Identify how many turns are in the secondary coil of the transformer.
- **c** Determine the power being supplied by the secondary coil.
- **d** Calculate the power supplied by the primary coil of the transformer assuming the transformer has an efficiency of 85%.

11 A student designs a simple solenoid valve system to control the flow of a liquid through flexible tubing by closing and opening the tubing. It is comprised of an iron rod with a spring coiled around it at one end. One end of the spring is attached at one end of the rod and its other end is attached to a rectangular housing. The tubing is fixed to a solid support. The system is represented by the diagram below.



- **a** Explain how the system will operate to close and open the tubing, using the appropriate physics concepts.
- **b** Identify two ways to increase the force with which the iron rod will push the tubing closed.

12 A practical investigation was carried out to determine the relationship between the force acting on a current-carrying wire in a magnetic field and the magnitude of the current.

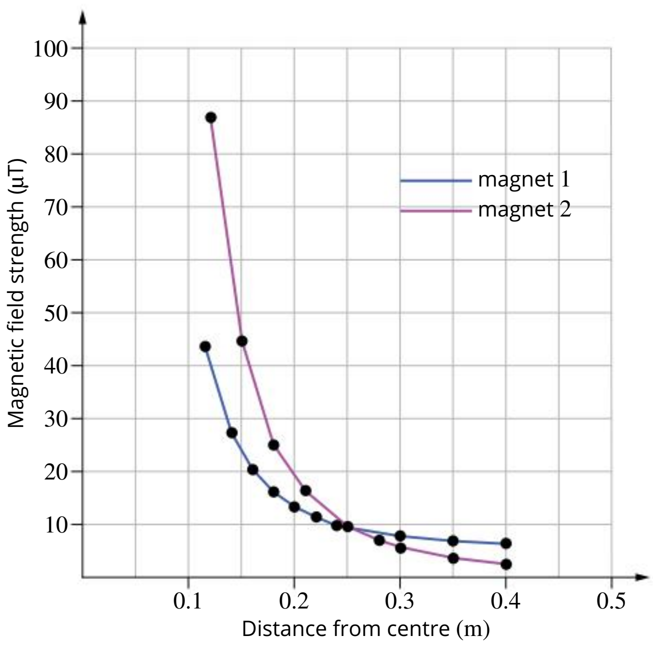
The wire was placed in a uniform magnetic field of strength 30 mT so that 12 cm of the wire is in the field. The current was varied, and the force on the wire was measured. The following results were obtained.

I (A)	*F* (mN)
0.5	1.7
1	3.6
1.5	5.4
2	7.1
2.5	9.8
3	10.8
3.5	12.5

- **a** State the independent and dependent variables for the experiment.
- **b** Describe a possible experimental set-up to obtain these results and minimise errors.
- **c** Draw a graph of the results.
- **d** Derive the equation of the trendline and compare it to the theoretical relationship.
- **e** State what the gradient of the trendline represents.

13 A student wishes to compare the strength of bar magnets of different lengths. The magnets will be used in different orientations, so the student decides that all distance measurements will be to the centre of the bar. Two magnets were measured and the following graph was produced.

Effect of distance from centre of magnet on field strength



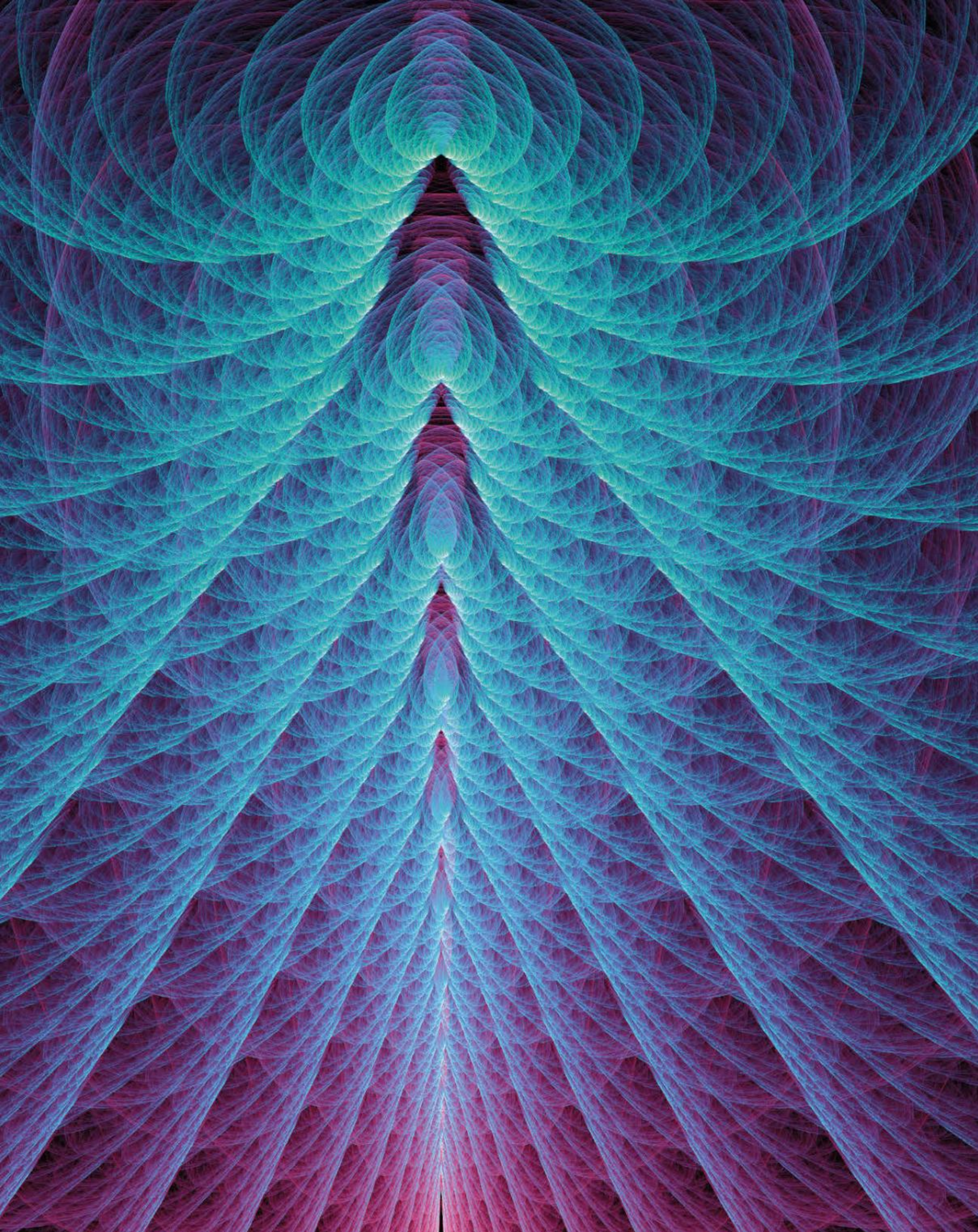
a Describe an apparatus and method that could be used to obtain this data.
b Compare the two magnets using the graph above.
c Propose a scenario in which magnet 1 would be preferable to magnet 2.

14 Use the information below to answer the questions that follow.

At its simplest, a mobile telephone works like a radio transmitter and receiver. When you speak into your mobile phone, the sound waves are converted to an electrical signal by a transducer. The electrical signal is called an audio signal because its frequencies are the same as the audible frequencies of sound wave, i.e. 20 to 20 000 Hz. The oscillating electrons from the alternating current of the electrical signal travel to the transmitting antenna where they are converted to electromagnetic waves.

The electromagnetic waves from the sender's phone are picked up and relayed by the mobile telephone towers in the network until they reach the receiver's telephone. The antenna in the receiver's phone picks up the electromagnetic waves, which cause the electrons in the receiving antenna to oscillate, creating an electrical signal. This signal is converted back to sound waves heard by the person receiving the telephone call.

a Compare the frequency of oscillations of the electrons in the transmitting antenna to the frequency of the electromagnetic waves sent out by the transmitting antenna.
b Calculate the wavelength of an electromagnetic wave resulting from an electrical signal with the maximum audio frequency.
c The electromagnetic wave generated by the audio input in a phone is carried by a carrier wave; that is, the audio wave is superimposed on the carrier wave. For many mobile networks in Australia, the frequency of the carrier wave is in the 850 MHz band.
  i Compare the wavelength of the carrier wave with the wavelength of the highest audio frequency. State which has the longer wavelength.
  ii Calculate the relative size of the wavelengths of the audio wave and the carrier wave.



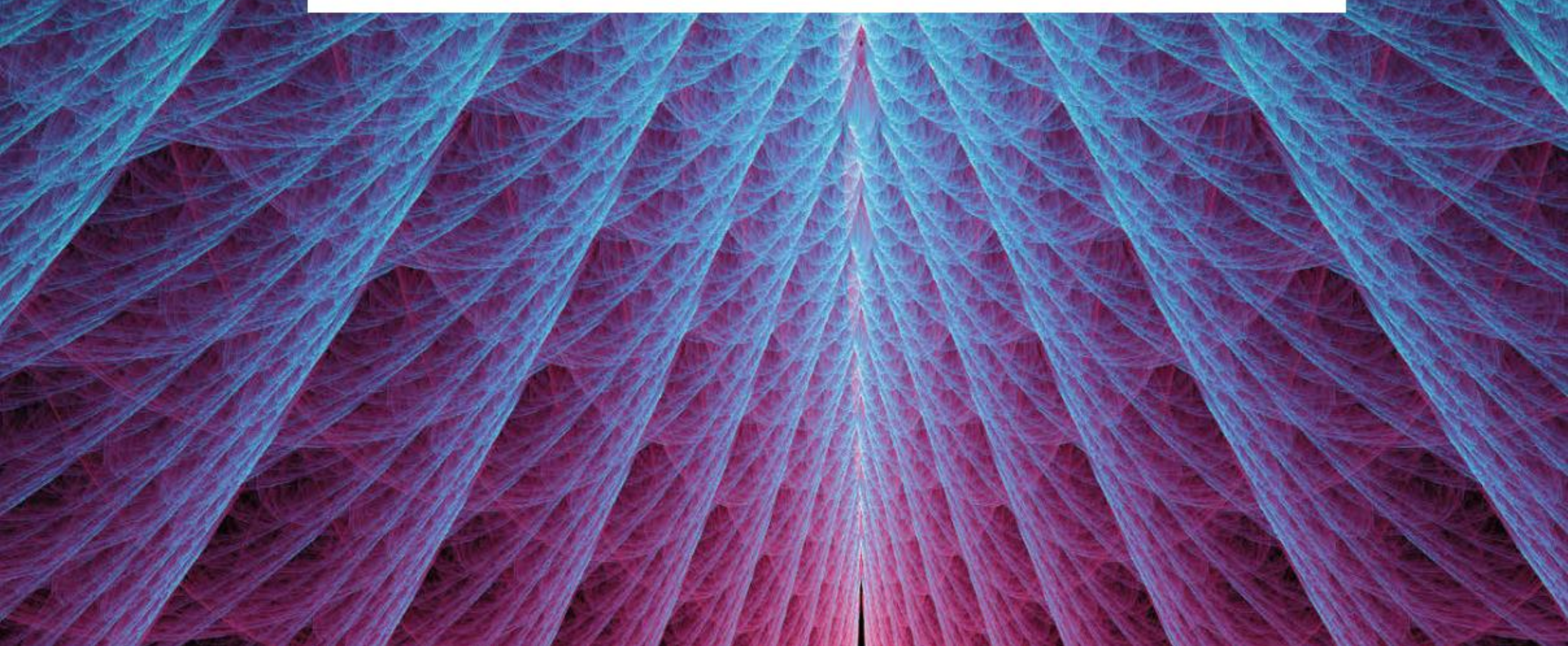
UNIT 4

Revolutions in modern physics

Unit 4 objectives

Students will:

- describe and explain special relativity, quantum theory and the Standard Model
- apply understanding of special relativity, quantum theory and the Standard Model
- analyse evidence about special relativity, quantum theory and the Standard Model
- interpret evidence about special relativity, quantum theory and the Standard Model
- investigate phenomena associated with special relativity, quantum theory and the Standard Model
- evaluate processes, claims and conclusions about special relativity, quantum theory and the Standard Model
- communicate understandings, findings, arguments and conclusions about special relativity, quantum theory and the Standard Model.



CHAPTER

10 Special relativity

Galileo and Newton laid the foundations of the 'clockwork universe', a mechanical picture of the world that has underpinned most modern world views. Einstein, along with others such as Bohr and Heisenberg, presented a much richer and more mysterious universe, one that challenges people to think beyond the mechanical picture they so often take for granted.

In this chapter, you will explore the concepts of classical physics, as described by Galileo and Newton, and the evidence that pointed towards the need for some different thinking. Einstein's special relativity is presented as a solution to the problem of classical physics at speeds approaching the speed of light.

Syllabus subject matter

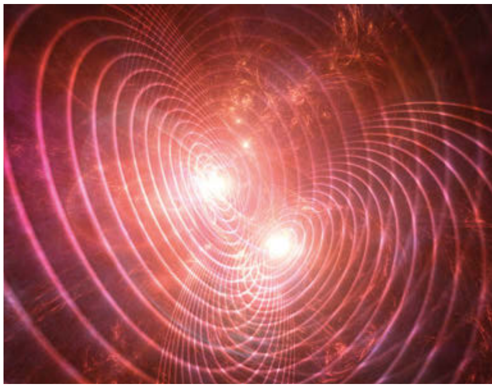
WS 4.1.1

Topic 1 • Special relativity

SPECIAL RELATIVITY

- describe an example of natural phenomena that cannot be explained by Newtonian physics, such as the presence of muons in the atmosphere
- define the terms *frame of reference* and *inertial frame of reference*
- recall the two postulates of special relativity
- recall that motion can only be measured relative to an observer
- explain the concept of simultaneity
- recall the consequences of the constant speed of light in a vacuum, e.g. time dilation and length contraction
- define the terms *time dilation, proper time interval, relativistic time interval, length contraction, proper length, relativistic length, rest mass* and *relativistic momentum*
- describe the phenomena of time dilation and length contraction, including examples of experimental evidence of the phenomena
- solve problems involving time dilations, length contraction and relativistic momentum
- recall the mass–energy equivalence relationship
- explain why no object can travel at the speed of light in a vacuum
- explain paradoxical scenarios such as the twins' paradox, flashlights on a train and the ladder in the barn paradox.

10.1 Einstein and relativity



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

- explain the Galilean principle of relativity and the principle behind Newtonian mechanics, including an explanation of the link to Einstein's theory of special relativity
- identify two statements about time and space that Newton assumed to be evident and true
- describe why magnetism cannot be observed using Newton's laws
- explain why the observation of muons above Earth is an unexpected occurrence.

GALILEAN RELATIVITY AND NEWTONIAN MECHANICS

FIGURE 10.1.1 Albert Einstein statue in Washington, D.C., USA

Galileo and Newton developed theories of motion. These theories allowed the relative motion of low-speed objects to be modelled mathematically. This section presents the observations that challenged Galilean relativity and Newtonian physics, and explains the key principles that led to the new physics described by Albert Einstein (Figure 10.1.1) known as the theory of special relativity.

Galilean principle of relativity

Galileo was particularly interested in relative motion. One of his famous experiments involved the dropping of a cannon ball from the top of the mast of a moving ship. Galileo found that the motion of the cannon ball was not affected by the motion of the ship: the cannon ball landed next to the base of the mast. His principle of relativity was that you cannot tell if you are moving or not without looking outside of your own **frame of reference.**

> A frame of reference is the physicist's way of describing a particular system of measurement coordinates. Our usual frame of reference is the Earth's surface, but this does not have to be the case. As long as we make our measurements from a frame of reference that is moving at constant velocity or zero velocity, any measurements of changes of velocity will agree with those made by observers in other steadily moving frames of reference.

Newtonian principle

Based on the work of Galileo, Isaac Newton established detailed models for the motion of objects such as planets, moons and comets, even falling oranges. According to his equations, the velocity of objects can be calculated relative to any frame of reference, as long as the velocity of the frame of reference is known. The Newtonian principle states that the velocities of objects and frames of reference can be added together to determine the velocity of the object in another frame of reference. This theory is common throughout all his equations and laws.

Consider an object moving in frame of reference A. This frame of reference is moving in another frame of reference, B. The velocity of the object in B is given by:

$$v_{\text{A rel B}} = v_{\text{A rel stationary observer}} - v_{\text{B rel stationary observer}}$$
$$v_{\text{object in B}} = v_{\text{object in A}} + v_{\text{A in B}}$$

A practical example of this could be when a person runs forwards on a train. Here, the train is frame of reference A and the track along which the train moves is frame B. Imagine that the person runs at $5\,\text{m s}^{-1}$ forwards while the train travels at a velocity of $20\,\text{m s}^{-1}$ forwards. The velocity of the person relative to B, the track, is:

$$v_{\text{person rel train}} = v_{\text{person rel track}} - v_{\text{train rel track}}$$
$$5 = v_{\text{person rel track}} - 20$$
$$v_{\text{person rel track}} = 25\,\text{m s}^{-1}$$

That is, the person is moving with a velocity of $25\,\text{m s}^{-1}$ forwards when measured against the track.

Worked example 10.1.1

RELATIVE VELOCITY

You are in the passenger seat of a car travelling at 100.0 km h^{-1} forwards as observed by somebody watching by the side of the road. A hoon overtakes your car at, according to their speedometer, 120.0 km h^{-1}.	
a Calculate the velocity of the hoon's car with respect to your car.	
Thinking	**Working**
Identify the known variables.	$v_{\text{hoon rel road}} = 120.0\ \text{km h}^{-1}$ $v_{\text{you rel road}} = 100.0\ \text{km h}^{-1}$
Recall the formula for relative velocity: $v_{\text{A rel B}} =$ $v_{\text{A rel stationary observer}} - v_{\text{B rel stationary observer}}$ Substitute the values from the question and solve for $v_{\text{hoon rel you}}$.	$v_{\text{hoon rel you}} = v_{\text{hoon rel road}} - v_{\text{you rel road}}$ $= 120.0 - 100.0$ $= 20.0\ \text{km h}^{-1}$ You see the hoon's car move forwards at 20.0 km h^{-1}.
b Calculate the velocity of your car with respect to the hoon's car.	
Thinking	**Working**
Identify the known variables.	$v_{\text{hoon rel road}} = 120.0\ \text{km h}^{-1}$ $v_{\text{you rel road}} = 100.0\ \text{km h}^{-1}$
Recall the formula for relative velocity: $v_{\text{A rel B}} = v_{\text{A rel stationary observer}} - v_{\text{B rel stationary observer}}$ Substitute the values from the question and solve for $v_{\text{you rel hoon}}$	$v_{\text{you rel hoon}} = v_{\text{you rel road}} - v_{\text{hoon rel road}}$ $= 100.0 - 120.0$ $= -20.0\ \text{km h}^{-1}$ The hoon sees your car move backwards at 20.0 km h^{-1}.

➤ Try yourself 10.1.1

RELATIVE VELOCITY

Michelle is seated on a bus that is traveling with a velocity of 5 m s^{-1}. Assume she remains in her seat.

a Calculate Michelle's velocity relative to the road.

b Michelle now gets up and walks at 1.0 m s^{-1} towards the back of the bus. Calculate her velocity relative to the road.

In 1687, Isaac Newton published his famous *Principia*. At the start of this incredible work, which was the basis for all physics in the following two centuries and beyond, he notes the following assumptions, which he took as evident and true:

- Absolute, true and mathematical time, of itself, and from its own nature, flows equably without relation to anything external.
- Absolute space, in its own nature, without relation to anything external, remains always similar and immovable.

Newton based all of his laws on these two assumptions: that space and time are constant, uniform and straight. So according to Newton, space is like a big set of *xyz* axes that always have the same scale, and in which distances can be calculated exactly by Pythagoras' theorem. You expect a metre ruler to be the same length whether it is held vertically or horizontally, north–south or east–west, in your classroom or in the International Space Station.

In this space, time flows at a constant rate, which is the same everywhere. One second in Perth is the same as one second in Brisbane, and one second on the ground is the same as one second up in the air or in deep space.

OBSERVATIONS THAT NEWTON'S LAWS CANNOT EXPLAIN

With the invention of more accurate measuring devices for time and distance, it became evident that some of the measurements of events didn't agree with the values predicted based on Newton's laws acting in a framework of Galilean relativity.

Einstein realised that Newton's assumptions might not be valid, at least not on scales involving huge distances and at speeds approaching the speed of light. One natural phenomenon that cannot be explained by Newtonian physics is that of cosmic rays.

Long-lived muons

In the Earth's atmosphere, high-energy cosmic rays interact with the nuclei of oxygen atoms 15 km above the surface of Earth to create a cascade of high-velocity subatomic particles. One of these particles is the **muon**, which is unstable. The mean lifetime of a stationary muon, as measured by an **atomic clock**, is 0.000 002 196 s (2.196 μs). The muons created by cosmic radiation typically travel at 99.97% of the speed of light, so at this speed Newtonian physics would predict that a muon would travel about 659 m:

$$\begin{aligned} s &= v\Delta t \\ &= 0.9997 \times 3 \times 10^{8} \times 2.196 \times 10^{-6} \\ &= 658.6\,\text{m (or roughly 659 m)} \end{aligned}$$

After 10 lifetimes, you can expect there to be essentially no muons remaining. So after beginning at a height of 15 km and travelling through a distance of 6.59 km, to a height of about 8.41 km above the surface of Earth, you would expect that no muons would be detected.

However, muons created by cosmic radiation are actually detected at the Earth's surface. This means that the fast-moving muons have existed for a much longer period of time than they should have. A muon that strikes the surface would have existed at least 22.8 times its predicted life span as a stationary muon, based on Newtonian physics. Once again, Newtonian physics and Galilean relativity cannot explain this observation; however, we will soon see how special relativity explains this.

10.1 Review

SUMMARY

- Galileo's principle of relativity was that you cannot tell if you are moving or not moving without looking outside of your own frame of reference.
- The Newtonian principle states that the velocities of objects and frames of reference can be added together to determine the velocity of the object in another frame of reference.
- Newton based all of his laws on two assumptions: that space and time are constant, uniform and straight.
- High-speed muons created in Earth's upper atmosphere should not last long enough to reach Earth's surface, but they do. The moving muons have longer lifetimes than stationary muons. This cannot be explained by Newtonian physics or Galilean relativity.

KEY QUESTIONS

Retrieval

1 State the property of muons that provides evidence that special relativity is a real phenomenon.

2 List three objects that are in a moving car's reference frame and three objects that are not in the car's reference frame.

3 Recall the properties of muons by selecting the correct term in bold to complete the sentences.

Muons have **very short/prolonged** lives. On average, muons live for approximately 2.2 **s/μs**. Their speeds are measured as they travel through the atmosphere. A muon's speed is **about a tenth of/very similar to** the speed of light. According to Newtonian laws, muons **should/should not** reach the Earth's surface. However, many **do/do not**.

Comprehension

4 Determine the speed at which the sound from a fire truck siren would appear to be travelling in the following situations. The speed of sound in air is $340\,m\,s^{-1}$.

- **a** You are driving towards the stationary fire truck at $30\,m\,s^{-1}$.
- **b** You are driving away from the stationary truck at $40\,m\,s^{-1}$.
- **c** You are stationary and the fire truck is heading towards you at $20\,m\,s^{-1}$.
- **d** You are driving at $30\,m\,s^{-1}$ and about to overtake the fire truck, which is travelling at $20\,m\,s^{-1}$ in the same direction.

Analysis

5 Anna is at the front end of a train carriage that is moving at $10.0\,m\,s^{-1}$. She throws a ball back to Ben, who is 5.0 m away at the other end of the carriage. Ben catches it 0.20 s after it is thrown. Chloe is watching all of this from the side of the track.

- **a** Determine the velocity at which Chloe sees the ball travel.
- **b** Calculate how far, in Chloe's frame of reference, the ball moved while in flight.
- **c** Determine the time of flight of the ball as measured in Chloe's frame of reference.

6 Imagine that the speed of light has suddenly slowed down to only $50.0\,m\,s^{-1}$ and this time Anna (still at the front of the 5.0 m train carriage moving at $10.0\,m\,s^{-1}$, as in question 5) sends a flash of light towards Ben. Consider this information and question 5, to answer the following:

- **a** Calculate how long it takes the light flash to reach Ben from Anna's point of view.
- **b** Calculate how fast the light was travelling in Ben's frame of reference.
- **c** Determine how far the train travelled in 0.10 s in Chloe's frame of reference.
- **d** Calculate how fast the light was travelling in Chloe's frame of reference.
- **e** Explain why the time measured by Chloe for the light to reach Ben is not the same as that measured by Anna.

10.2 Frames of reference

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

- distinguish between an inertial frame of reference and a non-inertial frame of reference
- define 'aether'
- explain why scientists believed the aether to exist.

FIGURE 10.2.1 Einstein as a teenager.

> *Gedanken* experiments consider hypotheses and theories for the purpose of thinking about the experiment's consequences. This type of experiment may not be possible to perform.

When Albert Einstein was just 5 years old, his father gave him a compass. He was fascinated by the fact that it was responding to some invisible field that enveloped the Earth. His curiosity was aroused and, fortunately for physics, he never lost it. In his teens he turned his attention to the question of light (Figure 10.2.1).

Perhaps it was lucky that in his early twenties Einstein was not part of the physics 'establishment'. He was working as a patent clerk in the Swiss Patent Office. It was an interesting enough job, but it left him time to think about electromagnetic waves (light) and their relationship to the Galilean principle of relativity.

INERTIAL FRAME OF REFERENCE

Einstein was a typical theoretician: the only significant experiments he ever did were thought experiments, or ***Gedanken* experiments**, as they are called in German.

Many of Einstein's *Gedanken* experiments involved thinking of situations that involved two frames of reference moving with a steady relative velocity, in which the principles of Galilean relativity applied. For example, a person stationary in a moving car could be the first frame of reference, and an observer on the road watching that 'stationary' person moving at speed could be the second frame of reference. Newton had referred to these as **inertial frames of reference**, as the law of inertia applied within them (refer to *Pearson Physics 11 Queensland*, Chapter 7).

An inertial frame of reference is one that is not accelerating. For example, in an aircraft moving at constant velocity, the passengers will feel they are stationary and are therefore in an inertial frame of reference. When a body does not seem to be acting in accordance with inertia, it is in a **non-inertial frame of reference**, i.e. is accelerating. Consider the same aircraft starting to descend for landing. It will undergo deceleration. This means the passengers are now in a non-inertial frame of reference and will feel a slight 'force' forwards that appears, to them, to come from nowhere.

Consider the motion experienced when you are a passenger in a car and the driver suddenly slams on the brakes. The car comes to a stop but you feel you are 'forced' forwards. If you make the incorrect assumption that your frame of reference isn't decelerating, then you're going to have to insist that there are some other forces making your body lean forwards as the car brakes, which isn't the case. These extra forces, or pseudo-forces, do not exist. Rather, they appear to exist if you cannot tell that you are in a non-inertial frame of reference.

EINSTEIN AND GALILEAN RELATIVITY

Einstein decided that the elegance of the principle of Galilean relativity was such that it simply had to be true. However, nature did not appear to have a special frame of reference, and Einstein could see no reason to believe that there was one waiting to be discovered. In other words, there is no such thing as an absolute velocity. It is not possible to have a velocity relative to space itself, only to other objects within space. So the velocity of any object can always be stated as relative to some other object. In the case of the person running on the train at $5\,m\,s^{-1}$ while the train travels at a speed of $20\,m\,s^{-1}$ from Module 10.1, the velocity of the runner can be stated as either $5\,m\,s^{-1}$ relative to the train or $25\,m\,s^{-1}$ relative to the track.

$$\begin{aligned} v_{\text{person rel train}} &= v_{\text{person rel track}} - v_{\text{train rel track}} \\ &= 25 - 20 \\ &= 5\,m\,s^{-1} \end{aligned}$$

Einstein expanded the Galilean principle to state that all inertial frames of reference must be equally valid, and that the laws of physics must apply equally in any frame of reference that is moving at a constant velocity. So there is no physics experiment you can do that is entirely within a frame of reference that will tell you whether or not you are moving. In other words, as you speed along in your *Gedanken* train with the blinds down, you cannot measure your speed. You can tell if you are accelerating easily enough: you just hang a pendulum from the ceiling, as seen in Figure 10.2.2c and d. However, the pendulum will hang straight down whether you are travelling steadily at $100\,km\,h^{-1}$ or are stopped at the station. Consider Figure 10.2.2a and b. There is no way of telling which of the trains is stationary relative to the ground, or which is moving at a constant velocity.

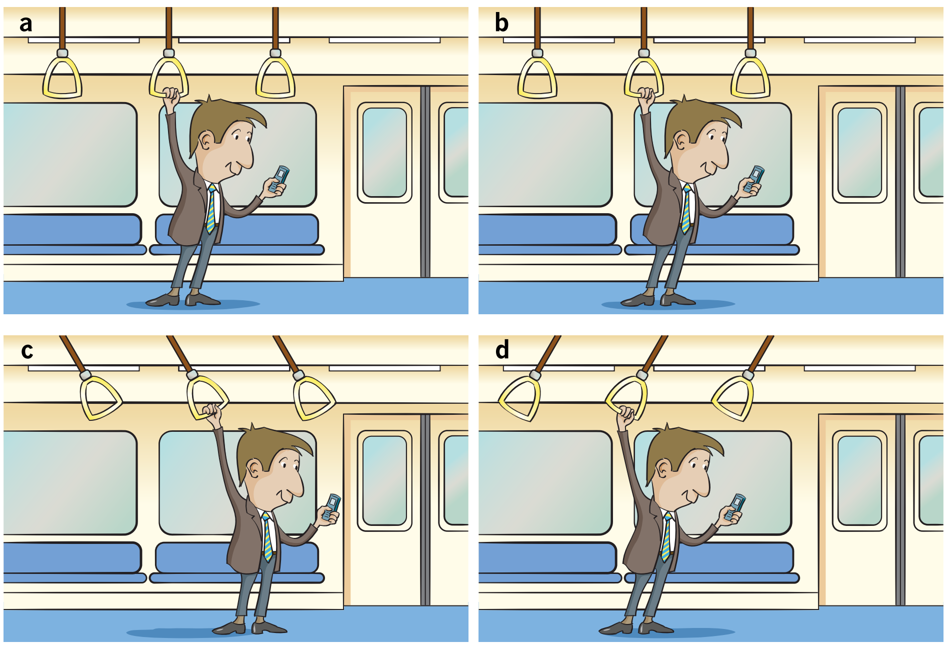


FIGURE 10.2.2 There is no observation or experiment that shows the difference between two inertial frames of reference (a) and (b). In one of the situations illustrated, the train is stationary, and in the other it is moving smoothly at $100\,km\,h^{-1}$. There is no observation that will tell which one is which. In (c) and (d), the motion of the handles hanging from the ceiling of the train indicate that these trains are not moving at a constant speed.

Einstein's fascination with the nature of light had led him to a deep understanding of Maxwell's work on the electromagnetic nature of light waves. He was convinced of the elegance of Maxwell's equations and their prediction of a constant speed of light. Most physicists believed that the constant speed predicted by Maxwell's equations referred to the speed of light relative to a **medium** (a substance it travelled through). It was thought that the speed predicted would be the speed in the medium in which light travelled, and the measured speed would have to be adjusted for one's own speed through that medium.

As light travelled through the vacuum of space between the Sun and Earth, clearly the medium was no ordinary material. Physicists gave it the name **aether**, as it was an 'ethereal' substance. It was thought, following Maxwell's work, that the aether must be some sort of massless, rigid medium that 'carried' electric and magnetic fields.

This was a real problem for Einstein. If light was emitted from an object that was travelling at a speed through the aether, then the total speed of light relative to the aether would be greater than the fixed speed of light in the aether, according to the principle of Galilean relativity.

10.2 Review

SUMMARY

- Newton had referred to two frames of reference moving with a steady relative velocity as inertial frames of reference, as the law of inertia applied within them.
- When a body does not seem to be acting in accordance with inertia, it is in a non-inertial frame of reference or accelerating.
- Einstein decided that the elegance of the principle of Galilean relativity was such that it simply had to be true.
- Einstein expanded the Galilean principle to state that all inertial frames of reference must be equally valid, and that the laws of physics must apply equally in any frame of reference that is moving at a constant velocity.

KEY QUESTIONS

Retrieval

1 Describe why the physicists of the late 19th century felt the need to invent the idea of the aether.

2 Name two examples of objects experiencing inertial frames of reference.

3 Name two examples of objects experiencing non-inertial frames of reference.

Comprehension

4 Determine, from the view point of a stationary observer on a train station platform, the velocity of a passenger running at the same speed as the train he is in, but in the opposite direction to the train.

5 Two spaceships are travelling at a constant relative velocity. Then one begins to accelerate. A passenger uses a device that measures velocity and sees the relative velocity increase. Explain how this passenger could tell whether it was his own or the other ship that began to accelerate.

6 Explain these two observations using Galileo's principle of relativity.

- **a** A ball thrown straight up in a uniformly moving car comes straight back down.
- **b** A ball thrown straight up in a car that suddenly stops falls down in front of the person who threw it.

Analysis

7 Max is behind the safety rail holding a ball while watching his little sister go around on a merry-go-round. He sees her come around the bend and throws the ball straight at her, hoping she will catch it. Max's throw misses his sister. Later, his sister wants to know how Max made the ball curve in the air, but Max says he threw it straight. Discuss the reason for their different opinions.

10.3 Postulates of relativity

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

- identify how Einstein resolved the problem of the aether
- explain the Michelson–Morley experiment, including their conclusion
- state Einstein's two postulates of special relativity
- recognise the assumptions Einstein had to make for his two postulates to be true
- identify the consequence of accepting the two postulates that goes against Newtonian physics.

After Maxwell's discovery that light was nothing more than an electromagnetic wave, the necessity for the existence of the aether was further strengthened, as it was believed that electric and magnetic fields must have a medium in which to travel. The next step for scientists was the detection of the aether.

THE MICHELSON–MORLEY EXPERIMENT

The existence of an aether appeared to be a serious blow for the principle of relativity. It seemed that there may be a frame of reference attached to space itself after all. If this was the case, there was the possibility of an absolute zero velocity.

Scientists needed to test the idea of electromagnetic waves moving through the aether. As Earth is in orbit around the Sun, an aether 'wind' should be blowing past Earth, as Earth moved relative to the aether. This suggested to American physicist Albert Michelson that it should be possible to measure the speed at which Earth was moving through the aether by measuring the small changes in the speed of light as Earth changed its direction of travel. For example, if the light was travelling through the aether in the same direction as Earth, its apparent speed should be slower than usual, at $c - v$, where v is the velocity of Earth (Figure 10.3.1). It would be as if the light was travelling against an aether 'wind' created by the motion of Earth through it. If the light was travelling against Earth's motion, its apparent speed should be faster, as it would be travelling with the 'wind', at $c + v$ (Figure 10.3.1). The differences would be tiny, less than 0.01%, but Michelson was confident that he could measure them.

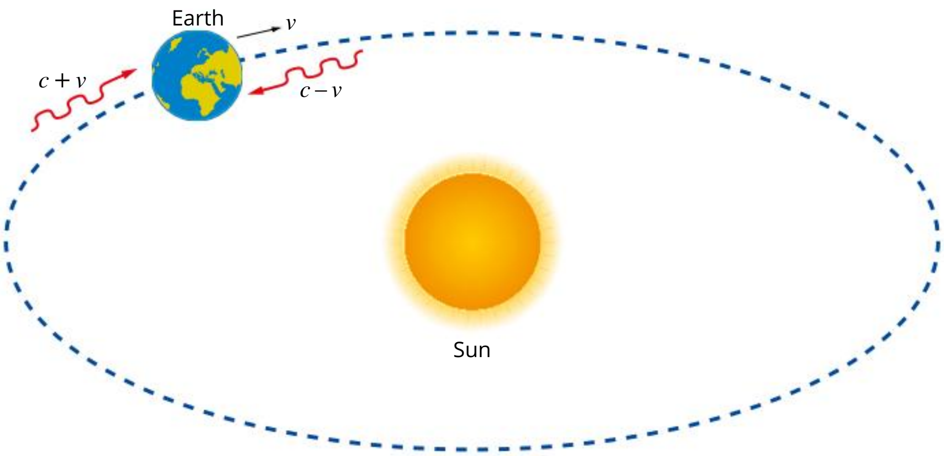


FIGURE 10.3.1 The basic principle of the Michelson–Morley experiment. If the aether is fixed relative to the Sun, and the light is travelling at c relative to the aether and in the same direction as Earth, the apparent speed should be less than c, i.e. $c - v$. If the light was travelling in the opposite direction to Earth it should appear faster than c, i.e. $c + v$.

In the 1880s, Michelson and his collaborator Edward Morley set up a device known as an interferometer. This device could not measure the speed of light, but it could detect changes in the speed of light that might have been due to the aether wind. The interferometer could measure any difference in the time taken for light to travel in two mutually perpendicular directions. One of these directions was the same as the direction the Earth was travelling, and the other at right angles. Michelson and Morely expected there to be a small difference between the two measurements. However, they found none. Perhaps, then, the Earth at that time was stationary with respect to the aether? Six months later, however, when Earth would have to be travelling in the opposite direction relative to the aether, there was still no difference in the measured speeds! Other people performed similar experiments, virtually always with the same null result. Whatever direction Earth was moving in it seemed to be at rest in the aether. Or perhaps there was no aether at all.

While Michelson and Morley's results were consistent with Maxwell's prediction that the speed of light would always appear to be the same for any observer, the apparent absurdity of such a situation led most physicists to believe that some flaw in the theory behind the experiment, or in its implementation, would soon be discovered. Einstein, however, wondered about the consequences of actually accepting their prediction about the speed of light but at the same time holding on to the principle of Galilean relativity.

EINSTEIN'S POSTULATES

Although Einstein accepted both Galileo's and Maxwell's theories despite the apparent contradiction, this still left the question: How could two observers travelling at different speeds see the same light beam travelling at the same speed? The answer, Einstein said, was in the very nature of space and time.

In 1905 he sent a paper to the respected physics journal *Annalen der Physik*. The paper was entitled 'On the electrodynamics of moving bodies'. In this paper he put forward two simple **postulates of special relativity** (statements assumed to be true) and followed them to their logical conclusion. It was this conclusion that was so astounding.

Einstein's two postulates:

- The laws of physics are the same in all inertial (non-accelerated) frames of reference.
- The speed of light has a constant value for all observers regardless of their motion or the motion of the source.

(The first postulate means that there is no preferred frame of reference and so is sometimes stated as: no law of physics can identify a state of absolute rest.)

The first postulate is basically that of Newton, but Einstein extended it to include the laws of electromagnetism, so elegantly expressed by Maxwell. The second postulate simply takes Maxwell's prediction about the speed of electromagnetic waves in a vacuum at face value.

These two postulates sound simple enough; the only problem was that, according to early Newtonian physics, they were contradictory.

Consider the example illustrated in Figure 10.3.2. Binh is in his spaceship travelling away from Clare at a speed v, and Clare turns on a laser beam to signal Binh. The first postulate seems to imply that the speed of the laser light, as measured by Binh, should be $c - v$, where c is the speed of light in Binh's frame of reference. This is what you would expect if, for example, you were to measure the speed of sound as you travel away from its source: as your velocity gets closer to the speed of sound, the slower the sound waves appear to be travelling.

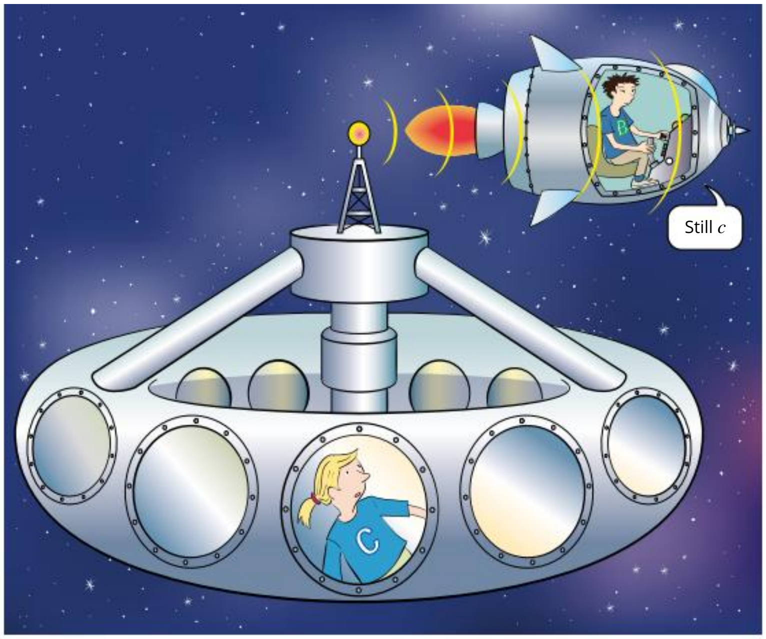


FIGURE 10.3.2 Einstein's two postulates are seemingly contradictory. His first postulate indicates that the speed of the laser light, as measured by Binh, should be $c - v$, whereas his second postulate indicates it should be c. Einstein revisited Newton's assumptions to resolve this problem.

The second postulate, however, tells you that when Binh measures the speed of Clare's laser light, he will find it to be c, that is, $3 \times 10^8\,\mathrm{m\,s^{-1}}$. So at first glance, these two postulates appear to be mutually exclusive. To resolve this problem, Einstein went back to the two assumptions on which Newton had based his theories:

- **Absolute, true, and mathematical time, flows equably without relation to anything external.**
- **Absolute space, without relation to anything external, always remains similar and immovable.**

Newton based all of his laws on the assumptions that space and time are constant, uniform and straight. Einstein realised that these assumptions might not be valid, at least not on scales involving huge distances and speeds approaching the speed of light. The only way in which Einstein's two postulates can both be true is if both space and time are not fixed and unchangeable.

EINSTEIN'S *GEDANKEN* TRAIN

To illustrate the consequences of accepting the two postulates he put forward, Einstein discussed a simple thought experiment. It involves a train moving at a constant velocity.

Amaya and Binh have boarded Einstein's *Gedanken* train and Clare is outside the train (Figure 10.3.3). This train has a flashing light bulb set right in the centre of the carriage. Amaya and Binh are watching the flashes of light as they reach the front and back walls of the carriage. They find that the flashes reach the front and back walls at the same time, which is not surprising. Outside, Clare is watching the same flashes of light. Einstein was interested in when Clare saw the flashes reach the end walls.

To appreciate Einstein's ideas, you need to contrast them with what you would normally expect. Consider a situation in which Amaya and Binh are rolling balls towards opposite ends of a train carriage. It is important to appreciate that, although Clare, the outside observer, measures the ball's velocity to be different from that measured by Amaya and Binh, the times at which the various events (balls hitting the ends of the carriage) occur must be the same.

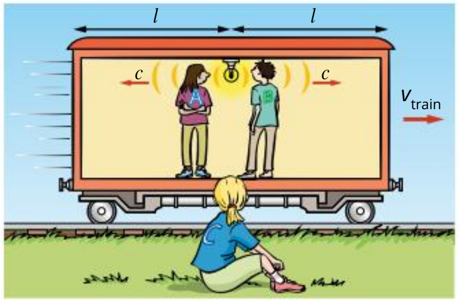


FIGURE 10.3.3 Amaya and Binh see the light take the same time, $\frac{l}{c}$ seconds, to reach the front and back walls.

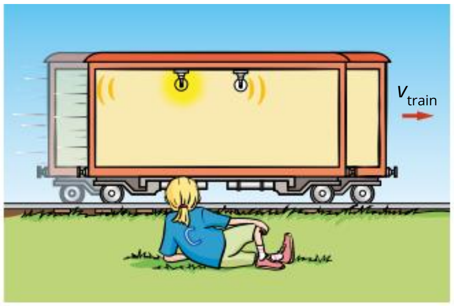


FIGURE 10.3.4 Clare sees the light reach the back wall first, and then the front wall.

If you had discussed a pulse of sound waves travelling from the centre of the train, you would find exactly the same result: Clare always agrees with Amaya and Binh that the time taken for balls, or sound waves, to reach the end walls is the same. But what about something that moves much faster: light?

Einstein's second postulate tells you that all observers see light travel at the same speed. Amaya, Binh and Clare will all see the light travelling at $3 \times 10^8\,\mathrm{m\,s^{-1}}$; they do not add or subtract the speed of the train.

If Clare sees the light travelling at the same speed in the forwards and backwards directions, she will see the light reach the back wall first (Figure 10.3.4). This is because that wall is moving towards the light, whereas the front wall is moving away from the light, and so the light will take longer to catch up to it. This is against the principles of Newtonian physics. Amaya and Binh saw the light flashes reach the ends of the carriage at the same time; Clare saw them reach the walls at different times.

The idea that two events that are **simultaneous** (occur at the same time) for one set of observers but are not simultaneous for other observers was considered outrageous. This will be discussed in more detail in the next module.

10.3 Review

SUMMARY

- When Michelson and Morley performed their experiment they did not detect any change in the speed of light whatsoever, which meant that they did not detect any aether wind.
- Einstein's two postulates are:
  1. The laws of physics are the same in all inertial (non-accelerated) frames of reference.
  2. The speed of light has a constant value for all observers regardless of their motion or the motion of the source.
- Einstein realised that accepting both of these postulates implied that space and time were not absolute and independent, but were related in some way.
- Einstein put forward a simple experiment to illustrate the consequences of accepting the two postulates, involving the *Gedanken* train, which lead to the idea that two events that are simultaneous for one set of observers may not be simultaneous for another.

KEY QUESTIONS

Retrieval

1 In order to resolve the apparent conflict resulting from his two postulates, Einstein rejected some of Newton's assumptions. Identify the consequence of this rejection.

2 State whether the aim of the Michelson and Morley experiment was to test the presence of aether, to measure the speed of Earth relative to aether, or both.

Comprehension

3 Describe the consequence of the two postulates with an example other than the Einstein *Gedanken* train.

Analysis

4 Tom, who is in the centre of a train carriage moving at constant velocity, rolls a ball towards the front of the train while at the same time he blows a whistle and shines a laser towards the front of the train. Compare what Jana, who is on the platform outside the train, observes with what Tom observes regarding the speed of the ball, the sound and the light.

5 Compare Einstein's postulates and Newtonian physics.

6 Assess the accuracy of the following statement:

Some fish are swimming downstream. One of the fish swims upstream and returns with food, while another swims across the current and back searching for food. This scenario represents the Michelson–Morley experiment, in which the water indicates 'the ray of light', the food-seeking fish represent 'the aether' and the other fish still moving downstream represent 'Earth'.

10.4 Simultaneity

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

- define a simultaneous event
- discuss the statement 'lack of simultaneity' in terms of light
- explain what is meant by spacetime.

For Einstein's postulates to be true, two events that might be simultaneous for one observer are not necessarily simultaneous for all observers. This theory has some interesting applications to space travel.

SIMULTANEITY AND SPACETIME

The big difference between light and balls (and sound), discussed in the previous module, is the strange notion that two sets of observers always see the speed of light as being exactly the same. The velocity of a thrown ball or the velocity of sound in Amaya and Binh's frame of reference will always be different from that in Clare's frame of reference by exactly the velocity of the train. For light, however, there is no difference. As a result, events that are simultaneous for one set of observers might not be simultaneous for others. This is a very strange situation that is referred to as a lack of **simultaneity**.

MEASUREMENT IN A THOUGHT EXPERIMENT

The people in the *Gedanken* train would need extremely precise devices, such as an atomic clock, and amazingly quick reflexes to take their measurements.

Under normal circumstances, there is no chance of detecting the lack of simultaneity of light beams hitting the front and back walls of a train. This is because the differences in time are about a millionth of a microsecond, well beyond the capacity of even the best stopwatches. The reflexes required to see the light reach the back wall, then see the light encounter the front wall, would also be beyond human ability.

Although Einstein's *Gedanken* experiments are purely hypothetical, other experiments based on these ideas are well within the capacity of modern experimental physics. In all cases they confirm Einstein's ideas to a high degree of accuracy.

Einstein said that the only reasonable explanation for how two events that were simultaneous to one set of observers were not simultaneous to another is that time itself is behaving strangely. The amount of time that has elapsed in one frame of reference is not the same as that which has elapsed in another (Figure 10.4.1).

FIGURE 10.4.1 The famous clock tower in Bern, Switzerland, near Einstein's apartment. Its hands move at one minute per minute, but only in the same frame of reference as the clock.

In the example shown in Figure 10.3.3 (page 257), Amaya and Binh saw the light flashes that went forwards and backwards take the same time to reach the walls. In Clare's frame of reference the times were different. Time, which has one dimension, seems to depend on the frame of reference in which it is measured, and a frame of reference is just a way of defining three-dimensional space. Clearly time and space are somehow interrelated. This four-dimensional relationship, which includes the three dimensions of space and the one dimension of time, is called **spacetime**. Special relativity is all about spacetime.

This was a profound shock to the physicists of Einstein's time. Many of them refused to believe that time was not the constant and unchanging quantity that it was assumed always to have been. And to think that it might 'flow' at a different rate in a moving frame of reference was too mind-boggling for words. That could mean that if you went on a train trip, your clock would go slower, and you would come back having aged slightly less than those who stayed behind.

Einstein's idea was that time and distance are relative. They can have different values when measured by different observers. Simultaneous events in one frame of reference are not necessarily simultaneous when observed from another frame of reference. This is difficult to comprehend at first and will take some time to fully appreciate. Our basic understanding of time and distance (and perhaps mass too) needs adjustment when objects travel at close to the speed of light. A certain observer might see light travelling through a distance d in a time t at a speed c. A different observer might see light travelling through a different distance, d', in a different time, t', but still at the same speed, c.

Probably because of the tiny differences involved and the highly abstract nature of the work, many physicists simply disregarded the concepts and got on with their work. They thought it could never have any practical results.

10.4 Review

SUMMARY

- Simultaneous events in one frame of reference are not necessarily simultaneous when observed from another frame of reference.
- Time depends on the frame of reference in which it is measured.
- A four-dimensional relationship exists between the three dimensions of space and the one dimension of time. This is called spacetime.

KEY QUESTIONS

Retrieval

1 Recall why Einstein said that we must use four-dimensional spacetime to describe events that occur in situations where high speeds and large distances are involved.

Comprehension

2 Imagine that Amaya is at the front end of a train carriage moving forward at $10.0\,m\,s^{-1}$. She shines a laser towards Binh, who is at the other end of the carriage. Clare is watching all this from the side of the track. Determine the velocity at which the light is travelling as measured by Clare.

Analysis

3 Barry is standing at an equal distance between two light sources. The sources each emit an instantaneous flash. The flashes reach him at the same time, so Barry concludes that the flashes were emitted at the same time. However, Stephen, who is moving towards the left light source disagrees with this statement. Deduce why Stephen disagrees.

4 Reflect on the term 'simultaneity' and demonstrate its meaning in the form of an analogy.

10.5 Time dilation

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

- define the term 'time dilation'
- explain how the *Gedanken* clock is used to prove time dilation
- define the term 'relativistic'
- recall the equation used to calculate relativistic time
- define the term 'proper time'
- identify how the Lorentz factor is used
- explain how high-altitude muons can reach the surface of Earth.

When certain unstable particles such as pions, which have a precisely known decay rate, are accelerated to almost the speed of light, their life spans are measured to be longer than when the particles are stationary. For example, the mean lifetime of the positive pion, π, is 0.000 000 026 033 s (26.033 ns) when it is stationary relative to an extremely precise atomic clock that is measuring it. However, when it is moving at 99% of the speed of light, its mean lifetime as measured by the stationary atomic clock is 184.54 ns. This means that the moving pion exists seven times longer than a stationary pion. This section explores the concept of time dilation as an explanation for these observations.

TIME IN DIFFERENT FRAMES OF REFERENCE

The consequences of Einstein's two postulates have been discussed in general terms, when they were applied to a simple *Gedanken* situation such as a moving train. Observers inside the train see two simultaneous events while those outside see the same two events occurring at different times. Certainly the differences are extremely small and would not be noticeable by an observer in any actual train, unless they had an atomic clock. For aircraft flying at supersonic speeds, the differences, although very small, become measurable by the most precise clocks. For subatomic particles, such as pions, created in accelerators like the Australian Synchrotron, the differences in time become more significant, and so in situations like this, where speeds approach the speed of light, it is important to use calculations that take Einstein's theory into account.

The light clock

Consider Amaya and Binh riding in a *Gedanken* spaceship that can travel at speeds close to the speed of light. Clare is going to watch from a space station which, according to Clare, is a stationary frame of reference. Amaya and Binh have taken along a clock, which (it is assumed) Clare can read, even from a large distance away.

Like any clock, this clock is governed by a regular oscillation that defines a period of time.

Amaya's *Gedanken* clock has a light pulse that bounces back and forth between two mirrors. One mirror is on the floor and the other on the ceiling, as shown in Figure 10.5.1. When a light pulse oscillates from one mirror to the other and back, you can consider that period of time to be 'one unit'. Clare has an identical clock in her own space station, which she can compare to Amaya's clock.

The advantage of this clock is that it can be used to predict how motion will affect the time measured by using Pythagoras' theorem and some algebra. The clock has been set up in the spaceship so that a person in the spaceship sees the light pulses oscillate up and down a distance d that is at right angles to the direction of travel.

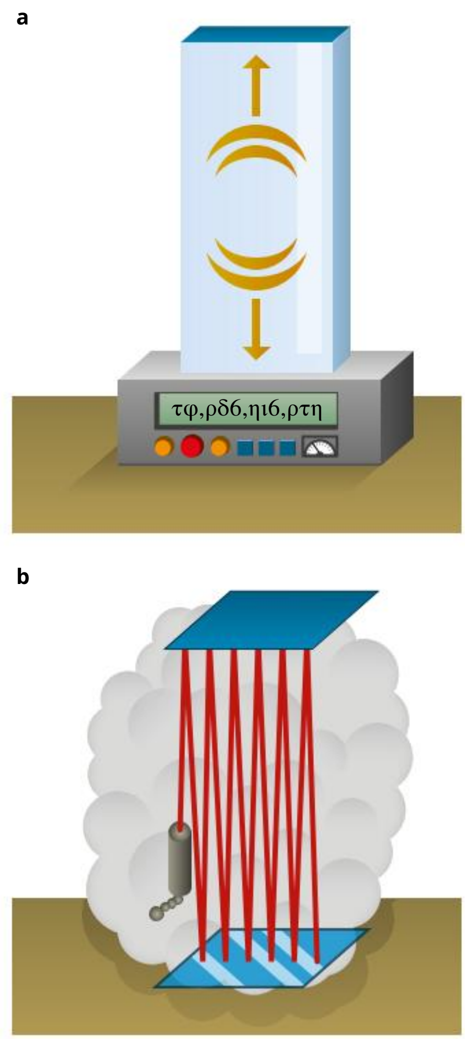


FIGURE 10.5.1 The *Gedanken* light clock 'ticks' each time the light pulse reflects off the bottom mirror. (a) illustrates the movement of the light and (b) shows the up-and-down motion of the light rays. (In reality the light rays would be superimposed and on top of each other.)

The distance d is shown by a green arrow in Figure 10.5.2. As the spaceship speeds along, an observer outside of the spaceship sees the light trace out a zigzag path, as shown by the red dotted line in Figure 10.5.2.

Only one of the oscillations of the light pulse needs to be considered, as all the other oscillations will have the same geometry. One 'unit of time' will be the time taken for the light pulse to oscillate once. In the frame of reference of the spaceship, Amaya and Binh see a unit of time equal to t_a. Clare, from her frame of reference, will see a different time, t_c. The relationship between these two times will now be determined.

Amaya and Binh see the light pulse travel at the speed of light, c, along the distance $2d$, from the bottom mirror to the top and back again, in time t_a. So the distance that the light pulse travels is given by:

$$2d = c \times t_a$$

Clare sees the light travel a longer path, shown as the red dotted line in Figure 10.5.2.

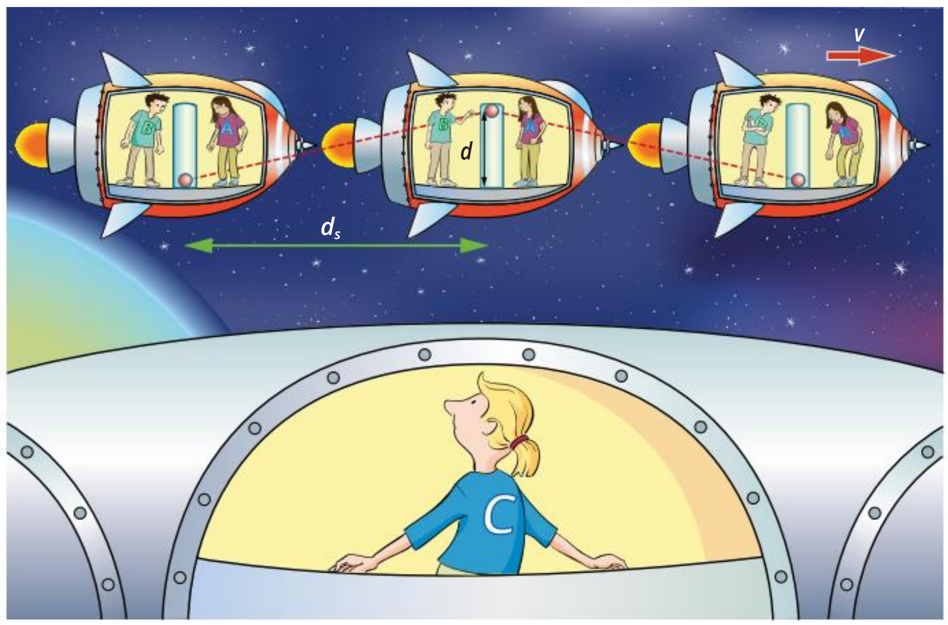
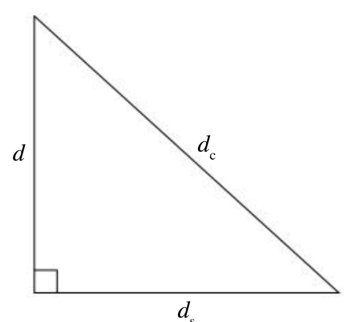


FIGURE 10.5.2 Clare can see that in one unit of time the *Gedanken* light clock 'ticks' each time the light pulse reflects off the bottom mirror. She also sees that the light pulses travel a zigzag path between the mirrors.

The ship moves with a speed v, and so in one unit of time as seen by Clare, t_c, the spaceship will travel a distance $2 \times d_s$, equal to the velocity multiplied by the time taken for her to see one oscillation:

$$2d_s = v \times t_c$$

Consider only half of the light oscillation for now. The light pulse not only travels the vertical distance d in the clock, but it also travels forwards as the spaceship moves through the distance d_s, making the combined distance d_c. Therefore, according to Pythagoras' theorem:



$$d_c^2 = d^2 + d_s^2$$

$$d_c^2 = d^2 + \left(\frac{vt_c}{2}\right)^2$$

$$d_c = \sqrt{\left(d^2 + \left(\frac{vt_c}{2}\right)^2\right)}$$

Clare sees this light pulse travelling twice this combined distance at the speed of light, c, in the period of time t_c measured on her clock. So:

$$2d_c = c \times t_c$$

Equating and rearranging the two expressions for d_c gives:

$$\frac{c \times t_c}{2} = \sqrt{\left(d^2 + \left(\frac{vt_c}{2}\right)^2\right)}$$

$$c \times t_c = 2 \times \sqrt{\left(d^2 + \left(\frac{vt_c}{2}\right)^2\right)}$$

$$= \sqrt{\left(4d^2 + 4 \times \left(\frac{vt_c}{2}\right)^2\right)}$$

$$t_c = \frac{\sqrt{4d^2 + (vt_c)^2}}{c}$$

From Amaya and Binh's frame of reference, in which they see the light pulse travelling a distance $2d$ at speed c in a time t_a, the previously given equation can be rewritten in terms of d as:

$$d = \frac{c \times t_a}{2}$$

Note that you have used the same value for c in both of these equations, something you would never do in **classical physics**, but something Einstein insists you must do, since it is a postulate of special relativity.

Substituting this expression for d into the previous equation gives:

$$t_c = \frac{\sqrt{4 \times \left(\frac{ct_a}{2}\right)^2 + (vt_c)^2}}{c}$$

Now square both sides and simplify to make t_c^2 the subject:

$$t_c^2 = \frac{\frac{4(ct_a)^2}{4} + (vt_c)^2}{c^2}$$

$$= \frac{c^2 t_a^2 + v^2 t_c^2}{c^2}$$

$$= \frac{c^2 t_a^2}{c^2} + \frac{v^2 t_c^2}{c^2}$$

$$= t_a^2 + \frac{v^2 t_c^2}{c^2}$$

Group the terms with t_c^2 together and factorise:

$$t_c^2 - \frac{v^2 t_c^2}{c^2} = t_a^2$$

$$t_c^2\left(1 - \frac{v^2}{c^2}\right) = t_a^2$$

Take the square root of both sides and make t_c the subject:

$$t_c\sqrt{\left(1 - \frac{v^2}{c^2}\right)} = t_a$$

$$t_c = \frac{t_a}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

As v can never be larger than c, the denominator in the equation above must be less than one. Any number divided by a number less than one must result in a larger number, so $t_c > t_a$.

This final equation shows that the time measured by Clare, t_c, is greater than the time measured by Amaya and Binh, t_a, for the same event.

Generally:

$$t = \frac{t_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

The symbol t is known as **relativistic time**. It is the time that is described only by the theory of relativity.

The symbol t_0 is the time that passes on the moving clock according to the clock or a person moving with the clock. This time interval is known as the **proper time**. In the example above, the proper time would be Amaya and Binh's unit of time, while the relativistic time is Clare's time.

The proper time is the time between two events that occur at the same point in space. For example, when a light bulb in the train flashes and Amaya measures the time for the flash to reflect off a mirror and return to her, as shown in Figure 10.5.3, she measures the proper time. This is because the clock remained at the point in space inside the frame of reference where the light originated and where it ended up.

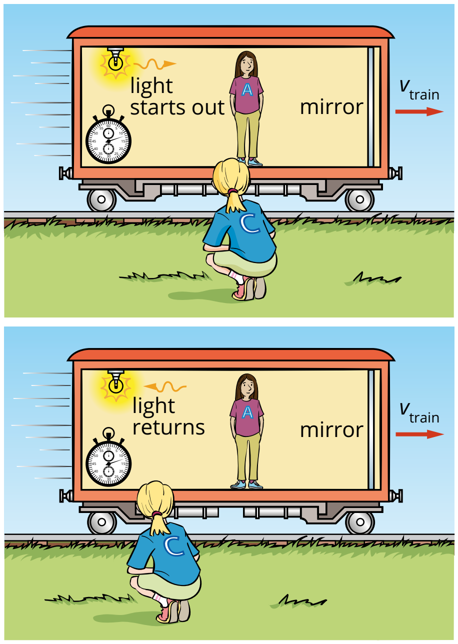


FIGURE 10.5.3 The clock measures proper time. The clock is positioned at the place where the event starts (the light starting out) and is at the same place when the event ends (the light returning).

It is important that a clock isn't moved from one place to another if you want to measure proper time. This is because, as soon as the clock is in motion, the time for that clock slows slightly.

Mathematically, you can see that time dilation results from the strange behaviour of light. As light travels on the diagonal zigzag path, it does so at speed c, not at a faster speed resulting from the additional component of the spaceship's motion as, for example, would be true for a boat zigzagging across a river as it is carried along by the current.

THE LORENTZ FACTOR

In Einstein's equation for time dilation, the symbol t is used to represent the time that a stationary observer (Clare) measures using a stationary clock for an event that the observer sees occurring in a moving frame of reference. The factor that the proper time is multiplied by to give relativistic time is given the symbol gamma, γ, so that:

$t = t_0\gamma$

where

$$\gamma = \frac{1}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

v is the speed of the moving frame of reference

c is the speed of light in a vacuum ($3 \times 10^8\,\mathrm{m\,s^{-1}}$)

t is the time observed in the stationary frame

t_0 is the time observed in the moving frame (proper time).

The physicist H. A. Lorentz first introduced the factor γ in an attempt to explain the results of the Michelson–Morley experiment, so it is often known as the **Lorentz factor**.

The Lorentz factor or Lorentz term is the factor by which time, length and relativistic mass change for an object while that object is moving. (Relativistic mass will be explored in Module 10.7.)

Table 10.5.1 and Figure 10.5.4 show the effect of varying the value of v on the value of γ.

TABLE 10.5.1 The value of the Lorentz factor at various speeds

v (m s^{-1})	$\frac{v}{c}$	γ
3.00×10^2	0.000 001	1.000 000 000
3.00×10^5	0.001 00	1.000 000 5
3.00×10^7	0.100	1.005
1.50×10^8	0.500	1.155
2.60×10^8	0.866	2.00
2.70×10^8	0.900	2.29
2.97×10^8	0.990	7.09
2.997×10^8	0.999	22.4

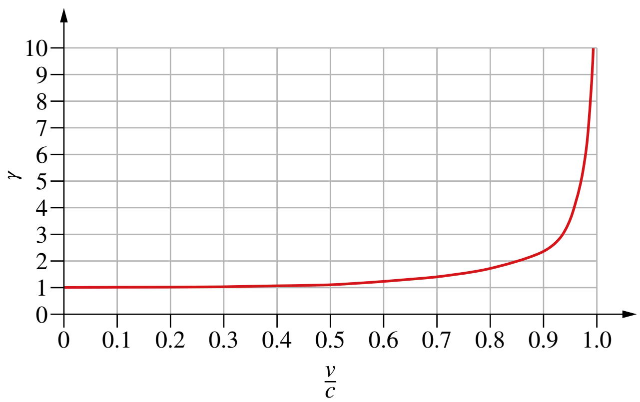


FIGURE 10.5.4 The graph of the Lorentz factor versus $\frac{v}{c}$

From the data in Table 10.5.1, a velocity of 300 m s^{-1} results in a Lorentz factor of essentially 1. So for relatively low-speed spaceships, a stationary observer measures the oscillation of light in the light clock on the spaceship to be the same as in her own stationary light clock. This implies that time is passing at essentially the same rate in both frames of reference.

When the spaceship is travelling at $0.990c$, a stationary observer such as Clare will measure that a single oscillation of light in the spaceship's light clock will take seven oscillations of her own stationary light clock. According to Clare, time for the objects and people in the moving frame of reference has slowed down to one-seventh of 'normal' time.

As the speed approaches the speed of light, time in the moving frame, as viewed from the stationary frame, slows down more and more. So, if you were able to see the clock travelling on a light wave, the clock would not be 'ticking' at all. In other words, time would be seen to stand still.

> Sometimes it is useful to make v the subject in the equation for the Lorentz factor. This produces:
>
> $$v = c\sqrt{\left(1 - \frac{1}{\gamma^2}\right)}$$

It is important to realise that Amaya and Binh do not perceive their time slowing down at all. To them, their clock keeps ticking away at the usual rate and events in their frame of reference take the same time as they normally would. It is the series of events that Clare sees and measures in Amaya and Binh's frame that go slowly. Binh and Amaya are moving in slow motion because, according to Clare's observations, time for them has slowed down (Figure 10.5.5), i.e 'moving clocks run slow'. This is known as **time dilation**.

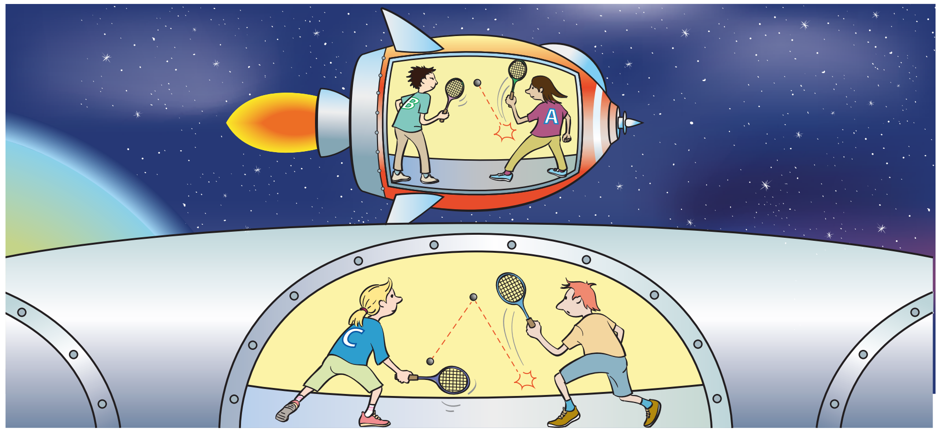


FIGURE 10.5.5 As Clare watches Amaya and Binh play space squash, the ball seems to be moving much more slowly than in her own game.

Worked example 10.5.1

TIME DILATION

Assume *Gedanken* conditions exist in this example. A stationary observer on Earth sees a very fast car passing by, travelling at $2.50 \times 10^8\,\text{m}\,\text{s}^{-1}$. In the car is a clock on which the stationary observer sees 3.00 s pass. Calculate how many seconds pass on another clock held by the stationary observer during this observation. Use $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.	
Thinking	**Working**
Identify the variables: the time observed by the stationary observer is t, the proper time for the moving clock in its own reference frame is t_0 and the velocity of the car is v.	$t = ?$ $t_0 = 3.00\,\text{s}$ $v = 2.50 \times 10^8\,\text{m}\,\text{s}^{-1}$ $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$
Use Einstein's time dilation formula and the Lorentz factor.	$t = t_0\gamma$ $= \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$
Substitute the values for t_0, v and c into the equation and calculate the answer, t.	$t = \frac{3.00}{\sqrt{1-\frac{(2.50\times10^8)^2}{(3\times10^8)^2}}}$ $= \frac{3.00}{0.55277}$ $= 5.43\,\text{s}$

➤ Try yourself 10.5.1

TIME DILATION

Assume *Gedanken* conditions exist in this example. A stationary observer on Earth sees a very fast scooter passing by, travelling at $2.98 \times 10^8\,\text{m}\,\text{s}^{-1}$. On the wrist of the rider is a watch on which the stationary observer sees 60.0 s pass. Calculate how many seconds pass on the stationary observer's clock during this observation. Use $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.

LOOKING BACK TO THE STATIONARY OBSERVER

So far you have been looking at the situation from Clare's point of view, not Amaya and Binh's. Galileo said that all inertial frames of reference are equivalent. It follows then that, according to Amaya and Binh, as they look out their window at Clare in her space station receding from them, they can consider that it is they who are at rest and it is Clare in her space station who is moving away at a velocity near the speed of light. This is what Galileo's principle of relativity and Einstein's first postulate are all about.

If Amaya and Binh watch the light clock in Clare's space station, they see that time has slowed down for Clare, as they would observe Clare's moving light clock oscillation taking longer than the oscillation on their stationary light clock. This raises the question: Whose time actually runs slowly?

The answer is that they are both right and symmetrical. The whole point of relativity is that you can only measure quantities relative to some particular frame of reference, not in any absolute sense. Certainly Amaya and Binh see Clare in slow motion and Clare sees them in slow motion. Remember that there is no absolute frame of reference and so there is no absolute clock ticking away the absolute 'right' time. All that you can be sure of is that time in your own inertial frame of reference is ticking away at a rate of one second per second.

EXPLAINING HIGH–ALTITUDE MUONS

In Module 10.1, the observation of high-speed muons originating 15 km up in the atmosphere but still reaching the surface of Earth was discussed. It could only be explained if the mean lifetime of the short-lived particles were extended far beyond their normal mean lifetime.

Time dilation explains this unusual observation.

The 'normal' mean lifetime of a muon is about 2.2 μs. However, this is the mean lifetime when measured in a stationary frame of reference; that is, in the muon's frame of reference. Muons travel very fast; in fact a speed as great as $0.999c$ is very possible. At this speed, an observer on Earth will see the lifetime of a muon as far greater than 2.2 μs:

$$t = t_0\gamma$$

$$= \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$= \frac{2.2\times10^{-6}}{\sqrt{1-\frac{(0.999c)^2}{c^2}}}$$

$$= \frac{2.2\times10^{-6}}{\sqrt{1-0.999^2}}$$

$= 49.21\,\mu\text{s}$ (This is more than 22 times as long as in the stationary frame.)

An observer on Earth would see the muon's time run much slower. The slower time means that many muons live long enough to reach the Earth's surface.

WS 4.1.2

10.5 Review

SUMMARY

- The pulses in a light clock in a moving frame of reference have to travel further when observed from a stationary frame.
- Because of the constancy of the speed of light, this effectively means that time appears to have slowed in a moving frame.
- Proper time is the time as measured by an observer who is at rest with respect to a clock or is moving with the clock. It is always the shortest possible time interval.
- Time in a moving frame seems to pass more slowly according to the equation $t = t_0\gamma$, where t_0 is the time measured by an observer in the moving frame (proper time), t is the time observed of the same event from the stationary frame, and γ is the Lorentz factor:

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

- Observers in relative motion both see time slowing in the other frame of reference; that is, each sees the other ageing more slowly.
- Time dilation provides the explanation for the occurrence of muons reaching the Earth's surface after originating 15 km up in the upper atmosphere, when they should all decay within 7 km of the start of their journey according to classical physics.

KEY QUESTIONS

For the following questions, assume *Gedanken* conditions exist and let $c = 3 \times 10^8\,\text{m s}^{-1}$.

Retrieval

1 Indicate the correct terms from those in bold, to complete the sentence.
In a device called a **light/mechanical/digital** clock, the **speed/oscillation/wavelength** of light is used as a means of measuring **time/mass**, as the speed of light is **unknown/variable/constant** no matter from which inertial frame of reference it is viewed.

2 Define 'proper time', t_0.

Comprehension

3 Einstein once said that a clock at the Earth's equator should run slightly slower than one at the Earth's poles. Explain why this is not a problem.

4 Explain two reasons why time dilation is not observed in everyday life.

Analysis

5 Imogen is standing on a train platform as a very fast train passes by at a speed of $1.75 \times 10^8\,\text{m s}^{-1}$. She notices the time on a passenger's phone as the passenger drops the phone to the floor. According to the clock on the phone, it takes 1.05 s to hit the floor. Analyse this information to determine how much time has passed on Imogen's clock during this time.

6 Sylvia is standing on a comet watching as a satellite approaches at a speed of $2.30 \times 10^8\,\text{m s}^{-1}$. On her watch she observes that the solar panels on the satellite unfold in 75.0 s. Determine how much time passes on a clock on the satellite.

7 Nathan is standing by the side of a road and sees a very fast sports car driving past. The driver times on his car's clock that it takes 5.50 s for Nathan to pick up his bag. Determine how much time the driver sees has passed on Nathan's watch as he picks up the bag if the car is moving at a speed of $2.75 \times 10^8\,\text{m s}^{-1}$.

8 Calculate how long, in Anna's frame, it would take Ben's clock to tick 1.00 s if she saw Ben fly by at 0.500*c*.

9 Anna's *Gedanken* light clock has a height of 1.00 m between the mirrors. Relative to Chloe, her spaceship is travelling at 90.0% of the speed of light. One tick is the time for light to go from one mirror to the other.

- **a** Calculate how far the light flash travels in Anna's frame of reference in one tick, t_a.
- **b** Determine what the tick time, t_a, is for the clock in Anna's frame.

As the light takes a zigzag path in her frame, Chloe sees the clock ticking at a slower rate, t_c.

- **c** Calculate the length of the zigzag path that the flash travels in one tick in Chloe's frame, in terms of *c* and t_c.
- **d** Determine the tick time of the clock in Chloe's frame.
- **e** Determine the ratio of Chloe's tick to Anna's tick.

10 A muon created at an altitude of 15.0 km above Earth is moving at a speed of 0.992 times the speed of light. The mean lifetime of a muon at rest is 2.20×10^{-6} s.

- **a** Determine the lifetime of the moving muon as timed by a stationary observer on the Earth's surface.
- **b** Calculate the non-relativistic distance and the relativistic distance travelled by the moving muon during one lifetime, using classical physics equations and the results from question 10a.

11 A high-speed, subatomic particle is accelerated by a linear accelerator to a speed of $2.83 \times 10^8\,\text{m s}^{-1}$. A researcher measures that it only leaves, on average, a track that is 2.50 cm long in the bubble chamber. Determine the mean lifetime of the same particle if it were at rest relative to the researcher and her timer.

10.6 Length contraction

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

- identify that relative motion affects length in the direction of the travel
- recall the equation used to calculate length contraction
- explain why the length of an object measured in a moving frame of reference is shorter than that measured by a stationary observer and vice versa
- define the term 'proper length'.

The previous module described how time can only be measured relative to some particular frame of reference, and not in any absolute sense. Because of the constancy of the speed of light, this effectively means that time appears to slow down in a moving frame relative to the frame of an observer. Einstein describes how space and time are interrelated, so it follows then that space, and therefore length, is also not absolute (Figure 10.6.1).

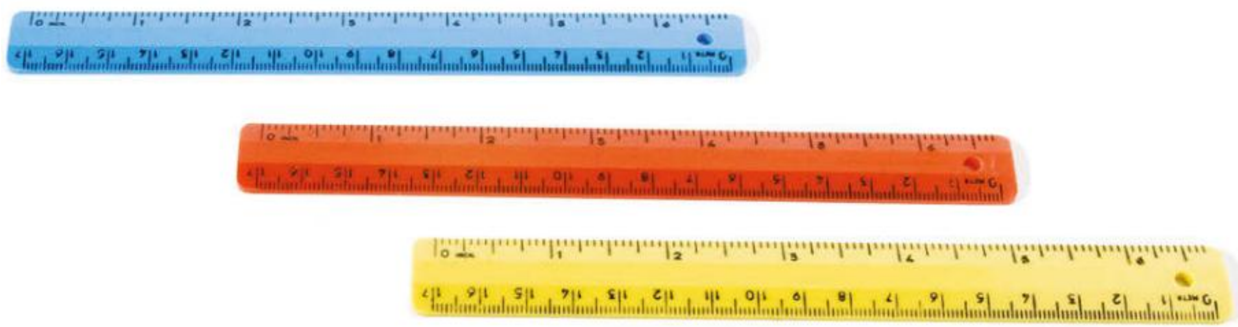


FIGURE 10.6.1 Length is relative to the frame of reference and the direction of motion.

LENGTH IN DIFFERENT INERTIAL FRAMES

You already have a clue to the fact that length depends on who is doing the measuring and the frame of reference in which they make their measurement.

The light clock analysis is appropriate to compare the proper time on the clock in the moving frame of reference (*observed* by Clare in the examples provided in Module 10.5) and the time measured on a clock in the stationary frame (*with* Clare). The light clock was used as it only depends on light, not some complicated mechanical arrangement that may well include other factors that are altered by relative motion. There was, however, one other condition in this clock analysis—that both Amaya and Clare would agree on the distance, d, between the mirrors. This enabled the two expressions for d to be equated in order to find the relationship between proper time, t_0, and relativistic time, t.

The clock was deliberately set up in the spaceship so that this light path, of distance d, was perpendicular to the velocity. Distances in this perpendicular direction are unaffected by motion. Indeed, Einstein showed that relative motion affects length only in the direction of travel (Figure 10.6.2).

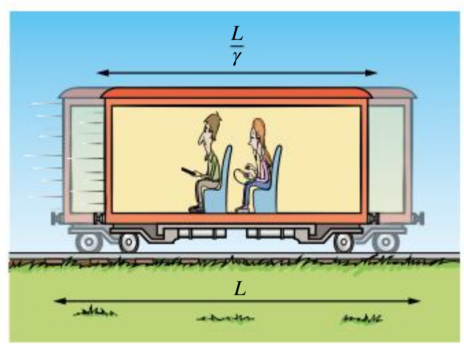


FIGURE 10.6.2 Einstein showed that the length of a moving object is foreshortened by the Lorentz factor, γ. The height and width of the carriage remain unchanged.

PROPER LENGTH

Recall that proper time is the time between two events that occur at the same point in space. Like proper time, proper length is a quantity measured by the observer who is in the same frame of reference as the object being measured.

The **proper length** is the distance between two points whose positions are measured by an observer at rest with respect to the two points.

If Amaya has a measuring tape which she lays from one end of the carriage to the other, and is at rest with respect to the train, her measurement of the carriage will be the proper length. If Clare lays out a measuring tape along the platform and takes a measurement of the carriage as it travels by at speed, her measurement of the carriage will be of a contracted length.

On the other hand, Clare measures the length of the platform as the proper length, while Amaya and Binh see the platform as contracted in length.

LENGTH CONTRACTION

Length contraction and time dilation are easy to confuse. One way to remember how it works is to think that stationary clocks tick faster and an object is longer when viewed from its own frame of reference. When viewed from a frame of reference in which objects are seen to be moving, they appear shorter and their clocks tick slower.

Consider the *Gedanken* situation in which Clare is standing on a train platform while Amaya and Binh pass by at a speed v. Both Clare and Binh want to measure the length of the train platform on which Clare is standing. Using a measuring tape, Clare measures the length of the platform (which is at rest according to her) as L_0, and says that Binh and Amaya cover this distance in a time equal to:

$$t = \frac{L_0}{v}$$

Binh observes the platform passing in a time t_0 as he and Amaya move past the station. The relationship between the time in Binh's frame of reference and the time measured by Clare is:

$$\begin{aligned} t_0 &= \frac{t}{\gamma} \\ &= t\sqrt{1 - \frac{v^2}{c^2}} \end{aligned}$$

Substituting the first equation into the equation above gives us:

$$t_0 = \frac{L_0}{v}\sqrt{1 - \frac{v^2}{c^2}}$$

Binh sees the platform moving at a velocity of v relative to him, so he can say that the distance from the start to the end of the platform is:

$$L = vt_0$$

Substituting the previous equation for t_0 into the equation above gives us:

$$L = v \times \frac{L_0}{v}\sqrt{1 - \frac{v^2}{c^2}}$$

This simplifies to:

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

This is Einstein's **length contraction** equation that incorporates the Lorentz factor. This equation shows that an object with a proper length of L_0, when measured at rest, will have a shorter length L, parallel to the motion of its moving frame of reference when measured by an observer who is in a stationary frame of reference. (L is also known as the **relativistic length**.) The proper length is contracted by a factor of $\frac{1}{\gamma}$. Length contraction can be represented as:

$$L = \frac{L_0}{\gamma}$$

where

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

L_0 is the proper length, i.e. the length measured at rest, in the stationary frame of reference

L is the length in the moving frame, measured by an observer.

Remember that length contraction occurs only in the direction of travel, not in any perpendicular direction. To Clare, the carriage will appear shortened, but its width and height (the dimensions of the train perpendicular to the direction of travel) will remain unaltered.

An example of length contraction is shown with a tennis ball in Figure 10.6.3. The length in the direction of the motion is contracted, but the height is not.

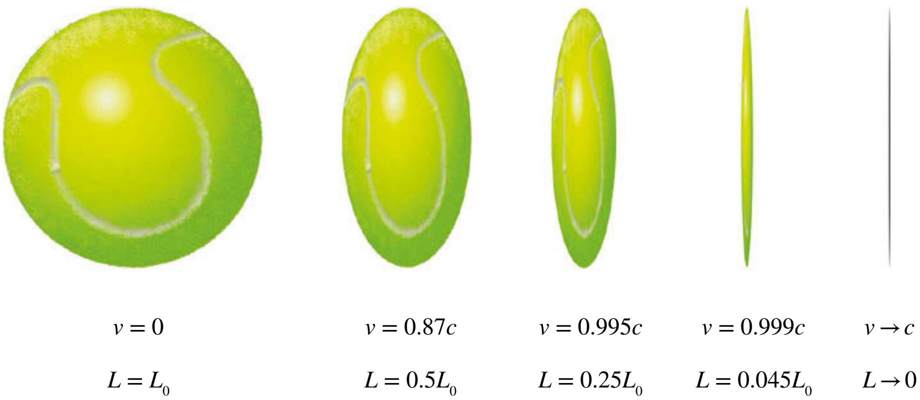


FIGURE 10.6.3 As the tennis ball moves faster to the right, its length in this dimension is contracted, but its height and depth remain the same.

Worked example 10.6.1

LENGTH CONTRACTION

Assume *Gedanken* conditions exist in this example. Aiden, stationary on Earth, sees a very fast car travelling by at $2.50 \times 10^8\,\text{m}\,\text{s}^{-1}$. When stationary, the car is 3.00 m long. Calculate the length of the car in the direction of travel as seen by Aiden. Use $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.

Thinking	Working
Identify the variables: the length measured by Aiden is L, the proper length of the car is L_0 and the velocities are v and the constant c.	$L = ?$ $L_0 = 3.00\,\text{m}$ $v = 2.50 \times 10^8\,\text{m}\,\text{s}^{-1}$ $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$
Use Einstein's length contraction formula.	$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$
Substitute the values for L_0, v and c into the equation and calculate the answer, L.	$L = 3.00 \times \sqrt{1 - \frac{(2.50 \times 10^8)^2}{(3 \times 10^8)^2}}$ $= 3.00 \times 0.553$ $= 1.66\,\text{m}$

➤ Try yourself 10.6.1

LENGTH CONTRACTION

Assume *Gedanken* conditions exist in this example. Annabelle is stationary on Earth and sees a very fast scooter travelling by at $2.98 \times 10^8\,\text{m}\,\text{s}^{-1}$. She measures the scooter's length as 45.0 cm in the direction of travel. Calculate the proper length of the scooter, measured when the scooter is at rest. Use $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.

LOOKING OUT OF THE WINDOW

So far you have been looking at situations in which objects that are in a moving frame of reference are seen as being shorter in the direction of the motion according to an observer who is in a stationary frame of reference. You can also apply length contraction to the distance that a moving object covers as it travels at very high speed.

Recall that no inertial frame of reference is special. Consider Amaya and Binh in their spacecraft travelling to the Moon. According to them, they are stationary and it is space itself that rushes by at high speed. As space zooms by Amaya and Binh, they are travelling a proper distance of 384 400 km from Earth to the Moon. This is the proper length, as it is measured by a device that is in the same frame of reference as Earth and the Moon. As Binh looks out of the window, he measures a much shorter distance to travel.

Worked example 10.6.2

LENGTH CONTRACTION FOR DISTANCE TRAVELLED

Assume *Gedanken* conditions exist in this example. Keely pilots a spaceship travelling at 0.997*c* that is travelling from Earth to the Moon. The proper distance from Earth to the Moon is 384 400 km. When Keely looks out of the window, the distance between the Earth and the Moon looks much less than that. Calculate the distance that she sees.

Thinking	Working
Identify the variables: the length seen by the pilot is L, the proper length of the distance is L_0 and the velocity is v.	$L = ?$ $L_0 = 384\,400\text{ km}$ $v = 0.997c\text{ m s}^{-1}$
Use Einstein's length contraction formula.	$L = L_0\sqrt{1-\frac{v^2}{c^2}}$
Substitute the values for L_0 and v into the equation. Cancel c and calculate the answer, L.	$L = 384\,400 \times \sqrt{1-\frac{(0.997c)^2}{c^2}}$ $= 384\,400 \times \sqrt{1-(0.997)^2}$ $= 384\,400 \times 0.0774$ $= 29\,800\text{ km}$

➤ Try yourself 10.6.2

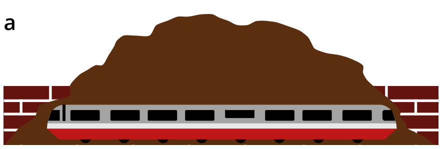
LENGTH CONTRACTION FOR DISTANCE TRAVELLED

Assume *Gedanken* conditions exist in this example. Jane is a stationary observer on Earth who sees a very fast train approaching a tunnel at a speed of 0.986*c*. She measures the tunnel's length as 123 m in her reference frame. Calculate the length of the tunnel as seen by the train driver.

Try yourself 10.6.2 leads to an interesting phenomenon. If the proper length of the train is 100 m, then the driver could park the train in the 123 m tunnel with 11.5 m of tunnel extending beyond each end of the train. But when the train is moving at 0.986*c*, then according to the train driver the train will not fit in the tunnel. There will be approximately 39.7 m of train extending past each end of the tunnel (Figure 10.6.4).

Similarly, a train that is longer than the tunnel will fit completely inside the tunnel if its length is measured by a stationary observer as the train moves past very quickly. In this scenario, the length of the train is contracted according to the stationary observer (Figure 10.6.5).

a



Both train and tunnel are stationary.

b

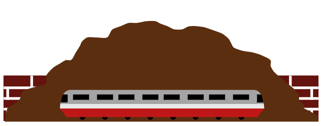
The tunnel is moving towards the observer in the train.

FIGURE 10.6.4 The train both fits in the tunnel and doesn't fit in the tunnel, depending on your frame of reference.

a

The stationary train does not fit in the tunnel.

b



The train is contracted.

FIGURE 10.6.5 The train both doesn't fit in the tunnel and does fit in the tunnel, also depending on your frame of reference.

10.6 Review

SUMMARY

- The theory of special relativity states that time and space are related. Motion affects space in the direction of travel.
- The proper length, L_0, is the length measured by an observer at rest with respect to the object being measured.
- A moving object will appear shorter, or appear to travel a shorter distance, by the inverse of the Lorentz factor, γ.
- Einstein's length contraction equation is given by:

  $L = \frac{L_0}{\gamma}$, where L_0 is the proper length in the stationary frame, L is the contracted length as seen in the moving frame and γ is the Lorentz factor:

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

KEY QUESTIONS

For the following questions, assume Gedanken conditions exist and let $c = 3 \times 10^8\,\text{m}\,\text{s}^{-1}$.

Retrieval

1 Define the term 'proper length', L_0.

2 Describe what you would notice about the dimensions of a speeding rocket if you are standing on Earth observing it.

Comprehension

3 Sina is standing on a train platform as a very fast train passes by at a speed of $1.75 \times 10^8\,\text{m}\,\text{s}^{-1}$. He notices that a passenger is holding a metre rule in line with the direction in which the train is moving. Determine the length of the metre rule that Sina sees.

4 Alexander is standing on a comet watching as a satellite approaches at a speed of $2.30 \times 10^8\,\text{m}\,\text{s}^{-1}$. He knows that the proper length of the satellite in the direction of its motion is 5.25 m. Determine the length of the satellite that he sees as it passes.

5 Bob makes a mistake and builds a garage too short for the owner's car to fit in. The proper length of the garage is 1.50 m and the proper length of the car is 3.50 m. Bob suggests that if the owner drives fast enough, Bob could stand by the garage and the car would fit. Assess the above information to answer the following:

- **a** Calculate the speed at which the car would need to travel to just fit in the garage when observed by Bob.
- **b** Explain why the car owner would not be happy about Bob's suggestion by calculating the length of the garage as seen by the driver travelling at Bob's suggested speed.

6 An observer on a platform measures the time for a train carriage, moving at 0.99c, to pass by. Determine whether the time she has measured is t or t_0. Explain your answer.

Analysis

7 Emily is standing by the side of the track watching Dan run in an 800.0 m race in a straight line.

- **a** Determine the speed Dan must run in order for the race to be only 400.0 m long in his frame of reference.
- **b** Emily notices that Dan is thinner than he normally is, but just as wide and just as tall. Compare the fraction of Dan's thickness while he is running to his normal thickness while standing still.

8 A jet plane zooms past Cassie at a speed of $660\,\text{m}\,\text{s}^{-1}$. Determine the length of the jet as seen by Cassie, who is standing on the ground, if the length of the jet is 23.5 m when parked on the tarmac.

9 Jordan is in his spaceship speeding at 0.900c to the Moon. He is holding a fishing rod that is 2.75 m long, facing the direction in which the spaceship is moving.

- **a** Determine the length of the rod as observed by an astronaut in the International Space Station, assuming that the space station is at rest with respect to the Moon.
- **b** Calculate the length of the fishing rod as observed by Jordan.

10.7 Mass in relativity

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

- provide an example where relativistic mass can be observed on Earth
- apply the equation used to calculate relativistic mass
- compare the terms 'relativistic mass' and 'rest mass'
- explain what is meant by 'relativistic increase in mass'.

FIGURE 10.7.1 Mass is relative to the frame of reference in which it is measured.

In classical physics and chemistry, the conservation of mass is assumed: applying a force to an object classically does not change its mass and the particles that start out in a chemical reaction are still there at the end. Now it is time to look at the implications of Einstein's relativistic principles on mass.

PARTICLES GAINING MASS

Recall from Chapter 4 that when an object moves in a circular path, it does so as a result of a centripetal force that acts towards the centre of the circular path. Centripetal force therefore acts continuously at a right angle to the velocity of the object. There are a number of actions that could cause the centripetal force on an object, such as the tension in a string tied to a rubber stopper or the gravitational force of Earth on the Moon.

Another action that causes circular motion is the force on a charged particle that is moving at right angles to a magnetic field. Recall from Chapter 8 that the equation that represents the relationship between the magnetic force (F_B) and the centripetal force (F_c) is:

$$F_B = F_C$$
$$qvB = \frac{mv^2}{r}$$
$$r = \frac{mv}{qB}$$
$$= \frac{m}{qB} \times v$$

The final relationship shows that if the mass m, charge q and magnetic field B are all constant, then the radius of the circular path is directly proportional to the velocity of the charged particle. So, theoretically, if the velocity increases by a factor of 2, then the radius will also increase by a factor of 2. However, this is not the case.

In circular accelerating devices such as cyclotrons and the Australian Synchrotron, it is evident that as the velocity of a charged particle increases, the radius of its path also increases, but to a much greater degree than that expected. According to the relationship shown above, if the charge q and the magnetic field B don't change, then the only explanation for the extra increase in radius is that the mass of the particle, m, must have increased.

In fact, the mass of an electron travelling at 99.999999% of the speed of light seems to increase to 7000 times the mass of an electron at rest. There is no explanation for this phenomenon in Galileo's relativity or Newtonian physics.

MASS INCREASE WITH VELOCITY

Recall the Lorentz factor that was introduced in Module 10.5:

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

At low speeds, γ is so close to 1 that the effects of special relativity can be ignored; however, γ rapidly increases as the speed, v, approaches the speed of light, c. At 99.9% of the speed of light, γ has a value of approximately 22 (see Table 10.5.1, page 265), and so anything moving at that speed, relative to a stationary observer, will appear to have shrunk to $\frac{1}{22}$ of its normal length. If, as a stationary observer, you could watch the action inside a spaceship travelling at that speed, events would appear to be going 22 times more slowly than they would if they occurred in a stationary observer's frame of reference.

The closer that the speed of the spaceship gets to the speed of light, the more the Lorentz factor increases towards infinity. It is reasonable to wonder what happens at the speed of light. According to Einstein's equations, the length of the spaceship shrinks to zero and time inside it appears to stop altogether. Einstein took this to mean that it is not possible to reach the speed of light in any real spaceship. However, the difficulties with time and length for the spaceship were not the only reasons Einstein came to this conclusion. The Lorentz factor can also be applied to mass.

Another result of special relativity is the increase in mass with velocity. For example, suppose that rocket ship A (R_A) and rocket ship B (R_B) each have a mass on Earth of 500 000 kg when at rest with respect to each other. If people in R_B measure the mass of R_A while the rockets are moving relative to each other, they will find that the mass of R_A appears to have increased, while also experiencing length contraction and time dilation (Figure 10.7.2).

FIGURE 10.7.2 Rocket A is in motion and therefore is undergoing length contraction and mass increase. This can be compared to rocket B.

By applying the conservation of momentum and energy, its mass can be given by:

$$m = \gamma m_0$$

This equates to:

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

The mass of an object m in motion is called the **relativistic mass**, γm_0, which is the mass measured as the object is moving relative to the observer and is dependent on γ and the **rest mass**, m_0. The rest mass is essentially the mass of the object at rest.

As the Lorentz factor increases with the increase in the velocity, then the relativistic mass also increases. Einstein was never happy with the term 'relativistic mass', and preferred that people only spoke of the **relativistic momentum** of an object. (This will be discussed further in Module 10.8.)

The closer the speed of the object is to the speed of light, the greater the increase in its mass. This means that to reach the speed of light would require an infinitely strong force acting on the body; that is, if mass is very large, then even for a small acceleration, the force acting must be very large (since force is proportional to mass). This reinforces the idea that it is not possible to reach the speed of light in any real spaceship.

To return to the example of the two rocket ships. The relativistic mass formula means that if R_A and R_B both have a mass of 500 000 kg when at rest with respect to each other on Earth, then if they are approaching or separating at a relative velocity of, say, $1.5 \times 10^8\ m\,s^{-1}$, their observed mass will have increased significantly. Worked example 10.7.1 shows by how much the mass of R_A would have increased.

Worked example 10.7.1

RELATIVISTIC MASS

Calculate the relativistic mass of R_A, as seen by R_B, when the rockets are separating at a relative velocity of $1.50 \times 10^8\,\text{m s}^{-1}$. The rest mass of each rocket is 5.0×10^5 kg. Assume *Gedanken* conditions exist in this example.	
Thinking	**Working**
Identify the variables: the rest mass is m_0, and the velocity of the rocket ship is v.	$m = ?$ $m_0 = 5.0 \times 10^5$ kg $v = 1.5 \times 10^8\,\text{m s}^{-1}$
Use the relativistic mass formula.	$m = \gamma m_0$
Substitute the values for m and v into the equation and calculate the answer m.	$m = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} m_0$ $= \frac{500\,000}{\sqrt{1 - \frac{(1.5 \times 10^8)^2}{(3 \times 10^8)^2}}}$ $= \frac{500\,000}{\sqrt{1 - 0.25}}$ $= 5.8 \times 10^5$ kg This is 80 000 kg heavier than its rest mass of 500 000 kg.

➤ Try yourself 10.7.1

RELATIVISTIC MASS

Calculate the relativistic mass as measured by Ayden, who is stationary in a laboratory, of an electron that is travelling at a speed of $2.85 \times 10^8\,\text{m s}^{-1}$ if the rest mass of the electron is 9.109×10^{-31} kg. Assume *Gedanken* conditions exist in this example.

It is important to think about this increase in 'mass' as an increase in inertial mass. **Inertial mass** is the mass measured by its resistance to changes in motion. Rest mass is considered as an invariant quantity, which means it doesn't change according to the reference frame. The faster the speed at which the object is travelling, the more difficult any further acceleration becomes, due to the inertial mass increasing (its resistance to change in motion), not the mass itself increasing. The increase in inertial mass is part of a more general phenomenon, the relativistic *equivalence of mass and energy*, which will be discussed further in Module 10.9.

10.7 Review

SUMMARY

- Rest mass is the mass of an object as measured in its own reference frame and does not change according to a moving observer.
- At high speeds (close to the speed of light) the same rest mass now exerts greater inertia (relativistic mass), thereby requiring greater force to accelerate to the speed of light.
- By applying the conservation of momentum and energy, the increase in mass can be determined by: $m = \gamma m_0$. This equates to:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- The mass of an object m in motion, is called the relativistic mass, γm_0, which is the mass measured as the object is moving relative to the observer. It is dependent on γ and the rest mass, m_0.
- Inertial mass increases (object's resistance to change in motion) the closer the speed of the object approaches the speed of light.

KEY QUESTIONS

Retrieval

1 Describe how scientists measured the relativistic mass of an electron.

2 Recall what would happen to the mass of an object travelling at the speed of light.

Comprehension

3 Harriet was explaining relativistic mass to her friend. She said 'In simple terms, relativistic mass is the increased mass, because of the increased speed'. Explain why this definition does not correctly explain relativistic mass, based on that definition of relativistic mass.

Analysis

4 A body in motion has mass of a 52 kg and travels in the air with velocity 0.87c. Determine its rest mass.

5 Calculate how massive you would appear in the Earth's reference frame if you were to board a rocket ship travelling at $2.00 \times 10^8 \, \text{m s}^{-1}$. Assume your rest mass is 70.0 kg.

10.8 Relativistic momentum and mass–energy equivalence

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

- identify the difference between Newtonian momentum and Einstein's relativistic momentum
- apply the equation used to calculate relativistic momentum
- explain why relativistic momentum further proves that no object can travel at the speed of light
- explain the origin of Einstein's famous equation
- state what is meant by the mass–energy equivalence.

One of, if not the, most famous equations in science arose because of the special theory of relativity. Einstein proposed that a comparatively small amount of matter is equivalent to an enormous amount of energy. This section will examine how he developed his famous equation. It will also look at the effects of relativistic momentum.

CLASSICAL AND RELATIVISTIC MOMENTUM

Recall that the momentum of an object relates to both its mass and its velocity. The more momentum an object has due to its mass or velocity, the more momentum it has to lose before it stops. Recall from Chapter 7 *Pearson Physics 11 Queensland* that the equation for momentum is $p = mv$ where m is the mass of the object and v is the velocity of the object.

For calculations of change in momentum in a single dimension, we can use the sign conventions of positive and negative. The term 'impulse' means change in momentum, so the impulse or change in momentum of an object moving in one dimension is calculated using:

$$\begin{aligned}\text{impulse} &= \Delta p = m\Delta v\\ &= p_{\text{final}} - p_{\text{initial}}\\ &= mv - mu\end{aligned}$$

When the speed of an object approaches the speed of light, its momentum does not behave according to the simple equations above. Consider a rocket ship like the one in Figure 10.8.1 travelling at $0.99c$. Why can't it simply turn on its rocket motor and accelerate up to c, or even faster? A full answer to this question was not given in Einstein's original 1905 paper on relativity, but some years later he showed that as the speed of a spaceship approaches c its momentum increases, but this was not reflected in a corresponding increase in speed.

Although his analysis is beyond the scope of this course, you can get a feel for his approach if you take some shortcuts.

The acceleration, a, of any object is inversely proportional to its mass, m, according to Newton's second law:

$$F = ma$$

Newton originally stated this law as a force, F, is equal to the rate of change in momentum p; that is:

$$F = \frac{\Delta p}{\Delta t}$$

As noted above, a change in momentum is classically defined as the change in the product of the mass, m, and the velocity, v. If you rearrange the above equation and substitute the relationship $\Delta p = m\Delta v$, you get:

$$F\Delta t = m\Delta v$$

ℹ Impulse $= \Delta p = m\Delta v$
$= p_{\text{final}} - p_{\text{initial}}$
$= mv - mu$

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}).

FIGURE 10.8.1 This rocket ship is moving at 0.99*c* and accelerating, and yet it can never reach a speed of *c*.

Now you see that time is involved, but at relativistic speeds you know that time is not the constant entity it was once believed to be.

Imagine that you have a rocket ship accelerating from rest to a high speed as viewed by an observer in a stationary frame of reference. You can say that the change in momentum of the ship will be given by:

$$F\Delta t_0 = m_0 \Delta v$$

where t_0 is the time in the ship's frame of reference, and $m_0\Delta v$ is just the classical Newtonian change in momentum.

In the stationary observer's frame, the time is dilated:

$$\Delta t = \gamma \Delta t_0$$

$$\Delta t_0 = \frac{\Delta t}{\gamma}$$

Substituting Δt_0 into the change of momentum equation above:

$$F\frac{\Delta t}{\gamma} = m_0 \Delta v$$

$$F\Delta t = \gamma m_0 \Delta v$$

That is, the impulse as seen by the stationary observer is equal to the product of the Lorentz factor, γ, and the change in Newtonian momentum. This means that as the spaceship approaches the speed of light, the impulse is multiplied by a factor that grows very rapidly. You can interpret this as meaning that the change in momentum in the stationary observer's frame of reference is equal to:

$$\Delta p = \gamma m_0 \Delta v$$

$$\Delta p = \gamma \Delta p_0$$

If we assume an object starts at zero velocity in an observer's reference frame, the final relativistic momentum becomes:

$$p = \gamma p_0 = \gamma m_0 v = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where

p_0 is the momentum $m_0 v$, as defined in classical mechanics

p is the relativistic momentum.

If velocity, v, is needed and the mass and relativistic increase in momentum are known, the formula $p = \gamma m_0 v$ can be rearranged to give:

$$v = \frac{p}{m_0\sqrt{\left(1 + \frac{p^2}{m_0^2 c^2}\right)}}$$

Although some shortcuts have been taken to reach this result, the result itself is perfectly valid.

The momentum increases very rapidly as a spaceship approaches the speed of light. You might argue that this is expected—after all, momentum is a function of velocity. If you graph the relativistic momentum, p, against the velocity, v, and on the same graph show the classical momentum, you can see that the relativistic momentum increases at a rate far greater than it would if it were due to the increase in velocity alone (Figure 10.8.2).

Notice too that the classical treatment allows the object to have a speed greater than the speed of light, but the relativistic treatment causes the mass to become very large so that the speed of light is never actually reached.

Now return to the example of the rocket ship that is attempting to increase its velocity to the speed of light. With the increase in the relativistic mass of the rocket ship, it becomes harder for the force of the engines to cause a change in velocity. The closer the rocket ship approaches c, the greater the amount of impulse

Einstein said that at the speed of light distances shrink to zero and time stops. No ordinary matter can reach c, but light always travels at c. Strange though it may seem, for light there is no time. It appears in one place and disappears in another, having got there in no time (in its own frame of reference, not ours!). When you stay still, you travel through spacetime in the time dimension only. Light does the opposite: all its spacetime travel is through space and none through time.

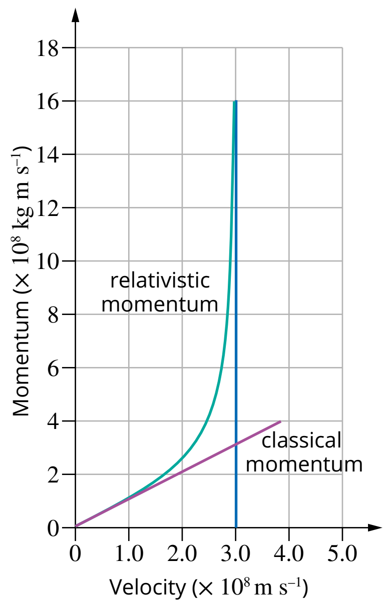


FIGURE 10.8.2 The relationship between classical momentum and velocity, and the relationship between relativistic momentum and velocity, for a 1 kg mass. Note: the blue line represents the speed of light, but according to relativistic momentum, objects will get close but never reach that line, whereas according to classical momentum it is achievable.

that is required to accelerate the ship to the speed of light. In fact, as the velocity approaches c, the relativistic mass, γm_0, approaches infinity. You can now see why your rocket ship cannot reach the speed of light.

Worked example 10.8.1 illustrates this point. Notice that the result in part **(b)** shows that if you double the impulse required to get the rocket ship to $0.99c$, you will only add $0.007c$ to your top speed. When you've completed Try yourself 10.8.1, consider the change in velocity achieved by tripling the impulse.

Worked example 10.8.1

RELATIVISTIC MOMENTUM

a Calculate the momentum, as seen by Lachie who is stationary, provided to a rocket ship as it travels at a speed of 0.990c. The rocket ship has a rest mass of 1000.0 kg. Assume *Gedanken* conditions exist in this example.	
Thinking	**Working**
Identify the variables: the rest mass is m_0, and the velocity of the rocket ship is v.	$p = ?$ $m_0 = 1000.0$ kg $v = 0.990 \times 3 \times 10^8$
Use the relativistic momentum formula.	$p = \gamma m_0 v$
Substitute the values for m_0 and v into the equation and calculate the answer p.	$p = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} m_0 v$ $= \frac{1}{\sqrt{1-\frac{0.990^2 c^2}{c^2}}} \times 1000 \times 0.990 \times 3 \times 10^8$ $= 2.11 \times 10^{12}$ kg m s^{-1}
b Calculate the new final speed of the rocket ship in terms of c if twice the impulse (i.e. change in momentum) of part **a** is applied to the stationary rocket ship.	
Thinking	**Working**
Identify the variables: the rest mass is m_0, and the relativistic momentum of the rocket ship is p.	$p = 2 \times 2.11 \times 10^{12}$ $= 4.21 \times 10^{12}$ kg m s^{-1} $m_0 = 1000$ kg $v = ?$
Use the relativistic momentum formula, rearranged.	$p = \gamma m_0 v$ $= \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} m_0 v$ $v = \frac{p}{m_0\sqrt{\left(1+\frac{p^2}{m_0^2 c^2}\right)}}$
Substitute the values for m_0 and p into the rearranged equation and calculate the answer v.	$v = \frac{4.21 \times 10^{12}}{1000\sqrt{1+\frac{(4.21 \times 10^{12})^2}{1000^2 \times (3 \times 10^8)^2}}}$ $= \frac{4.21 \times 10^{12}}{1000 \times 14.07}$ $= 2.99 \times -10^8$ ms^{-1} $= 0.997c$

➤ Try yourself 10.8.1

RELATIVISTIC MOMENTUM

a Calculate the momentum, as seen by stationary observer Sevda, provided to an electron as it goes from rest to a speed of 0.985c. The electron has a rest mass of 9.109×10^{-31} kg. Assume *Gedanken* conditions exist in this example.

b Calculate the new final speed of the electron in terms of *c* observed by Sevda if three times the relativistic momentum from part (a) is applied to the electron.

EINSTEIN'S FAMOUS EQUATION

Recall from earlier in this module that relativistic momentum includes the Lorentz factor, γ, and hence as more impulse is added, the mass seems to increase towards infinity as the speed gets closer, but never equal, to *c*. As the momentum of an object increases, so does its kinetic energy. The classical relationship between the two can be written as:

$$E_k = \tfrac{1}{2} m_0 v^2$$
$$= \tfrac{1}{2} \times m_0 v \times v$$
$$= \tfrac{1}{2} pv \text{ or } \frac{p^2}{2m_0}$$

This form of the equation shows that the kinetic energy of an object is related to its momentum as well as its velocity and mass.

Einstein showed, however, that the classical expression for kinetic energy was not correct at high speeds. The mathematics involved is beyond the scope of this course, but Einstein, working from the expression for relativistic momentum and the usual assumptions about work, forces and energy, was able to show that the kinetic energy of an object was given by the expression:

$$E_k = (\gamma - 1) m_0 c^2$$

Although it is not very obvious from this expression, if the velocity (which is hidden in the γ term) is small, this expression actually reduces to the classical equation for E_k of $\frac{1}{2}mv^2$. A small velocity in this context means small in comparison to *c*. But even for speeds up to 0.10*c*, the classical expression is accurate to better than ±1%.

Einstein's expression can be expanded to:

$$E_k = \gamma m_0 c^2 - m_0 c^2$$

This kinetic energy equation, in turn, can be rearranged as:

$$\gamma m_0 c^2 = E_k + m_0 c^2$$

Einstein interpreted the left-hand side of this expression as being an expression for the total energy of the object:

$$E_{total} = \gamma m_0 c^2$$

The right-hand side appeared to imply that there were two parts to the total energy: the kinetic energy, E_k, and another term that only depended on the rest mass, *m*. The second term, mc^2, he referred to as the rest energy of the object, as it does not depend on the speed of the object. This appeared to imply that somehow there was energy associated with mass. An astounding proposition to a classical physicist, but, as you have seen, in relativity mass increases as you add kinetic energy to an object. The conservation of energy relationship is therefore:

$$E_{total} = E_k + E_{rest}$$

You will have seen part of this equation before:

$$E = mc^2$$

ℹ $E_{total} = \gamma m_0 c^2$

or

$\Delta E_{total} = \Delta mc^2$

where

Δm is the relativistic mass (kg)

m_0 is the rest mass (kg)

c is the speed of light (m s^{-1})

E_{total} is the total energy (J).

This equation tells you that mass and energy are interrelated. In a sense, you can say that mass has energy, and energy has mass. Recall that in Units 1 and 2 this relationship was used to calculate the energy absorbed and released during fission and fusion nuclear reactions.

Worked example 10.8.2

FUSION

Consider the fusion reaction shown below, in which a proton fuses with a deuterium nucleus (a hydrogen nucleus with one neutron) in the Sun. A helium nuclide is formed and a γ ray released. A very small amount of mass is converted to energy. 20.0 MeV of energy is released during this process. $^{1}_{1}p + ^{2}_{1}H \rightarrow ^{x}_{2}He + \gamma$	
a Convert the energy released to joules.	
Thinking	**Working**
1 eV = 1.6×10^{-19} J	20.0 MeV = $20 \times 10^{6} \times 1.6 \times 10^{-19}$ = 3.20×10^{-12} J
b Calculate the amount of mass lost (the mass defect) for this reaction.	
Thinking	**Working**
Use $\Delta E = \Delta mc^2$.	$\Delta m = \frac{\Delta E}{c^2}$ $= \frac{3.2 \times 10^{-12}}{(3 \times 10^{8})^2}$ $= 3.56 \times 10^{-29}$ kg

➤ Try yourself 10.8.2

FUSION

A fusion reaction in the Sun fuses two helium nuclides. A helium nucleus and two protons are formed and a very small amount of mass has been converted to 30 MeV of energy.

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{x}_{2}He + 2^{1}_{1}H$$

a Convert the energy released to joules.

b Calculate the amount of mass lost (the mass defect) for this reaction.

10.8 Review

SUMMARY

- In Newtonian mechanics, the more momentum an object has the more mass or velocity it must have, according to the formula $p = mv$.
- As an object approaches the speed of light, the equation $p = mv$ is no longer valid, so an equation for relativistic momentum must be used instead:

$$p = \gamma p_0 = \gamma m_0 v$$

- Einstein found that the total energy of an object was given by:

$$E_{total} = E_k + E_{rest} = \gamma m_0 c^2$$

or

$$\Delta E_{total} = \Delta mc^2$$

- The rest energy, which is the energy associated with the rest mass of an object, is given by:

$$E_{rest} = m_0 c^2$$

- Mass and energy are seen as different forms of the same thing. This means that mass, m, can be converted into energy, and energy can be converted into mass.

KEY QUESTIONS

Retrieval

1 Describe at least two ways in which impulse can be found. State the formulas in each case.

2 State why a spaceship travelling at 99% of the speed of light cannot simply turn on its engine and accelerate to and beyond the speed of light, c.

3 Show how the kinetic energy of an object is related to its momentum as well as its velocity.

Comprehension

4 Describe what would happen to the velocity of an object if it experienced a large increase in impulse when moving at a speed near that of light.

Analysis

For questions 5–7, include a comparison with classical momentum.

5 Calculate the relativistic momentum of the Rosetta spacecraft as observed by the scientists at the European Space Agency. Rosetta has a rest mass of 1230 kg and its speed is $775\,\text{m}\,\text{s}^{-1}$.

6 Calculate the relativistic momentum of a carbon-12 nucleus in a linear accelerator if its rest mass is $1.992\,648\,24 \times 10^{-26}$ kg and it is travelling at 0.850c.

7 Calculate the relativistic momentum of another carbon-12 nucleus in the solar wind if its rest mass is $1.992\,648\,24 \times 10^{-26}$ kg and it is travelling at a speed of $800.0\,\text{m}\,\text{s}^{-1}$.

8 Calculate the energy equivalent of 1.00 kg using the mass–energy relationship.

9 Determine how much mass must be converted for the equivalent of 4.019×10^{-9} J of energy.

10.9 Apparent paradoxes

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

- explain the twin paradox and how Einstein resolved it
- identify two apparent paradoxes that arise from the law of simultaneity
- describe the grandfather paradox and its implications.

THE TWIN PARADOX

As discussed in Module 10.5, time in a moving frame seems to pass more slowly. Theoretically you could live long enough to reach distant parts of the universe—if you were travelling at close to the speed of light. Recall from Module 10.5 the scenario of Amaya and Binh riding in a *Gedanken* spaceship at speeds close to the speed of light while Clare watched from a space station. According to Clare, Binh and Amaya were moving in slow motion because, according to Clare's observations, time for them has slowed down. However, according to Binh and Amaya, time has slowed down for Clare.

If Clare sees time for Amaya and Binh running slowly, then Amaya and Binh will age more slowly. But if Amaya and Binh see that time for Clare has slowed down, then Clare will age more slowly. So what happens when Amaya and Binh decide to turn their spaceship around and come home? Who will have aged more?

To solve this paradox, or contradiction, Einstein described a thought experiment in which one of a set of twins heads off on a long space journey while the other twin stays on Earth.

The travelling twin finds that when she returns, her remaining twin has become quite elderly (Figure 10.9.1). Although each twin is in constant motion relative to the other, they both see the other twin ageing more slowly; that is, the Earth twin sees spaceship twin move away from her, but spaceship twin sees Earth twin move away from her at the same speed. So why did the twin on the spaceship age more slowly than the twin on Earth?

The key to this apparent paradox is that only one twin has spent the entire time in an inertial (non-accelerating) frame of reference. The other twin spent some time in non-inertial frames of reference. The twin on the spaceship accelerated away from Earth, decelerated as she slowed down, then accelerated back towards Earth, and finally decelerated as she slowed down to land back on Earth. It is the acceleration that makes all the difference.

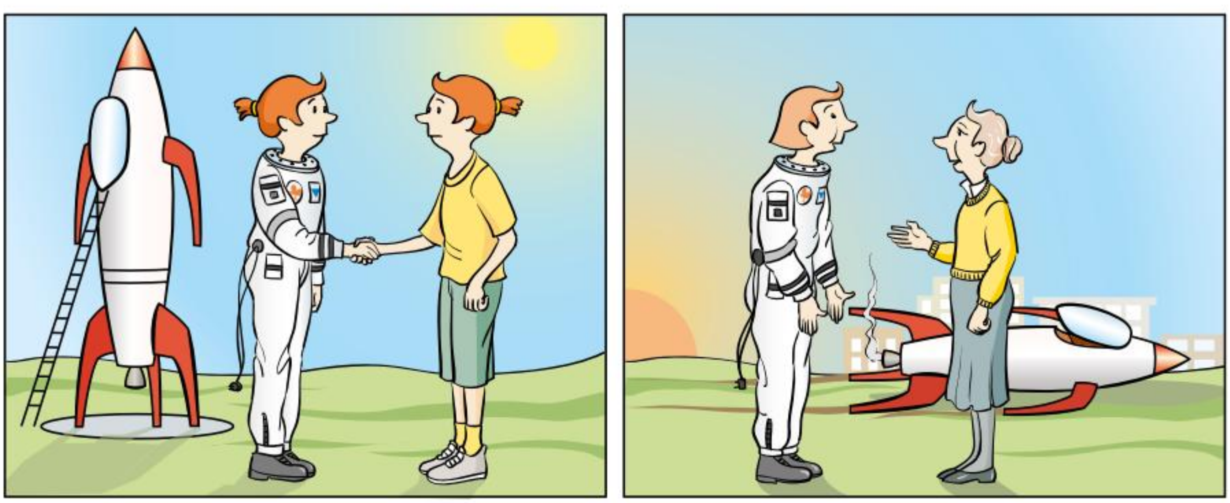


FIGURE 10.9.1 The twin paradox describes the phenomenon where one twin ages less quickly than the other after travelling in a non-inertial frame.

It is important to point out that Einstein's 1905 theory of relativity deals only with frames of reference that are in uniform motion; that is, inertial frames of reference. For this reason, it is called the *special* theory of special relativity. Special relativity does not deal with accelerated frames of reference. Ten years later, Einstein put forward the *general* theory of relativity, which does deal with situations in which acceleration occurs; that is, non-inertial frames of reference. As part of this theory, he showed that in an accelerated frame of reference, time also slows down.

If you apply the twin paradox situation to Amaya, Binh and Clare, as Clare watched from her inertial frame of reference, the general theory of relativity tells you that her view of Amaya and Binh in the non-inertial frame shows them ageing slowly. During this time, Amaya and Binh see Clare's time passing quickly. As a result, they will see Clare age more rapidly while they are accelerating, and more slowly when they are travelling at constant velocity. Clare sees Amaya and Binh aging more and more slowly as they gain speed, then aging constantly but slowly as they travel at a constant speed. Amaya and Binh never age rapidly.

But how do you know that it is Amaya and Binh who have accelerated and not Clare, because that is what it would look like to Amaya and Binh looking out of their window at Clare? For the answer to this you need to ask Amaya and Binh if they noticed anything unusual (such as forces that appear to come from nowhere) in their frame of reference; for example, did the surface of the water in their bottles tilt at an angle to the horizontal, or did the handles hanging down from the ceiling lean forwards or backwards. If you asked Clare these questions she would say no, while Amaya and Binh would say yes. So it was Amaya and Binh who accelerated and not Clare.

Although it is often called a paradox, there is actually nothing impossible or illogical about this story. Einstein himself pointed out that, due to Earth's rotation and therefore centripetal acceleration, a clock on the equator would run a little more slowly than one at the poles. This has now actually been found to be the case. In fact, in 1971 accurate atomic clocks were flown around the world on commercial flights. When compared with those left behind, the difference of about a quarter of a microsecond was just what Einstein's theory predicted. Now there are many satellites in orbit around the Earth, so the theory has been well and truly tested many times. Indeed, global positioning systems (GPS) must take the relativistic corrections into account to ensure their accuracy.

FLASHES ON A TRAIN

Recall from Modules 10.3 and 10.4 that one of the consequences of accepting the two postulates that Einstein put forward was that two events that are simultaneous for one set of observers may not be simultaneous for another. This led to the apparent paradox of two observers witnessing the same event but reporting different observations. The example in Module 10.4 had Amaya and Binh boarding Einstein's *Gedanken* train while Clare was outside the train. This train had a flashing light bulb set right in the centre of the carriage where Amaya, Binh and Clare could all view it. Amaya and Binh found that the flashes from the light bulb reach the front and back walls at the same time; however, Clare, who is watching the same flashes of light, sees the light reach the back wall first. In this example, it was because the back wall is moving towards the light, whereas the front wall is moving away from the light and so the light will take longer to catch up to it. Einstein said that the only reasonable explanation is that time itself is behaving strangely. The amount of time that has elapsed in one frame of reference is not the same as that which has elapsed in another.

> Events that are simultaneous to one observer may not be simultaneous to another observer, but the order they occur in will still be the same.

LADDER IN THE BARN PARADOX

The result of length contraction leads to an interesting phenomenon. Consider the example of the train in the tunnel in Module 10.6. The proper length of the train is 100 m, which means the driver could park the train in the 123 m tunnel. However, when the train is moving at 0.986*c*, it will not fit in the tunnel, as the length of the tunnel is contracted according to the train driver. Similarly, a train that is longer than the tunnel will fit completely inside the tunnel if its length was measured by a stationary observer as the train was moving past very quickly. So, will the train fit; who is correct? This paradox can be explained using a ladder in a barn.

Observer A is moving a ladder at speeds close to the speed of light towards a barn where observer B is standing. This barn contains two doors, one at the front (where the ladder will enter) and one at the back (Figure 10.9.2). As observer A moves towards the barn, the ladder contracts, and so observer B directs observer A to place the ladder inside the barn. Usually the ladder does not fit because the barn is too small to contain it. From observer A's point of view, the barn is moving towards him and therefore contracts in the direction of motion, which means that from this view the ladder will not fit inside the barn. Will the ladder fit or not? As discussed in the paradox of torches on a train, in relativity, simultaneity is relative to the observer. This means the question of whether the ladder fits inside the barn is relative to each observer. As simultaneity is relative, the two doors did not need to be shut at the same time, and the ladder did not need to fit inside the barn.

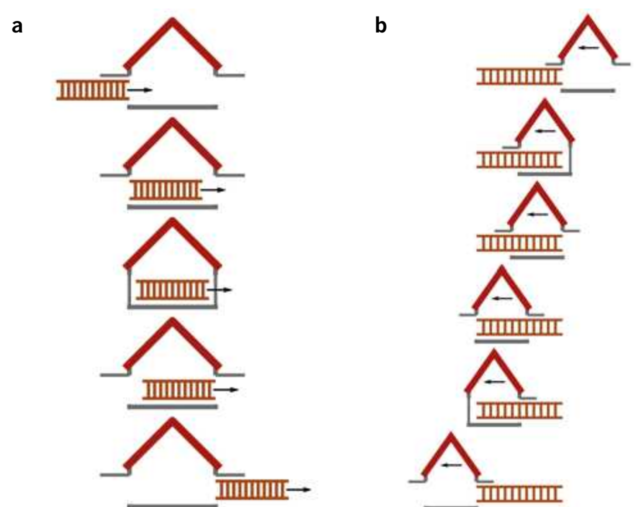


FIGURE 10.9.2 The ladder in the barn paradox. (a) The ladder relative to the observer near the barn (observer B). The ladder's length appears contracted. (b) The ladder relative to the observer carrying the ladder (observer A). The barn's length appears contracted.

GRANDFATHER PARADOX

Einstein's theory of special relativity is restricted to observers with constant relative velocity. Special relativity shows that time slows down or speeds up depending on how fast you are moving relative to another object. Einstein's theory of general relativity, which incorporates gravity, shows that massive objects bend spacetime. This theory provides scenarios that could allow travellers to go back in time. However, this has never been achieved. Suppose that you could travel back in time. What would happen to you if you went back in time and killed your grandfather? Presuming that you killed him before the conception of your parents, this would prevent you from being born, so how would you have gone back in time to kill your grandfather? This paradox is called the grandfather paradox and is a paradox of time travel.

WS 4.1.3

10.9 Review

SUMMARY

- Time dilation and length contraction give rise to several apparent paradoxes, all of which can be explained by special and general relativity.
- Two events that are simultaneous in one frame of reference are not necessarily simultaneous in another.
- Observers in relative motion both see time slowing in the other frame of reference; that is, each sees the other age more slowly.
- Special relativity applies only in inertial frames of reference, and not in accelerated (non-inertial) frames of reference.
- Einstein's theory of general relativity applies in accelerated (non-inertial) frames of reference, in which time also slows down. It incorporates gravity, which can bend time, and therefore provides scenarios that could allow travellers to go back in time.

KEY QUESTIONS

Retrieval

1 Spaceships A and B leave Earth and travel towards Vega, both at a speed of 0.9c. Observer C back on Earth sees the crews of A and B moving in 'slow motion'. Describe how the crew of A see the crew of B, and how they see C and the Earthlings moving.

2 State why you can say in the twin paradox explanation that the twin who stays at home ages faster than the twin who goes on the journey.

Comprehension

3 You are in a spaceship travelling at very high speed past a new colony on Mars. Determine whether time will go slowly for you; for example, determine if your heart rate would be slower than normal. Consider whether people on Mars appear to be moving normally. Explain your answers.

Analysis

4 Reflect on one other time travel paradox, or a situation where confusion over time results when a person travels backwards in time.

Chapter review

WS 4.1.4 WS 4.1.5

10

KEY TERMS

aether
atomic clock
classical physics
frame of reference
Gedanken experiments
inertial frame of reference
inertial mass
length contraction
Lorentz factor
medium
muon
non-inertial frame of reference
postulates of special relativity
proper length
proper time
relativistic length
relativistic mass
relativistic momentum
relativistic time
rest mass
simultaneity
simultaneous
spacetime
time dilation

KEY QUESTIONS

Retrieval

1 Recall Einstein's first postulate by selecting the best description from the options below:
A Light always travels at $3 \times 10^8\,m\,s^{-1}$.
B Absolute velocity is that measured with respect to the Sun.
C Velocities can only be measured relative to something else.
D There is no way to tell how fast you are going unless you can see what's around you.

2 Identify one or more of the following conditions that is sufficient to ensure we measure the proper time between two events. The observer must:
A be stationary
B be in the same frame of reference
C not be accelerating with respect to the frame of the two events
D be in a frame of reference that is travelling at the same velocity as the frame of the two events

3 Spaceships A and B depart Earth and travel at a speed of 0.99*c* towards planet Eth. The crew on Spaceship A see a person on Earth moving in slow motion. Identify how the observer on Earth sees the crew of both Spaceship A and B.
A None of these.
B Both crews appear to have sped up.
C Both crews appear to have slowed down.
D The crew on Spaceship A appears to be moving at normal speed, the crew on Spaceship B appears to have sped up.
E The crew on Spaceship A appears to be moving at normal speed, the crew on Spaceship B appears to have slowed down.

4 Identify the condition in which the twin who stays at home ages faster than the twin who goes on the journey.
A during the acceleration phase
B during the deceleration phase
C during the constant velocity portion of the journey
D during both the acceleration and deceleration phases

5 Explain why a spaceship travelling at 99% of the speed of light cannot simply turn on its engine and accelerate to and beyond the speed of light, *c*.
A The law of impulse equals change in momentum does not apply at speeds close to *c*.
B Given enough impulse the spaceship could exceed *c*, but no real spaceship could carry enough fuel.
C Because the momentum increases with the impulse, the relativistic mass increases towards infinity.
D The spaceship does actually exceed *c*, but it doesn't appear to from another frame of reference because of length contraction of the distance it covers.

6 Recall the basis of Einstein's considerations, which eventually led to the theory of special relativity, by selecting the best option below.
A his own experiments in electromagnetism
B the work of Isaac Newton and Michael Faraday
C the results of numerous experiments to determine the speed of light
D his consideration of the consequences of accepting the implications of Maxwell's equations

7 One of the fastest objects made on Earth was the Galileo probe which, as a result of Jupiter's huge gravity, entered Jupiter's atmosphere in 1995 at a speed of nearly $50\,000\,m\,s^{-1}$. State the best estimate of the Lorentz factor for the probe.
A 2
B exactly 1
C less than 1
D 1.000 000 01

Comprehension

8 Show that for an object travelling at any possible velocity, the value of the term below must be less than 1.

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

9 Describe where on the surface of Earth we are closest to an inertial frame of reference.

10 Explain why Einstein said that we must use four-dimensional spacetime to describe events that occur in situations where high speeds and large distances are involved.

11 Imagine that Amaya is at the front end of a train carriage moving forwards at $10.0\,\text{m}\,\text{s}^{-1}$. She shines a laser towards Binh, who is at the other end of the carriage. Clare is watching all of this from the side of the track. Discuss the velocity of the light as measured by Clare.

12 You are riding in a very smooth, quiet train with the blinds drawn. Explain how or whether you could tell the difference between the train:

i being stopped in the station

ii accelerating away from the station

iii travelling at a constant speed.

13 The ancient Greek philosopher Aristotle suggested that the 'natural' state of motion for any object is rest. Galileo introduced the principle of inertia, which suggested that the natural state of motion is constant velocity (zero velocity being just one example). Explain why Aristotle's view was so hard to discard, and why, if we had spent time as an astronaut in a space station, Galileo's principle would be much easier to accept.

Analysis

14 Determine which statement is incorrect if you were travelling at high speeds (0.99c). Explain your answer.

A Your heart rate is slower than normal.

B You will have a normal life expectancy.

C You will age slower than a person on Earth.

15 In the mid-1970s the fastest artificial objects were launched into space. These were two Helios probes that were designed to study the Sun and its function. Both probes were officially recorded moving at $252\,792\,\text{km}\,\text{h}^{-1}$. Consider this information and provide an estimate of the Lorentz factor for the probes to eight decimal places.

16 Akshay is sitting in a very fast jet plane and looking out of the window at a clock placed on top of a mountain. He notes that a goat takes 20.0 s to run along a rocky ridge using the clock on the mountain. Calculate how much time has passed on Akshay's clock if the plane is flying at a speed of $2.00 \times 10^8\,\text{m}\,\text{s}^{-1}$.

17 In a spaceship travelling at $2.25 \times 10^8\,\text{m}\,\text{s}^{-1}$ there is a pool where a swimmer is completing laps. A stationary observer watches the spaceship go past and times the swimmer completing one stroke in 1.50 s.

Calculate how much time the spectator measures passing on the swimmer's wristwatch.

18 a Determine the speed of a rocket ship that was observed to be half of its normal length.

b The rocket ship is then observed to accelerate to a certain speed so that its length halved again. Determine if that means the rocket doubled its speed. Determine to what speed it accelerated.

19 Binh and Amaya are playing table tennis in their spaceship. They rush past Clare in her space station at a relative speed of $240\,000\,\text{km}\,\text{s}^{-1}$. Binh says that after he hits the ball it returns to his bat after 1.00 s. The table is 3.00 m long in the direction of their spaceship's motion and is 1.00 m high.

a Calculate the time between hits as measured by Clare.

b Calculate the length and height of the table as measured by Clare.

20 Star Xquar is at a distance of 5.0 light-years from Earth. Space adventurer Raqu is travelling from Earth towards Xquar at a speed of 0.90c.

a Determine how long in years it will take Raqu to reach Xquar for those watching from Earth.

b Determine how long in years will it take Raqu to reach Xquar from her point of view.

c Raqu knew that Xquar was 5.0 light-years from Earth, and that she was to travel at 0.90c. Explain why it took much less travel time than might be expected from these figures.

21 A space shuttle is travelling at close to $8000\,\text{m}\,\text{s}^{-1}$. Imagine that as it travels east–west it takes a photograph of Australia, which is close to 4000 km wide. Because of its speed, the space camera will see everything on Earth slightly contracted.

a Determine approximately how much less than 4000 km wide will Australia appear to be in this photograph.

b Deduce whether the north–south dimension of Australia will be smaller as well.

22 Imagine that as we watch a space traveller journeying from Earth to the star Vega travelling at 99.5% of the speed of light, we see their clock slow down by a factor of about 10 times.

a Explain how this factor of 10 was arrived at.

b Deduce whether this means that the traveller is experiencing this slowing down of time.

c Vega is about 25 light-years from Earth, so in our frame of reference it takes light from Vega 25 years to reach Earth. Calculate how long it will take the traveller to reach Vega in Earth's frame.

d Predict how long it takes the traveller to travel to Vega according to them.

e Determine if your answer to part **d** implies that they were able to get to Vega in less time than light. Explain your answer.

23 A proton in a linear accelerator attains an energy of 1.00 TeV.

The rest mass of a proton is 1.673×10^{-27} kg.

a Calculate the relativistic mass of this proton.

b Calculate the velocity of this proton as a fraction of *c* with respect to the accelerator's frame, to seven decimal places.

Knowledge utilisation

24 Rest masses of particles can also be expressed in units of MeV c^{-2} or GeV c^{-2}. This is the energy equivalent (in MeV or GeV) of the particle's relativistic mass.

a Prove that the rest mass in eV c^{-2} of a particle of rest mass m_0 in kg can be written as

$$m_0 = \frac{E}{e} \text{ (in eV c}^{-2}\text{)}$$

where E is the energy equivalent in joules and e is the elementary charge 1.602×10^{-19}.

For example, the rest mass of a single electron ($m_0 = 9.11 \times 10^{-31}$ kg) is 5.118×10^{5} eV c^{-2}, or 511.8 keV c^{-2}.

Calculate the relativistic mass of the following particles.

b a proton of rest mass 1.673×10^{-27} kg

c an alpha particle of rest mass 6.644657×10^{-27} kg

25 You might have read about the 'Oh my God' particle. This was a single cosmic ray that originated from somewhere outside of the Earth that was observed, in 1991, to have a velocity of 99.999 999 999 999 999 999 999 51% of the speed of light.

It is thought that the particle was accelerated through galactic magnetic fields and ended up being detected on Earth with an energy roughly that of a cricket ball of mass 160 g moving at 100.0 km h^{-1}. Of the particles you have studied so far in physics (proton, electron, alpha particle, positron, and neutron), decide which particle is the best candidate for the 'Oh my God' particle.

26 The Sun has a power output of 3.828×10^{26} W. Predict how much matter must be converted into energy each second to sustain the Sun's power based on this information.

27 A group of space voyagers is travelling to the star Sirius, which is 8.6 light-years away, at 90.0% of the speed of light. One light-year is equivalent to 9.46×10^{15} km.

The spaceship sends out a radio signal, at a frequency of 4.5×10^{5} Hz, from Sirius back to Earth to say they have arrived. Decide on a frequency that the people on Earth have to tune into to receive the signal. Assume that the signal was sent just before the spaceship slowed down to land on a planet orbiting Sirius.

CHAPTER 11

Quantum physics

Quantum theory explains the behaviour of very small things in our universe: photons and electrons. The quantum world is quite different from our everyday world, which is explained by the laws of classical physics.

The nature of light has been discussed and debated since the time of Isaac Newton in the 17th century. The debate arose because light displays characteristics of waves in some contexts and characteristics of particles in others. Quantum theory was developed during the 20th century and described light as photons—quantised packets of energy. Along with relativity, quantum theory forms part of modern physics.

The behaviour of light is very important for fibre optics and the optical storage of information, while the quantum behaviour of electrons is important in understanding the behaviour of the semiconductors that make up computer components, including chips, diodes and transistors.

Syllabus subject matter

WS 4.2.1

Topic 2 • Quantum theory

QUANTUM THEORY

- explain how Young's double slit experiment provides evidence for the wave model of light
- describe light as an electromagnetic wave produced by an oscillating electric charge that produces mutually perpendicular oscillating electric fields and magnetic fields
- explain the concept of black-body radiation
- identify that black-body radiation provides evidence that electromagnetic radiation is quantised into discrete values
- describe the concept of a photon
- solve problems involving the energy, frequency and wavelength of a photon
- describe the photoelectric effect in terms of the photon
- define the terms *threshold frequency*, *Planck's constant* and *work function*
- solve problems involving the photoelectric effect
- recall that photons exhibit the characteristics of both waves and particles

MANDATORY PRACTICAL 4

- Conduct an experiment (or use a simulation) to investigate the photoelectric effect.

11.1 Light as a wave

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

- outline the evidence that supports the wave nature of light
- perform calculations relating the energy, wavelength and frequency of light
- list forms of radiation that make up the electromagnetic spectrum
- perform calculations of the wavelength of light based on Young's double-slit experiment.

THE NATURE OF LIGHT

In *Pearson Physics 11 Queensland* Chapter 11, you were introduced to light as a **wave** and the nature of light and other forms of electromagnetic radiation was discussed in Chapter 9 of this textbook. In brief, if a changing electric field is produced, for example by a charged particle moving backwards and forwards, then this changing electric field will produce a changing magnetic field at right angles to it (Figure 11.1.1).

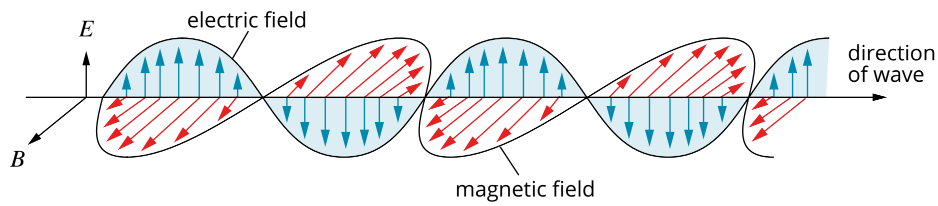


FIGURE 11.1.1 The electric and magnetic fields in electromagnetic radiation are perpendicular to each other and both are perpendicular to the direction of propagation of the radiation.

The changing magnetic field will, in turn, produce a changing electric field and the cycle will be repeated. In effect, this produces two mutually propagating fields and the electromagnetic radiation is self-propagating—it can extend outwards into space at the speed of light. Both the electric and magnetic fields oscillate at the same frequency: the frequency of the light wave. Forms of electromagnetic radiation include **visible light**, **infrared** and **ultraviolet radiation**, radio waves, microwaves, X-rays and gamma rays.

YOUNG'S DOUBLE-SLIT EXPERIMENT

Between the 17th and 19th centuries, most scientists considered light to be a stream of particles. This idea was based on the 'corpuscular' theory proposed by Sir Isaac Newton.

In 1803, an English scientist called Thomas Young performed a now-famous experiment in which he shone monochromatic light on a screen containing two very tiny slits. On the far side of the double slits he placed another screen on which he observed the pattern produced by the light passing through the slits. Young's observation of **interference** patterns in light (Figure 11.1.2) was a pivotal moment in the history of science. It tipped the scales in a long-running dispute between scientists about the nature of light, and paved the way for a series of discoveries and inventions that fundamentally changed scientists' understanding of energy and matter.

According to Newton's particle theory, light should have passed directly through the slits to produce two bright lines or bands on the screen (Figure 11.1.3a). Instead, Young observed a series of bright and dark bands or 'fringes' (Figure 11.1.3b).

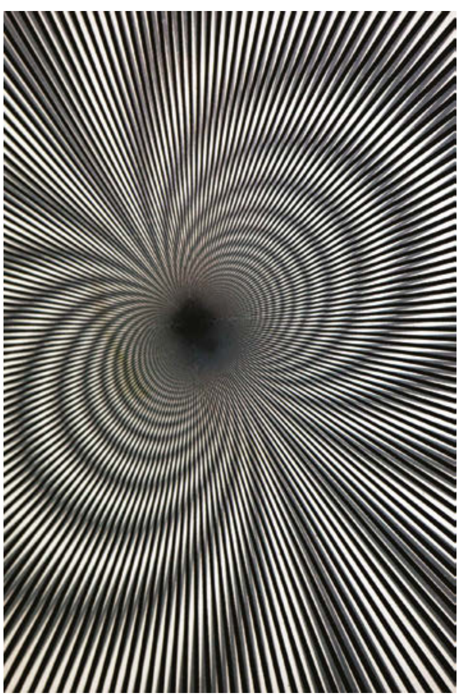


FIGURE 11.1.2 Optical interference can produce spectacular patterns.

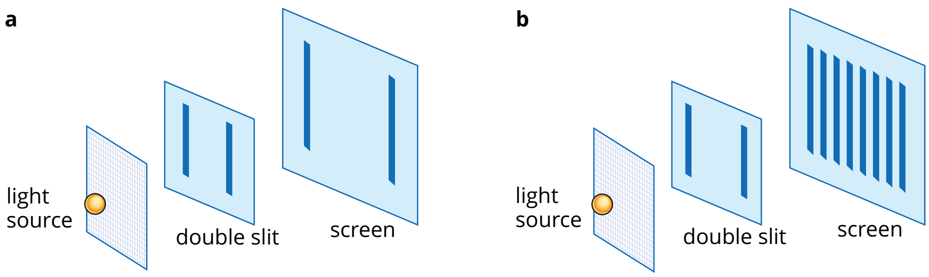


FIGURE 11.1.3 (a) The particle theory of light predicted that Young's experiment should produce two bright bands. (b) The actual experiment produced a series of bright and dark bands or 'fringes'.

Young was able to explain this bright and dark pattern by treating light as a wave. He assumed that the monochromatic light was like plane waves and that, as they passed through the narrow slits, these plane waves were diffracted into **coherent** (in phase) circular waves as shown in Figure 11.1.4. The circular waves would interact, causing interference. The interference pattern produced by these two waves would result in lines of **constructive** (antinodal) and **destructive** (nodal) **interference** that would match the bright and dark fringes respectively.

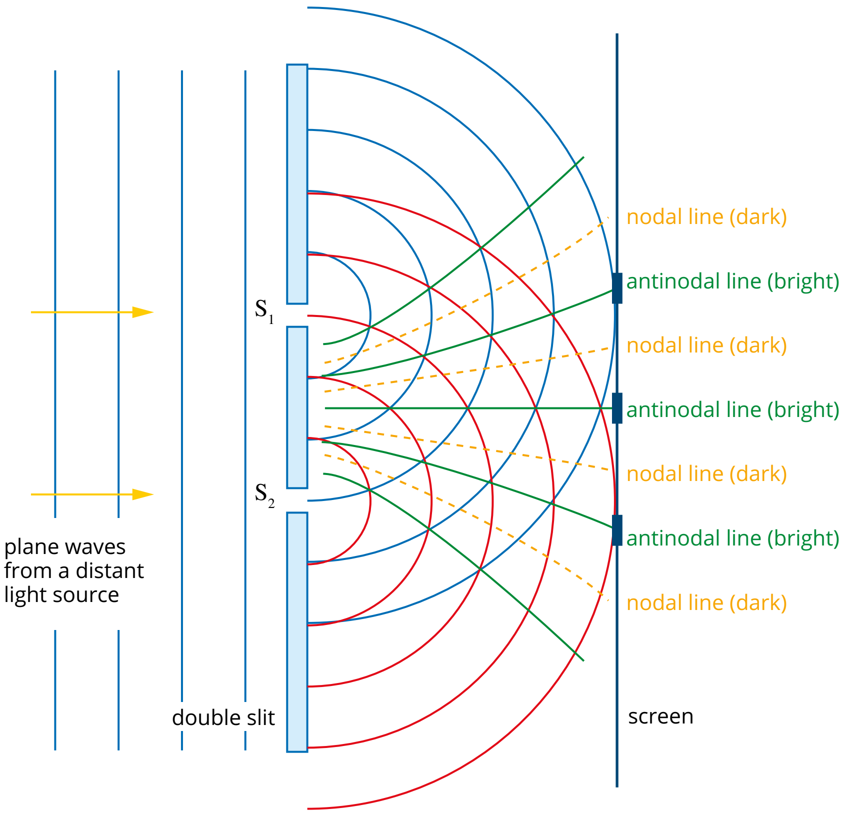


FIGURE 11.1.4 The interaction of two circular waves can produce a pattern of antinodal (constructive interference) and nodal (destructive interference) lines.

Earlier in his scientific career, Young had observed similar interference patterns in water waves (Figure 11.1.5). This gave greater credibility to the wave model for light proposed by Christiaan Huygens and Robert Hooke many years earlier. Figure 11.1.6 on page 294 shows the light intensity pattern of the bright and dark fringes.

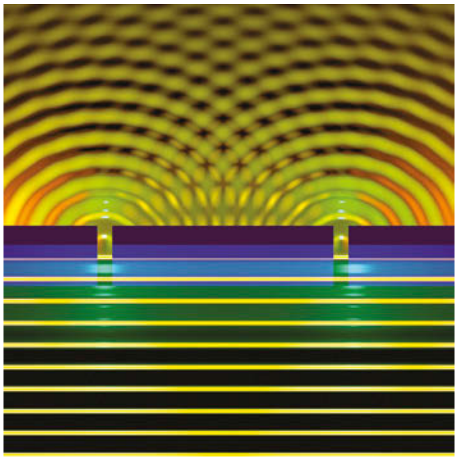
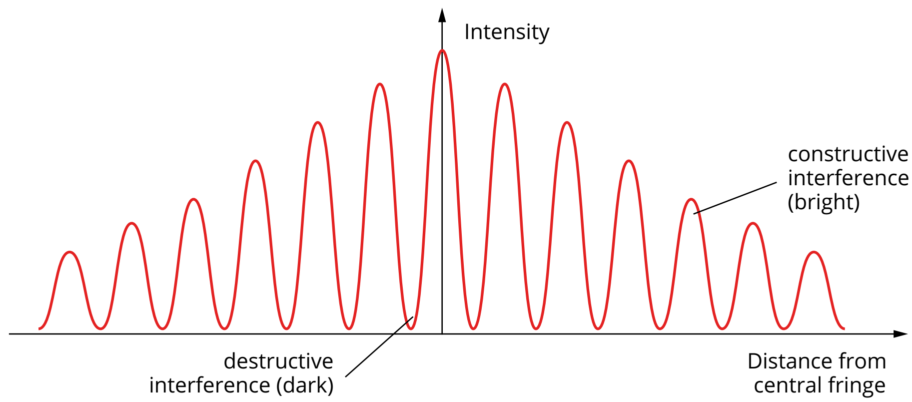


FIGURE 11.1.5 Interference patterns can be observed in water waves (lit here in yellow).



PA 4.2.1

FIGURE 11.1.6 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, the central maximum.

WS 4.2.2

When Young used his data to calculate the wavelength of light, it became clear why no one had ever noticed the wave properties of light before—light waves have tiny wavelengths, with typical values of less than 1 micrometre ($1\,\mu m = 0.001\,mm$).

11.1 Review

SUMMARY

- Young's double-slit interference experiment provided evidence to support the wave model of light.
- Young observed interference patterns in light which were similar to interference patterns seen in water waves.

KEY QUESTIONS

Retrieval

1 According to the particle model of light, Young's double-slit experiment should have produced two bright lines on the screen. Describe what was actually observed on the screen.

Comprehension

2 Gregor and Lily are trying to replicate Young's double-slit experiment. One uses torch light and the other uses light from a laser. Explain why the student using the laser light is more likely to obtain the expected interference pattern.

3 Explain why Young's double-slit experiment led to a significant change in scientists' understanding of the nature of light.

4 Draw what would be observed on the screen in Young's double-slit experiment if the particle (or corpuscle) model of light was correct.

5 Explain why there is always a bright fringe exactly half-way between dark fringes on an interference pattern.

6 In Figure 11.1.4 on page 293, bright fringes are found when a crest of a wave from S_1 intersects a crest of a wave from S_2. Explain what is happening when two waves interfere to produce a fringe that is about 50% of the intensity of the bright fringes.

7 Explain why the intensity of the bright fringes seen in Figure 11.1.6 above decreases as the distance from the central axis increases.

Analysis

8 Discuss reasons why Young's experiment and his interpretation of the results was considered so revolutionary at the time when it occurred.

11.2 Black-body radiation

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

- state Wien's law
- perform calculations using Wien's law
- describe the differences between absorbed and emitted radiation
- describe how a quantum view of the nature of light includes both particle and wave characteristics.

TEMPERATURE AND RADIATION

Electromagnetic radiation is emitted by all objects and systems. The EMR is emitted in a continuous spectrum, with a peak wavelength or frequency that depends almost entirely on the temperature of the object and not on the characteristics of the material itself.

The higher the temperature of an object or system, the higher the frequency, and the shorter the wavelength of the emitted radiation. As temperature increases, electromagnetic radiation is emitted at increasingly higher frequencies. Consider the following examples.

- Cool objects, such as the human body, emit radiation at long wavelengths with lower energy, such as infrared radiation. Infrared radiation is not visible to the naked human eye under normal circumstances.
- At higher temperatures, objects emit radiation with a higher frequency and you can see them glow red. An example is a bar heater that glows red hot.
- At even higher temperatures, say 2000 K, objects such as the filament of an incandescent light glow yellow or white.
- Very hot objects, at temperatures of 10^6 K or more, emit most of their radiation within the gamma and X-ray regions of the electromagnetic spectrum.

Wien's law

Wilhelm Wien, a German physicist, formulated laws that describe the properties of heat radiation. Wien discovered that the peak wavelength at which an object will emit the maximum intensity of radiation is dependent on its surface temperature. Wien's displacement law, more commonly known just as Wien's law, can be used to determine the peak wavelength for an object at a particular surface temperature.

Wien's law states that

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

where

λ_{max} is the peak wavelength of the emitted radiation in metres (m)

b is a constant = 2.898×10^{-3} m K

T is the surface temperature of the object in kelvin (K).

Rearranging this equation into the form $\lambda_{max} T = b = 2.898 \times 10^{-3}$ m K we see that, no matter what the surface temperature of an object, the product of the temperature and the wavelength at which the peak intensity of the emitted radiation occurs is a constant and is equal to about 2.898×10^{-3} m K.

The graph in Figure 11.2.1 shows the continuous spectrum emitted by any solid, liquid or even a dense gas at particular temperatures. An object at a temperature of about 12 000 K will emit its peak wavelength in the ultraviolet range. That is, the wavelength corresponding to the highest intensity for the 12 000 K curve will occur in the ultraviolet range.

Intensity versus wavelength for different temperatures

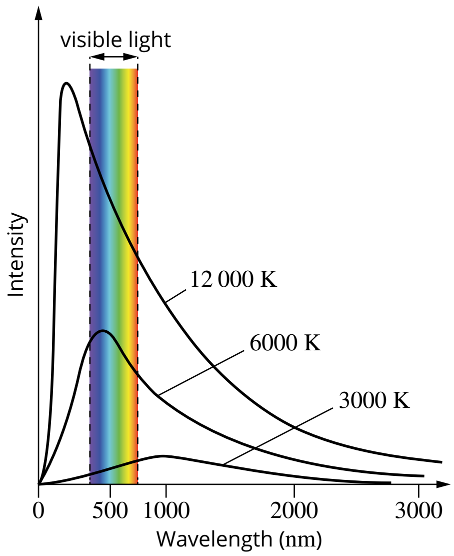


FIGURE 11.2.1 The spectrum of wavelengths emitted at different temperatures. The radiation approximates the surface temperature of many real objects.

The 6000 K curve in the graph in Figure 11.2.1 corresponds to the surface temperature of our Sun. The intensity maximum corresponds to a peak wavelength within the visible band of the electromagnetic spectrum, at about 500 nm.

The surface temperature of the Sun means that the electromagnetic radiation emitted by the Sun peaks in the visible range and is emitted mainly within the range between ultraviolet and infrared, including visible light.

Black-body radiation

Wien's work on the wavelength of the radiation emitted by a hot, dense object was based initially on a theoretical object called a **black body**. A black body does not necessarily have to be black. An incandescent lamp or a light bulb may be, to a certain extent, regarded as a black body.

This theoretical object completely absorbs all the rays of electromagnetic radiation incident on it regardless of the wavelength of the radiation. In other words, a black body does not reflect any radiation. The radiation emitted by many objects, such as the Sun, can be approximated as the radiation emitted by a black body at the same temperature. Figure 11.2.1 is based on the wavelengths emitted by a black body. The spectrum emitted by a hot solid, liquid or dense gas is continuous, but has a peak intensity at a wavelength inversely proportional to the surface temperature. This relationship is more simply stated by rearranging Wien's law:

$$\lambda_{max} \propto \frac{1}{T} \text{ and also } T \propto \frac{1}{\lambda_{max}}$$

Wien's law makes it possible to determine the approximate temperature of stars, assuming that they emit radiation similar to that emitted by a black body. During astronomic observations, it was discovered that stars at different temperatures have peaks in the graph of emissive power at different wavelengths. When the wavelength that corresponds to the peak of the power emitted by a star is known, the temperature of the star can be found by applying Wien's law.

Worked example 11.2.1

THE TEMPERATURE AT A STAR'S SURFACE

The Sun emits a continuous electromagnetic spectrum with a peak wavelength of approximately 500 nm. Estimate the surface temperature of the Sun based on this wavelength.

Thinking	Working
Express the peak wavelength in metres.	$\lambda_{max} = 500\,\text{nm} = 5.0 \times 10^{-7}\,\text{m}$
Rearrange Wien's law to solve for T.	$\lambda_{max}T = 2.898 \times 10^{-3}\,\text{m K}$ $T = \frac{2.898 \times 10^{-3}}{\lambda_{max}}$
Substitute the value for λ_{max} and solve for T.	$T = \frac{2.898 \times 10^{-3}}{500 \times 10^{-9}}$ $= 5796\,\text{K}$

➤ Try yourself 11.2.1

THE TEMPERATURE AT A STAR'S SURFACE

A newly discovered star is observed to have a peak emitted radiation wavelength of approximately 90 nm. Estimate the surface temperature of this star based on this wavelength.

Re-radiated electromagnetic radiation

Radiant energy interacts with matter in three ways. It can be:

- reflected
- transmitted
- absorbed.

More often than not it will be a combination of two or more of these modes. For example, absorption of radiant energy by the surface of Earth leads to the heating of the surface and re-radiation of radiant energy.

Earth's atmospheric gases absorb very narrow wavelengths of the incoming solar radiation, depending upon the nature of the gas. The smaller molecules of oxygen and nitrogen absorb very short wavelengths of solar radiation. The larger molecules of water vapour and carbon dioxide absorb primarily longer infrared radiant energy. About 17% of the radiant energy from the Sun is absorbed by the atmosphere, leading to the heating of the upper layers of the atmosphere.

The lower layers of the atmosphere are not predominately heated by the Sun's radiant energy but, rather, by radiation from the surface of Earth. Earth is much cooler than the Sun, and so emits much longer wavelength radiation. With the temperature of the Sun's surface being approximately 6000 K, the peak wavelength of solar radiation is about 500 nm. This corresponds to the visible part of the electromagnetic spectrum. Earth has an average temperature of about 16°C or 289 K. At that significantly lower temperature, the Earth emits most of its energy in the infrared range of the electromagnetic spectrum. This can be seen in the infrared image in Figure 11.2.2.

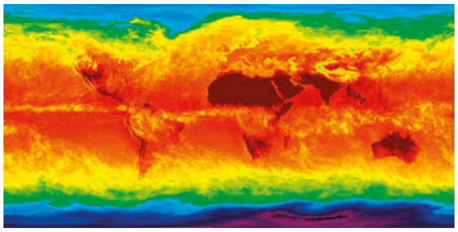


FIGURE 11.2.2 The Atmospheric Infrared Sounder (AIRS) instrument aboard NASA's Aqua satellite senses temperature using infrared wavelengths. This image shows the temperature of the Earth's surface or clouds covering it for the month of April 2003.

If Earth is modelled as a black body, the peak wavelength of re-radiated energy from Earth can be calculated using Wien's law.

Worked example 11.2.2

RE-RADIATED ENERGY FROM THE EARTH

The Earth's average surface temperature is 289 K. Calculate the peak wavelength of the re-radiated electromagnetic radiation.	
Thinking	**Working**
State Wien's law.	$\lambda_{max} = \frac{2.898 \times 10^{-3}}{T}$
Substitute the value for T and solve for λ_{max}.	$\lambda_{max} = \frac{2.898 \times 10^{-3}}{289}$ $= 1.00 \times 10^{-5}$ m $= 10.0\,\mu$m

➤ Try yourself 11.2.2

RE-RADIATED ENERGY FROM THE EARTH

The average surface temperature at the equator is 300.0 K. Calculate the peak wavelength of the re-radiated electromagnetic radiation from this part of Earth.

WS 4.2.3

11.2 Review

SUMMARY

- Electromagnetic radiation is emitted in a continuous spectrum by all objects whose temperature is above absolute zero.
- The peak wavelength at which an object will emit the maximum intensity of radiation is dependent on the object's surface temperature and is given by Wien's law. Wien's law states that $\lambda_{max}T = 2.898 \times 10^{-3}$ m K.
- The surface temperature of the Sun is approximately 6000 K. This means that the electromagnetic radiation emitted by the Sun peaks in the visible range and is emitted mainly within the range between ultraviolet and infrared light.
- The average surface temperature of Earth is approximately 289 K. Re-radiated energy from Earth will lie in the infrared section of the electromagnetic spectrum. The peak wavelength can be calculated using Wien's law.

KEY QUESTIONS

Retrieval

1 State Wien's law.

Comprehension

2 Describe the region of the electromagnetic spectrum radiation where the peak wavelength of ice (approximately 10^{-5} m) lies.

3 Calculate the temperature of the surface of a star, if the star emits a continuous electromagnetic spectrum with a peak wavelength of 800.0 nm.

4 The element of an electric heater is just seen to glow a dull red. This colour corresponds to the lower end of the visible spectrum at 700.0 nm. Calculate the temperature, in kelvin, of the element of the heater.

Analysis

5 Calculate the peak wavelength of the energy being emitted by the star, if a star has a surface temperature of 9320 K.

11.3 Quantisation of energy

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

- state Planck's equation
- perform calculations using Planck's equation in both joules (J) and electron volts (eV).
- identify that black-body radiation provides evidence that electromagnetic radiation is quantised into discrete values.

By the end of the 19th century, most scientists had accepted that the wave model of light had replaced Newton's earlier corpuscular (particle) model. The wave model explained a number of phenomena (e.g. diffraction, interference and polarisation) that could not be explained using the particle model. Some scientists believed that all that was left to be done in the field of optics was to measure some constants, such as the speed of light, as accurately as possible. Few scientists expected what was to come—that the inability of the wave model to explain a couple of key observations would lead to a fundamental revolution in our understanding of both light and matter.

PLANCK'S EQUATION

In 1900, the German physicist Max Planck was studying black-body radiation—the spectrum of EMR emitted by all objects. Planck and other scientists had discovered that certain features of this spectrum could not be explained using a wave model for light.

Planck proposed a controversial solution to this problem by assuming that light was emitted as discrete packets. He called the discrete packets of energy 'quanta', and developed an equation for the energy, E, of each **quantum**:

$E = hf$

where

E is the energy of a quantum of light (J)

f is the frequency of the electromagnetic radiation (Hz)

h is the constant 6.626×10^{-34} J s, now known as Planck's constant.

We now use the term **photon** to describe a single quantum of light or any other electromagnetic radiation. Since electromagnetic radiation is more commonly described according to its wavelength, scientists often combine Planck's equation with the wave equation for light, $c = f\lambda$, as follows:

$$E = hf \text{ and } f = \frac{c}{\lambda}$$

where c is the speed of light.

So:

$$E = \frac{hc}{\lambda}$$

At the time, most scientists disregarded Planck's work because the particle model it suggested was so much at odds with the wave model that had become widely accepted as the correct explanation for light.

THE ELECTRON VOLT

The **electron volt** was introduced in Chapter 3 of *Pearson Physics 11 Queensland*. Recall that an electron volt is the amount of energy an electron gains when it moves through a potential difference of 1V. Since the charge on an electron is -1.6×10^{-19} C, then:

$$\begin{aligned} 1\,\text{eV} &= 1e \times 1\,\text{V} \\ &= 1.60 \times 10^{-19}\,\text{C} \times 1\,\text{J}\,\text{C}^{-1} \\ &= 1.60 \times 10^{-19}\,\text{J} \end{aligned}$$

Here is a simple way to convert between the units for energy:

> To convert a value expressed in J into eV, divide it by $1.60 \times 10^{-19}\,\text{J}\,\text{eV}^{-1}$.
> To convert a value expressed in eV into J, multiply it by $1.60 \times 10^{-19}\,\text{J}\,\text{eV}^{-1}$.

For convenience, Planck's constant can also be given in terms of electron volts:

$$\begin{aligned} h &= 6.626 \times 10^{-34}\,\text{J}\,\text{s} \\ &= \frac{6.626 \times 10^{-34}}{1.60 \times 10^{-19}} \\ &= 4.14 \times 10^{-15}\,\text{eV}\,\text{s} \end{aligned}$$

Worked example 11.3.1

USING PLANCK'S EQUATION

Calculate the energy of a quantum of ultraviolet light that has a frequency of 2.00×10^{15} Hz. Give the answer in joules and electron volts.	
Thinking	**Working**
Recall Planck's equation.	$E = hf$
Substitute in the appropriate values to solve in joules.	$E = 6.626 \times 10^{-34} \times 2.00 \times 10^{15}$ $= 1.33 \times 10^{-18}$ J
Convert the energy to electron volts.	$= \frac{1.33 \times 10^{18}\,\text{J}}{1.60 \times 10^{-19}\,\text{JeV}^{-1}}$ $= 8.31$ eV

➤ Try yourself 11.3.1

USING PLANCK'S EQUATION

> Calculate the energy of a quantum of infrared radiation that has a frequency of 3.6×10^{14} Hz.
> Give the answer in joules and electron volts.

The ultraviolet catastrophe

The behaviour of black-body radiation was studied in detail by Wein and his contemporaries, and Wein's law is an empirical law—i.e., it came from experimental results. However, when attempts were made to predict the radiation from a black-body using the wave-based theories of the time, it was found that these predicted that the energy emitted by a body would increase to infinity at very small wavelengths. This was called the 'ultraviolet catastrophe'. Clearly, it was not the case. German physicist Max Planck came up with an equation that matched the experimental results, by assuming that the radiation from a black-body could only be emitted in discrete packets. In the next module, you will learn more about Planck's work on the quantisation of energy.

11.3 Review

SUMMARY

- At the atomic level, electromagnetic radiation is emitted or absorbed in discrete packets or quanta called photons.
- The energy of a photon is proportional to its frequency or inversely proportional to its wavelength:

$$E = hf = \frac{hc}{\lambda}$$

- The electron volt is an alternative (non-SI) unit of energy: $1\,\text{eV} = 1.60 \times 10^{-19}\,\text{J}$.

KEY QUESTIONS

Retrieval

1 Describe why the electron volt (eV), a non-SI unit, is used for the energy of photons rather than the SI unit the joule (J).

2 Define a photon.

Comprehension

3 Explain Planck's equation.

Analysis

4 Calculate the energy, in J, of a gamma ray photon with a frequency of $2.42 \times 10^{27}\,\text{Hz}$.

5 Calculate the energy of a photon of yellow light with a wavelength of 523 nm. Express your answer in:

a joules

b electron volts.

6 Calculate the energies (in joules) of the following wavelengths of light:

	Colour	Wavelength (nm)	Energy (J)
a	red	656	
b	yellow	589	
c	blue	486	
d	violet	397	

11.4 The photoelectric effect

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

- describe the features of the photoelectric effect, including work function, kinetic energy of electrons and the effect of frequency
- explain the features of the photoelectric effect using a quantum model of the nature of light.

THE LOOSE THREAD

At the turn of the 20th century, a number of scientists turned their attention to light phenomena that could not be readily explained using Maxwell's electromagnetic wave model. The study of these phenomena required the development of much more sophisticated models for light, and eventually led to a revolution in the scientific understanding of the nature of energy and matter.

Scientists noticed that when some types of electromagnetic radiation are incident on a piece of metal, the metal becomes positively charged. This positive charge is due to electrons being ejected from the surface of the metal. The electrons became known as **photoelectrons** because they were released due to light or other forms of electromagnetic radiation. The phenomenon is known as the **photoelectric effect**.

A common apparatus used to observe the photoelectric effect consists of a clean metal surface (the cathode) illuminated with light from an external source. If the light causes photoelectrons to be emitted, they are detected at the anode. The flow of electrons is called the **photocurrent** and is registered by a sensitive ammeter.

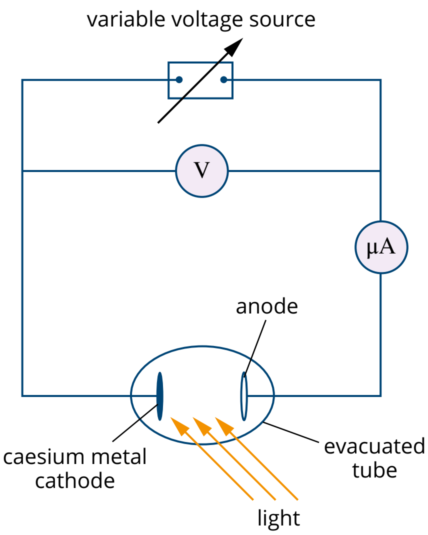


FIGURE 11.4.1 Circuit diagram of an experimental investigation of the photoelectric effect.

The circuit (Figure 11.4.1) includes a variable voltage supply that can be used to make the cathode negative (and the anode positive). When this is done, the photoelectrons will be helped by the resulting electric field across the gap to the anode. This happens because the electrons will be repelled by the negative potential at the cathode and attracted to the positive potential at the anode. As a result, a maximum possible current will be measured. Alternatively, the voltage may be adjusted to make the cathode positive and the anode negative. This repels the photoelectrons and slows them down. As the anode voltage is increased, the photoelectrons are repelled more and more until the photocurrent drops to zero.

Using apparatus such as that shown in Figure 11.4.1, the German physicist Philipp Lenard made a number of surprising discoveries about the photoelectric effect. He was awarded the Nobel Prize in Physics in 1905 for his discoveries.

Lenard used a filter to vary the frequency of the incident light. He discovered that, for a particular cathode metal, there is a certain frequency below which no photoelectrons are observed. This is called the **threshold frequency**, f_0. For frequencies of light greater than the threshold frequency (i.e. $f > f_0$), photoelectrons will be collected at the anode and registered as a photocurrent. For frequencies below the threshold frequency (i.e. $f < f_0$), no photoelectrons will be released and so no current flows.

Lenard also discovered that for light that has a frequency greater than the threshold frequency, i.e. $f > f_0$, the rate at which the photoelectrons are produced varies in proportion with the intensity (brightness) of the incident light as shown in Figure 11.4.2.

Photocurrent against voltage for different light intensities

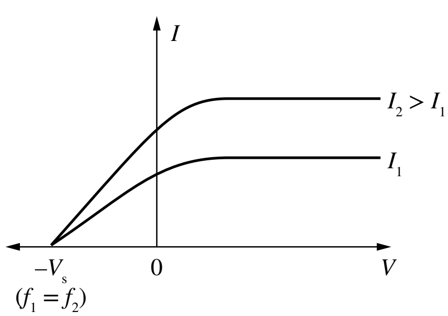


FIGURE 11.4.2 Photocurrent (I) plotted as a function of the voltage (V) applied between the cathode and the anode for different light intensities. For brighter light ($I_2 > I_1$) of the same frequency ($f_1 = f_2$), there is a higher photocurrent, but the same stopping voltage, V_s.

This graph shows a number of important properties of the photoelectric effect.

- When the light intensity increases, the photocurrent increases.
- When the applied voltage is positive, photoelectrons are attracted to the collector electrode (anode). A small positive voltage is enough to ensure that every available photoelectron is collected. The current therefore reaches a maximum value and remains there even if the voltage is increased.

- When the applied voltage is negative, photoelectrons are attracted back towards the illuminated cathode and repelled by the collector electrode (anode), and the photocurrent is reduced. The photocurrent is reduced because fewer and fewer photoelectrons have the energy to overcome the opposing electric potential. There is a voltage, V_s for which no photoelectrons reach the collector. This is known as the **stopping voltage**. For a particular frequency of light on a particular metal, this stopping voltage is a constant.

Recall from earlier studies of electricity that the work done on a charge (by an applied voltage) is given by $W = qV$. In this case, the voltage used is designated the stopping voltage, V_s, and the charge is equal to the magnitude of the charge on an electron, q_e, 1.60×10^{-19} C. Hence the work done on the electron is given by $W = q_e V_s$. Since the stopping voltage is large enough to stop even the fastest-moving electrons from reaching the anode, this expression gives the value of the maximum possible kinetic energy of the emitted photoelectrons. For example, for a stopping voltage of 2.5V, the maximum kinetic energy of any photoelectron is 2.5 eV.

When light sources of the same intensity but different *frequencies* are used, they produce the same maximum current. However, the higher-frequency light has a higher stopping voltage (Figure 11.4.3).

Finally, as long as the incident light has a frequency above the threshold frequency of the cathode material, photoelectrons are found to be emitted without any appreciable time delay. This fact holds true regardless of the intensity of the light.

When illuminated with light above the threshold frequency, some photoelectrons are emitted from the first layer of atoms on the surface of the metal and have the maximum kinetic energy possible. Other photoelectrons come from deeper inside the metal and lose some of their kinetic energy due to collisions on their way to the surface. Hence, the emitted photoelectrons have a range of kinetic energies from the maximum value down.

Photocurrent against voltage for different frequencies of incident light

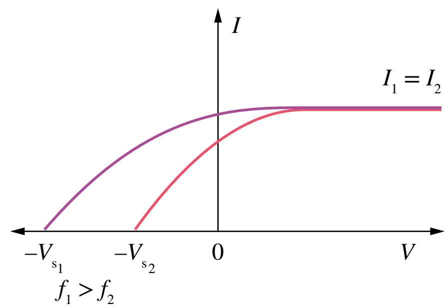


FIGURE 11.4.3 Photocurrent (I) plotted as a function of the voltage (V) applied between the cathode and the anode for different frequencies ($f_1 > f_2$) of incident light with the same intensity ($I_1 = I_2$). Both frequencies produce the same maximum photocurrent; however, light with the higher frequency requires a larger stopping voltage.

EXPLAINING THE PHOTOELECTRIC EFFECT

The characteristics of the photoelectric effect could not be explained using a wave model of light. According to the wave model, the frequency of light should be irrelevant as to whether or not photoelectrons are ejected. Since a wave is a form of continuous energy transfer, it would be expected that even low-frequency light should transfer enough energy to emit photoelectrons if left incident on the metal for long enough. Similarly, the wave model predicts that there should be a time delay between the light striking the metal and photoelectrons being emitted, as the energy from the wave builds up in the metal over time.

In 1905, Albert Einstein proposed a solution to this problem. Einstein drew on Planck's earlier work by assuming that light exists as particles, or photons (like Planck's 'quanta'), each with an energy of $E = hf$. This assumption made the properties of the photoelectric effect relatively easy to explain.

Einstein's work was actually a significant extension of Planck's ideas. Although Planck had assumed that light was being emitted in quantised packets, he never questioned the assumption that light was fundamentally a wave phenomenon.

Einstein's work went further, challenging scientists' understanding of the nature of light itself.

Einstein and the photoelectric effect

Einstein identified that, for a particular metal, the amount of energy required to eject a photoelectron is a constant value that depends on the strength of the bonding within the metal. This energy was called the **work function**, W, of the metal. For example, the work function of lead is 4.25 eV, which means that 4.25 eV of energy is needed to release just one electron from the surface of a piece of lead. Table 11.4.1 shows the work functions of some common metals.

TABLE 11.4.1 The work functions of some common metals

Metal	Work function (eV)
potassium	2.29
calcium	2.87
zinc	3.63–4.9
lead	4.25
silver	4.26–4.74
gallium	4.32
tin	4.42
mercury	4.475
iron	4.67–4.81
gold	5.10–5.47

According to Einstein's model, shining light on the surface of a piece of metal is equivalent to bombarding it with photons. When a photon strikes the metal, it can transfer its energy to an electron. That is, a single photon can interact with a single electron, transferring all of its energy at once to the electron. What happens next depends on whether or not the photon contains enough energy to overcome the work function.

If the energy of the photon is less than the work function, then photoelectrons will not be released as the electrons will not gain enough energy to let them break free of the metal atoms. For example, the photons of violet light ($f = 7.50 \times 10^{14}$ Hz) each contain 3.11 eV of energy. Remember that Planck's constant, h, when expressed in units of electron volt seconds (eV s), is 4.14×10^{-15} eV s.

$$\begin{aligned} E &= hf \\ &= 4.14 \times 10^{-15} \times 7.50 \times 10^{14} \\ &= 3.11 \text{ eV} \end{aligned}$$

This means that violet light shining on lead would not release photoelectrons since the energy of each photon, 3.11 eV, is less than the work function of lead, 4.25 eV.

However, ultraviolet photons of frequency 1.20×10^{15} Hz each contain 4.97 eV of energy.

$$\begin{aligned} E &= hf \\ &= 4.14 \times 10^{-15} \times 1.20 \times 10^{15} \\ &= 4.97 \text{ eV} \end{aligned}$$

Therefore ultraviolet light of this frequency would release photoelectrons from the lead since the energy of each photon, 4.97 eV, is greater than the work function of lead, 4.25 eV.

Each metal has a threshold frequency—this is the frequency at which the photons have an energy equal to the work function of the metal. The work function is given by:

$W = hf_0$

where

W is the work function (J or eV)

h is Planck's constant

f_0 is the threshold frequency for that metal (Hz).

Worked example 11.4.1

CALCULATING THE WORK FUNCTION OF A METAL

Calculate the work function (in J and eV) for aluminium, which has a threshold frequency of 9.8×10^{14} Hz.

Thinking	Working
Recall the formula for work function.	$W = hf_0$
Substitute the threshold frequency of the metal into this equation.	$W = 6.626 \times 10^{-34} \times 9.8 \times 10^{14}$ $= 6.5 \times 10^{-19}$ J
Convert this energy from J to eV.	$W = \frac{6.5 \times 10^{-19}}{1.60 \times 10^{-19}}$ $= 4.1$ eV

➤ Try yourself 11.4.1

CALCULATING THE WORK FUNCTION OF A METAL

Calculate the work function (in J and eV) for gold, which has a threshold frequency of 1.2×10^{15} Hz.

THE KINETIC ENERGY OF PHOTOELECTRONS

If the energy of the photon is greater than the work function of the metal, then a photoelectron is released. The energy in excess of the work function is transformed into the kinetic energy of the photoelectron.

Einstein described this relationship with his photoelectric equation:

> $E_{k\,max} = hf - W$
> where
> $E_{k\,max}$ is the maximum kinetic energy of an emitted photoelectron (J or eV)
> h is Planck's constant
> f is the frequency of the incident photon (Hz)
> W is the work function of the metal (J or eV).

Graphing Einstein's equation results in a linear (straight line) graph like the one shown in Figure 11.4.4. Such a graph is useful because it clearly shows key information, such as the work function and threshold frequency for a particular metal.

Einstein's equation $E_{k\,max} = hf - W$ can be compared with the equation of a straight line, $y = mx + c$. In making this comparison, it can be seen that extrapolating (extending) the graph back to the vertical axis will give the magnitude of the work function, W (Figure 11.4.4). The gradient of the graph is Planck's constant, h. From the graph it is also apparent how, as soon as the threshold frequency is exceeded, an electron is able to be ejected and escape with some kinetic energy. The greater the frequency of the light, the greater the kinetic energy of the photoelectron. At the threshold frequency, electrons are no longer bound to the metal, but they have no kinetic energy.

The y-intercept (i.e. negative of the work function), and x-intercept (threshold frequency) of the graph change when different metals are measured, but the gradient is always the same (Planck's constant).

Photoelectric properties of potassium and magnesium

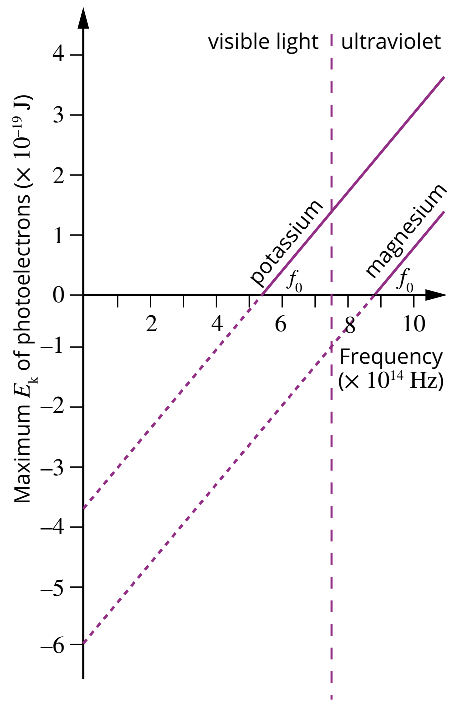


FIGURE 11.4.4 Magnesium has a high threshold frequency, which is in the ultraviolet region. The threshold frequency for potassium is in the visible region. The gradient of the graph for each metal is Planck's constant, h. The x-intercept gives the threshold frequency, f_0. The magnitude of the y-intercept gives the work function, W.

Worked example 11.4.2

CALCULATING THE KINETIC ENERGY OF PHOTOELECTRONS

Calculate the kinetic energy (in eV) of the photoelectrons emitted from lead by ultraviolet light with a frequency of 1.2×10^{15} Hz. The work function of lead is 4.25 eV. Use $h = 4.14 \times 10^{-15}$ eV s.	
Thinking	**Working**
Recall Einstein's photoelectric equation.	$E_{k\,max} = hf - W$
Substitute values into this equation.	$E_{k\,max} = 4.14 \times 10^{-15} \times 1.2 \times 10^{15} - 4.25$ $= 4.97 - 4.25$ $= 0.72$ eV

➤ Try yourself 11.4.2

CALCULATING THE KINETIC ENERGY OF PHOTOELECTRONS

Calculate the maximum possible kinetic energy (in eV) of the photoelectrons emitted from lead by ultraviolet light with a frequency of 1.5×10^{15} Hz. The work function of lead is 4.25 eV.
Use $h = 4.14 \times 10^{-15}$ eV s.

Resistance to the quantum model of light

This new particle or 'quantum' model of light was not initially well received by the scientific community. It had already been well established that a discrete, particle model for light could not explain many of light's properties such as polarisation and the interference patterns produced in Young's experiment.

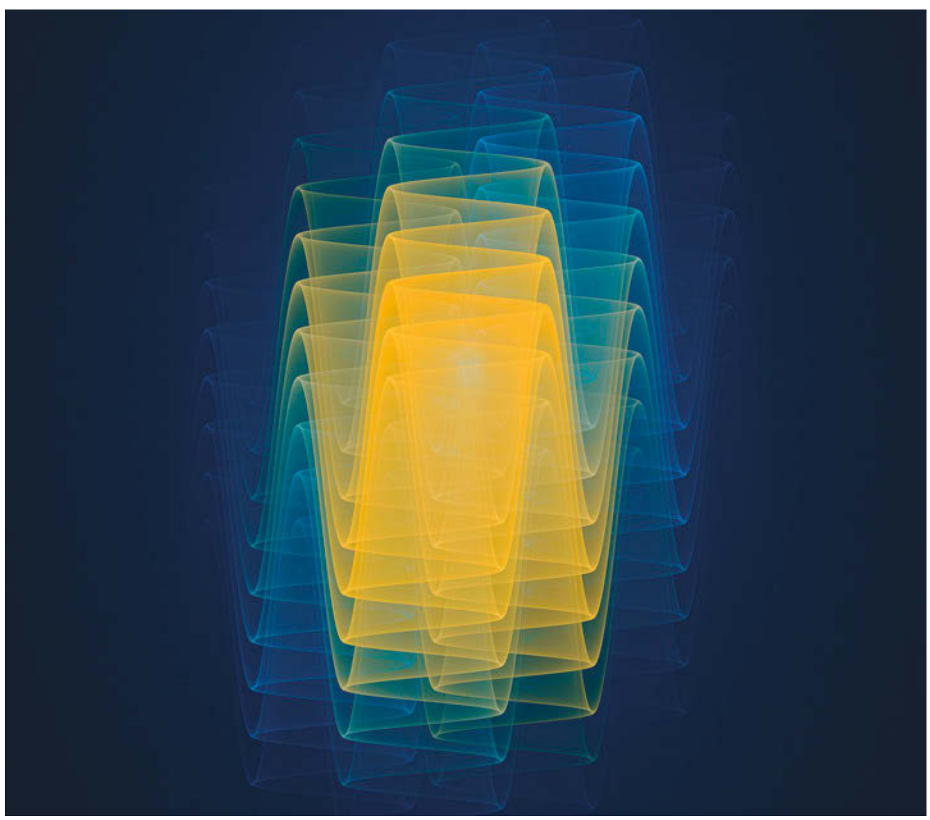
Most scientists believed instead that wave explanations for the photoelectric effect would eventually be found. However, eventually the quantum model of light was accepted and the Nobel Prize in Physics was awarded to both Planck (1918) and Einstein (1921) for their ground-breaking work in this field.

WAVE–PARTICLE DUALITY

In many ways, the wave and particle models for light seem fundamentally incompatible. Waves are continuous and are described in terms of wavelength and frequency. Particles are discrete and are described by physical dimensions such as mass and radius.

In order to understand how these two sets of ideas can be used together, it is important to remember that scientists describe the universe using models. Models are analogies that are used to illustrate certain aspects of reality that might not be immediately apparent.

Physicists have come to accept that light is not easily compared to any other physical phenomenon. In some situations, light has similar properties to a wave; in other situations, light behaves more like a particle. This understanding is called **wave–particle duality** (Figure 11.4.5). Although this may seem somewhat paradoxical and counterintuitive, in the century since Einstein did his work establishing quantum theory, many experiments have supported this duality and no scientist has come up with a better explanation. Wave–particle duality is explored in more detail in Chapter 12.



WS 4.2.4

FIGURE 11.4.5 An artist's attempt to represent wave-particle duality

11.4 Review

SUMMARY

- The photoelectric effect is the emission of photoelectrons from a clean metal surface due to incident light with frequency, f, that is greater than the threshold frequency, f_0, for that particular metal.
  - If $f < f_0$, no electrons are released.
  - If $f > f_0$, the *rate* of electron release (the photocurrent) is proportional to the intensity of the light and occurs without any time delay.
- Increasing the forward voltage does not alter the rate of electron release (i.e. the photocurrent).
- $E_{k\ max} = q_e V_s$, where q_e is the charge on an electron.
- The work function, W, for the metal is given by $W = hf_0$, and is different for each metal. If the frequency of the incident light is greater than the threshold frequency, then a photoelectron will be ejected with some kinetic energy up to a maximum value.
- A graph of $E_{k\ max}$ versus frequency will have a gradient equal to Planck's constant, h, and a y-intercept equal to the negative work function, W.
- The wave approach to light could not explain various features of the photoelectric effect:
- Einstein used Planck's concept of a photon to explain the photoelectric effect, stating that each electron release was due to an interaction with only one photon.
- The photon model of light explained the existence of a threshold frequency for each metal, the absence of a time delay for the photocurrent even for weak light sources and why brighter light resulted in a higher photocurrent.

KEY QUESTIONS

Retrieval

1 State whether the following statement is true or false. If the statement is false, rewrite it so that it is true.
'The photoelectric effect occurs when a beam of electrons is fired at a metal surface and ejects photons of light from the surface.'

2 State the unit in which the work function of a metal is measured.

Comprehension

3 Explain why a piece of metal might become positively charged when light shines on its surface.

4 Determine whether the following statements about the photoelectric effect are true or false. For those that are false, rewrite them to make them correct.

a When the intensity of light shining on the surface of the metal increases, the photocurrent always increases.

b When light sources of the same intensity but different frequencies are used, the higher-frequency light has a higher stopping voltage and produces a higher maximum current than the lower-frequency light.

5 Determine whether the following statements with respect to the value of the stopping voltage obtained when light is incident on a metal cathode are true or false. For those that are false, rewrite them to make them true.

a The stopping voltage indicates how much work must be done to stop the most energetic photoelectrons.

b The stopping voltage is reached when the photocurrent is reduced almost to zero.

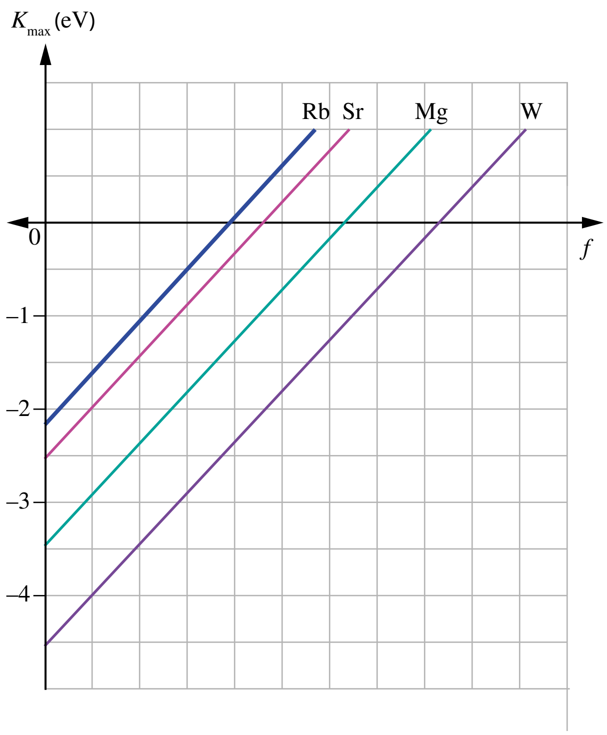
c If only the intensity of the incident light is increased, the stopping voltage will not alter.

d For a given metal, the value of the stopping voltage is affected only by the frequency of the incident light.

11.4 Review *continued*

6 From the graph, determine the value of the work function for each of the metals.

Photoelectric properties of four metals



Analysis

7 Calculate the work functions (in electron volts) of the following metals:

	Metal	Threshold frequency (Hz)	Work function (eV)
a	aluminium	9.85×10^{14}	
b	caesium	4.23×10^{14}	
c	platinum	1.5×10^{15}	

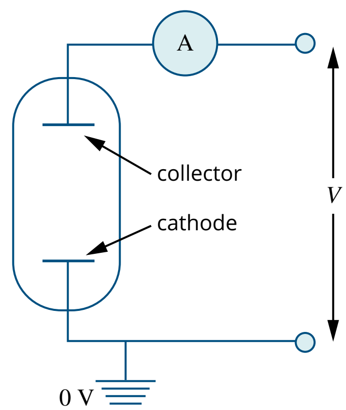
8 In an experiment on the photoelectric effect, different frequencies of light were shone on a piece of magnesium with a work function of 3.66 eV. Calculate the lowest frequency of incident light that would produce photoelectrons from a sample of magnesium.

9 Light with a frequency of 9.0×10^{14} Hz is shone onto a piece of magnesium with a work function of 3.66 eV. Calculate the maximum kinetic energy, in electron volts, of the emitted photoelectrons.

10 Blue light with a wavelength of 475 nm is shone on a piece of sodium with a work function of 2.36 eV. Calculate the maximum kinetic energy, in electron volts, of the emitted photoelectrons.

11 Yellow–green light of wavelength 500.0 nm shines on a metal whose stopping voltage is found to be 0.800 V. Calculate the work function of the metal in electron volts.

12 The cathode of a particular photocell, shown below, is coated with rubidium. Incident light of varying frequencies is directed onto the cathode and the maximum kinetic energy of the photoelectrons is logged. The results are summarised in the following table.



Frequency ($\times 10^{14}$ Hz)	$E_{k\,max}$ (eV)
5.20	0.080
5.40	0.163
5.60	0.246
5.80	0.328
6.00	0.411
6.20	0.494

a Plot the points from the table on a graph.
b Calculate the gradient of the graph.
c Determine the threshold frequency of rubidium from the graph.
d Determine whether red light of wavelength 680 nm causes photoelectrons to be emitted from the rubidium surface. Justify your answer.

MANDATORY PRACTICAL 4

Investigating the photoelectric effect

Conduct an experiment to investigate the photoelectric effect.

- Write a research question.
- Suggest modifications to the method used in class to improve the outcome.
- Collect sufficient data.
- Consider safety.

Research and planning

Aim

- To investigate the photoelectric effect, determine the stopping voltage, threshold frequency and work function of a cathode, and find a value for Planck's constant.

Rationale (scientific background to the experiment)

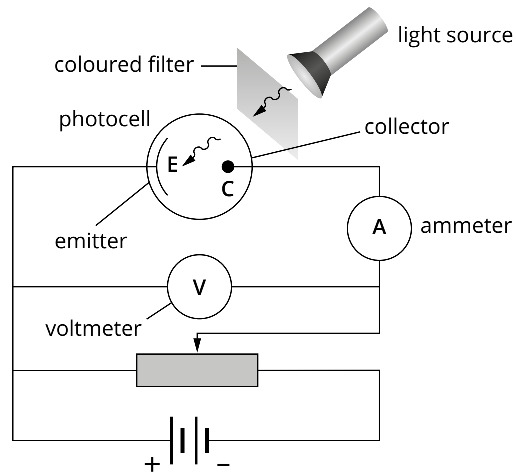
The 'photoelectric effect' refers to the emission of electrons from the surface of a metal when light of low wavelength is incident on the surface. This phenomenon cannot be sufficiently explained using the wave theory of light, and its explanation led to the development of the photon or particle-like dual-nature model of light we have today.

In the photon model, a beam of light consists of a stream of photons, each carrying an energy, $E_{photon} = hf$, where h is Planck's constant (6.626×10^{-34} J s) and f is the frequency of the incident light (Hz).

The work function, W, for the metal is given by $W = hf_0$, where f_0 is the threshold frequency and is different for each metal. If the frequency of the incident light is greater than the threshold frequency, then a photoelectron will be ejected with some kinetic energy up to a maximum value such that $E_{k\ max} = hf - W$.

This can be explored by experiment using the apparatus shown in the diagram at the right. If light is incident on the cathode, the photoelectrons emitted will be collected at the anode and registered as a photocurrent, which can be measured.

The maximum kinetic energy for the electrons (i.e. the fastest electron) can be found using a reverse voltage called the stopping voltage, V_s, so that $E_{k(max)} = eV_s$.



Timing

45 minutes

Materials

- photoelectric effect kit
- current detector and amplifier, or current sensor and interface
- lamp to suit kit (incandescent, fluorescent or mercury vapour)
- set of coloured filters
- voltmeter or voltage sensor
- electrical leads

Safety

If you are using a mercury lamp, avoid looking directly at it. It is advisable to wear protective glasses.

Method

Risk assessment

Assessment of risks include chemical hazards and physical hazards. 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.

The diagram above shows a typical circuit for a photoelectric effect kit. Check the instructions with your kit for the particular circuit that applies.

1 Set up the circuit as shown in the diagram, following any directions that are specific to your kit. (You may find most or all of the circuit is built into the kit.) The relative positions of the light source and the photocell should stay fixed. Start with the filter that transmits the longest wavelength of visible light (usually red).

2 Using the first filter, take a series of readings of *I* and *V*. Record your readings in a suitable table with an uncertainty for each reading.
 V is negative because it is the retarding voltage, slowing down the electrons as they are emitted.
 Start with small voltages (0.1 V). Take care to carefully note the stopping voltage, V_s (i.e. when the current *first* reaches zero). Repeat the approach to zero current a few times, increasing the sensitivity of the current reading (if possible with your kit) and average your results for V_s.
3 Increase the intensity of the light source and take readings of *I* and *V*. Once again determine V_s.
 This should be the same as previously measured, since V_s is independent of light intensity.
4 Replace the red filter with the filter with the next longest wavelength available. For this filter, determine only the stopping voltage. Repeat the approach to zero current a few times, each time increasing the sensitivity of the current reading (if possible with your kit) and average your results for V_s.
5 Repeat step 4 with the remaining filters and tabulate the frequency, *f*, of each filter and the stopping voltage, $V_{s,}$ with the uncertainties for each value.

Variables

i Independent: voltage, *V*
ii Dependent: current, *I*
iii Controlled: frequency of light, *f* (controlled using coloured filters), intensity of light, type of metal of cathode

Analysing

Raw and processed data

TABLE 1 Measured photocurrent with different voltages

Incident light colour: red

Intensity 1: _____

Measured voltage, *V* (± _____ V)				**Measured current, *I* (± _______ μA)**			
Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
			±				±
			±				±
			±				±
			±				±
			±				±

TABLE 2 Measured photocurrent with different voltages

Incident light colour: red

Intensity 2: _____

Measured voltage, *V* (± _____ V)				**Measured current, *I* (± _______ μA)**			
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 From the data in Tables 1 and 2, draw a graph with *V* on the *x*-axis and *I* on the *y*-axis. Clearly mark the different intensity for each set of data, and the stopping voltage, V_s. Did you get the same value for the stopping voltage for both intensities of light? Did your graph look like Figure 11.4.2 on page 302?
2 Calculate $E_{k\ max} = eV_s$, which corresponds to the maximum kinetic energy of the photoelectrons (in eV) as they left the surface of the emitter, for each frequency tested. Enter the values in Table 3. If your photoelectric-effect kit does not give the frequency for each filter, look up the frequency of light.

TABLE 3 Measured stopping voltage for different colour incident light

Colour of incident light	**Frequency of incident light**	**Measured stopping voltage, V_s (± _____ V)**				$E_{k\ max}$
		Trial 1	**Trial 2**	**Trial 3**	**Average**	
					±	
					±	
					±	
					±	
					±	

3 Draw a graph of f (on the x-axis) against $E_{k\ max}$ (on the y-axis).

4 The maximum kinetic energy of the electrons is given by $E_{k\ max} = hf - W$, which is the same format as the equation for a straight line, $y = mx + c$. From your graph, determine:
   a the work function, W (the point where the line crosses the y-axis) and its uncertainty
   b Planck's constant (the gradient of the line) and its uncertainty
   c the threshold frequency, f_0, for the metal of the cathode, and its uncertainty. This will be the point where the line crosses the x-axis, i.e. where $E_{k\ max} = 0$.

> **➤ 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 investigate the photoelectric effect. Summarise your results for the quantities found.

2 State the single most important contribution of the photoelectric effect to our understanding of the nature of light.

3 In the first part of the experiment, a lower current was obtained with a less intense light. Explain this in terms of a particle model of light.

4 Explain why the stopping voltage depends only on the frequency of the incident light and not on the intensity.

Evaluation

5 Considering your analysis and conclusion, did the experiment provide an effective method of exploring the photoelectric effect, and measuring the stopping voltage, threshold frequency and work function of the cathode? Was your value of Planck's constant close to the established value of 4.14×10^{-15} eV s? (Remember that the value for $E_{k\ max}$ was calculated in eV, so your value of Planck's constant will also use eV, not J.)

6 Was the level of uncertainty that you calculated in part 4 of the Analysis section reasonable?

Improvements

7 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

8 Could you identify the metal used in the cathode from your results?

9 Would this experiment work using any metal for the cathode?

10 Identify any limitations to using this method for other metals.

> **➤ 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

11

KEY TERMS

black body
coherent
constructive interference
destructive interference
electron volt
infrared
interference
photocurrent
photoelectric effect
photoelectron
photon
quantum
stopping voltage
threshold frequency
ultraviolet
visible light
wave
wave–particle duality
work function

KEY QUESTIONS

Retrieval

1 Identify which of the following events would correspond to nodal lines if Young's double-slit experiment was modelled using circular water waves in a ripple tank. (Note that more than one correct answer is possible.)

A crests meet crests
B troughs meet crests
C crests meet troughs
D troughs meet troughs

2 Identify why the wave model of light cannot satisfactorily explain the photoelectric effect, by selecting the best option below.

A The non-existence of interference patterns shows that light is not a wave.
B Energy in waves is not sufficient to eject photoelectrons from the surface of a metal.
C The energy in waves all arrives at the same moment, while multiple particles can all provide their energy to a single electron.
D Waves provide continuous energy that would accumulate over time to release photoelectrons even if its frequency was lower than the threshold frequency.

3 Identify which of these numbers represents Planck's constant expressed in electron volt seconds (eV s):

A 4.25
B 1.6×10^{-19}
C 6.626×10^{-34}
D 4.14×10^{-15}

4 Describe Young's experiment and explain why it is considered evidence for the wave theory of light.

5 State the term given to the electrons released from a metal surface due to the photoelectric effect.

Comprehension

6 In the constellation Orion, the star Rigel is blue-white, while the star Betelgeuse is reddish. Select the best explanation of these observations from the options below:

A Rigel is closer than Betelguese.
B Rigel is cooler than Betelguese.
C Rigel is hotter than Betelguese.
D Rigel is further way than Betelguese.

Analysis

7 An AM radio station broadcasts at a frequency of 612 kHz. Calculate the wavelength of the waves broadcast if the speed of light is $3 \times 10^8\,\text{m s}^{-1}$.

8 Calculate the energy (in eV) of a quantum of infrared radiation that has a frequency of 3.6×10^{14} Hz. Use $h = 4.14 \times 10^{-15}$ eV s.

9 Wien's law can be written as $\lambda_{max}T = 2.898 \times 10^{-3}$ m K where λ is in m and the temperature is in K.

a Calculate the peak radiation wavelength for Earth at 290 K.
b Calculate the temperature of a sample of molten (liquid) iron glowing hot in a furnace that radiates at 414 nm.

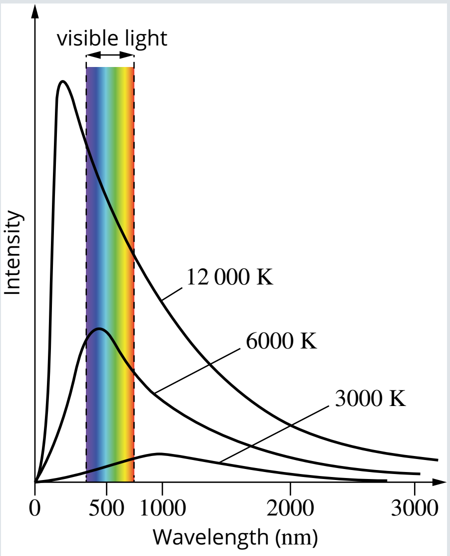
10 Wien's law can be used to calculate the temperature of radiating objects. The Sun's temperature is 5778 K and the peak wavelength at which it radiates is about 500 nm. Calculate the temperature of the star Betelgeuse, which has maximum emission at 875 nm.

11 A metal filament is heated as a current passes through it. Initially it glows a dull red. As the current is increased, the red becomes brighter, the wire then glows yellow and eventually glows bright white.

a Analyse the following graph and explain the reasons for the colour changes of the metal filament at each stage.

b Describe and explain the colour of the filament if the current was increased further.

Intensity versus wavelength for different temperatures



Knowledge utilisation

12 Create a plan for a self-driving car that can tell when traffic lights change. Use the photoelectric effect. Select one of the metals in Table 11.4.1 on page 303 that will emit photoelectrons when a blue light ($\lambda = 400$ nm) is shining on it but not when a red light ($\lambda = 800$ nm) is shining on it. (There is still work to be done on being able to detect green lights.)

13 When conducting a photoelectric effect experiment, Maree correctly observes that the energy of emitted electrons depends only on the frequency of the incident light and is independent of the intensity.

a Explain how the particle model accounts for this observation.

b Explain why the wave model cannot account for this observation.

c Make three statements about how the particle (photon) model of light is supported by features of the photoelectric effect and discuss the implications for the wave model of light in each case.

d Maree obtains the following data.

Wavelength (nm)	Maximum kinetic energy (eV)
350	1.4
400	0.91
450	0.60
500	0.25

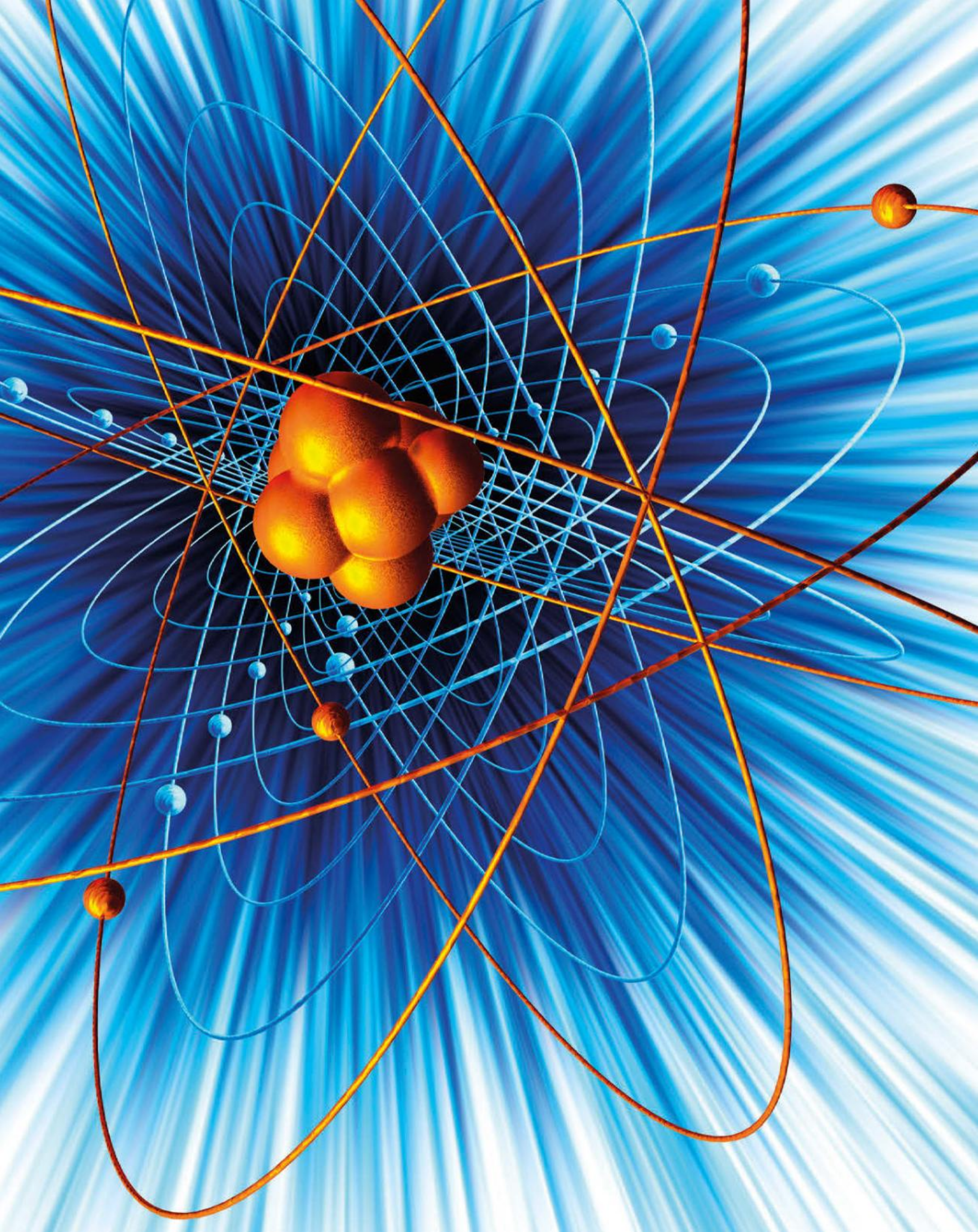
Copy this table into your workbook and add a column containing the frequency for each of these values.

e Create a graph of the energy as a function of frequency.

f Analyse the graph to find a value of Planck's constant and the work function of the metal.

g If there is an uncertainty of ±0.1 in the analysis of the work function, use the table below to find which metal was used in this experiment.

Metal	Work function
aluminium	4.08
carbon	4.8
copper	4.7
potassium	2.3
caesium	2.1



CHAPTER 12

The atom

The atom is one of the basic building blocks of all matter. Humans have developed models of the atom from as early as 400 BCE, when the Greek philosopher Democritus suggested that everything was made up of tiny, indivisible particles. Scientists have refined models of the atom over millennia to better explain their observations of the world. In the early 1900s, ground-breaking work by Ernest Rutherford and his students led to a new understanding of the atom, including the extraordinary idea that most of the atom is empty space. Problems with Rutherford's description of the atom led to a new explanation by Niels Bohr, who explained observed phenomena such as emission and absorption spectra. Further work to improve on Bohr's model of the atom by physicists such as Louis de Broglie led to the idea that, if light could be thought of as particles, then matter could also be thought of as waves. The strange world of the quantum mechanical model of the atom will be explored in this chapter.

Syllabus subject matter

Topic 2 • Quantum theory

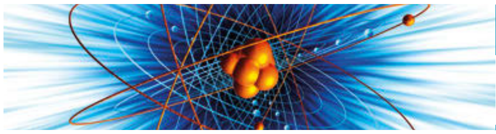
QUANTUM THEORY

- describe Rutherford's model of the atom including its limitations
- describe the Bohr model of the atom and how it addresses the limitations of Rutherford's model
- explain how the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum
- solve problems involving the line spectra of simple atoms using atomic energy states or atomic energy level diagrams
- describe wave–particle duality of light by identifying evidence that supports the wave characteristics of light and evidence that supports the particle characteristics of light.

SCIENCE AS A HUMAN ENDEAVOUR

- Development of the quantum model

12.1 Rutherford's model



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

- describe Rutherford's model of the atom, including its limitations.

In Units 1 and 2 you may have investigated two early models of the atom: Dalton's atomic theory and Thomson's plum pudding model. This module will illustrate Rutherford's model, which built on the work of these scientists. In 1909, the famous New Zealand physicist Ernest Rutherford and two of his students, Hans Geiger and Ernest Marsden, set out to test Thomson's plum pudding model of the atom. They wanted to probe this model using particles that Rutherford had discovered as Thompson's student: alpha particles.

GOLD FOIL SCATTERING EXPERIMENTS

A very thin piece of gold foil was set up in a vacuum in the middle of a circular track that allowed a microscope sensor to move a full 360° around the foil. Directed at the gold foil was a source of alpha particles (helium nuclei), which are heavy, fast moving and positively charged.

As the accepted model of the atom at the time consisted of evenly distributed, negatively charged electrons embedded in a 'pudding' of extended positive charge, the group expected the alpha particles to pass straight through the foil. This was because the alpha particles would be repelled from the positive pudding in all directions at once, and the net effect would be no deflection from the gold foil.

The sensor was moved around the track and a fluorescent screen used to detect any alpha particles that were deflected or scattered from the foil (Figure 12.1.1).

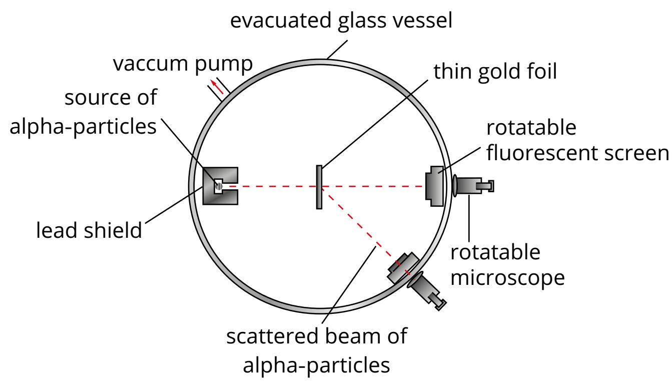


FIGURE 12.1.1 Rutherford's scattering experiment. Alpha particles are fired at thin gold foil (centre) and the scattering pattern is observed on the ring-shaped surface using the rotatable fluorescent screen and microscope. The experiment needs to take place in a vacuum so the alpha particles do not collide with particles other than the gold foil.

Rutherford's results

Rutherford and his group expected the alpha particles to pass straight through the foil, and support the plum pudding model of the atom. They found that most of the alpha particles did pass straight through the gold foil; however, some were deflected at small angles, while others were deflected at large angles and a few were even directed straight back at the source! Rutherford was later quoted as saying 'It was almost as incredible as if you fired a 15-inch shell at piece of tissue paper and it came back and hit you'.

These results led Rutherford to conclude that atoms contained a tiny, dense positively charged central nucleus. A comparison of the expected results and actual results is shown in Figure 12.1.2, in which the arrows represent the paths of the alpha particles and the red circle represents the newly discovered central region, or nucleus, of the gold atoms.

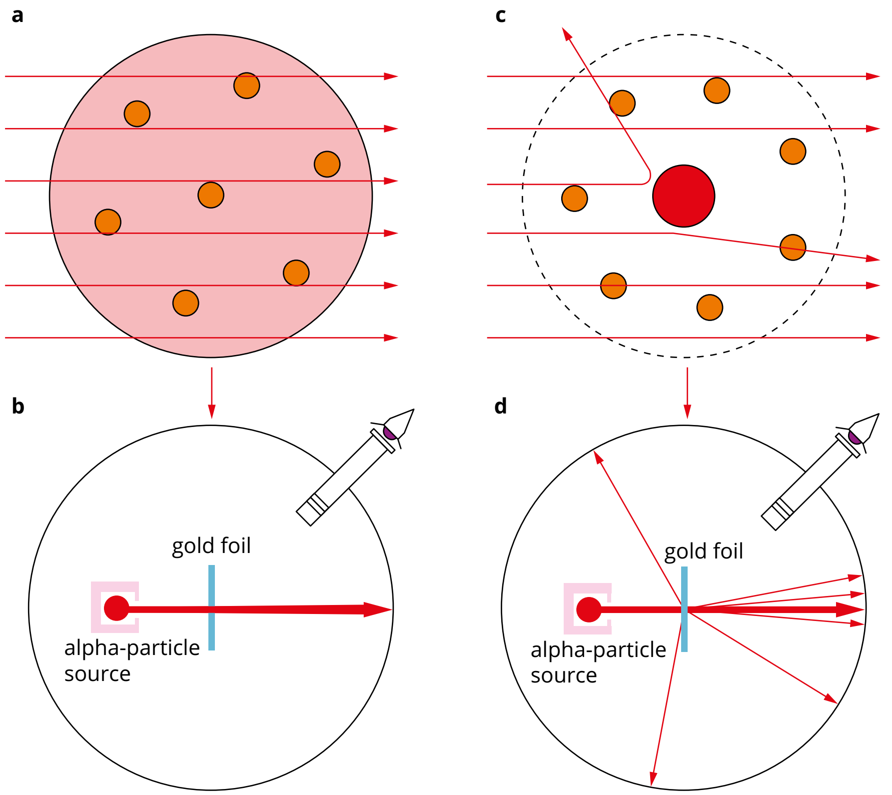


FIGURE 12.1.2 (a) In Thompson's atomic model the alpha particles would travel through the atom, affected only weakly by electrical forces, and (b) only low-angle scattering would be possible. (c) In Rutherford's atomic model most alpha particles travel through the atom, but some impact the nucleus and scatter, which is observed in the gold foil experiment (d).

RUTHERFORD'S ATOMIC MODEL

From the results of the gold foil experiments, and applying some mathematics, Rutherford concluded the following:

- The atom is mostly empty space with a tiny, very dense (about $10^{15}\,\mathrm{kg\,m^{-3}}$), positively charged nucleus in the centre surrounded by even tinier, much lighter, negatively charged electrons. Note that at the time the proton and neutron were not known, so the nucleus was just considered to be a positively charged 'thing'.
- Nearly 100% of the atom's mass is contained in the nucleus.
- The number of electrons equals the number of positive charges in the nucleus.
- An atom's nucleus is in the order of 10^{-15} m in diameter.
- An atom is in the order of 10^{-10} m in diameter.
- The nucleus is 100 000 times smaller than the atom.

You can visualise this last statement by imagining the nucleus is the size of a tennis ball. At this scale, the electrons would occupy a region a few kilometres away from the tennis ball.

Problems with Rutherford's atomic model

Rutherford's model of the atom is the basis for the one we now use, with some key refinements. It is important to understand that, although his work contributed to the basic picture of what an atom looks like, it did not explain all the observations.

Charged particles (such as electrons) radiate energy as they change velocity. Electrons orbiting a nucleus follow a circular path and so are constantly changing direction and thus velocity. This should cause the electrons to be constantly emitting energy. If the electrons are constantly losing energy in this process, they would eventually lose all their energy and spiral inwards towards the nucleus, imploding. This is not what we observe.

At about the same time that Rutherford was scattering alpha particles off gold foil, chemists found that excited atoms in their gaseous state emitted light. Not just any colour light but specific wavelengths of light called **emission spectra** (Figure 12.1.3a) that depended on the atom they were looking at. These emission spectra were like fingerprints for each element, that is, they were unique to each element. The hydrogen spectrum, in particular, was well studied by physicists. It will be covered in Module 12.4.

The problem with Rutherford's model is that it allowed the electrons to have *any* energy, and thus the light produced from them would be a **continuous spectrum** (Figure 12.1.3b) in which every wavelength of light is produced. This does not match the emission spectra observed in which only specific wavelengths are seen.

Bohr's model of the atom addresses these limitations and is discussed in Module 12.2.

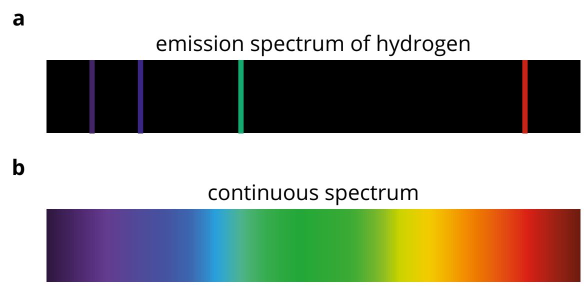


FIGURE 12.1.3 (a) The emission spectrum of hydrogen and (b) the continuous spectrum

12.1 Review

SUMMARY

- Rutherford's gold foil experiment consisted of a beam of alpha particles striking a gold foil. Most alpha particles travelled straight through; a few alpha particles bounced off and scattered backwards.
- Rutherford's model of the atom contained the following ideas:
  - Most of the atom is empty space.
  - The atom is of the order of 10^{-10} m in size.
  - In the centre of the atom is the nucleus, which is 100 000 times smaller than the atom itself (of the order of 10^{-15} m in size).
  - The nucleus contains all the positive charge of the atom.
  - Surrounding the nucleus are the negatively charged electrons.
  - There are as many electrons as there are positive charges in the nucleus.
- Rutherford's model does not explain:
  - why electrons don't spiral into the nucleus
  - why electrons don't emit energy continuously
  - the appearance of emission spectra where only discrete lines are observed.

KEY QUESTIONS

Retrieval

1 Describe the key features of Rutherford's model of the atom.

2 Describe the limitations of Rutherford's model of the atom.

3 Identify why the deflection of the alpha particles in the gold foil experiment at large angles was such a shock for Rutherford and his colleagues.

Comprehension

4 Explain why an alpha particle would be repelled by a positive nucleus.

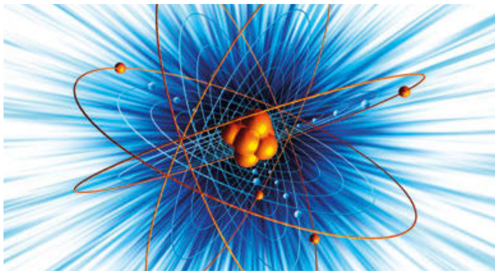
Analysis

5 Calculate how big the nucleus would be if a single atom was expanded to be the size of Earth. Use the diameter of Earth as 1.27×10^{7} m.

6 Calculate the thickness of the gold foil used in Rutherford's experiment, given that the foil was 400 gold atoms thick and a gold atom is 300 pm across.

7 Deduce what conclusion Rutherford could have drawn if many more alpha particles had demonstrated large deflection angles.

12.2 Bohr's model



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

- describe the Bohr model of the atom and how it addresses the limitations of Rutherford's model
- explain how the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum.

In 1913, Niels Bohr devised an improvement to Rutherford's model of the atom which addressed some of its problems and drew on the work of Planck and Einstein. Bohr's more sophisticated model focused on the electron **energy levels** in the atom. He was later awarded a Nobel Prize in Physics for this work.

FEATURES OF BOHR'S MODEL OF THE ATOM

Recall from Chapter 11 that Planck suggested that energy could be emitted in discrete packets called quanta. Bohr applied this idea to the energy levels of atoms to explain the specific wavelengths of the emission spectra. Bohr built on Rutherford's model by adding quantised electron energy levels based on Planck's ideas of quantised energy. These energy levels can be shown as a number of horizontal lines on what is known as an **energy level diagram**. Figure 12.2.1 shows the energy level diagram for sodium gas.

The energies of each level are considered to be negative in energy level diagrams, as this represents the energy required for an electron to gain before it is completely removed from the atom, or ionised.

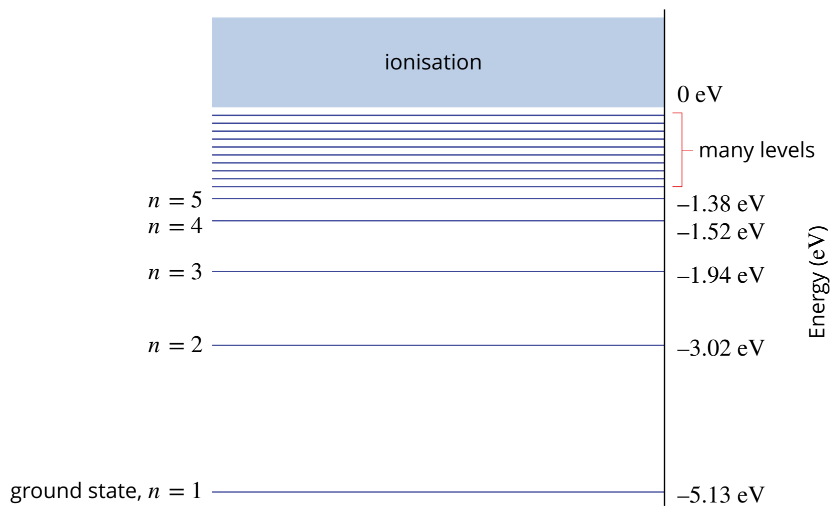


FIGURE 12.2.1 Energy levels in a sodium atom. $n = 1$ is the ground state. The highest level is where ionisation occurs and the electron escapes the atom.

Bohr's main ideas were as follows:

- The electron moves in a circular orbit around the nucleus of an atom.
- The force keeping the electron moving in a circle is the electrostatic force of attraction (the positive nucleus attracts the negative electron).
- A number of allowable orbits of different radii exist for each atom and are labelled $n = 1, 2, 3$, etc. The electron may occupy only these orbits.
- An electron ordinarily occupies the lowest energy orbit available.
- An electron does not radiate energy while it is in a stable orbit.
- An electron can jump to a higher energy level by absorbing some energy. The absorbed energy must be exactly equal to the difference between the electron's initial and final energy levels.

- Electromagnetic radiation is emitted by an excited atom when an electron falls from a higher energy level to a lower energy level. The energy of the emitted light will be exactly equal to the energy difference between the electron's initial and final levels.

These ideas are shown in Figure 12.2.2. In this particular example, the electron absorbs energy from light that strikes the atom. The energy absorbed is just the right amount for the electron to make the jump from its ground state to a higher level. In this diagram, the light is labelled as a photon.

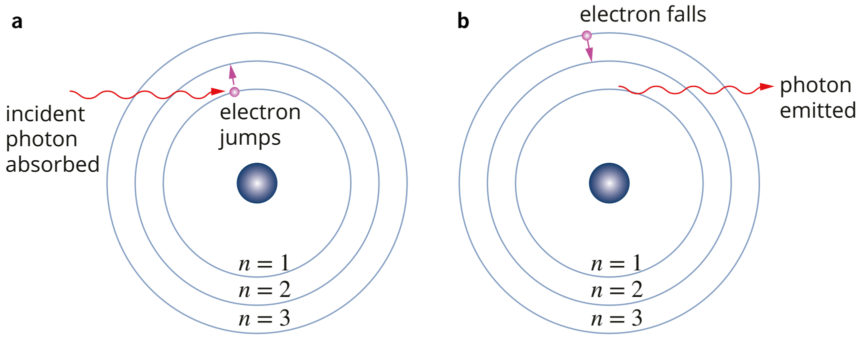


FIGURE 12.2.2 (a) If the incident photon (light) carries an amount of energy equal to the energy difference between two levels, the photon's energy can be absorbed, allowing the electron to jump to the higher level. The photon ceases to exist. (b) An atom will remain in an excited state for less than a millionth of a second. The electron will then fall to its ground state. The electron may fall in one step, or in a number of stages, emitting a photon or photons as it falls.

How Bohr's model improved on Rutherford's model

Recall from Module 12.1 that Rutherford's model did not explain three main observations:

- why electrons don't spiral into the nucleus
- why electrons don't emit energy continuously
- the appearance of emission spectra in which only discrete lines are observed.

Bohr's energy levels answer all three of these observations to some extent. Part of the conditions Bohr set for these energy levels is that the electron does not radiate energy while in these specific stable orbits. If the electrons don't continuously emit energy, the energy of the electron is constant so the electron won't spiral into the nucleus.

The appearance of emission spectra was explained by electrons emitting the specific energy required to jump down (or transition) to a lower energy level. Since the allowable energy levels are set, only certain energies can be released, resulting in specific lines in the emission spectrum rather than a continuous spectrum. Emission spectra will be discussed further in Module 12.4.

HYDROGEN LINE SPECTRUM AND BOHR'S MODEL

Bohr's model was based on measurements of the hydrogen line spectrum. Based on these measurements Bohr realised the following:

- The **absorption spectrum** of hydrogen showed that the hydrogen atom was only capable of absorbing a small number of different frequencies and therefore energies of very specific values. That is, the absorbed energy was quantised.
- The emission spectrum of hydrogen showed that hydrogen atoms were also capable of emitting quanta of the exact energy value that they were able to absorb.
- If the frequency, and hence energy, of the incident light was below a certain value for the hydrogen atom, the light would pass straight through the atom without any absorption occurring.
- Hydrogen atoms have an ionisation energy of 13.6 eV. Light of this energy or greater can remove an electron from a hydrogen atom, creating a positive ion.
- Photons of light with energies above the ionisation value for hydrogen are continuously absorbed.

Ionisation energy is the energy required to remove one electron from an atom of an element in the gas phase. It is measured in electron volts (eV).

Bohr labelled the possible electron orbits for the hydrogen atom with the energy level or principal quantum number (n), and he was able to calculate the energy associated with each. Using these energy levels, he was able to theoretically predict the wavelengths of all of the lines of the hydrogen emission spectrum using Planck's equation:

$$\Delta E = \frac{hc}{\lambda}$$

Figure 12.2.3 shows an energy level diagram for the hydrogen atom. These energies are expressed in terms of how much work needs to be done—how much energy needs to be added or absorbed—for the atom to be **ionised** (i.e. for the electron to be removed), which is shown as $n = \infty$. Ionisation is shown as $E = 0$, as the electron is no longer bound to the atom and so no longer has potential energy. For an electron in the ground state ($n = 1$) to escape the atom, 13.6 eV would be required.

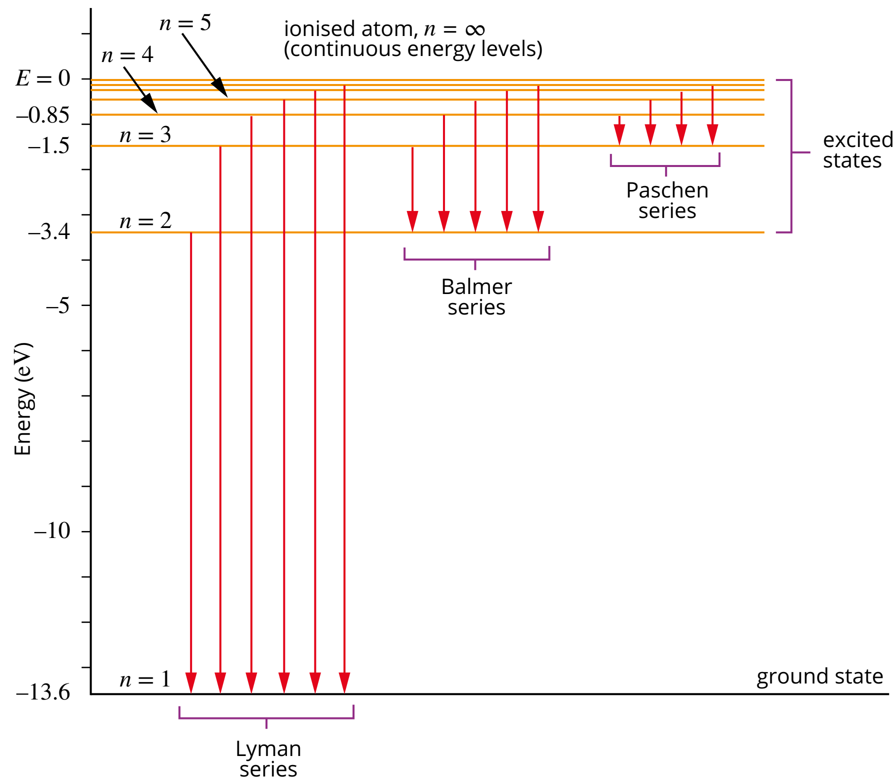


FIGURE 12.2.3 An energy level diagram for hydrogen. An electron in the ground state ($n = 1$) has an energy of (–)13.6 eV. For higher energy levels ($n > 1$), the energy levels can be seen to crowd together. Various names are given to electron transitions that finish at the same energy level but start at successively higher energy levels.

When a hydrogen atom gains energy, either by heating or from an electrical current, its electron moves from the ground level to one of the higher levels. This type of atom is described as 'excited'. Eventually, the electron will drop from the higher energy level to one of the lower levels and emit a photon with an energy equal to the difference in energy between the two levels.

You can see in Figure 12.2.3 that since a free electron (at $n = \infty$) must have zero potential energy, the energy levels within the atom are negative in value. To raise an electron from one energy level to another, the appropriate amount of energy must be delivered. As an electron falls, its energy value decreases. That is, it becomes a larger negative number.

Figure 12.2.3 also shows that the spectral lines of hydrogen can be explained in terms of electron transitions. The different series shown on the diagram (Lyman, Balmer, Paschen) represent the final level of specific transitions. The Balmer series, for example, shows transitions from various excited energy levels back to $n = 2$. These transitions represent wavelengths of the visible lines of the hydrogen emission spectrum. This is covered in more detail in Module 12.4.

The energy of the photon emitted is the difference between the energy it starts with and the energy after the transition.

$$\Delta E = E_i - E_f$$

where

ΔE is the energy of the photon emitted

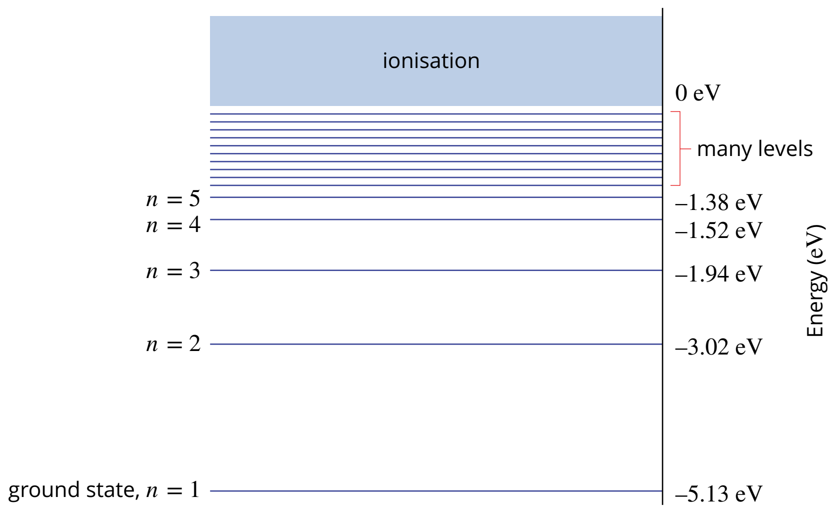
E_i is the energy of the initial energy level and

E_f is the energy of the final energy level.

Worked example 12.2.1

DETERMINING THE ENERGY EMITTED USING AN ENERGY LEVEL DIAGRAM

The energy levels for sodium gas are shown below. Calculate the energy and wavelength of the light that is produced in an emission spectra as an electron drops from the n = 4 to the n = 2 state.

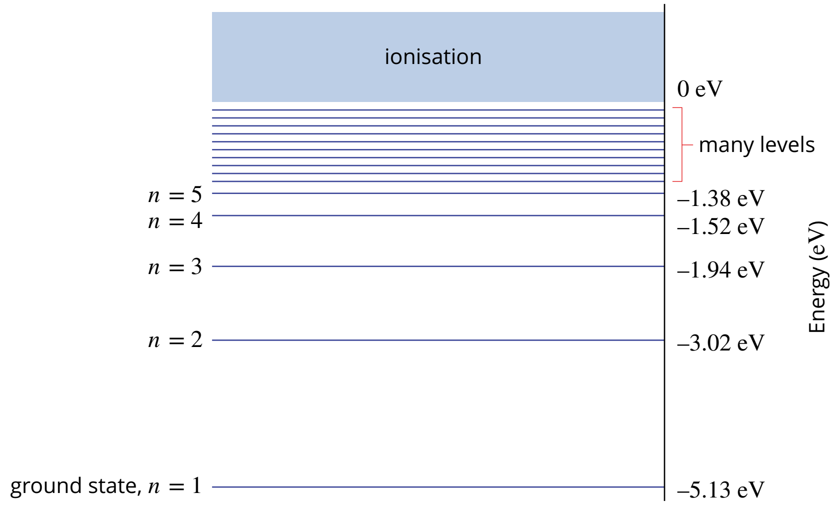


Thinking	Working
From the figure, find the energy (in eV) of each level involved.	$n_i = 4$, $E_i = -1.52$ eV $n_f = 2$, $E_f = -3.02$ eV
Calculate the difference between these levels.	$\Delta E = E_i - E_f$ $= -1.52 - -3.02$ $= 1.50$ eV
The energy difference between levels is equal to the energy of the photon emitted. Convert eV to J.	1.50 eV $= 1.50 \times 1.60 \times 10^{-19}$ $= 2.403 \times 10^{-19}$ J
Rearrange Planck's equation and calculate the wavelength.	$\Delta E = \frac{hc}{\lambda}$ $\lambda = \frac{hc}{\Delta E}$ $= \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{2.403 \times 10^{-19}}$ $= 8.27 \times 10^{-7}$ m

➤ Try yourself 12.2.1

DETERMINING THE ENERGY EMITTED USING AN ENERGY LEVEL DIAGRAM

The energy levels for sodium gas are shown below. Determine the energy and wavelength of the light that is produced as an electron drops from the $n = 4$ to the $n = 3$ state.



PROBLEMS WITH BOHR'S MODEL

The main postulate of Bohr's model was that the electrons could only occupy specific orbitals at set distances from the nucleus, which was an application of the quantisation of energy that Planck proposed. However, Bohr couldn't explain why the electrons should occupy these specific orbitals without losing energy or what physical significance these orbitals had.

Bohr's model of the hydrogen atom applied a quantum approach to the energy levels of atoms to explain a set of important, previously unexplained phenomena—the spectra of hydrogen. In principle, Bohr's work on the hydrogen atom could be extended to other atoms and, in 1914, the German scientists James Franck and Gustav Hertz demonstrated that mercury atoms contained energy levels similar to those of hydrogen atoms. To this extent, Bohr's model signified an important conceptual breakthrough.

However, Bohr's model was limited in its application. It was only comprehensively applicable to one-electron atoms—hydrogen, singly ionised helium, doubly ionised lithium, etc. It modelled inner-shell electrons well, but could not predict the higher energy orbits of multi-electron atoms. Nor could it explain the discovery of the continuous spectrum emitted by solids, described in Chapter 11. The model also could not explain the different intensities of spectral lines. Further studies even showed problems with the emission spectrum of hydrogen. Some of the observed emission lines could be resolved into two very close spectral lines—Bohr's model could not explain this.

WS 4.2.5

12.2 Review

SUMMARY

- The Bohr model of the atom consists of a positive central nucleus with electrons in specific orbits around this nucleus.
- Niels Bohr suggested that electrons in atoms orbit the nucleus in specially defined energy levels, and no radiation is emitted or absorbed unless the electron can jump from its energy level to another.
- The energy emitted can be calculated using

$$\Delta E = E_i - E_f$$

- As electrons transition from a higher to a lower energy level, they emit a photon with energy equal to the difference in energy of the two energy levels.
- Energy levels are labelled $n = 1, 2, 3 \ldots$ where n is the principal quantum number and $n = 1$ is the ground state and higher values of n are for excited states.
- Bohr's model had some limitations and couldn't explain:
  - why the energy levels should be quantised
  - why emission lines have different intensities
  - some emission lines of hydrogen
  - emission spectra of larger atoms
  - emission spectra of solids.

KEY QUESTIONS

Retrieval

1 Identify the force that keeps the electrons orbiting the positive nucleus in Bohr's model.

2 Recall why the energy of the different orbits is given a negative value.

Comprehension

3 Photons of energy 0.42 eV are emitted by a particular atom as an electron returns from the exited state to the ground state. Determine the corresponding wavelength of these photons.

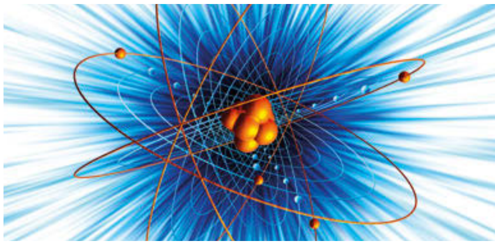
4 Determine the energy of the photon required to move an electron in a hydrogen atom from its ground state ($n = 1$) to the $n = 4$ energy level. Refer to the hydrogen energy level diagram in Figure 12.2.3 on page 322.

Analysis

5 An emission line of frequency 6.0×10^{14} Hz is observed when looking at the emission spectrum of a particular elemental gas. Calculate the energy, in joules, of photons corresponding to this frequency.

6 Bohr's quantised model of the atom was a significant development. Evaluate Bohr's model and outline what it was unable to explain, and hence the reason why it had limited application.

12.3 Particles as a wave



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

- define Planck's constant
- recall that photons exhibit the characteristics of both waves and particles
- solve problems involving the energy, frequency and wavelength of a photon.

Although Bohr's model explained atomic spectra and other observations very well, physicists still didn't understand why the electrons in Bohr's quantised energy levels didn't radiate energy and spiral into the nucleus. An extraordinary idea was needed to explain how Bohr's electron energy levels existed.

DE BROGLIE'S HYPOTHESIS

In 1924, a French physicist named Louis de Broglie proposed a groundbreaking theory. He suggested that as light, which had long been considered to be a wave, sometimes demonstrated particle-like properties, then perhaps matter, which was considered to be made up of particles, might sometimes demonstrate wave-like properties.

He quantified this theory by equating Planck's equation, $\Delta E = \frac{hc}{\lambda}$, with Einstein's $\Delta E = mc^2$:

$$\frac{hc}{\lambda} = mc^2$$

The wavelength of a photon is therefore given by:

$$\lambda = \frac{h}{p}$$

And the wavelength of a particle is given by:

$$\lambda = \frac{h}{mv}$$

> The wavelength of a particle is given by:
> $$\lambda = \frac{h}{mv}$$

where:

λ is the wavelength of the particle (m)
h is Planck's constant
m is the mass of the particle (kg)
v is the velocity of the particle ($m\,s^{-1}$).

Worked example 12.3.1

CALCULATING THE DE BROGLIE WAVELENGTH

In a famous experiment known as the Davisson–Germer experiment, electrons travelled at about $4.0 \times 10^6\,m\,s^{-1}$.

Calculate the de Broglie wavelength of these electrons. The mass of an electron is 9.109×10^{-31} kg.

Thinking	Working
Recall de Broglie's equation.	$\lambda = \frac{h}{mv}$
Substitute the appropriate values into the equation and solve it.	$\lambda = \frac{6.626 \times 10^{-34}}{9.109 \times 10^{-31} \times 4 \times 10^{6}}$ $= 1.8 \times 10^{-10}$ m or 0.18 nm

➤ Try yourself 12.3.1

CALCULATING THE DE BROGLIE WAVELENGTH

Calculate the de Broglie wavelength of a proton travelling at $7.0 \times 10^5\,\text{m s}^{-1}$. The mass of a proton is 1.673×10^{-27} kg.

Worked example 12.3.2

CALCULATING THE DE BROGLIE WAVELENGTH OF A MACROSCOPIC OBJECT

Calculate the wavelength of a cricket ball of mass $m = 160\,\text{g}$ travelling at $150\,\text{km h}^{-1}$.

Thinking	Working
Convert mass and velocity to SI units.	$m = 160\,\text{g} = 0.16\,\text{kg}$ $v = \frac{150}{3.6} = 42\,\text{m s}^{-1}$
Recall de Broglie's equation.	$\lambda = \frac{h}{mv}$
Substitute the appropriate values into the equation and solve it.	$\lambda = \frac{6.626 \times 10^{-34}}{0.16 \times 42}$ $= 9.9 \times 10^{-35}\,\text{m}$

➤ Try yourself 12.3.2

CALCULATING THE DE BROGLIE WAVELENGTH OF A MACROSCOPIC OBJECT

Calculate the de Broglie wavelength of a person of mass $m = 66\,\text{kg}$ running at $36\,\text{km h}^{-1}$.

As you can see from Worked example 12.3.1, the wavelength of an electron is smaller than that of visible light, but still large enough to be measurable. However, the wavelength of an everyday object such as the cricket ball in Worked example 12.3.2 is extremely small. Hence, you will never notice the wave properties of everyday objects. To illustrate this, consider the observable wave behaviour **diffraction**. For diffraction to be noticeable, the size of the wavelength needs to be comparable to the size of the gap or obstacle. Therefore, for an everyday object to produce noticeable diffraction, it would need to pass through a gap a million times smaller than the diameter of a proton.

Evidence for de Broglie's hypothesis

de Broglie's prediction that matter could exhibit wave properties was controversial. However, it was experimentally confirmed by two American scientists Clinton Davisson and Lester Germer in 1927, when they bombarded the surface of a piece of nickel with electrons and observed that diffraction patterns were produced (Figure 12.3.1).

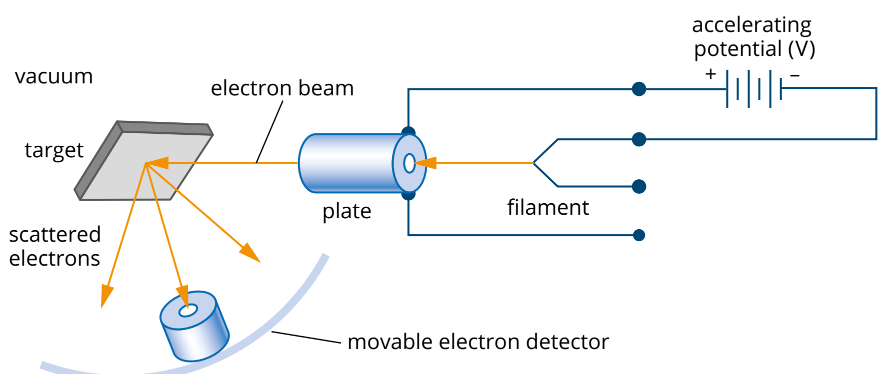


FIGURE 12.3.1 The Davisson and Germer apparatus is used to show electron diffraction patterns.

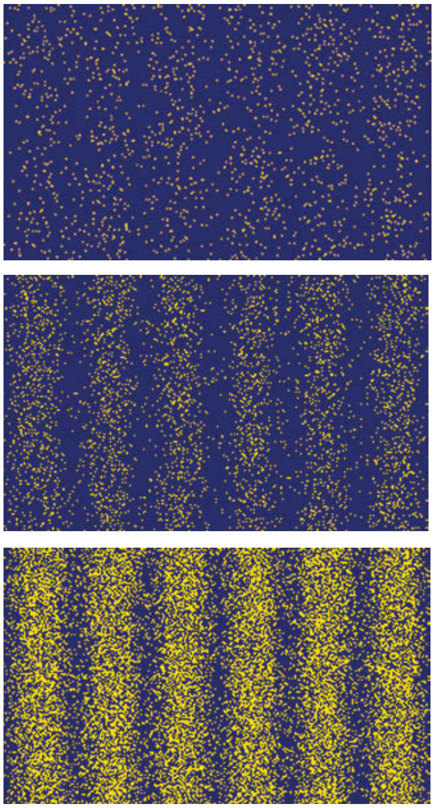


FIGURE 12.3.2 An electron diffraction pattern like the one observed by Davisson and Germer can be built over time from repeated observations.

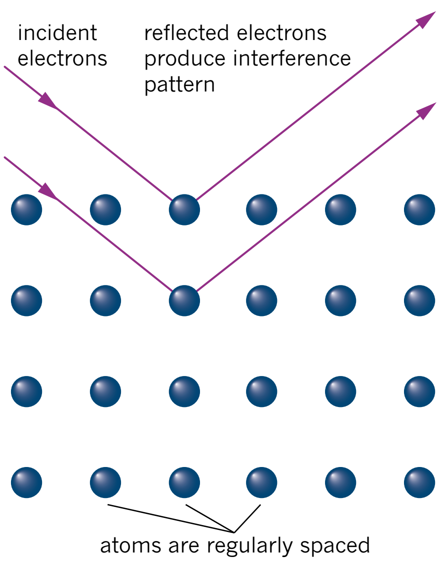


FIGURE 12.3.3 Electrons reflecting from different layers within the crystal structure create an interference pattern like those produced by a diffraction grating.

They used an electron gun to provide a beam of electrons. The speed of the electrons was known because they had been accelerated through a known voltage. The detector could be swung around on an axis so that it could intercept electrons scattered from the nickel target in any direction in the plane shown.

Davisson and Germer found that as they moved their detector through the different scattering angles, they encountered a sequence of maximum and minimum intensities (Figure 12.3.2).

Clearly, the electrons were being scattered by the different layers within the crystal lattice (Figure 12.3.3) and were undergoing interference. When Davisson and Germer analysed the diffraction pattern to determine the wavelength of the 'electron waves', they calculated a value of 0.14 nm, which was consistent with de Broglie's hypothesis.

Worked example 12.3.3

WAVELENGTH OF ELECTRONS FROM AN ELECTRON GUN

Calculate the de Broglie wavelength of an electron that has been accelerated from rest through a potential difference of 75 V. The mass of an electron is 9.109×10^{-31} kg and the magnitude of the charge on an electron is 1.60×10^{-19} C.

Thinking	Working
Recall that $W = qV$.	$W = qV$ $= 1.60 \times 10^{-19} \times 75$ $= 1.2 \times 10^{-17}$ J
Calculate the velocity of the electron.	$E_k = \frac{1}{2}mv^2$ $v = \sqrt{\frac{2E_k}{m}}$ $= \sqrt{\frac{2 \times 1.2 \times 10^{-17}}{9.109 \times 10^{-31}}}$ $= 5.1 \times 10^6\ \text{m s}^{-1}$
Use de Broglie's equation to calculate the wavelength of the electron.	$\lambda = \frac{h}{mv}$ $= \frac{6.626 \times 10^{-34}}{9.109 \times 10^{-31} \times 5.1 \times 10^6}$ $= 1.4 \times 10^{-10}$ m $= 0.14$ nm

➤ Try yourself 12.3.3

WAVELENGTH OF ELECTRONS FROM AN ELECTRON GUN

Calculate the de Broglie wavelength of an electron that has been accelerated from rest through a potential difference of 50.0 V. The mass of an electron is 9.109×10^{-31} kg and the magnitude of the charge on an electron is 1.60×10^{-19} C.

Photon momentum

An interesting corollary of de Broglie's hypothesis, $\lambda = \frac{h}{p}$, is that if a particle such as an electron has a wavelength λ, then a photon must have a momentum p. This is quite counterintuitive, since photons do not have any mass, and all photons travel at the speed of light, c. Nevertheless, de Broglie's equation allows the momentum of a photon to be calculated.

Worked example 12.3.4

CALCULATING PHOTON MOMENTUM

Calculate the momentum of a photon of red light with a wavelength of 650 nm.	
Thinking	**Working**
Convert 650 nm to m.	650 nm = 6.5×10^{-7} m
Transpose de Broglie's equation to make momentum the subject.	$\lambda = \frac{h}{p}$ $p = \frac{h}{\lambda}$
Substitute in the appropriate values and solve for *p*.	$p = \frac{6.626 \times 10^{-34}}{6.5 \times 10^{-7}}$ $= 1.0 \times 10^{-27}\ \text{kg m s}^{-1}$

PA 4.2.3

➤ Try yourself 12.3.4

CALCULATING PHOTON MOMENTUM

Calculate the momentum of a photon of blue light with a wavelength of 450 nm.

Clearly, the momentum of a single photon is tiny, which is why you will not feel any physical 'pressure' when light falls on you. However, it is possible to measure 'light pressure' using very sensitive equipment.

In interplanetary space, where other forces, such as friction, are negligible, light pressure can actually be used as a form of propulsion. Spacecraft such as the Mariner 10 and MESSENGER, which flew past Mercury and Venus, used deceleration caused by solar pressure to conserve fuel.

More recently, the Japanese Aerospace Exploration Agency launched IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun). IKAROS is the first spacecraft to draw its primary propulsion from a solar sail. A traditional sail propels a ship using the change of momentum that occurs when air molecules bounce off it. Similarly, a solar sail gains propulsion from changes in photon momentum as light is reflected from it. The IKAROS spacecraft has a 196 m^2 reflective sail, which produces a thrust of 1.12 mN. An artist's impression of IKAROS is shown in Figure 12.3.4.

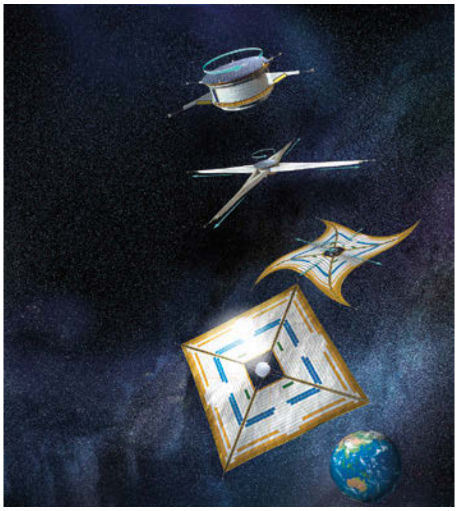


FIGURE 12.3.4 The IKAROS spacecraft is the first interplanetary spacecraft to use solar-sail technology.

Light pressure is also very important when attempting to predict the paths of asteroids and considering potential impacts from Earth. The photon pressure from the Sun, over long periods of time, can change the orbit of asteroids.

de Broglie's hypothesis and electron orbitals

Being able to describe electrons as waves suggested a new way to describe electron energy levels. If particles can be thought of as matter waves, then these matter waves must be able to maintain steady energy values if the particles are to be considered stable.

de Broglie applied his approach to the discussion of Bohr's model for the hydrogen atom. He viewed the electrons orbiting the hydrogen nucleus as matter waves. He suggested that the electron could only maintain a steady energy level if it established a **standing wave**. To fit a standing wave into a circular orbit, the orbit needs to be exactly equal to a whole number of wavelengths. This gives rise to only certain orbits being possible—Bohr's quantised electron energy levels. As a standing wave, the electron doesn't radiate energy as it accelerates, so it can maintain its orbit and not spiral into the nucleus.

These standing waves can be visualised by imagining a conventional standing wave pattern, like that of a vibrating string, which was discussed in *Pearson Physics 11 Queensland* Chapters 9 and 10, being looped around in three dimensions with the ends touching (Figure 12.3.5).

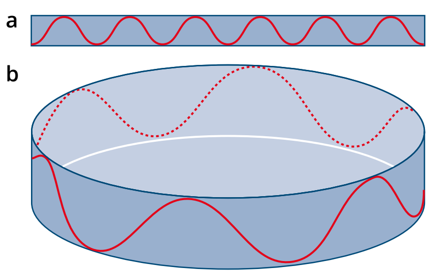


FIGURE 12.3.5 A standing wave pattern (a) can be looped around on itself to form a circle (b) where the circumference of the circle is equal to a whole number of wavelengths.

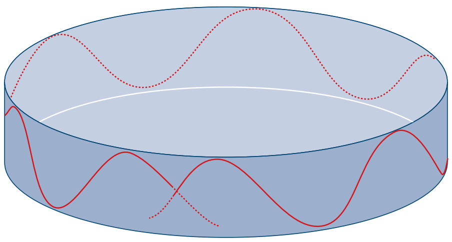


FIGURE 12.3.6 A circular standing wave pattern cannot be established if the circumference of the circle is not equal to a whole number of wavelengths.

If the circumference of the circle is not equal to a whole number of wavelengths, then destructive interference occurs, a standing wave pattern cannot be established and the orbit cannot represent an energy level (Figure 12.3.6).

The number of waves that fit around the orbit is the principal quantum number of the orbital (Figure 12.3.7).

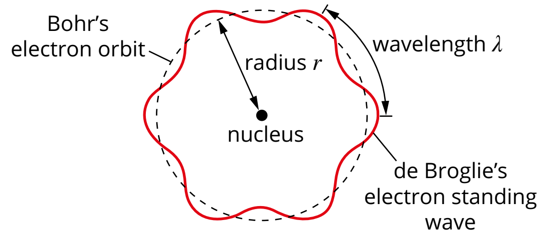


FIGURE 12.3.7 A representation of the standing wave electron orbitals proposed by de Broglie. Notice there are six wavelengths around this orbit so this is the energy level $n = 6$.

Consider the circumference of a circle:

$C = 2\pi r$

where

C is the circumference of the circle

r is the radius of the circle.

To be a standing wave, this circumference needs to be an integer number of wavelengths, so the condition becomes:

$n\lambda = 2\pi r$

where

λ is the wavelength of the electron in metres (m)

r is the radius of the circular orbit in metres (m)

n is an integer that is the principal quantum number or energy level.

The stable orbits of the hydrogen atom are those for which the circumference is exactly equal to a whole number of electron wavelengths.

This equation can also be expressed in terms of the mass and velocity of the electron using $\lambda = \frac{h}{p}$:

$$\frac{nh}{p} = 2\pi r$$

Now replacing the momentum p with $p = mv$:

$$\frac{nh}{mv} = 2\pi r$$

Multiply both sides by mv:

$$nh = 2\pi mvr$$

Dividing both sides by 2π to get the equation into its standard form:

$$mvr = \frac{nh}{2\pi}$$

where

m is the mass of the electron (kg)

v is the velocity of the electron ($m\,s^{-1}$)

r is the radius of the circular orbit (m)

n is an integer that is the principal quantum number or the energy level

h is Planck's constant.

This specific form of this equation is known as Bohr's condition and the quantised energy levels of Bohr's model must satisfy this condition.

Worked example 12.3.5

CALCULATING THE RADIUS OF AN ENERGY LEVEL OF THE HYDROGEN ATOM

Calculate the radius of the $n = 1$ energy level of the hydrogen atom if the electron's energy is 2.176×10^{-18} J.	
Thinking	**Working**
Rearrange the kinetic energy equation to make velocity the subject.	$E_k = \frac{1}{2}mv^2$ $v = \sqrt{\frac{2E_k}{m}}$
Use the kinetic energy provided and the mass of the electron to find the velocity of the electron. $m_e = 9.109 \times 10^{-31}$ kg	$v = \sqrt{\frac{2 \times 2.176 \times 10^{-18}}{9.109 \times 10^{-31}}}$ $= 2.186 \times 10^{6}\ \text{m s}^{-1}$
Rearrange the equation $mvr = \frac{nh}{2\pi}$ to make r the subject of the equation.	$mvr = \frac{nh}{2\pi}$ $r = \frac{nh}{2\pi mv}$
Calculate the radius of the electron orbit for the ground state ($n = 1$).	$r = \frac{nh}{2\pi mv}$ $= \frac{1 \times 6.626 \times 10^{-34}}{2\pi \times 9.109 \times 10^{-31} \times 2.186 \times 10^{6}}$ $= 5.296 \times 10^{-11}$ m

➤ Try yourself 12.3.5

CALCULATING THE RADIUS OF AN ENERGY LEVEL OF THE HYDROGEN ATOM

Calculate the radius of the first excited state ($n = 2$) of the hydrogen atom if the electron's energy is 5.44×10^{-19} J.

This model of the atom is the basis for what physicists use today. The current model used by physicists has developed Bohr's model even further, using principles of quantum mechanics that are beyond the scope of this course. Rather than thinking about electrons following exact paths around the nucleus, they are better described by the *probability* of locating an electron in an electron cloud that has different shapes based on the waves that create it (Figure 12.3.8). How this is created is beyond the scope of this course, but you might have seen the results of this if you study chemistry and looked at the shapes of the *s*, *p*, *d* and *f* orbitals.

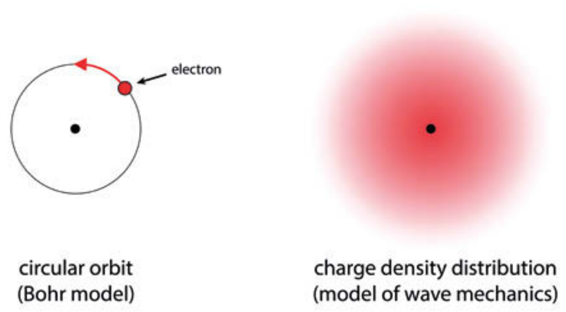


FIGURE 12.3.8 A comparison of the Bohr model and the current electron cloud model of the atom. The Bohr model predicts exact values of the location of the electron, while the wave mechanics model predicts a non-exact value of the electron's location.

12.3 Review

SUMMARY

- At the atomic level, energy and matter exhibit the characteristics of both waves and particles.
- The wavelength of a particle is given by the de Broglie equation: $\lambda = \frac{h}{p} = \frac{h}{mv}$.
- The de Broglie equation also gives the momentum of a photon.
- The wave nature of electrons explains the electron energy levels in Bohr's model of an atom, for which each energy level is a standing wave.
- The standing wave of the electron in Bohr's model of the atom needs to meet the following condition, known as Bohr's condition:

$$n\lambda = 2\pi r$$

This can also be written as $mvr = \frac{nh}{2\pi}$.

KEY QUESTIONS

Retrieval

1 State de Broglie's hypothesis.

2 Describe the experiment performed by Davisson and Germer which supported de Broglie's hypothesis that matter could also behave like a wave.

Comprehension

3 Draw the de Broglie waves for the first three energy levels of an electron bound to the hydrogen nucleus.

4 Explain why a cricket player does not have to consider the wave properties of a cricket ball while batting.

Analysis

In questions 5 and 6, use $m_e = 9.109 \times 10^{-31}$ kg and $h = 6.626 \times 10^{-34}$ J s.

5 Determine the de Broglie wavelength of an electron traveling at 1.0×10^6 m s^{-1}.

6 Determine the speed of an electron that has a de Broglie wavelength of 4.0×10^{-9} m.

7 In an experiment to determine the structure of a crystal, identical diffraction patterns were formed by a beam of electrons and a beam of X-rays with a frequency of 8.6×10^{18} Hz.

a Calculate the wavelength of the electrons.

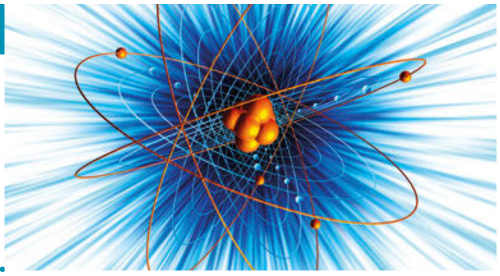
b Calculate the speed of the electrons.

8 A charge q of mass m is accelerated from rest through a potential difference of V. Determine an expression for the de Broglie wavelength of the mass, λ, in terms of q, m and V.

9 Calculate the energy of an electron in the $n = 4$ level of hydrogen if the radius of the orbit is 8.24×10^{-10} m.

10 Determine the radius of the $n = 3$ level of hydrogen, which has an energy of –1.5 eV, using Bohr's condition.

12.4 Atomic spectra



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

- explain how the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum
- solve problems involving the line spectra of simple atoms using atomic energy states or atomic energy level diagrams.

The analysis of atomic and molecular spectra is important in physics, chemistry and astronomy. It is used to study the structure of different atoms and molecules, and to determine constituent components of complicated substances.

Isaac Newton was the first to describe the rainbow of colours that form white light as a spectrum. In the 1800s as the available optics improved, physicists such as William Wollaston and Joseph von Fraunhofer noticed that the Sun's spectrum was not the continuous spectrum expected, but rather there were missing lines of colour. Scientists were also looking at the spectra of terrestrial-based light sources such as flames, and examining the spectra of different substances. With improvements in technology, such as diffraction gratings and the Bunsen burner, there were developments in the field of analytical spectroscopy.

HYDROGEN LINE SPECTRA

Hydrogen is the simplest atom, as it consists of just one electron and one proton. The lack of extra particles minimises interactions within the atom, making the hydrogen spectrum easier to model. Hydrogen is also predominant in stars for which some of the earliest spectra have been observed, so it was the first atomic spectrum examined in detail. The emission spectra of hydrogen and helium can be seen in in Figure 12.4.1.

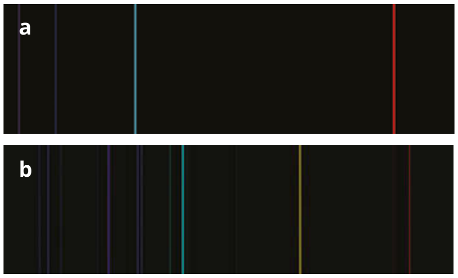


FIGURE 12.4.1 The visible spectral lines for hydrogen (a) and helium (b). The spectral lines of an element are unique to that element and are produced as electrons transition between different energy levels within the atom.

In Module 12.2, Bohr's model of the atom, including quantised energy levels for the electrons, was used to explain the hydrogen atom and the observed spectral lines. Recall that the spectral lines are produced by electron transitions between the quantised energy levels. The principal quantum numbers were used to label the quantised energy levels and are used to describe the transitions. The wavelength of each spectral line is determined by its energy. The spectral lines are the same wavelength in both emission and absorption spectra.

Emission spectra

When elements are heated to high temperatures or have an electrical current passed through them, they produce light. You will recall from Module 12.2 that when atoms absorb energy they become 'excited' and eventually the atom will return to the 'unexcited', or ground, state. When this happens, the energy that had been absorbed is released as a single photon. The colour of this photon will depend on the amount of energy it has.

Since atoms can usually have a number of different excited states, they can produce a number of different colours. The combination of colours produced by a particular element is distinctive for that element (Figure 12.4.2) and is known as its emission spectrum.

FIGURE 12.4.2 The different metals used in fireworks are responsible for the colours in this display. For example, strontium gives red, sodium gives yellow and copper gives green.

Absorption spectra

In 1814, the German physicist Joseph von Fraunhofer reported a number of dark lines appearing in the spectrum of sunlight (Figure 12.4.3).

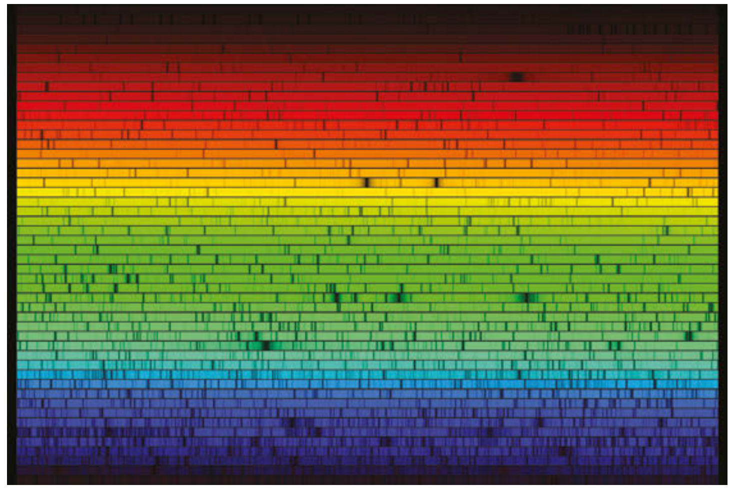


FIGURE 12.4.3 The spectrum of sunlight contains some missing colours known as Fraunhofer lines.

You will recall that a spectrum showing all the colours that make up white light can be obtained by passing sunlight through a prism. When Fraunhofer passed sunlight through a prism, he observed the spectrum (as expected) but he also noticed that there were some colours 'missing' from the spectrum. The missing colours appeared as black lines at various points along the spectrum. These apparently missing colours came to be known as Fraunhofer lines.

About 50 years later, scientists including Kirchhoff and Bunsen (of Bunsen burner fame) recognised that some of these lines corresponded to the colours emitted when certain gases were heated to high temperatures. They deduced that the dark lines were due to these colours (wavelengths) being absorbed by gases as light made its way through the outer atmosphere of the Sun. This absorption spectrum allowed astronomers to determine that the Sun is largely composed of hydrogen with small quantities of helium and some other heavier elements.

> The lines in the absorption spectrum of an element have the same wavelengths, and thus energies, as the lines in the emission spectrum of that element.

Absorption spectra are a valuable tool for scientists who wish to know what elements are present in a sample of gas or in a solution, so their use is not limited to analysing stars. Light is directed through a cool sample of a gas or through a solution containing a particular element or compound. Particular frequencies of light will be absorbed by the elements present in the sample, so that on viewing the spectrum, this particular frequency will be 'missing'. The particular frequencies that are absorbed are unique to each type of atom. For this reason, by analysing which frequencies are missing, scientists can determine exactly what elements and molecules are present in the sample.

Interpreting atomic spectra

In an emission spectrum, the electrons emit energy as they transition back to a lower energy level. On an energy level diagram, this is depicted with an arrow going downwards from a higher to a lower energy level, as in the hydrogen emission spectrum in Figure 12.4.4a. In an absorption spectrum, the electron is gaining energy (from the light) so it is transitioning from a lower to a higher energy level. Absorption is shown by an arrow going upwards from a lower to a higher energy level, as seen in the absorption spectrum for a singularly ionised helium ion in Figure 12.4.4b. Singularly ionised helium is a hydrogen-like ion, because it has one electron and its energy levels can be calculated using an extended version of the Rydberg equation, discussed on page 334. We can also use energy levels diagrams to analyse atoms other than hydrogen if the energies are provided, although calculating these energy levels is much more complicated. Remember that the absorption transition and the emission transmission for the same energy levels will have the same energy.

> On an energy level diagram, absorption transitions are shown with an arrow upwards and emission is shown with an arrow downwards.

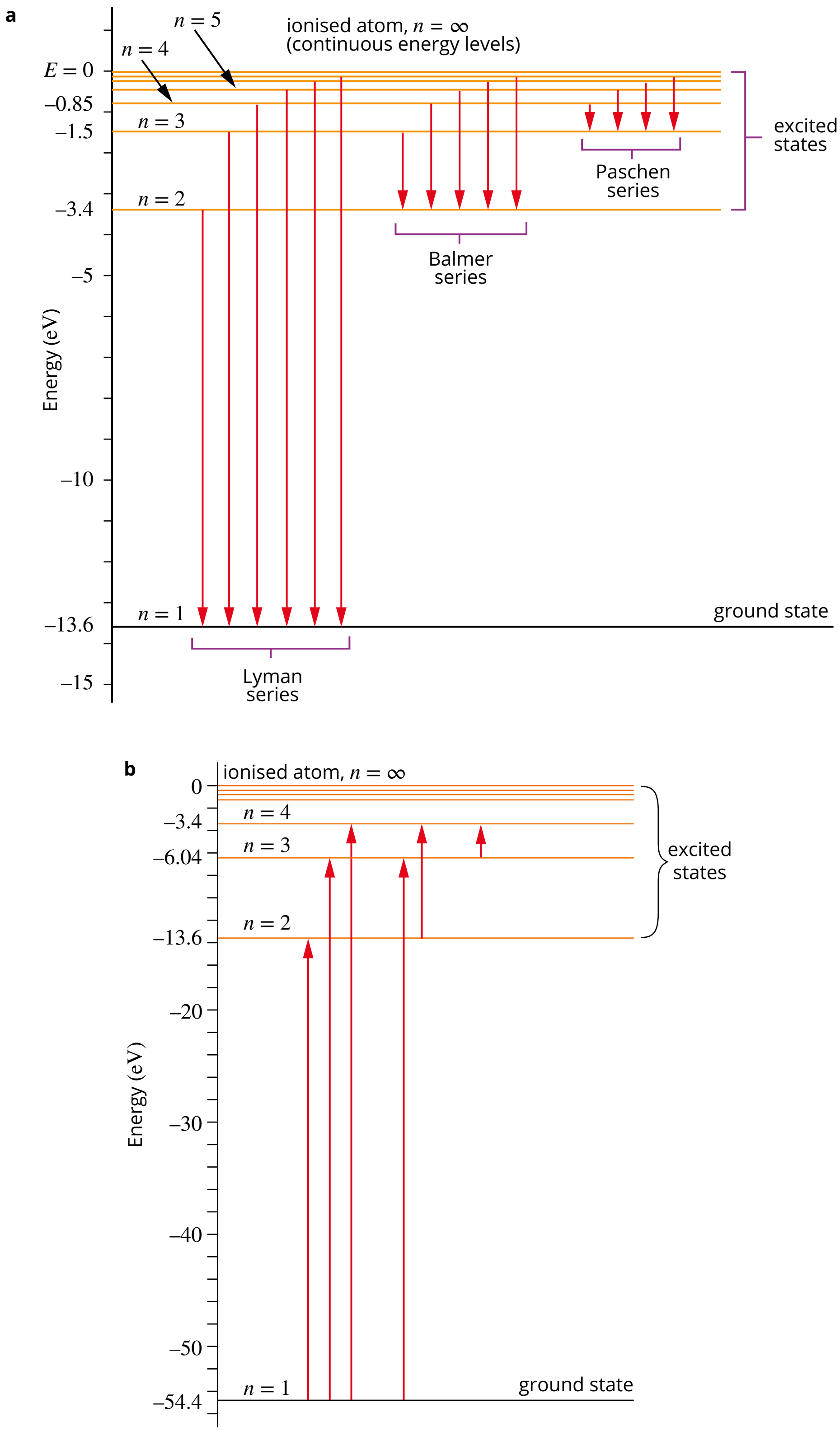


FIGURE 12.4.4 (a) An energy level diagram for hydrogen. Notice the arrows pointing downwards. This indicates an emission spectrum. (b) An energy level diagram for the singularly ionised helium ion. Notice the arrows pointing upwards. This indicates an absorption spectrum.

Worked example 12.4.1

DISTINGUISHING BETWEEN ABSORPTION AND EMISSION TRANSITIONS

An electron transitions from the $n = 3$ energy level to the $n = 2$ energy level. Identify whether this is an emission or absorption transition and describe the way this would be shown on an energy level diagram.

Thinking	Working
Identify n_i and n_f.	$n_i = 3$ $n_f = 2$
The energy level has decreased, so this is emission.	The transition from the $n = 3$ energy level to the $n = 2$ energy level is an emission transition. Emissions are shown with a downwards arrow on an energy level diagram.

➤ Try yourself 12.4.1

DISTINGUISHING BETWEEN ABSORPTION AND EMISSION TRANSITIONS

Draw in your notebook the hydrogen energy level diagram shown in Figure 12.4.4b. On this diagram draw an arrow to show the absorption transition between the $n = 3$ and $n = 5$ energy levels.

In Module 12.2 the most common convention of labelling atomic energy levels was described. By this convention, the energy given is the amount of energy required to remove an electron from an atom. This convention gives all the energy values as negative and the ionisation energy level ($n = \infty$) has a value of 0 eV. Another convention is one in which the ground state ($n = 1$) is allocated 0 eV and higher levels have positive values. It is important to be able to interpret both conventions. The two conventions can be seen by comparing the energy level diagrams in Figure 12.4.4 and the energy level diagram for doubly ionised lithium in Figure 12.4.5. Doubly ionised lithium is of interest as it is a hydrogen-like ion in that is has only one electron.

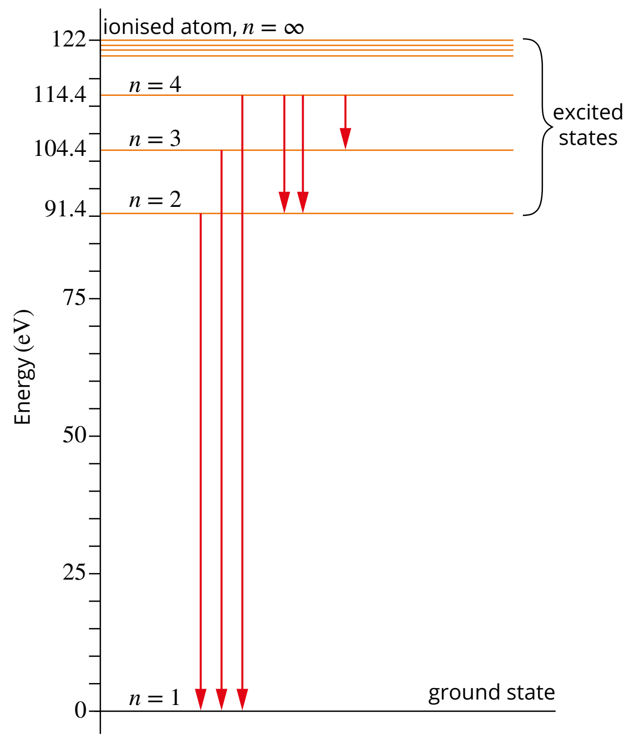


FIGURE 12.4.5 An energy level diagram for the doubly ionised lithium ion (Li^{2+}). Notice the alternative labelling convention for energy levels.

Using energy level diagrams to determine transitions

Recall that in Module 12.2 the energy difference of a transition was defined as the difference in energy between the initial and final states and was calculated using energy level diagrams. This gives the energy of an absorbed or emitted photon, and combined with the use of Planck's equation, the wavelength of that photon can be determined. This is one method to calculate the hydrogen spectral lines.

Each possible electron transition produces light of a different energy. The energy corresponds to a different coloured line in the emission or absorption spectrum for that atom. The greater the energy emitted, the higher the frequency and the shorter the wavelength of the light.

PA 4.2.2

RYDBERG FORMULA

Before Bohr's model explained the hydrogen emission spectra, scientists were hunting for a mathematical relationship between the lines that would also allow for the prediction of further lines. In 1885, Joseph Balmer found a relationship that described the visible lines of the hydrogen spectra as well as predicting a line in the ultraviolet region that hadn't yet been observed:

$$\lambda = \frac{Bm^2}{m^2 - n^2}$$

where

λ is the wavelength of the light in nanometres (nm)

B is Balmer's constant, which corresponds to the minimum wavelength observed for hydrogen (365 nm)

$n = 2$

m could take values of 3, 4, 5 or 6.

When Balmer put $m = 7$ into the equation, it gave an answer of 397 nm, which was a spectral line that had been independently observed by Anders Ångström. Consequently, this set of spectral lines in the visible part of the electromagnetic spectrum came to be known as the Balmer series.

Balmer's equation was later found to be a special case of a more general formula (but still empirical) proposed by Johannes Rydberg in 1888.

Rydberg's formula predicted that there should be spectral lines in other parts of the electromagnetic spectrum. The ultraviolet series was later observed by Theodore Lyman, and two different infrared series were observed by Friedrich Paschen and Frederick Brackett. This formula only applies for hydrogen but can be extended for other hydrogen-like elements.

Although Rydberg arrived at his formula by empirical methods, we can derive the Rydberg formula using Bohr's condition and by looking at the energy of the electron.

Using the Rydberg formula for hydrogen spectra

The Rydberg equation was originally used to predict spectral lines that hadn't yet been observed. It is used to calculate the wavelength of a transition. The energy levels of hydrogen can be determined using the Rydberg formula. An extended version of the Rydberg formula can be used to calculate the transitions of hydrogen-like atoms such He^+ and Li^{2+}.

The Rydberg formula for hydrogen

$$\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right)$$

where

λ is the wavelength of the radiation emitted

R is the Rydberg constant ($1.097 \times 10^7\ m^{-1}$)

n_i is the principal quantum number of the initial energy level of the transition

n_f is the principal quantum number of the final energy level of the transition.

Worked example 12.4.2

USING THE RYDBERG EQUATION TO CALCULATE HYDROGEN ENERGY LEVELS

Calculate the wavelength (in nm) of the transition from $n = 5$ energy level to the $n = 2$ energy level in hydrogen using the Rydberg equation.	
Thinking	**Working**
Identify n_i and n_f.	$n_i = 5$ $n_f = 2$
State the Rydberg equation.	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$
Substitute the values for n_i, n_f and the Rydberg constant into the Rydberg equation.	$\frac{1}{\lambda} = 1.097 \times 10^7 \times \left(\frac{1}{2^2} - \frac{1}{5^2}\right)$
Solve the right-hand side of the equation.	$\frac{1}{\lambda} = 1.097 \times 10^7 \times \left(\frac{1}{4} - \frac{1}{25}\right)$ $= 1.097 \times 10^7 \times 0.210$ $= 2.304 \times 10^6\ \text{m}^{-1}$
Find the inverse of both sides to solve for the wavelength.	$\lambda = \frac{1}{2.304 \times 10^6}$ $= 434.0\ \text{nm}$

➤ Try yourself 12.4.2

USING THE RYDBERG EQUATION TO CALCULATE HYDROGEN ENERGY LEVELS

Calculate the wavelength absorbed by a hydrogen atom when its electron goes from the $n = 1$ energy state to the $n = 6$ energy state. Use the Rydberg equation.

Worked example 12.4.3

USING THE RYDBERG EQUATION TO DETERMINE ENERGY LEVELS

Visible light of 656 nm was emitted from a hot sample of hydrogen gas. Determine the energy levels involved in this transition.	
Thinking	**Working**
Identify the final energy state considering that the emitted light is visible.	As the light is visible, it must be a Balmer series transition, so the final energy level must be $n_f = 2$.
Rearrange the Rydberg equation to move n_i to the left-hand side of the equation.	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$ $\frac{1}{R\lambda} = \frac{1}{n_f^2} - \frac{1}{n_i^2}$ $\frac{1}{n_i^2} = \frac{1}{n_f^2} - \frac{1}{R\lambda}$
Substitute the values for λ, n_f and the Rydberg constant into the equation.	$\frac{1}{n_i^2} = \frac{1}{2^2} - \frac{1}{1.097 \times 10^7 \times 656 \times 10^{-9}}$ $= 0.111$
Solve for n_i.	$n_i^2 = \frac{1}{0.111}$ $n_i = \sqrt{\frac{1}{0.111}}$ $n_i = 3$
State the energy levels involved in this transition.	The emission is from the $n = 3$ energy level to the $n = 2$ energy level of hydrogen.

➤ Try yourself 12.4.3

USING THE RYDBERG EQUATION TO DETERMINE ENERGY LEVELS

Light with wavelength of 1875 nm was produced from a hydrogen gas discharge tube. The final energy level for this transition was $n = 3$. Determine the initial energy level.

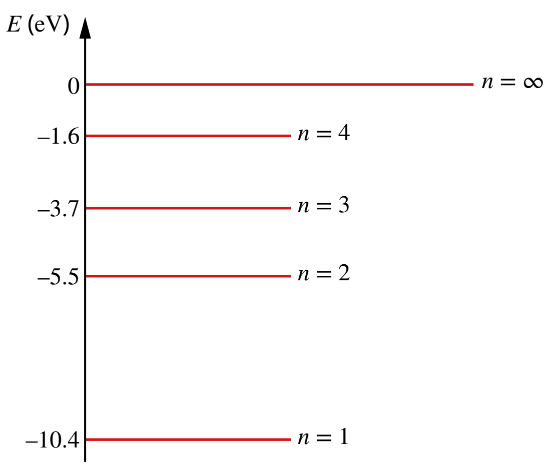
Absorption spectra and Bohr model

An electron ordinarily occupies the lowest energy orbit. Incident light carrying insufficient energy to raise an electron from this lowest energy level to the next level will be unable to be absorbed by the atom. It would simply pass straight through. If light with greater energy than the ionisation energy of an atom is incident, then any light energy will be absorbed. In this case, the excess photon energy will simply translate to extra kinetic energy for the released electron. If light of an energy equal to a difference in energy levels is incident, then the electron at that level will absorb all of the photon's energy and move up to the corresponding level.

Worked example 12.4.4

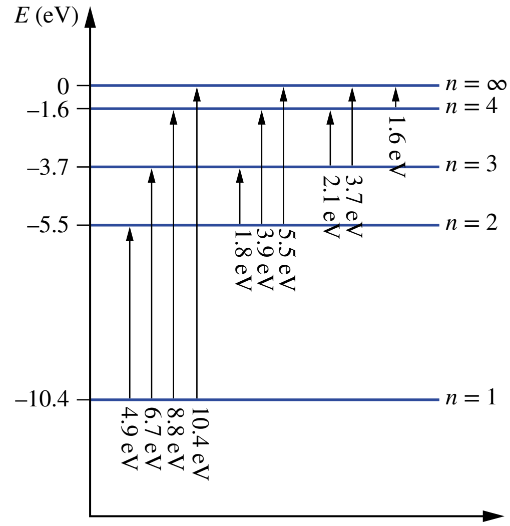
ABSORPTION OF PHOTONS

Some of the energy levels for atomic mercury are shown in the diagram below.



Ultraviolet light with photon energies 4.9 eV, 5.0 eV and 10.50 eV is incident on some mercury gas. Determine what could happen as a result of the incident light, assuming all electrons are in the ground state.

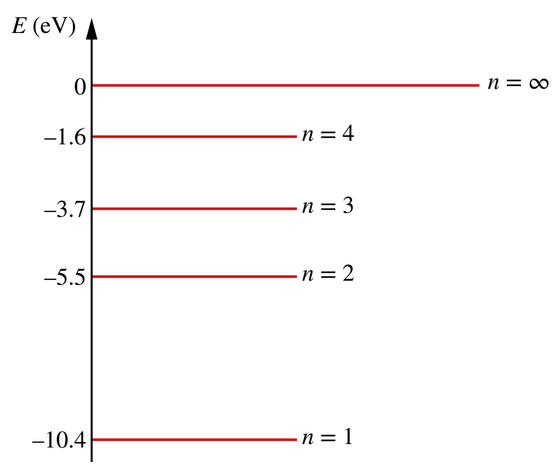
Worked example 12.4.4 *continued*

Thinking	Working
Check whether the energy of each photon corresponds to a difference between energy levels by determining the difference in energy between each level.	
Compare the energy of each photon with the energies determined in the previous step. Comment on the possible outcomes.	A photon of 4.9 eV corresponds to the energy required to promote an electron from the ground state to the first excited state (*n* = 1 to *n* = 2). The photon will be absorbed. A photon of 5.0 eV cannot be absorbed as there is no energy level above the ground state that corresponds exactly to 5.0 eV. A photon of 10.5 eV will ionise the mercury atom. The ejected electron will leave the atom with 0.1 eV of kinetic energy.

➤ Try yourself 12.4.4

ABSORPTION OF PHOTONS

Some of the energy levels for atomic mercury are shown in the diagram below.



Light with photon energies 6.7 eV, 9.0 eV and 11.0 eV is incident on some mercury gas. Determine what could happen as a result of the incident light, assuming all electrons are in the ground state.

12.4 Review

SUMMARY

- An emission spectrum is produced by energised atoms as electrons emit energy as they transition back to a lower energy level levels. The spectrum for each element is unique.
- An absorption spectrum is produced by atoms absorbing specific wavelengths from radiant light. This yields the full spectrum with those specific wavelengths missing. The wavelengths absorbed by an atom are the same as the wavelengths that are emitted when the atom is in an excited state.
- An electron in an atom which drops between energy levels emits a photon of energy equal to the difference between the energy levels. The energy of the photon determines the wavelength of the photon.
- The energy of a transition can be determined using the difference in energy between the two energy levels. These energies can be found on the energy level diagram for that species.
- The wavelength of the radiation emitted for hydrogen can be calculated using the Rydberg equation:

$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

KEY QUESTIONS

Retrieval

1 Describe a typical emission spectrum for an element.

2 Identify the link between an atom's emission spectrum and its structure.

3 Describe how an element such as sodium produces an emission spectrum.

4 Describe how the energy levels (not the transitions) within an atom are commonly represented on a graph.

Comprehension

5 James is arguing that when an electron falls from a higher energy level to a lower energy level, the atom emits a random amount of energy (as a photon). Explain what is wrong with that statement.

6 Explain how an absorption spectrum is produced and describe what it looks like.

7 Explain how orange light is produced by a sodium vapour street light.

8 A transition occurs from the $n = 5$ energy level to the $n = 7$ energy level of an atom. Determine if this is an absorption or emission transition and explain how to determine this.

Analysis

Use the hydrogen energy level diagram in Figure 12.4.4a on page 335 to answer questions 9–12.

9 Determine the energy level for hydrogen (that is, the principal quantum number) that is the:

a ground state
b ionisation level
c excited states.

10 Calculate the energy of the photon that is released as an electron in the $n = 2$ excited state of a hydrogen atom drops back to the ground state. Calculate the wavelength of the photon.

11 Light with the following energies is shone on a sample of hydrogen gas. Determine what could happen to the hydrogen's electron for each of these energies.

a 10.2 eV
b 5 eV
c 14.2 eV

12 Calculate the wavelength of the photons absorbed in the transition from ground state to the $n = 4$ excited state in hydrogen.

13 Use the helium ion (He^+) energy level diagram in Figure 12.4.4b on page 335 to answer this question. A helium ion sample absorbs light with an energy level of 40.9 eV. Determine the transition that occurs.

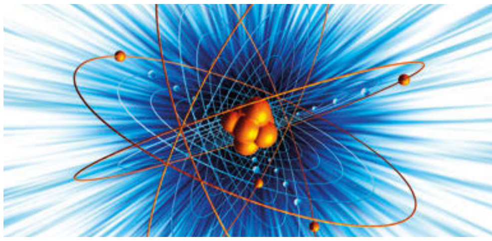
14 When an electron drops from the $n = 5$ energy level of the hydrogen atom to the $n = 2$ energy level, a 434 nm photon is released. Calculate the energy of the $n = 5$ orbit if the $n = 2$ orbit has an energy of –3.4 eV.

15 A hydrogen discharge tube produces light at a wavelength of 410.2 nm. Determine which transition in hydrogen this corresponds to. Hint: this wavelength is in the visible spectrum.

16 In high school level physics we focus on the spectra of hydrogen, ionised helium and doubly ionised lithium. Evaluate why these three atoms are of particular interest.

17 The energy levels of hydrogen-like atoms can be calculated using the full version of the Rydberg equation, $\frac{1}{\lambda} = RZ^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$, where Z is the atomic number (the number of protons). Calculate the wavelength for the helium ion transition from the $n = 2$ to $n = 1$ energy levels using this formula.

12.5 The wave–particle dual nature of light



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

- recall that photons exhibit the characteristics of both waves and particles
- describe the wave–particle duality of light by identifying evidence that supports the wave characteristics of light and evidence that supports the particle characteristics of light.

In order to explain the photoelectric effect, Einstein used the photon concept that Planck had developed. However, like many great discoveries in science, the development of the quantum model of light raised almost as many questions as it answered. It had already been well established that a wave model was needed to explain such phenomena as diffraction and interference. How could these two contradictory models be reconciled to form a comprehensive theory of light?

Answering this question was one of the great scientific achievements of the 20th century, and led to the extension of the quantum model to matter as well as energy. It led to a fundamental shift in the way the universe is viewed. Some of the greatest scientists of that time are shown in the historic photograph in Figure 12.5.1.

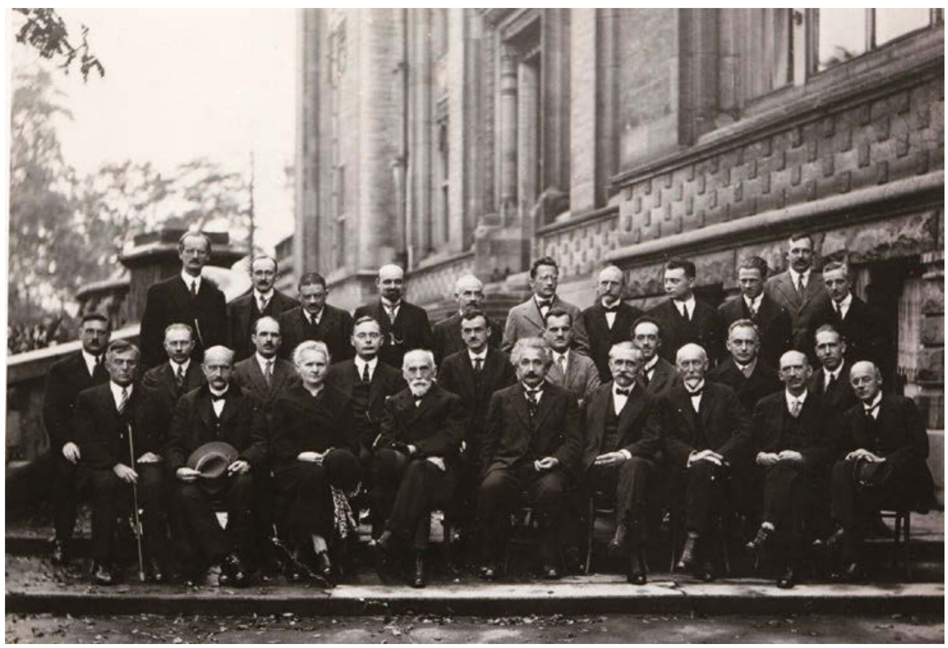


FIGURE 12.5.1 In the early 20th century, scientists worked closely together and built on each other's ideas. This photo shows attendees at the Fifth Solvay Conference on Protons and Electrons in Brussels in 1927. It was attended by great scientists including Albert Einstein, Max Planck, Niels Bohr, Marie Curie, Paul Dirac, Erwin Schrödinger and Louis de Broglie. All these scientists contributed to the current knowledge of the universe, the atom and quantum mechanics.

EVIDENCE FOR WAVE CHARACTERISTICS OF LIGHT

The key piece of evidence for the wave nature of light was provided well before quantum mechanics by Young's double-slit experiments (refer to Chapter 11), which demonstrated the interference of light as is observed with waves.

In the early years of quantum theory, some scientists believed that the wave properties of light observed in Young's double-slit experiment may have been due to some sort of interaction between photons as they passed through the slits together.

Experiments were done with light sources that were so dim scientists were confident that only one photon was passing through the apparatus at a time. These experiments produced identical interference patterns to those done with bright sources (Figure 12.5.2). They were consistent with wave behaviour, even through single particles were passing through the slits, thus demonstrating the dual nature of light.

Interference isn't the only wave-like behaviour displayed by light. Diffraction is a property of waves and is the bending of a wave around the corners of an obstacle or aperture. It is also accounts for how waves spread out as they travel. The bending is most pronounced when the obstacle is approximately the same size as the wavelength of the wave. The diffraction of light is readily observed in many situations, such as with diffraction gratings (Figure 12.5.3) and when light passes through a pinhole. Diffraction as light passes through the atmosphere produces the ring we can see around bright objects. It also accounts for the fact that light can be seen from around a bend.

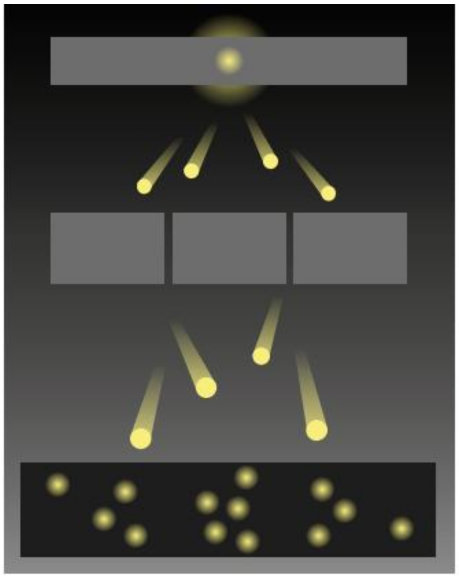


FIGURE 12.5.2 An interference pattern can be built up over time by a series of single photons passing through an apparatus like that used in Young's experiment, demonstrating the wave–particle duality of light.

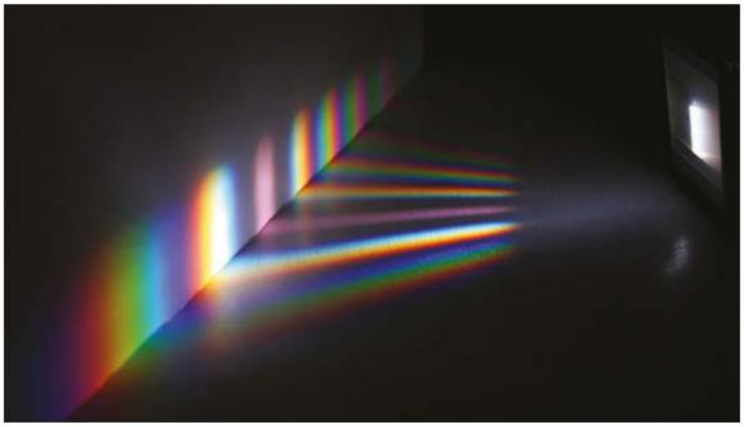


FIGURE 12.5.3 This is the diffraction pattern produced by white light passing through a diffraction grating. Diffraction allows waves to bend around an obstacle. When white light diffracts, longer wavelengths show more diffraction, producing a rainbow effect. The diffraction of light demonstrates its wave nature.

Another property of light that is evidence for its wave nature is polarisation. Recall that polarisation occurs when a transverse wave is only allowed to oscillate in one plane. One way light can be polarised is by passing it through a polarising filter (Figure 12.5.4), which blocks all other planes of oscillation. Polarisation can only occur for transverse waves, so it is evidence for the wave nature of light.

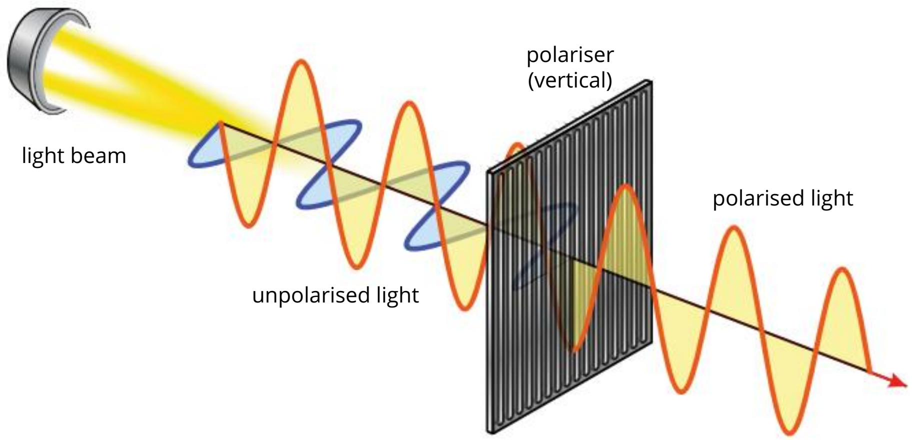


FIGURE 12.5.4 A diagram of the process of polarising light. For light that is polarised, the wave oscillates in one plane only. Light must be a wave for this to occur.

EVIDENCE FOR PARTICLE CHARACTERISTICS OF LIGHT

Einstein was the key early proponent for the particle theory of light because this allowed for the explanation of the newly observed photoelectric effect (see Chapter 11). Recall that the photoelectric effect is the emission of electrons when light of sufficient frequency shines on a material. An incident photon transfers its energy to an electron, causing the electron to be ejected from the material (Figure 12.5.5). Wave theory predicted that as the intensity of light increased, the kinetic energy of the ejected photon would increase, and that if the light was very dim, there would be a time lag between the light and the subsequent ejection of a photon, as the energy built up. But this was not observed in experiments.

What was observed was that electrons were ejected only if the incident light was above a threshold frequency and that there was no time lag between photon absorption and electron emission. The kinetic energy of the electrons was also not dependent on intensity by rather the photon frequency. Einstein explained these results by proposing that light was a collection of discrete particles each with the energy hv (from Planck's work).

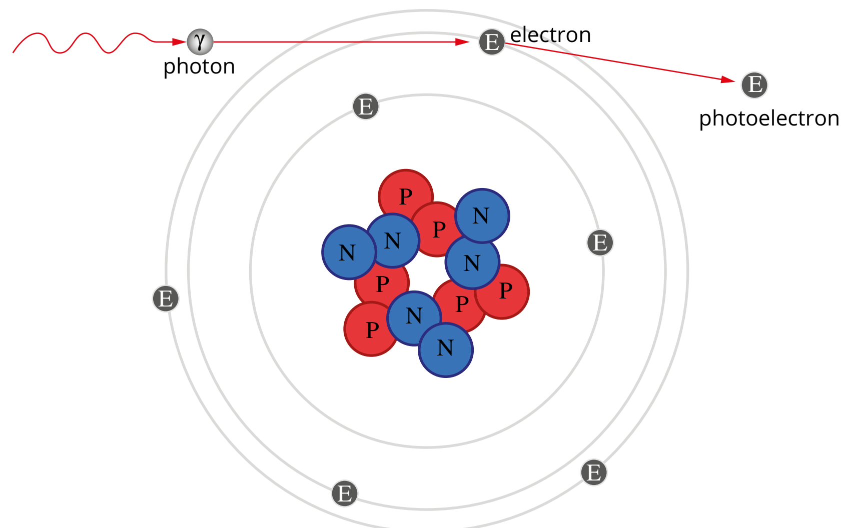


FIGURE 12.5.5 A diagram of the process of the photoelectric effect. A photon transfers energy to the electron, providing enough energy for the electron to be ejected from the atom.

Definitive proof for the particle nature of light came from Arthur Compton's experiments. Compton proved that light had momentum, which is a property of particles. Compton was looking for direct evidence of the particle nature of light and so studied collisions of photons with electrons. He fired X-rays at a graphite target that contained weakly bound electrons. In the collision, part of the energy of the photon is transferred to the electron, so it recoils and the photon is re-emitted in a different direction from the original so the overall momentum is conserved. The photons were emitted with a longer wavelength than the incident photons, indicating that the scattered photons had lost energy to the electron during the collision. This is known now as **Compton scattering**. The collision (Figure 12.5.6) is just as if tiny billiard balls are colliding. This can only be explained if the photon has momentum and is a particle.

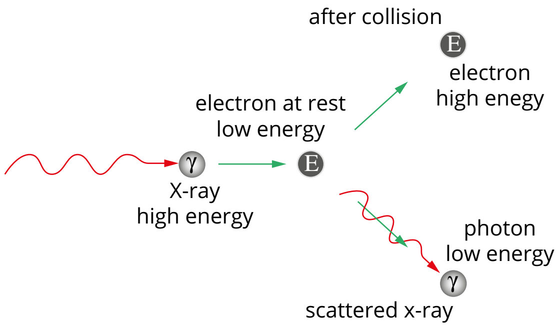


FIGURE 12.5.6 A diagram of Compton scattering. Photons were fired at electrons at rest. Part of the photon's energy is transferred to the electron and a photon with a longer wavelength, and thus less energy, is re-emitted in a new direction. This can only occur if photons have momentum.

THE WAVE–PARTICLE DUALITY OF LIGHT AND MATTER

de Broglie proposed that the wave nature of light be extended to matter as well (refer to Module 12.3). In the quantum world, the wave nature of matter is very important. This has been observed in diffraction experiments performed with electrons as well as with protons, neutrons and molecules, including quite large molecules up to the mass of 10 000 u (which is approximately the mass of 10 000 hydrogen atoms).

Comparing the wavelengths of photons and electrons

In the same year that Davisson and Germer conducted their experiment (refer to Module 12.3), other evidence supporting the wave nature of electrons was coming from G. P. Thomson (son of J. J. Thomson, discoverer of the electron). Thomson produced a diffraction pattern by passing a beam of electrons through a tiny crystal. He then repeated the experiment, using X-rays of the same wavelength in place of the electrons. The X-ray diffraction pattern was very similar to the one made with electrons (Figure 12.5.7).

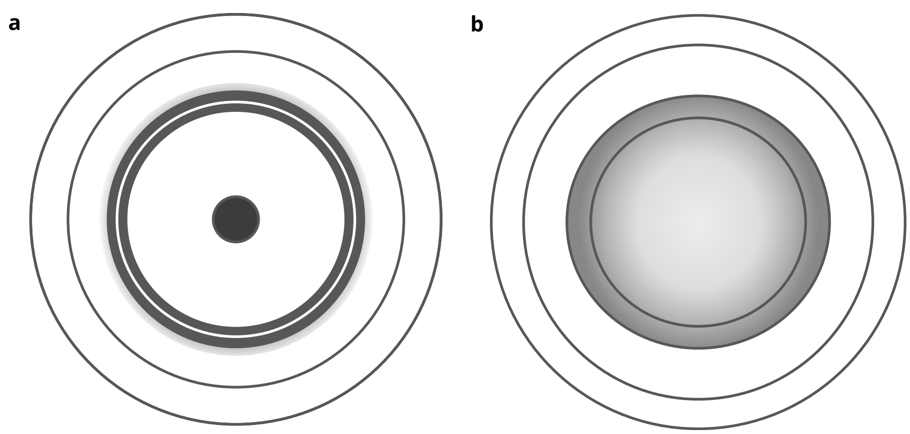


FIGURE 12.5.7 These diffraction patterns were taken by passing (a) X-rays and (b) a beam of electrons through the same target crystal. Their similarity suggests a wave-like behaviour for electrons, with a similar de Broglie wavelength to that of X-rays.

As the diffraction patterns obtained for the X-ray photons and electrons were the very similar and as both were passed through the same gaps to obtain the patterns, an important conclusion could be made: the electrons must have a wavelength similar to that of X-rays. Since their wavelengths are similar, the momentum of the electrons and the X-ray photons must also be comparable (but not their speeds).

Electron microscopes

The discovery of the wave properties of electrons had an important practical application in the invention of the electron microscope. Just as an optical microscope makes use of the wave properties of photons to magnify tiny objects, so too can the wave properties of electrons be used to create magnified images (Figure 12.5.8).

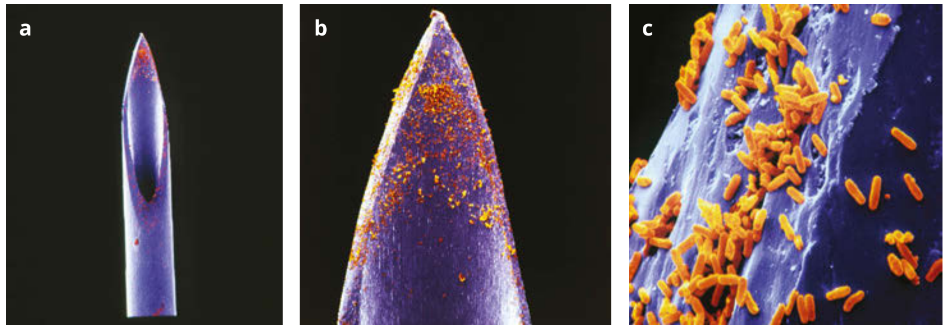


FIGURE 12.5.8 Images formed by an electron microscope: rod-shaped bacteria (orange) clustered on the point of a syringe used to administer injections. The magnifications are (a) ×9, (b) ×36 and (c) ×560 at 35 mm size.

One of the limitations of an optical microscope is that it can only create a clear image of structures that are similar in size to the wavelength of the light being used. This is because the light diffracts around these structures. So a light microscope is only useful for seeing things down to about 390 nm, the lower wavelength end of the visible light spectrum.

However, the wavelength of a beam of electrons is smaller than the wavelength of a beam of light. This means that electron microscopes can create images with much finer detail than optical microscopes.

Understanding the intersection of the wave and particle models

In many ways, the wave and particle models for light seem fundamentally incompatible. Waves are continuous and are described in terms of wavelength and frequency. Particles are discrete and described by physical dimensions such as mass and radius.

In order to understand how these two sets of ideas can be used together, it is important to remember that scientists describe the universe using models. Models are analogies that are used to illustrate certain aspects of reality that might not be immediately apparent.

Through many experiments the model that sees light as both a wave and a particle has held firm. When light interacts with light, producing diffraction, interference and polarisation, light behaves as a wave. When light interacts with matter, as in the photoelectric effect and Compton scattering, light behaves as a particle.

Physicists have come to accept that light is not easily compared with any other physical entity. Unlike anything else in nature, light appears to be both a wave and a particle. This view of light is called the **wave–particle duality**. Although this may seem somewhat paradoxical and counterintuitive, in the century since Einstein did his work establishing quantum theory, many experiments have supported this duality, and no scientist has come up with a better explanation.

WS 4.2.6

SCIENCE AS A HUMAN ENDEAVOUR

Development of the quantum model: the dual characteristics of light

The nature of light has been investigated and debated for centuries, with each generation of scientists building on the work of the last. In the 20th century, scientists came to a realisation that light behaves both as a wave and as a particle.

Christiaan Huygens published his wave theory of light in 1690. It was the first mathematical description of light. Huygens' theory explained geometrical optics in terms of wavefronts and rays, and the propagation of light by means of spherical waves produced along the wavefront. Huygens had quite an interest in lenses, and ground the lenses he used in experiments himself. Huygens based his ideas on experiments involving refraction. Wave theory could explain why light that is shone through a pinhole or slit would spread out rather than travelling in a straight line. Initially, Huygens' wave theory was based on light being a longitudinal wave that cannot undergo polarisation. But without polarisation it was not possible to explain the recently (for Huygens) discovered birefringence that had been observed in such materials as Icelandic spar (calcite). Because it was not able to explain birefringence, Huygens' theory was not widely accepted in the scientific community of the time. This was resolved much later when it was realised that light was a transverse wave, as birefringence is a polarisation effect.

Opposing Huygens' wave theory of light, Sir Isaac Newton proposed a corpuscular theory of light in his 1704 book *Optiks*. Newton considered that light is made of small discrete particles known as corpuscles which travel in a straight line in rays with a finite velocity. Newton argued that because waves don't tend to travel in straight lines, the only way to explain reflection and refraction is if light is composed of particles. The key demonstration of this was passing white light through a pair of prisms set up so that the light produced a spectrum after the first prism and reformed the beam of white light with the second prism (Figure 12.5.9). Mostly due to Newton's reputation, the corpuscular theory of light was predominant until Thomas Young performed his double-slit experiments in 1801, the results of which could not be explained by the corpuscular theory of light.

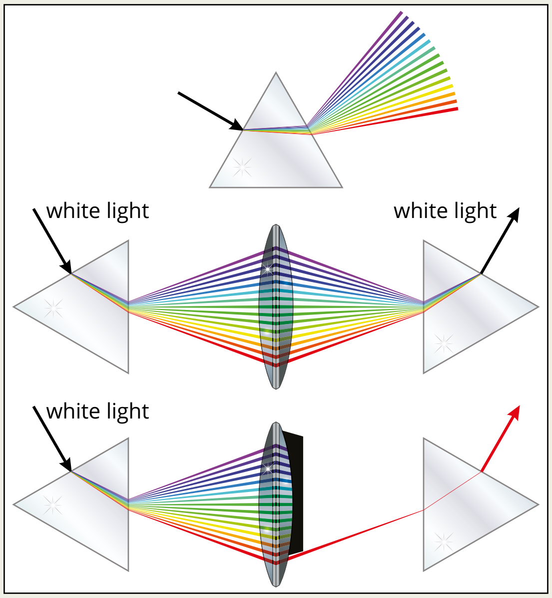


FIGURE 12.5.9 A diagram showing Newton's observations. The first prism breaks the white light into a spectrum and the second prism combines the spectrum back into white light. By blocking most of the spectrum between the two prisms, a single colour can be selected.

Beginning in the early 1800s, the dominant theory in the scientific community was that light consisted of waves. Young's double-slit experiments had shown that light travelling through two slits produced an interference pattern. If light was a particle, no interference pattern would be observed.

In 1900 Max Planck solved the black-body problem with the notion of quantised energy. His calculations revealed the quantisation of light, which seemed to indicate that light is a particle. Planck (and other scientists) viewed this at the time as a problem with his approximations rather than reality.

However, Einstein built on Planck's work, using it as the basis for his explanation of the photoelectric effect. His explanation, published in 1905, required that light travels as particles (later called photons). Although Einstein later won the Nobel prize for that work, his explanation was not widely accepted by the physics community.

SCIENCE AS A HUMAN ENDEAVOUR • CONTINUED

Scientists were still expecting a wave-based explanation of the photoelectric effect to emerge at some time. The turning point for the particle view of light came in 1923 when Arthur Compton, looking for direct evidence of the particle nature of light, performed experiments in which he aimed X-rays and gamma rays at electrons. Compton showed that the rays emerged from the collisions just as particles would. Thus light had momentum and must be a particle.

At about the same time, theorist Louis de Broglie was arriving at his discoveries. de Broglie started with Einstein's ideas about light being a particle and combined this with Einstein's special relativity, which established the equivalence of mass and energy. de Broglie argued that light, being electromagnetic radiation, has energy, and if energy is equivalent to mass, then perhaps light could exhibit the same properties as particles. The leap that de Broglie made in 1923 was that if light (a wave) can behave like a mass (particles), then why couldn't particles behave like a wave?

Erwin Schrödinger in 1926 built on de Broglie's work to explain the properties of electrons in atoms behaving as waves. Werner Heisenberg had already done similar work, but in his mathematical description, electrons were particles. There was also experimental evidence that electrons showed both wave and particle behaviour.

With mounting evidence on both sides of the wave–particle debate, Bohr, in 1927, developed his complementarity principle: some mutually exclusive views of nature could both be true, just not at the same time. The wave–particle duality of both photons and matter was his key example. For any given phenomenon, light can behave as a particle or as a wave, but never both.

Bohr used what was a thought experiment based on Young's double-slit experiments to illustrate this (Figure 12.5.10). A beam of electrons is fired at a barrier. If there was only one slit in the barrier, electrons behave like particles and produce a single line on a detector. Add a second slit, and the electrons interfere and produce interference bands. But even if only one electron at a time is allowed through the barrier, an interference pattern would still be observed even though each electron can only go through one slit.

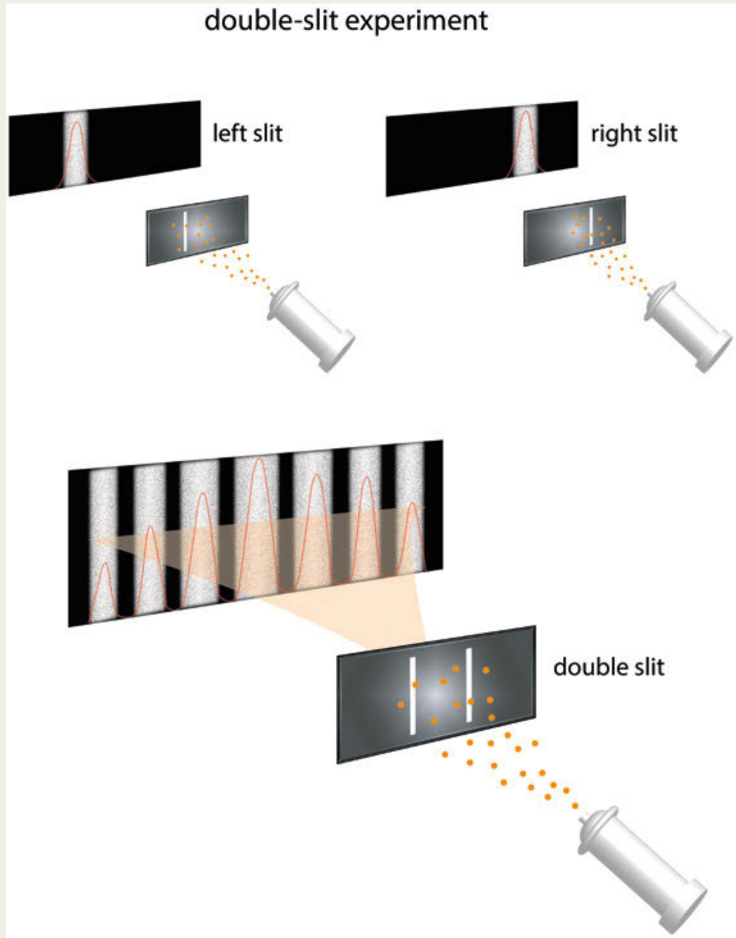


FIGURE 12.5.10 If electrons hit a barrier with just one slit, they produce a single line on the detector, as the electrons behave as a particle. If there are two slits, a diffraction pattern is formed, as the electrons behave as a wave.

This was a thought experiment in Bohr's day, but real experiments of this description have since confirmed that Bohr was correct. Bohr's complementarity principle is now known as the Copenhagen interpretation of quantum mechanics, named after Bohr's home city.

Review

1 Recall why Newton rejected the idea of light behaving as a wave.

2 Create a timeline of the major developments in the investigation of the nature of light. Use the information above and conduct some further research.

12.5 Review

SUMMARY

- Evidence for wave characteristics of light:
  - diffraction
  - interference
  - polarisation
- Evidence for particle characteristics of light:
  - photoelectric effect
  - Compton scattering, which showed light had momentum
- When light interacts with light, generally it does so as a wave.
- When light interacts with matter, it behaves as a particle.

KEY QUESTIONS

Retrieval

1 List the evidence for considering light as a wave.

2 List the evidence for considering light to be a particle.

3 Identify if light is acting like a wave or a particle in the situations listed below.

a the ‘rainbow effect’ seen on the surface of a CD or DVD

b in a photovoltaic cell (solar cell)

c seeing the glow from a light on in a different room

Comprehension

4 Explain why an electron microscope can resolve images in finer detail than an optical microscope.

5 When conducting a photoelectric effect experiment, Hollie and Adith correctly observe that the energy of emitted electrons depends only on the frequency of the incident light and is independent of the intensity.

a Explain how the particle model accounts for this observation.

b Explain why the wave model cannot account for this observation.

Analysis

6 Electron microscopy depends on being able to resolve smaller structures than optical microscopy. The resolving power of a microscope is limited by the wavelength of the probing wave (i.e. light or electrons), and the smaller the wavelength, the better the resolution. Consider the de Broglie wavelength of an electron. Determine whether better resolution is provided by the electron’s velocity being faster or slower.

7 Currently, microprocessor chips are manufactured using electron lithography. This is a process in which a beam of electrons is shone through a mask to etch a coated substrate below, thus creating the patterns required. This process is limited by the diffraction of the electrons through the mask, meaning the structures cannot be smaller than the wavelength of the electrons used. In the hope of seeing smaller structures, current research is being undertaken to see if this this process can be performed with cooled metastable atoms. Calculate the wavelength of cooled neon atoms with a mass of 3.32×10^{-26} kg and a velocity of $525\,\text{m}\,\text{s}^{-1}$.

Chapter review

WS 4.2.7 WS 4.2.8

12

KEY TERMS

absorption spectra
Compton scattering
continuous spectrum
diffraction
emission spectra
energy level diagram
energy levels
ionise
standing wave
wave–particle duality

KEY QUESTIONS

Retrieval

1 Identify why Rutherford and his group ignored any deflections from the electrons in the plum pudding model. Select the best option.
  - **A** Electrons were very evenly spread out, so any deflections would have been cancelled out.
  - **B** The electrons were far too light to cause any deflection of the much heavier alpha particles.
  - **C** They didn't know how many electrons were acting on the alpha particles, so they just ignored their contribution.
  - **D** Being negatively charged, electrons would cause deflections in the opposite direction to the positively charged alpha particles.

2 Recall which of the following series corresponds to visible light.
  - **A** Lyman series
  - **B** Balmer series
  - **C** Paschen series
  - **D** Brackett series

3 Identify which of the following conclusions can be drawn from Louis de Broglie's investigation into the existence of matter waves.
  - **A** All particles exhibit wave behaviour.
  - **B** Only moving particles exhibit wave behaviour.
  - **C** Only charged particles exhibit wave behaviour.
  - **D** Only moving, charged particles exhibit wave behaviour.

4 Select the correct ending to this statement. For an electron and a proton to have the same wavelength:
  - **A** the electron must have the same speed as the proton.
  - **B** the electron must have the same energy as the proton.
  - **C** the electron must have the same momentum as the proton.
  - **D** It is impossible for an electron and a proton to have the same wavelength.

5 Identify which of the following is not a hydrogen-like species:
  - **A** H
  - **B** Li^{2+}
  - **C** Be^{2+}
  - **D** He^{+}

6 Identify which of the following phenomena did not support the idea of light being a wave.
  - **A** single-slit diffraction
  - **B** photoelectric effect
  - **C** polarisation of light
  - **D** double-slit diffraction

7 Describe the plum pudding model of the atom in terms of positive and negative charges.

8 Name the lowest energy level within an atom.

9 Define the term 'energy level'.

Comprehension

10 Describe Rutherford's model of the atom.

11 Describe the limitations of Rutherford's model of the atom.

12 Explain Bohr's model of the atom and how it addressed the limitations of the Rutherford model of the atom.

13 Parvathi wants to know why it is impossible for individual atoms to be observed by an electron microscope. Explain to her why this is not possible.

14 Explain what de Broglie's matter wave concept and a bowed violin string have in common.

15 Explain why all the frequencies of light above the ionisation energy value for a particular atom are continuously absorbed.

16 Explain how our wave and particle models of light parallel the ideas related to electrons and matter waves.

17 Summarise in three statements how the particle (photon) model of light is supported by features of the photoelectric effect. Discuss the implications for the wave model of light in each case.

18 Describe how the wave–particle duality of electrons can be used to explain the quantised energy levels of the atoms.

19 Describe how Niels Bohr explained the observation that when the frequency of incident light was below a certain value, the light would simply pass straight through a sample of hydrogen gas without any absorption occurring.

20 A hydrogen atom in the ground state collides with a 10.0 eV photon. Describe the result of such a collision.

Analysis

21 Elizabeth and Caroline are using spectroscopes to analyse the light emitted by a incandescent light globe and a sodium vapour lamp. Compare their observations. (You could try this at school.)

22 An electron is accelerated across a potential difference of 65 V.
- a Calculate the kinetic energy the electron will gain.
- b Calculate the speed the electron will reach.
- c Determine the de Broglie wavelength of the electron.

23 Discuss why the gold film needed to be very thin in Rutherford's experiments.

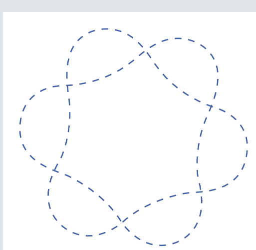
24 Calculate how many gold atoms thick the foil was if the foil used in Rutherford's experiment was 75 nm thick and a gold atom is 300.0 pm across.

25 Consider how Bohr's model of hydrogen includes light quanta and atomic energy states to explain the specific wavelength observed in the hydrogen spectra.

26 a Calculate the de Broglie wavelength of a 160 g ball that has been thrown at 17 $m s^{-1}$.
- b Explain whether it makes sense to treat the ball as wave.

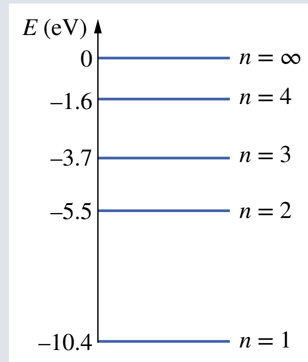
27 Calculate the speed of an electron that has a de Broglie wavelength of 410 nm.

28 The diagram below represents the 'standing-wave state' of an electron in an atom of hydrogen. Determine the value of n that de Broglie would allocate to this pattern.



29 Compare the energy of the ground state for hydrogen (H) (Figure 12.4.4a), the helium ion (He^+) (Figure 12.4.4b) and the lithium ion (Li^{2+}) (Figure 12.4.5). Explain why Li^{2+} has a much greater ground state energy level than He^+ and both have a greater ground state energy level than H.

Use the energy level diagram for mercury below to answer questions 30 and 31.



30 Determine the frequency and wavelength of the light when a mercury atom makes the following transitions.
- a $n = 4$ to $n = 1$
- b $n = 2$ to $n = 1$
- c $n = 4$ to $n = 3$

31 An electron beam of energy 7.0 eV passes through some mercury vapour in the ground state and excites the electrons to the $n = 3$ energy level.
- a List all the possible photon energies that would be present in the emission spectrum when the electrons return from the $n = 3$ energy level to the ground state.
- b Determine the shortest wavelength of light present in the emission spectrum.
- c A photon collides with a mercury atom in the ground state. As a result, a 30.4 eV electron is ejected from the atom. Calculate the wavelength of the incident photon.

32 Refer to Figure 12.2.1 on page 320.
Consider electrons that drop back to the ground state from $n = 3$ in sodium.
- a Determine how many different photon energies can be produced.
- b Calculate the energies, in eV, of the emission transmissions from $n = 3$.

33 A doubly ionised lithium gas sample emits light with a wavelength of 207 nm.
- a Determine the energy of the light emitted in eV.
- b Determine the transition this light corresponds to. (Refer to the energy level diagram for doubly ionised lithium in Figure 12.4.5.)

34 Apply the knowledge that the ground state of hydrogen has an energy of –13.6 eV together with the Rydberg equation to calculate the energy of the $n = 7$ energy level of hydrogen.

35 Consider the energy level diagram for the hydrogen atom shown in Figure 12.4.4a. A photon of energy 14.0 eV collided with a hydrogen atom in the ground state.

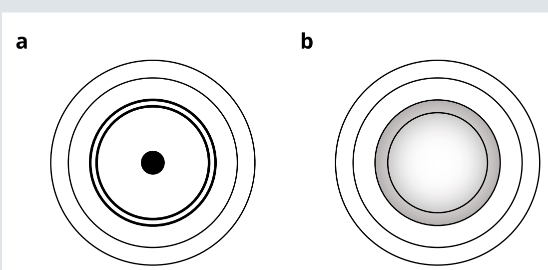
- **a** Explain why this collision will eject an electron from the atom.
- **b** Calculate the energy of the ejected electron in electron volts and in joules.
- **c** Determine the momentum of the ejected electron.
- **d** Determine the wavelength of the ejected electron.

36 Eleanor and Charlie are investigating the spacing of atoms in a powdered crystal sample using electron diffraction. This involves accelerating electrons to known speeds using an accelerating voltage. In a particular experiment, electrons of mass 9.109×10^{-31} kg are accelerated to a speed of $1.75 \times 10^{7}\,\mathrm{m\,s^{-1}}$. The electrons pass through the powdered crystal and the diffraction pattern is observed on a fluorescent screen.

- **a** Calculate the de Broglie wavelength (in nm) of the accelerated electrons.
- **b** Describe the main features of the expected diffraction pattern.
- **c** Determine the difference you would expect to see in the diffraction pattern produced if the accelerating voltage is increased. Explain your answer.
- **d** Explain, using the de Broglie hypothesis, the light and dark rings produced when a beam of electrons is fired through a sodium chloride crystal.

37 A photon with wavelength 640 nm has the same energy as a neutral particle with a velocity of $1.926 \times 10^{4}\,\mathrm{m\,s^{-1}}$. Determine the mass of the particle.

38 The image below shows diffraction images that have been obtained by scattering (a) X-rays and (b) electrons off the same sample, which is made up of many tiny crystals with random orientation. The X-rays have a frequency of 8.3×10^{18} Hz.



- **a** Explain why the electrons and the X-rays have produced the same diffraction pattern.
- **b** Determine the wavelength of the X-ray photons.
- **c** Determine the de Broglie wavelength of the electrons.
- **d** Calculate the momentum of the electrons.
- **e** Determine if the X-rays and the electrons have the same energy.

Knowledge utilisation

39 Observe the energy level diagrams for hydrogen (Figure 12.4.4a), the helium ion (Figure 12.4.4b) and doubly ionised lithium (Figure 12.4.5). Notice that as the principal quantum number n increases, the energy levels get closer together. Hypothesise why this trend occurs.

40 The Rydberg equation used to calculate energy levels for hydrogen atoms is

$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right).$$

Although Rydberg arrived at this formula by empirical methods, the formula can be derived using Bohr's condition and considering the energy (both kinetic and potential) of the electron in a hydrogen atom. Derive the Rydberg equation, and prove that the Rydberg constant is $1.097 \times 10^{7}\,\mathrm{m^{-1}}$. Start by considering the electrical potential energy between the electron and the positive nucleus will be given by:

$$E_e = \frac{-ke^2}{r}$$

where $k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^{9}\,\mathrm{N\,m^2\,C^{-2}}$

e is the magnitude of the charge on the electron (1.60×10^{-19} C)

r is the distance between the nucleus and electron. This is also the radius of the electron's orbit.

CHAPTER 13

The Standard Model

As an extension from the investigations into nuclear physics that were conducted towards the end of World War II, particle physicists began to predict and discover new subatomic particles. Subatomic particles are those smaller than an atom.

At first, physicists built particle detectors and waited for high-energy cosmic rays from space to smash into their targets in order to see what nuclear fragments they could identify. However, these physicists realised that they would need to build more powerful machines such as particle accelerators to probe more effectively into the nucleus. Particle accelerators can accelerate protons and electrons to energies high enough to form particles that theoretical physicists had predicted would exist.

These experiments resulted in the discovery of many previously unknown particles, and led to the development of the Standard Model of particle physics. The Standard Model is the best description so far of the fundamental building blocks of matter and the forces that govern them. This chapter will explore the particles of the Standard Model, how they interact, and how they make up all known matter.

Syllabus subject matter

WS 4.3.1

Topic 3 • The Standard Model

THE STANDARD MODEL

- define the concept of an elementary particle and antiparticle
- recall the six types of quarks
- define the terms *baryon* and *meson*
- recall the six types of leptons
- recall the four gauge bosons
- describe the strong nuclear, weak nuclear and electromagnetic forces in terms of the gauge bosons
- contrast the fundamental forces experienced by quarks and leptons.

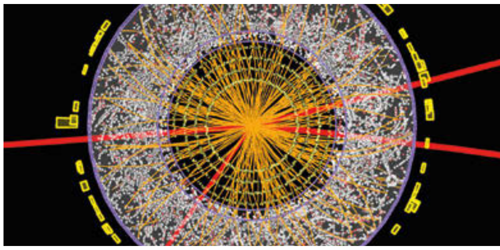
PARTICLE INTERACTIONS

- define the concept of lepton number and baryon number
- recall the conservation of lepton number and baryon number in particle interaction
- explain the following interactions of particles using Feynman diagrams
  - electron and electron
  - electron and positron
  - a neutron decaying into a proton
- describe the significance of symmetry in particle interactions.

SCIENCE AS A HUMAN ENDEAVOUR

- Evidence for the Higgs boson particle

13.1 The Standard Model of particle physics



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

- understand how the Standard Model was developed
- understand the main particles of the Standard Model
- understand that gauge bosons mediate forces between particles
- understand that each matter particle has an antiparticle equivalent.

Currently, the **Standard Model** of particle physics is the most successful theory for predicting the behaviour and properties of the particles that exist in nature. The Standard Model was developed by experiment and theory together. As technology improved, new particles were discovered, and as the model developed, more particles were predicted and then found. The Standard Model is a mathematical description of all known particles and three of the four forces acting between them.

MATTER PARTICLES

In Chapter 12 you learnt about the development of models of the atom, and how the first subatomic particles were discovered. You will be familiar with the idea that the matter around us, and within us, is made of particles, and that the atoms in your body are comprised of protons, neutrons and electrons (Figure 13.1.1).

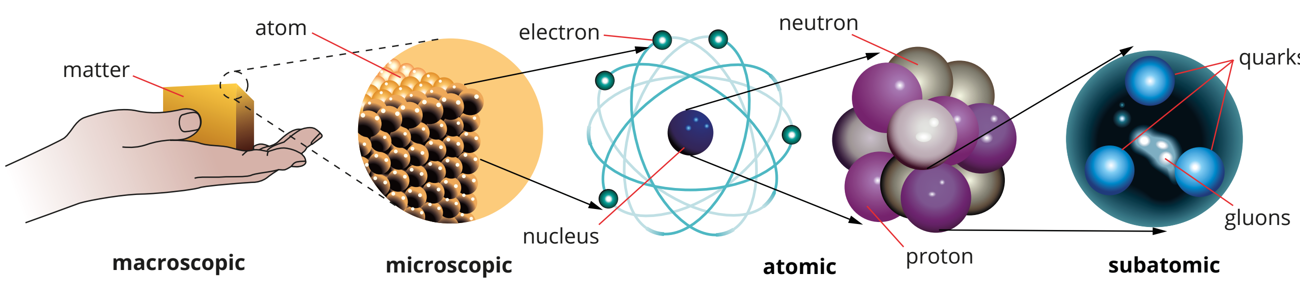


FIGURE 13.1.1 The structure of matter is shown, starting on the left with the macroscopic, and progressing through the microscopic, atomic and subatomic levels.

Since World War II, further research has uncovered about 300 other subatomic particles! Examples include pi-mesons, mu-mesons, kaons, tau leptons and neutrinos. For many years, physicists found it difficult to make sense of this huge array of subatomic particles, once commonly known as the 'particle zoo'. At the time, it was not known that all these particles had an underlying commonality. They were all thought to be fundamental or **elementary particles** at the time and to not be composed of other particles.

Then in 1964, the American physicist Murray Gell-Mann put forward a simple theory. He suggested that most subatomic particles were themselves composed of more fundamental particles called **quarks**. Currently, it is accepted that there are six different quarks, each with different properties (and strange names!): up, down, charm, strange, top and bottom. The latest quark to be identified was the top quark, whose existence was confirmed in 1995.

Subatomic particles that consist of quarks are known as **hadrons**. Quarks are always found bound together to make hadrons; they are not found alone, but they combine to form hundreds of different particles. These particles come in two types: **baryons**, which are made of three quarks, and **mesons**, which are made of a quark and an antiquark (called a quark–antiquark pair). Protons and neutrons are baryons. Protons consist of two up quarks and one down quark, and neutrons consist of one up quark and two down quarks. Hadrons interact via the strong nuclear force—the same force that binds together protons and neutrons in a nucleus.

Electrons belong to another group of particles called **leptons**. This group has six members: electron, electron-neutrino, muon, muon-neutrino, tau and tau-neutrino. Leptons are fundamental particles; they are not composed of quarks, and they interact via the **weak nuclear force**. Quarks and leptons are part of a group of particles that makes up all matter: **fermions**.

> The Standard Model states that all particles of matter are made of one or more of the 12 fundamental or elementary particles (six quarks and six leptons) and their antimatter opposites. An elementary particle is one that, to the best of scientific knowledge, is not comprised of other smaller particles.

Force particles

There is another type of particle in the Standard Model: the particles that mediate interactions between other particles (in other words, they transmit the force between particles). These are called **gauge bosons**, and they describe three of the four fundamental forces in nature:

- the **photon**, which mediates the electromagnetic force
- the **gluon**, which mediates the strong nuclear force
- the $\mathbf{W}^+$, $\mathbf{W}^-$ and $\mathbf{Z}^0$ particles, which mediate the weak nuclear force.

A theoretical particle called the graviton has been predicted to mediate the gravitational force, but it has not yet been found, and is not included in the Standard Model. Figure 13.1.2 illustrates how the known particles are classified under the Standard Model.

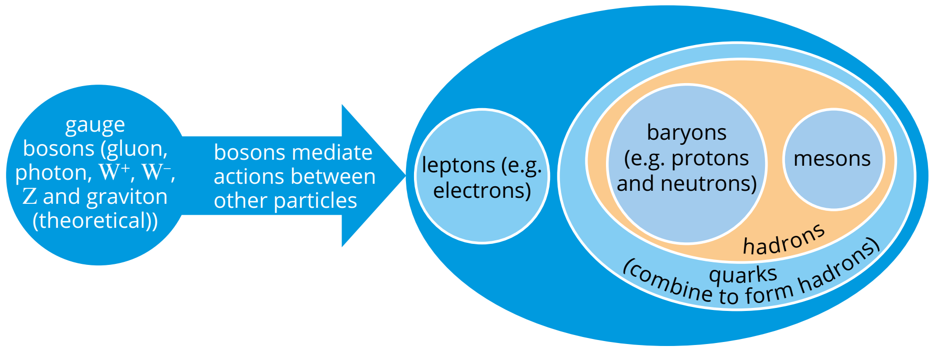


FIGURE 13.1.2 This diagram shows the different groups of elementary and composite particles.

Matter and antimatter

The British theoretical physicist Paul Dirac developed a set of equations that enabled him to make predictions about electrons travelling close to the speed of light. His equations combined the wave equations of quantum mechanics with aspects of Einstein's theory of relativity. From these equations, Dirac predicted the existence of several phenomena, including a particle similar to an electron with a positive charge, which we now know as the positron. He went on to predict the existence of antimatter particles for all particles. This prediction was confirmed by experiment by Carl Anderson at California Institute of Technology in the USA in 1932.

Dirac predicted that particles have what is called an **antiparticle**. Recall from Unit 1 that beta decay can be either beta negative, when an electron is emitted from a nucleus, or beta positive, when a positron is emitted. The positron is the antiparticle of the electron. It has the same properties of mass, charge and lifespan as the electron, but its electric charge and **quantum numbers** (which were introduced in Chapter 12 and will be covered in more detail in the rest of this chapter) are the same in magnitude but have the opposite sign. This is true for all particles and their antiparticles.

When including antiparticles in equations or diagrams, two conventions are used.

- The antiparticle of some particles (including quarks and uncharged leptons) is indicated by placing a bar above the symbol for the normal matter particle. For example, the antiparticle of the electron neutrino (ν_e) is the electron antineutrino ($\bar{\nu}_e$); the antiparticle of the up quark (u) is the antiup quark ($\bar{u}$).
- The antiparticles of some charged particles are given the symbol of the particle but with the opposite sign; for example, the antiparticle of the muon (μ^-) is the antimuon (μ^+).

The existence of quarks is just the beginning. The universe is a vastly more complex and beautiful place than most people realise. The existence of quarks and the strong nuclear force are just two pieces of the puzzle that belong to the discipline of particle physics. The Standard Model of particle physics has developed over more than 100 years and is the life work of many brilliant people.

A significant amount of effort and money has been directed to testing the Standard Model, both theoretically and experimentally. This has led to the construction of larger and larger particle accelerators, such as Fermilab in Chicago, USA, and CERN in Geneva, Switzerland (Figure 13.1.3).

Although the current theory suggests that quarks and leptons are the ultimate fundamental particles that cannot be further divided, the nature of scientific theories and models is such that they can change as new experimental data is obtained. Are quarks and leptons also made of smaller particles? Only time will tell!

Antimatter particles have the same properties of mass, charge and lifespan as their corresponding matter particle, but have electric charge and quantum numbers of opposite sign.

FIGURE 13.1.3 The particle accelerator is at CERN, the European centre for high-energy physics. It accelerates protons from rest to 99.99995% of the speed of light in under 20 s.

13.1 Review

SUMMARY

- The Standard Model of particle physics is the best model physicists have to explain the behaviour of matter and the forces that act on matter.
- The Standard Model of particle physics explains three of the four fundamental forces in the universe (electromagnetism, the strong nuclear force and the weak nuclear force). These forces are mediated by particles called gauge bosons.
- All particles of matter are made of one or more of the 12 fundamental particles (six quarks and six leptons) and their antimatter opposites.
  - Quarks combine to form hadrons and cannot exist alone. The hadrons include baryons (made of three quarks) and mesons (made of a quark–antiquark pair).
  - Leptons are fundamental particles and include the electron.
- Gauge bosons are particles that mediate forces between other particles. They are the photon, which mediates the electromagnetic force, the gluon, which mediates the strong nuclear force, and the W^+, W^- and Z^0 particles, which mediate the weak nuclear force.
- All matter particles have a corresponding antiparticle. Antiparticles have the same properties of mass, charge and lifespan as their corresponding matter particle, but have electric charge and quantum numbers of opposite sign.

KEY QUESTIONS

Retrieval

1 The Standard Model of particle physics explains three of the four fundamental forces in the universe. State which force it does not explain.

2 Refer to the Standard Model of particle physics. State the name that is given to:
- **a** force-mediating particles
- **b** the two types of fundamental particles that make up matter.

3 Electrons are fundamental particles that interact via the weak nuclear force. State what group of particles they belong to.

4 Recall the antimatter particle of the electron.

Comprehension

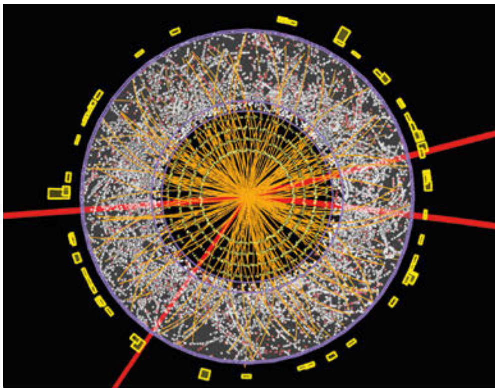
5 Explain the properties of antimatter particles.

6 Lee is explaining the concept of antimatter to his brother and states that neutrons are the antimatter equivalent of protons, because they are similar in mass but have different properties. Explain whether or not he is correct.

Analysis

7 In the 1990s physicists first created anti-hydrogen. Identify the particles that would be needed to create a single antihydrogen atom, given that hydrogen consists of a single electron in a bound state around a single proton.

13.2 Quarks and leptons



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

- understand the difference between baryons and mesons, and how they are made up of six different flavours of quark
- understand baryon number and colour charge
- understand how the electromagnetic charges of individual quarks combine to make up the electromagnetic charge of a particle
- understand that leptons are fundamental particles that interact via the weak nuclear force, and are not made of quarks
- understand the six types of leptons and their properties.

Quarks are fundamental particles. They come in six flavours: up (u), down (d), strange (s), charm (c), bottom (b) and top (t), and interact via the strong nuclear force.

Whether the word 'quark' is pronounced to rhyme with 'stork' or 'bark' is a matter of debate. The name comes from the line 'Three quarks for Muster Mark!', from the book *Finnegan's Wake* by James Joyce.

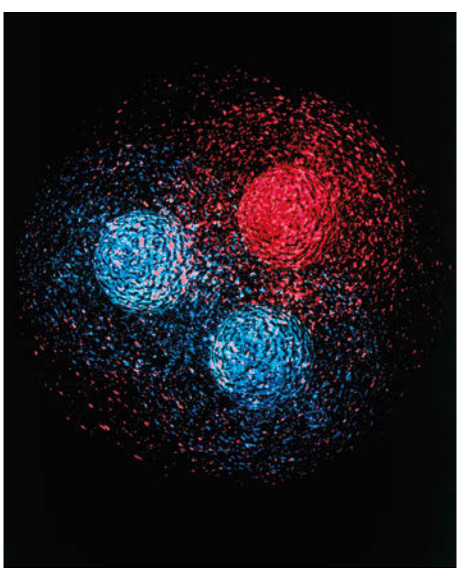


FIGURE 13.2.1 This is an artist's representation of the three quarks that make up a proton.

QUARKS

As you have seen in Module 13.1, protons and neutrons, in the group of particles called hadrons in the Standard Model, are made of even smaller particles called quarks. So far, quarks have only been found as part of larger particles; they have not been found alone. It is thought that they may have existed alone in the very energetic first fractions of a second of the early universe. Quarks, and the particles they make up, interact via the strong nuclear force (the same force that binds together protons and neutrons in a nucleus, as seen in Unit 1).

Quarks have a series of properties that govern how they behave and how they combine to form particles. For this course, you don't need to memorise the different properties of the quarks that make up each particle, but you do need to understand the basics of how quarks combine (Figure 13.2.1).

As explained in the previous module, there are six different types of quarks, which are referred to as the six 'flavours' of quarks. These are:

- up (u)
- down (d)
- strange (s)
- charm (c)
- bottom (b)
- top (t).

Just as electrons have an antimatter particle—the positron—quarks also have antimatter opposites called antiquarks, which have the same quantum numbers but with the opposite sign. The antiquark of the up quark is antiup, not the down quark, and the antiquark of the top quark is the antitop, not the bottom quark. An antiquark has the same symbol as its corresponding quark, but with a line above it: for example, up (u) and antiup ($\overline{u}$). Quarks have the properties of **baryon number** and charge, which must add together to give the total baryon number and charge of the particles that they combine to make (Table 13.2.1). Quarks also have properties called strangeness (s), charm (c), bottomness (b) and topness (t), which are called flavour quantum numbers. These are all conserved when quarks form particles, and in particle interactions.

The charge of particles and ions is compared to the charge on a proton ($+e = +1.60 \times 10^{-19}$ C), so that a proton has a charge of +1 and an electron has a charge of –1. Quarks have non-integer charge; their charge is a fraction (one-third or two-thirds) of the charge on a proton. Leptons have electromagnetic charges of –1 or 0 multiples of 1.60×10^{-19} C.

Table 13.2.1 shows the properties of the six types of quark and six types of antiquark.

TABLE 13.2.1 The quantum numbers for quarks

Particle/ antiparticle name	Symbol	Electromagnetic charge (Q)	Baryon number (B)	Strangeness (S)	Charm (c)	Bottomness (b)	Topness (t)
up	u	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	0
down	d	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	0	0
strange	s	$-\frac{1}{3}e$	$\frac{1}{3}$	–1	0	0	0
charm	c	$+\frac{2}{3}e$	$\frac{1}{3}$	0	+1	0	0
bottom	b	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	–1	0
top	t	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	+1
antiup	$\bar{u}$	$-\frac{2}{3}e$	$-\frac{1}{3}$	0	0	0	0
antidown	$\bar{d}$	$+\frac{1}{3}e$	$-\frac{1}{3}$	0	0	0	0
antistrange	$\bar{s}$	$+\frac{1}{3}e$	$-\frac{1}{3}$	+1	0	0	0
anticharm	$\bar{c}$	$-\frac{2}{3}e$	$-\frac{1}{3}$	0	–1	0	0
antibottom	$\bar{b}$	$+\frac{1}{3}e$	$-\frac{1}{3}$	0	0	+1	0
antitop	$\bar{t}$	$-\frac{2}{3}e$	$-\frac{1}{3}$	0	0	0	–1

All of these different properties might suggest that quarks could combine in thousands of ways to form thousands of different particles. However, there are rules for how quarks combine that limit the number of particles they can form, as will be shown in the next section.

TYPES OF HADRONS

Recall from Module 13.1 that hadrons are particles that are made of quarks. Hadrons are further categorised into two groups, the baryons and the mesons. These are separated according to how many quarks they contain, and a property called baryon number.

Baryons

Baryons are a type of hadron made of three quarks. Examples of baryons include the proton (two up quarks and one down quark, or uud) and the neutron (one up quark and two down quarks, or udd). This group of particles also includes the antiproton ($\bar{p}$) and the antineutron ($\bar{n}$), as well as hundreds of other particles of the particle zoo and their antiparticles, such as lambda-zero (Λ^0) and antilambda-zero ($\bar{\Lambda}^0$), sigma-plus (Σ^+), sigma-zero (Σ^0) and sigma-minus (Σ^-), xi-zero (Ξ^0) and omega-minus (Ω^-).

Quarks also have a property called **colour charge**. Colour charge comes in three different types: red, green and blue for quarks, and antired, antiblue and antigreen for antiquarks. Each quark in a particle must have a different colour charge. These must always combine to give a total colour charge of 'white', in the same way that adding red, green and blue light with make white light. For example, baryons such as the proton and neutron consist of three quarks, and they must have one red, one green and one blue charged quark (Figure 13.2.2a on page 360).

Baryons consist of three quarks, and include protons (uud) and neutrons (udd).

Baryon antiparticles must have one antired, one antigreen and one antiblue charged antiquarks.

Colour charge is a useful way to remember why there are never any 'free' individual quarks by themselves.

Note that the quarks are not actually these colours; these are names given to properties of quarks to help model their properties.

The quarks in a proton must also combine to have the total electromagnetic charge of the proton, which is one 'fundamental charge' ($+e$ or $+1.60 \times 10^{-19}$ C). Therefore quarks must have an electromagnetic charge that is less than the fundamental unit. In fact, quarks have an electromagnetic charge of either $+\frac{2}{3}e$ (up, charm and top) or $-\frac{1}{3}e$ (down, strange and bottom).

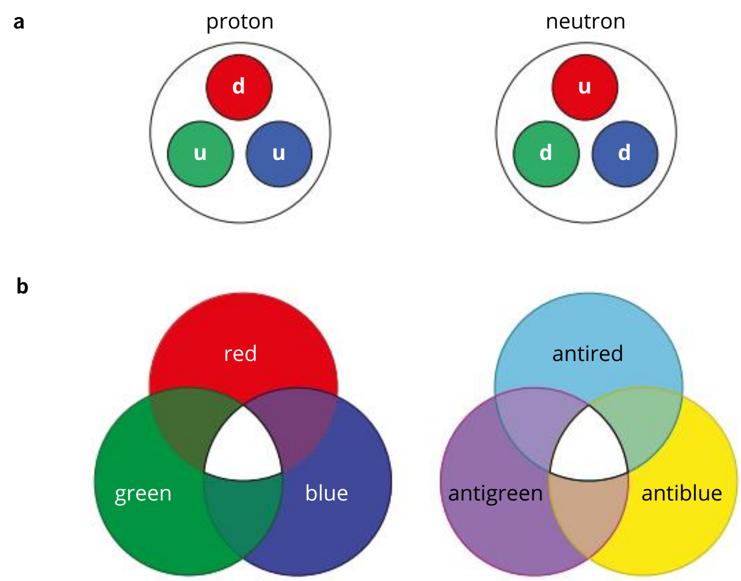


FIGURE 13.2.2 (a) The proton and neutron are both baryons, which are made of three quarks. Each quark in a baryon has a different colour charge. (b) The colour charge of quarks in a particle or antiparticle combines to make white.

The electromagnetic charge of a proton (uud) is therefore made up of:

$$\left(+\frac{2}{3}e\right)+\left(+\frac{2}{3}e\right)+\left(-\frac{1}{3}e\right)=\left(+\frac{3}{3}e\right)=+1e$$

A neutron is made up of two down quarks and an up quark (udd) of different colours, which equates to an electromagnetic charge of:

$$\left(-\frac{1}{3}e\right)+\left(-\frac{1}{3}e\right)+\left(+\frac{2}{3}e\right)=\left(+\frac{0}{3}e\right)=0$$

Worked example 13.2.1

ELECTROMAGNETIC AND COLOUR CHARGE IN BARYONS

a The lambda particle, Λ^0, is made of one up, one down and one strange quark (uds). Using the properties of quarks given in Table 13.2.1 (page 359), prove that the electromagnetic charge of the Λ^0 particle is zero.

Thinking	Working
State the electromagnetic charges of the individual quarks that make up the lambda particle.	The electromagnetic charges of the quarks are: $u = +\frac{2}{3}e$ $d = -\frac{1}{3}e$ $s = -\frac{1}{3}e$
Add the charges to find the charge on the particle.	$\left(+\frac{2}{3}e\right)+\left(-\frac{1}{3}e\right)+\left(-\frac{1}{3}e\right)=0$

b A particular lambda-plus particle, Λ^+, is found to contain one green up quark, one blue down quark and one other unknown quark. The Λ^+ has an electromagnetic charge of +1*e*. Use the properties of quarks given in Table 13.2.1 to determine the electromagnetic charge and colour charge of the other quark, and suggest the types of quark it could be.

Thinking	Working
State the electromagnetic charges of the known quarks that make up the lambda-plus particle and the electromagnetic charge of the lambda-plus particle.	The electromagnetic charges of the quarks and Λ^+ are: $u = +\frac{2}{3}e$ $d = -\frac{1}{3}e$ $\Lambda^+ = +1$
Find the charge on the third quark.	$1-\left(+\frac{2}{3}e\right)-\left(-\frac{1}{3}e\right)=\left(+\frac{2}{3}e\right)$
Find the colour charge of the third quark.	The third quark must be red since the total colour must be white and the green and blue colour charges are already given.
Use Table 13.2.1 to identify the types of quark it could be.	Quarks with a $+\frac{2}{3}e$ charge are up, charm and top. (In fact, it is a charm quark, and the Λ^+ is udc.)

➤ Try yourself 13.2.1

ELECTROMAGNETIC AND COLOUR CHARGE IN BARYONS

a The sigma-minus particle, Σ^-, is made of two down quarks and one strange quark (dds). Use the properties of quarks given in Table 13.2.1 to prove that the electromagnetic charge of the Σ^- particle is −1*e*.

b A particular sigma-zero particle, Σ^0, is found to contain one red up quark, one green down quark and one other unknown quark. The Σ^0 has an electromagnetic charge of zero. Use the properties of quarks given in Table 13.2.1 to determine the electromagnetic charge and colour charge of the other quark, and suggest what types of quark it could be.

Table 13.2.2 gives a summary of some baryons and their constituent quarks. It also shows baryon number. The baryon number of each quark is $+\frac{1}{3}$, so the three quarks that make up a baryon add to give a baryon number of +1. Antiquarks have a baryon number of $-\frac{1}{3}$, so three antiquarks together have a baryon number of −1.

TABLE 13.2.2 Baryons and their constituent quarks

Baryon name	Symbol	Baryon number (B)	Strangeness (S)	Charm (c)	Bottomness (b)	Topness (t)	Quarks
proton	p	+1	0	0	0	0	uud
antiproton	$\bar{p}$	−1	0	0	0	0	$\bar{u}\bar{u}\bar{d}$
neutron	n	+1	0	0	0	0	udd
antineutron	$\bar{n}$	−1	0	0	0	0	$\bar{u}\bar{d}\bar{d}$
lambda-plus	Λ^+	+1	0	+1	0	0	udc
lambda-zero	Λ^0	+1	−1	0	0	0	uds
sigma-plus	Σ^+	+1	−1	0	0	0	uus
sigma-zero	Σ^0	+1	−1	0	0	0	uds
sigma-minus	Σ^-	+1	−1	0	0	0	dds
xi-zero	Ξ^0	+1	−2	0	0	0	uss
xi-plus	Ξ^+	+1	−2	0	0	0	dss
omega-minus	Ω^-	+1	−3	0	0	0	sss

Mesons

The other type of hadron is the meson. Mesons are unstable, short-lived particles, with lifetimes of billionths of a second or less. Due to their short lifetime, they are harder to study than baryons such as protons and neutrons. In this group are many particles and their antimatter particles, such as the pion (π^+), antipion (π^-) and pi-zero (π^0), the kaon (K^+) and antikaon (K^-), and the eta (η^0). (The antimatter particle of the eta is considered to be itself. Understanding this is beyond the scope of this course.)

Mesons consist of two quarks: a quark–antiquark pair.

Mesons are made of two quarks: a quark and an antiquark, called a quark–antiquark pair. For example, the pion-plus (π^+) consists of an up quark and an antidown quark ($u\bar{d}$) (Figure 13.2.3). Each quark has a colour charge, and, like baryons, their colour charges must add up to 'white'; for example:

- red + antired
- blue + antiblue
- green + antigreen.

As for baryons, the electromagnetic charges of the quarks in a meson add to give the total charge of the particle they make up. For example, the electromagnetic charge of the pion-plus $(u\bar{d})$ is $\left(+\frac{2}{3}e\right)+\left(+\frac{1}{3}e\right)=\left(+\frac{3}{3}e\right)=+1e$.

The baryon number of a meson is zero. This is because the baryon numbers of the quarks that make up the meson cancel out. For example, a pion-plus is made up of an up quark and an antidown quark $(u\bar{d})$: $\left(+\frac{1}{3}\right)+\left(-\frac{1}{3}\right)=\left(\frac{0}{3}\right)=0$. You can think of the baryon number as indicating whether a particle is a baryon (1) or not (0). There is no corresponding quantity called a meson number. Table 13.2.3 shows some of the many mesons and their constituent quarks.

TABLE 13.2.3 Various mesons and their constituent quarks.

Meson name	Symbol	Baryon number (B)	Strangeness (S)	Charm (c)	Bottomness (b)	Topness (t)	Quarks
pion-plus	π^+	0	0	0	0	0	$u\bar{d}$
pion-minus	π^-	0	0	0	0	0	$\bar{u}d$
kaon-plus	K^+	0	+1	0	0	0	$u\bar{s}$
kaon-minus	K^-	0	–1	0	0	0	$\bar{u}d$
rho-plus	ρ^+	0	+1	0	0	0	$u\bar{d}$
rho-minus	ρ^-	0	–1	0	0	0	$\bar{u}d$
phi	ϕ	0	0	0	0	0	$\bar{s}s$
D-plus	D^+	0	0	+1	0	0	$c\bar{d}$
D-zero	D^0	0	0	+1	0	0	$c\bar{u}$
D-plus-s	Ds^+	0	+1	+1	0	0	$c\bar{s}$
B-minus	B^-	0	0	0	–1	0	$b\bar{u}$
upsilon	Υ	0	0	0	0	0	$b\bar{b}$

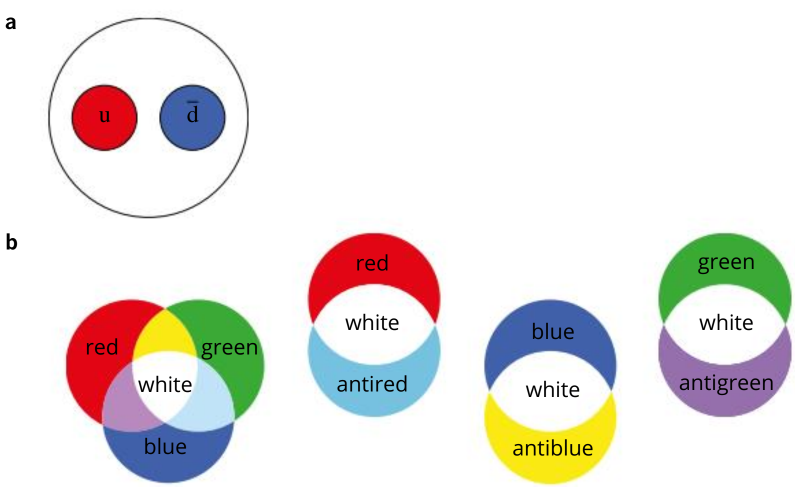


FIGURE 13.2.3 (a) The pion-plus (π^+) meson consists of an up quark and an antidown quark ($u\bar{d}$). (b) Baryons always have red, green and blue colour charge combinations, as shown on the left. Mesons always have a colour–anticolour charge, as shown in the other three diagrams.

LEPTONS

The other group of matter particles, apart from hadrons, are leptons. The particles in this group interact by the weak nuclear force. Leptons that carry an electromagnetic charge can also interact via the electromagnetic force. Leptons do not interact via the strong nuclear force as quarks and hadrons do, and they are fundamental particles—they are not made up of smaller particles. Leptons do not carry a colour charge.

The leptons you will be most familiar with are the electron and the electron neutrino, but the group also includes the muon and tau particles, as well as their corresponding neutrinos, and their antimatter opposites. Recall from Chapter 10 that particles called muons could reach the surface of Earth before they decayed because of time dilation and length contraction.

Leptons are thought to come in only six types: electrons (e^-), muons (μ^-) and tau (τ^-), and their corresponding neutrinos—the electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). Each of these six particles has a corresponding antimatter particle: the positron, electron antineutrino, antimuon, muon antineutrino, antitau and tau antineutrino.

Recall from Unit 1 that an electron ejected from the nucleus in a beta negative decay is always emitted with an antineutrino. In a beta positive decay, an antimatter positron is emitted with a **neutrino**.

Leptons are fundamental particles, and interact via the weak nuclear force. They include the electron, muon and electron neutrino.

Neutrinos have a very small mass compared to an electron, and they interact so weakly with matter that they can go through the entire Earth in the way that photons (light) go through a pane of glass. As neutrinos have zero charge, they do not experience the electromagnetic force. Another lepton particle, the muon (μ^-), can also be emitted from the nucleus along with the muon antineutrino ($\bar{\nu}_\mu$) in a way similar to the beta particle. Muons are very similar to electrons, but 207 times larger, and do not make up everyday matter.

Leptons have electron, muon and tau **lepton numbers**. These are the equivalent of the baryon number for hadrons. An electron has an electron lepton number of +1, a muon lepton number of 0 and a tau lepton number of 0. An electron neutrino has an electron lepton number of +1, a muon lepton number of 0, and a tau lepton number of 0, and so on. The antimatter equivalents have negative lepton numbers—the positron and electron antineutron both have an electron lepton number of –1, and so on. Lepton numbers help to explain why particles decay in the way they do. This will be discussed in Module 13.4.

Table 13.2.4 is a summary of leptons and their properties.

TABLE 13.2.4 The properties of leptons

Lepton name	Symbol	Charge	Electron lepton number	Muon lepton number	Tau lepton number
electron	e^-	–1	+1	0	0
electron neutrino	ν_e	0	+1	0	0
muon	μ^-	–1	0	+1	0
muon neutrino	$\nu\mu$	0	0	+1	0
tau	τ^-	–1	0	0	+1
tau neutrino	ν_τ	0	0	0	+1

Table 13.2.5 shows the six antileptons and their properties.

TABLE 13.2.5 The properties of antileptons

Antiparticle name	Symbol	Charge	Electron lepton number	Muon lepton number	Tau lepton number
positron	e^+	+1	–1	0	0
electron antineutrino	$\bar{\nu}_e$	0	–1	0	0
antimuon	μ^+	+1	0	–1	0
muon antineutrino	$\bar{\nu}_\mu$	0	0	–1	0
antitau	τ^+	+1	0	0	–1
tau antineutrino	$\bar{\nu}_\tau$	0	0	0	–1

Table 13.2.6 is a summary of the fundamental particles that make up matter, and some of their properties.

TABLE 13.2.6 A summary of the fundamental particles and their properties

Particle type	Quark	Lepton
particles	up (u) down (d) charm (c) strange (s) top (t) bottom (b)	electron (e) electron neutrino (ν_e) muon (μ) muon neutrino (ν_μ) tau (τ) tau neutrino (ν_τ)
antiparticles	antiup ($\bar{u}$) antidown ($\bar{d}$) anticharm ($\bar{c}$) antistrange ($\bar{s}$) antitop ($\bar{t}$) antibottom ($\bar{b}$)	positron (e^+) electron antineutrino ($\bar{\nu}_e$) antimuon (μ^+) muon antineutrino ($\bar{\nu}_\mu$) antitau (τ^+) tau antineutrino ($\bar{\nu}_\tau$)
interacts via	strong nuclear force	weak nuclear force
exists alone?	No, is always part of a larger particle.	yes
makes up	hadrons, split into: mesons (quark + antiquark) baryons (three quarks or three antiquarks)	–

13.2 Review

SUMMARY

- Quarks are fundamental particles and interact via the strong nuclear force.
- There are six flavours of quark: up, down, strange, charm, top and bottom.
- Quarks combine to make up hadrons, which are subdivided into baryons and mesons.
- Baryons contain three quarks or three antiquarks, and have a baryon number of 1 for matter, and –1 for antimatter.
- Mesons consist of a quark–antiquark pair, and have a baryon number of 0.
- Quarks have a property called colour charge, which can be red, green or blue (or antired, antigreen or antiblue). The colour charge of baryons and mesons must always be white: either red + green + blue or antired + antigreen + antiblue for baryons, and red + antired, blue + antiblue or green + antigreen for mesons.
- Quarks also have electromagnetic charge, which adds to give the charge of the particle.
- Leptons are fundamental particles, and interact via the weak nuclear force. They also interact via the electromagnetic force if they carry charge.
- The group of leptons consists of six particles: the electron, the muon and the tau, and their neutrinos.
- Each of these leptons has a corresponding antimatter particle.
- Leptons interact via the weak nuclear force, and also by the electromagnetic force if they carry charge.
- Leptons have a property called the lepton number, which helps explain why subatomic particles decay in the way they do.

KEY QUESTIONS

Retrieval

1 State two ways in which leptons differ from hadrons.

2 Recall the quarks that make up:
   - **a** a proton
   - **b** a neutron
   - **c** a pion-plus
   - **d** an antiproton.

3 State the six types of leptons and their antimatter equivalents.

4 State the two forces that leptons can experience.

Comprehension

5 Explain, with reference to colour charge, why quarks are not seen on their own.

6 Describe the difference between baryons and mesons, with reference to their constituent quarks and baryon number.

7 Explain the difference between the electromagnetic charge on lepton particles (e.g. the electron), on neutrinos and on lepton antiparticles.

Analysis

8 Determine why a proton is a baryon, but a pion-plus is not. Refer to the baryon numbers of their constituent quarks.

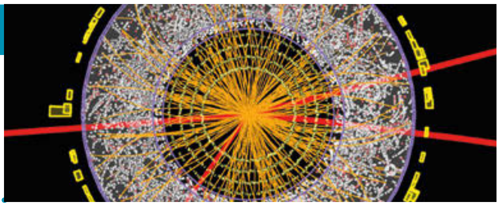
9 If the up, charm and top quarks have an electromagnetic charge of $+\frac{2}{3}e$ and the down, strange and bottom quarks have an electromagnetic charge of $-\frac{1}{3}e$, and antiquarks have an electromagnetic charge that is equal but of opposite sign, calculate the electromagnetic charge on:
   - **a** a proton (uud)
   - **b** a neutron (udd)
   - **c** a kaon-plus ($u\bar{s}$).

10 George and Johannah are arguing over antimatter particles. George says that the antiparticle of an antiproton is a proton, while Johannah says that the antiparticle of an antiproton is a positron. Determine who is correct, and explain why with reference to its constituent quarks.

13.3 Gauge bosons

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

- understand how forces can be thought of in terms of the exchange of particles called gauge bosons
- understand which gauge boson mediates which force.



In the previous modules of this chapter, you learnt about three of the four fundamental forces that can act between particles and which govern their behaviour:

- the strong nuclear force
- the electromagnetic force
- the weak nuclear force.

Each of these forces has a different strength and acts over different distances. For example, the strong nuclear force, which acts on quarks (and the particles made of quarks, such as protons and neutrons), acts over very short distances (i.e. on the subatomic scale), but is very large. Like gravity, the electromagnetic force acts over an infinite range, but is much stronger than gravity and much weaker than the strong nuclear force. The weak nuclear force is stronger than gravity, but is weaker than the electromagnetic and strong nuclear forces.

One of the fundamental assumptions of the Standard Model is that these forces arise through the exchange of particles called gauge bosons. Bosons are often called force-carrying, force-mediating or exchange particles. (Note that *gauge* bosons are commonly referred to as bosons, as we do here; however, gauge bosons are a subgroup of the larger boson group of particles with their own distinct properties. This larger boson group includes the famous Higgs boson, which interacts with particles to give them mass.)

Each force has its own boson. According to the notion of wave–particle duality, each of these forces can be considered as particles. (Wave–particle duality was described in detail in Chapters 11 and 12.)

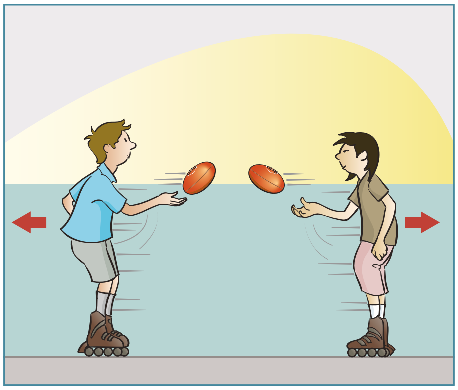


FIGURE 13.3.1 Inline skaters exchanging footballs act as an analogy for particles experiencing repulsive forces due to the exchange of gauge bosons.

FORCES THROUGH EXCHANGE OF PARTICLES

Previously, forces were thought of as being exerted on particles by fields. For example, you have seen in your studies of physics that there is a region around a charged particle where another charged particle experiences a force. This may seem quite puzzling as the force is applied without any direct interaction by the two particles. The same effect is felt when two magnets are brought together. The magnets do not need to touch in order to feel the force between them. In the Standard Model this puzzlement is resolved, as forces are thought to be exerted through the exchange of other particles.

To use an analogy to see how a force can be exerted on two particles through the exchange of another particle, consider Figure 13.3.1. Two inline skaters stand stationary and then begin to pass footballs back and forth to each other. As they do this, they will begin to move away from each other. This is due to the conservation of momentum each time they throw and catch the ball. This situation could be likened to two particles experiencing a repulsive (pushing away) force.

A force of attraction can also be illustrated using the same analogy (Figure 13.3.2). If the two skaters now exchange the footballs by trying to grab them out of each other's hands, they will exert a force of attraction on each other. This would cause them to move together and can be likened to two particles experiencing an attractive force.

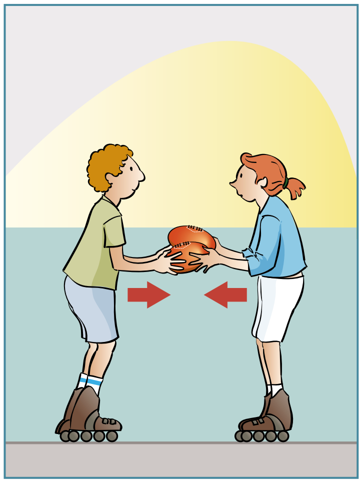


FIGURE 13.3.2 Inline skaters trying to grab footballs act as an analogy for particles experiencing attractive forces due to the exchange of gauge bosons.

Going back to a particle level, Figure 13.3.3 (page 368) represents an electron approaching another electron. Each electron emits a photon that is absorbed by the other.

This causes each electron to experience a force of repulsion due to their electric charges. The photon is responsible for the electromagnetic force acting on the two electrons.

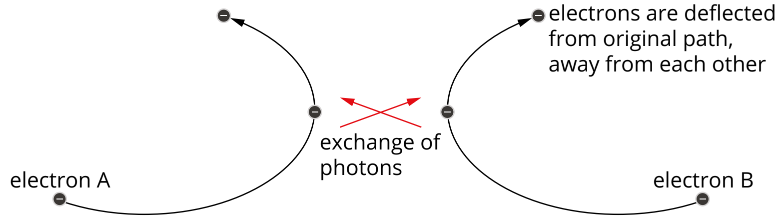


FIGURE 13.3.3 Two electrons approach each other, are repelled and then move away from each other. The two electrons exchange a photon that is the carrier of the electromagnetic force.

Table 13.3.1 gives a summary of the nature of these particles, their strengths and the range over which they can exert a force.

TABLE 13.3.1 Features of the various gauge bosons and the force they are responsible for. (Gravity is included here for completeness, although it is not part of the Standard Model.)

Force	Nature	Relative strength	Range (m)	Force carrier (gauge boson)
strong nuclear	bonds nucleons together, acts between quarks	1	10^{-15} (~size of nucleus)	gluon
electromagnetic	responsible for both electric and magnetic fields exerting forces of attraction or repulsion	$\frac{1}{137} \approx 0.0073$	infinite	photon
weak nuclear	causes radioactive decay	10^{-6}	10^{-18} (less than the width of a proton)	W^+, W^- and Z^0
gravity	a force of attraction between any two objects with mass	6×10^{-39}	infinite	graviton (theoretically predicted but not yet observed)

In the Standard Model, three of the four fundamental forces are exerted via the exchange of particles called gauge bosons. These are:

- strong nuclear force—gluon
- electromagnetic force—photon
- weak nuclear force—W^+, W^- and Z^0 particles.

Gravity and the graviton

The Standard Model of particle physics successfully describes the strong nuclear, electromagnetic and weak nuclear forces. Theoretical physics predicts that there should be a gauge boson for gravity too, called a graviton. If this existed, physicists might be able to create a grand unified theory (GUT) that could explain the fundamental behaviour of *all* matter in the universe. However, the graviton has not yet been found.

The behaviour of objects due to the force of gravity is described with spectacular accuracy by Einstein's general theory of relativity. This theory basically says that mass tells space how to bend, and bent space tells mass how to move. It applies on the largest scales in the universe and even correctly predicted how binary black holes would emit gravitational waves.

Quantum mechanics mathematically describes the behaviour of subatomic particles. This theory covers the interactions of matter and energy that occur on the smallest scales and is one of the foundations of the Standard Model of particle physics.

Einstein's theory of general relativity does not work for small scales and high energies. Subatomic particles exist on very small scales and, in many cases, are at very high energies. Therefore, the Standard Model of particle physics cannot accommodate gravity and its theoretical exchange particle, the graviton. General relativity and quantum mechanics meet in the physics of black holes. Physicists still do not know exactly what is happening inside a black hole, and until there is an accepted theory that can explain the gravity of particles, black holes remain a mystery.

The following chart (Figure 13.3.4) summarises the classification of particles in the Standard Model of particle physics.

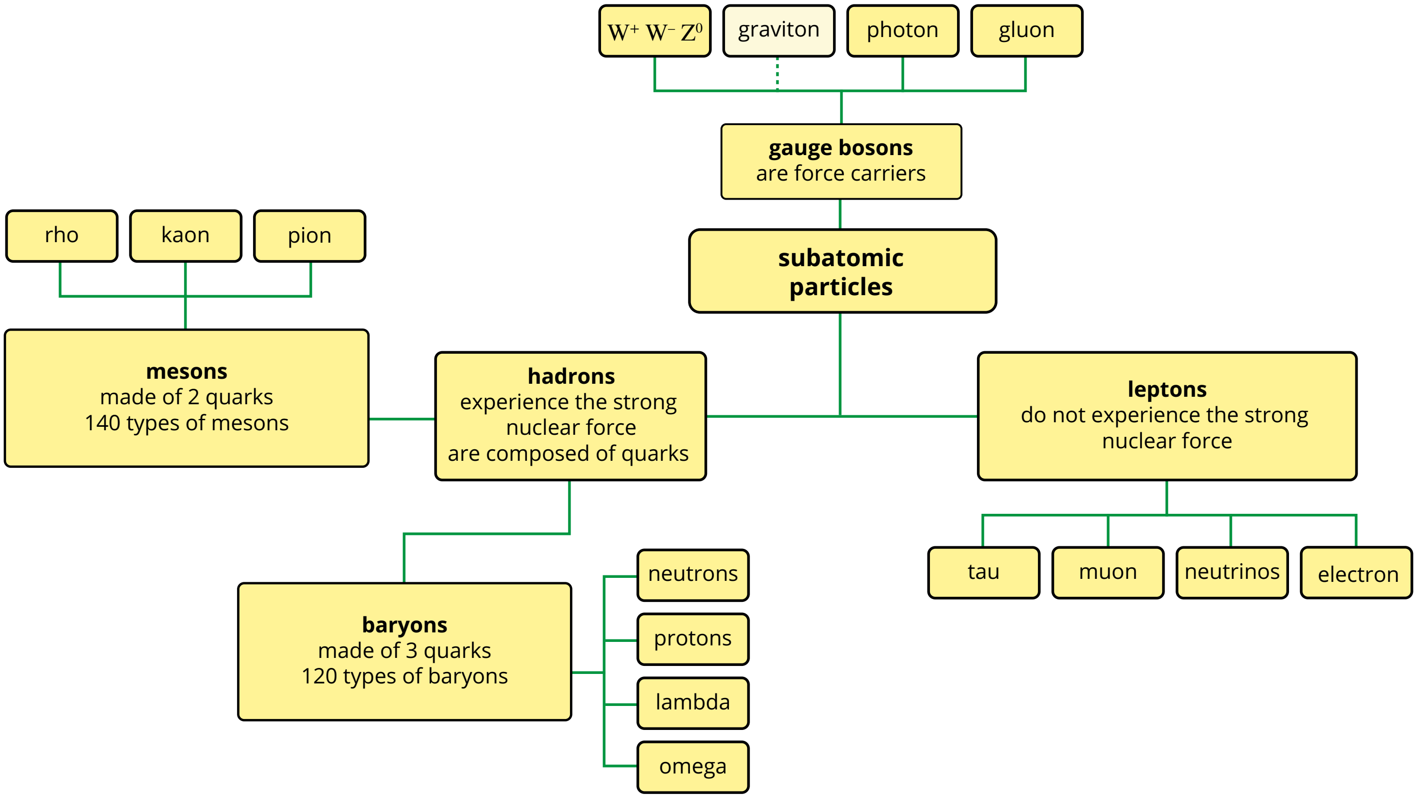


FIGURE 13.3.4 Classification of particles in the Standard Model of particle physics

13.3 Review

SUMMARY

- The four forces are the strong nuclear force, the electromagnetic force, the weak nuclear force and the gravitational force.
- In the Standard Model, three of these forces are mediated by the exchange of particles called gauge bosons:
  - strong nuclear—gluon
  - electromagnetic—photon
  - weak nuclear—W^+, W^- and Z^0
- Gravity is not a part of the Standard Model—its theoretical gauge boson, the graviton, has not yet been found.

KEY QUESTIONS

Retrieval

1 Define ‘gauge boson’.

2 A common analogy used to explain how forces are mediated by the exchange of particles involves two skaters passing balls to each other. State what the balls represent in this analogy.

3 State the four fundamental forces and the particles that mediate three of them.

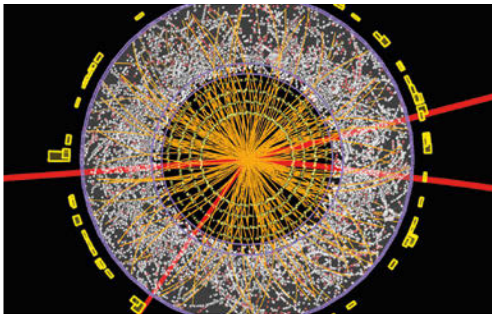
Comprehension

4 Physicists have not yet managed to successfully integrate gravity into the Standard Model of particle physics. Explain why the omission of gravity is not a disaster for the accuracy of the Standard Model.

Analysis

5 Some elementary particles are their own antiparticle. For this to be the case, the particle needs to be electrically neutral. Determine which of the gauge bosons (photon, Z^0, W^-) are their own antiparticles.

13.4 Particle interactions



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

- understand what happens when matter and antimatter meet
- understand basic particle interactions and how they are represented using Feynman diagrams
- understand how mass and energy are conserved in particle interactions
- understand the role of symmetry and conservation laws in particle interactions.

Particle physicists strike a serious problem when they study new particle interactions. Even with the laws of conservation of energy, momentum and charge, many products are theoretically possible with the energy available.

Observations show that only a small number of the possible outcomes of an interaction actually occur. Once a large number of events have been observed, it may become clear there are other 'rules' that are important. This means that other properties and conservation laws are needed to summarise the rules, such as the baryon number and lepton number discussed earlier in this chapter.

In this module, you will learn about the conservation laws that govern particle interactions. You will also learn how to show particle interactions graphically in Feynman diagrams.

CONSERVATION LAWS: MASS–ENERGY

You will recall from *Pearson Physics 11 Queensland* that momentum is conserved in all collisions, and that energy too is conserved, even if it is sometimes transformed into other forms such as heat and sound. Energy and momentum are also conserved in particle interactions. In addition, since mass and energy are equivalent, it is necessary to consider:

- the total energy contained in the rest masses of the particles
- the kinetic energy before and after the event.

A simple example is the decay of a stationary neutron to produce a proton, an electron, and an electron antineutrino (Figure 13.4.1).

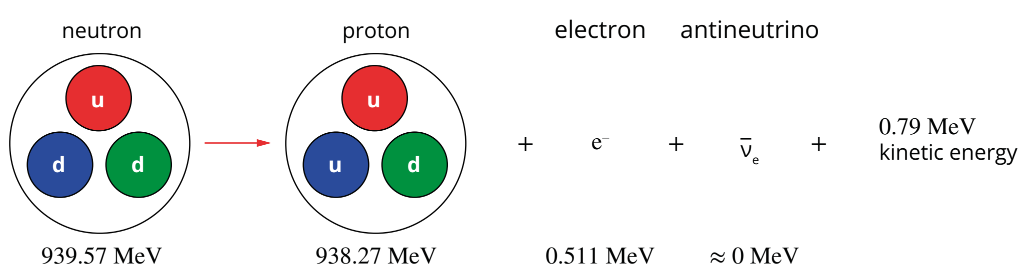


FIGURE 13.4.1 The decay of a stationary neutron is shown to illustrate the conservation of mass–energy. The total energy of the system is conserved.

The mass of the products of the decay of a stationary neutron is less than the mass of the original neutron. Since the neutron is originally stationary, the balance of the energy must be carried away as the kinetic energy of the products. The energy in the mass of the particles is determined using $E = mc^2$, where m is their rest masses. So the mass of a particle is often expressed in units of energy such as MeV, as seen in Figure 13.4.1.

This decay will obey the law of conservation of energy, as the energy stored within the mass of the neutron before the decay is equal to the sum of the energies stored within the mass of the products, plus their kinetic energies, after the decay.

The momentum carried away by the products would have to be in different directions so that it adds to zero. This would mean that the law of conservation of momentum is obeyed so that the total momentum before (zero) is equal to the total momentum after (zero).

MATTER VERSUS ANTIMATTER: ANNIHILATION

An interesting example of the conservation of energy is seen when matter and antimatter meet. A matter particle and its antimatter particle will destroy, or **annihilate**, each other when they collide, releasing energy according to $E = mc^2$. This is observed and exploited on a daily basis in experiments and applications involving antimatter.

Figure 13.4.2 shows an antiproton entering along the track marked L (top), before colliding with a proton. When the proton and antiproton mutually annihilate, the mass of the proton and antiproton is converted to energy.

Another example is the annihilation of an electron and positron. The matter in the electron and positron is converted into energy in the form of two photons. These photons have an energy equivalent to the mass of the electron and positron, according to $E = mc^2$.

The opposite of annihilation is also observed. This is called particle–antiparticle **pair production**. Energy in the form of a photon can create a particle–antiparticle pair if the photon has energy greater than or equal to the mass of the particle–antiparticle pair. Pair production also illustrates the relationship between mass and energy in Einstein's equation. The tracks of the new particles form the 'star' pattern that can be seen in Figure 13.4.2.

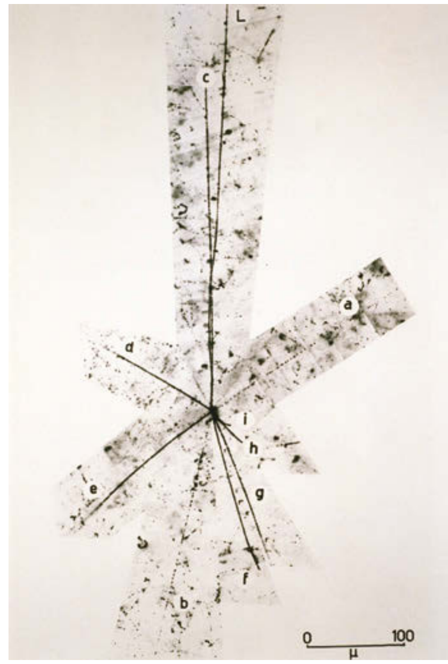


FIGURE 13.4.2 This image records a proton–antiproton annihilation. This event was recorded in 1955 in a photographic emulsion at the Bevatron accelerator at the Lawrence Berkeley Laboratory, California, USA.

Worked example 13.4.1

CONSERVATION OF MASS–ENERGY

A 2.00 MeV gamma ray photon interacts with an atomic nucleus and an electron–positron pair is produced. Each particle created has a mass of 0.511 MeV. Calculate how much kinetic energy is carried away by the particle–antiparticle pair produced.

Thinking	Working
The energy of the gamma ray photon is conserved and is equal to the total mass–energy of the particles produced plus the kinetic energy (E_k) of those particles.	$2.00\ \text{MeV} = 2 \times 0.511\ \text{MeV} + E_k$
Solve for the kinetic energy.	$2.00\ \text{MeV} = 1.022\ \text{MeV} + E_k$
Calculate the answer.	$E_k = 0.978\ \text{MeV}$

➤ Try yourself 13.4.1

CONSERVATION OF MASS–ENERGY

A 1.20 MeV gamma ray photon interacts with an atomic nucleus and an electron–positron pair is produced. Each particle created has a mass of 0.511 MeV. Calculate how much kinetic energy is carried away by the particle–antiparticle pair produced.

Matter and antimatter particles are annihilated when they meet, with a release of energy according to $E = mc^2$.

CONSERVATION LAWS: CHARGE, LEPTON AND BARYON NUMBERS

In Module 13.2, you learnt about the properties called baryon and lepton numbers. These are just two of a number of properties that describe particles, and must also be conserved in all particle interactions.

Conservation of lepton number can be seen when a muon decays into an electron, an electron antineutrino and a muon neutrino:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

> Conservation laws can be used to predict the outcome of particle interactions.

Lepton numbers in this decay must be conserved.

For the electron lepton number: $0 \rightarrow 1 + (-1) + 0 = 0$

For the muon lepton number: $+1 \rightarrow 0 + 0 + (+1) = +1$

You can see that each type of lepton number is the same before and after the decay. Note that the different types of lepton number are conserved separately, rather than being combined.

Similarly, electromagnetic charge is conserved before a nd after the decay: the muon has a charge of $-1e$, as does the electron; the neutrinos do not carry charge.

Figure 13.4.4 on page 373 shows beta-minus decay, which involves a neutron changing into a proton within a nucleus, with the emission of an electron and an electron antineutrino from the nucleus:

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

Lepton numbers, baryon numbers and electromagnetic charge must all be conserved in this decay.

For the electron lepton number: $0 \rightarrow 0 + (+1) + (-1) = 0$

For the baryon number: $+1 \rightarrow (+1) + 0 + 0 = +1$

For the electromagnetic charge: $0 \rightarrow (+e) + (-e) + 0 = 0$

You can see that the electromagnetic charge is conserved at all points of this decay. The W^- boson carries a charge of $-1e$, which balances the $+1e$ charge of the proton, so that the products of the decay have a combined charge of zero, which matches the charge on the original neutron. The W^- boson then becomes an electron (charge of $-1e$) and electron antineutrino (charge of zero), so charge is conserved. At the quark level, a down quark (charge $-\frac{1}{3}e$) changes to an up quark (charge $+\frac{2}{3}e$), a difference of $+1e$, which is balanced by the $-1e$ charge on the W^- boson.

Other properties are conserved in interactions, such as strangeness, charm and bottomness. Quantities called spin and parity are also conserved, but these are beyond the scope of this course.

Worked example 13.4.2

CONSERVATION IN PARTICLE INTERACTIONS

Prove that the following interaction is possible using conservation of electromagnetic charge, lepton number and baryon number:

$$p \rightarrow n + e^{+} + \nu_e$$

Thinking	Working
Consider the electromagnetic charge in the interaction.	charge on a proton = +1*e* charge on a neutron = 0 charge on a positron = +1*e* charge on an electron neutrino = 0 (+1) = 0 + (+1) + 0, therefore charge is conserved
Consider the baryon numbers in the interaction.	lepton number of proton = 0 lepton number of neutron = 0 electron lepton number of positron = –1 electron lepton number of electron neutrino = +1 0 = 0 + (–1) + (+1), therefore lepton number is conserved
Consider the lepton numbers in the interaction. The only leptons in this interaction are an antielectron (a positron) and an electron neutrino, so we do not need to consider the conservation of muon lepton number or tau lepton number.	baryon number of a proton = +1 baryon number of a neutron = +1 baryon number of a positron = 0 baryon number of an electron neutrino = 0 (+1) = (+1) + 0 + 0, therefore baryon number is conserved

➤ Try yourself 13.4.2

CONSERVATION IN PARTICLE INTERACTIONS

Prove that the following interaction is not possible by considering, in turn, the conservation of electromagnetic charge, baryon number and lepton number:

$$\bar{\nu}_e + n \rightarrow p + e^-$$

FEYNMANN DIAGRAMS

Particle interactions and decays can be illustrated using a simple diagram called a **Feynman diagram**.

Interactions between particles that produce some change, or are observed by a particle detector, are commonly known as events. Those interactions that result in the formation of new particles are sometimes referred to as reactions. Interactions can involve attractive or repulsive forces, decay, annihilation, or pair production.

An example of a repulsive interaction involving the electromagnetic force would be the scattering of one electron by another. This example is illustrated using a Feynman diagram in Figure 13.4.3. It shows two electrons approaching each other (on the vertical axis) over time (the horizontal axis) and exchanging a photon. This causes each electron to be repelled and therefore change direction.

It is important to note that the directions of the arrows in Figure 13.4.3 do not indicate the direction in which the particles travel, rather it indicates how each particle travels in time; for example, an antiparticle is always shown as moving backwards in time. The simplest information you can gather from these diagrams are the particles involved. There are complex rules that govern these diagrams, as they are a graphical representation of mathematical expressions.

Figure 13.4.4 shows beta-minus decay, a decay you may be familiar with from *Pearson Physics 11 Queensland* Chapter 3. The equation for this is:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Part b shows what happens to the neutron's quarks: a down quark changes to an up quark. This is only possible via the weak nuclear force and the emission of a W^- gauge boson.

ℹ Feynman diagrams are a simple way to illustrate particle decays and interactions.

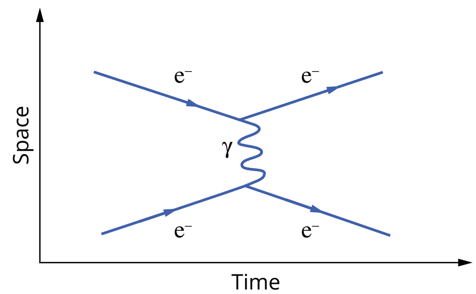


FIGURE 13.4.3 A Feynman diagram showing the interaction of two electrons. During this scattering event, a photon is exchanged.

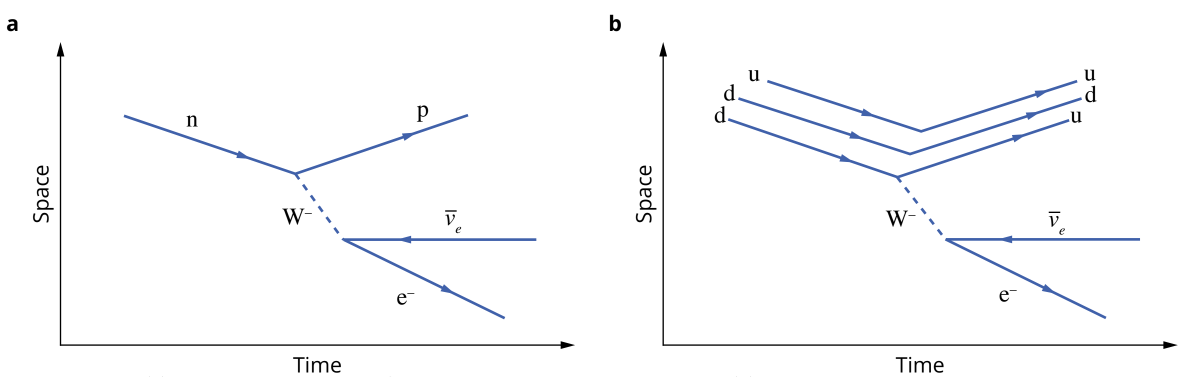


FIGURE 13.4.4 (a) The Feynman diagram for a neutron decaying into a proton. (b) The Feynman diagram for the same decay, showing what happens at the quark level

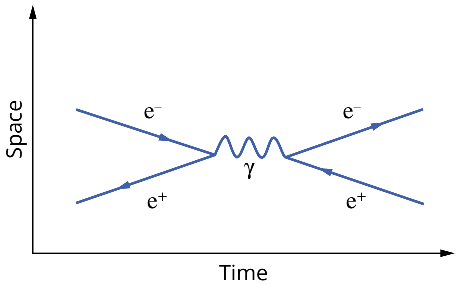


FIGURE 13.4.5 The Feynman diagram for electron–positron annihilation followed by pair production. Note that during this event the positron appears to be going backwards in time, but this is just a convention for antiparticles in Feynman diagrams.

Figure 13.4.5 shows the annihilation of an electron and a positron, followed by an electron-positron pair production. Their mass is converted into energy in the form of the kinetic energy of a photon, which then produces an electron and positron pair.

SYMMETRY

Symmetry is very important in physics, as it helps us understand and predict how the universe works. When physicists talk about symmetry, they are saying that the laws of physics do not vary under certain transformations. For example, the laws of physics are the same wherever you are in spacetime. Newton's second law, $F = ma$, is the same in your classroom as it is on the other side of the world, or on Mars. This property is called translational symmetry or translational invariance. The same applies for the direction you are facing (rotational symmetry or rotational invariance). These laws apply to particle physics as much as they apply to objects on our scale. There are also a number of other symmetries in particle physics. It might seem like a very simple, and almost insignificant, point, but symmetry in particle physics allows physicists to predict the behaviour of particles, and their conservation laws enable physicists to determine which particle interactions can happen, and which can't.

Particles also have an internal symmetry, which can help predict the existence of other particles. For example, the baryon number introduced in Module 13.2 is a type of internal symmetry. If a particle exists with a baryon number of +1 (e.g. a proton), symmetry suggests that there must be a corresponding antiparticle with a baryon number of −1 (e.g. an antiproton).

Physicists have searched for a theory that can unite the different forces in nature, and have found similarities between the weak nuclear force and the electromagnetic force, which led to the idea that these could be a single electroweak force. However, the force carriers involved are different—W and Z bosons have a relatively high mass, but photons have no mass. Symmetry suggests that the W and Z bosons should have no mass, so the Higgs boson was predicted to explain this, as described in the Science as a Human Endeavour on the next page.

Supersymmetry is an extension of the Standard Model that attempts to explain phenomena not currently explained. Supersymmetry predicts a partner for each particle in the Standard Model that will explain differences in mass between particles. It also could link fermions (a group of elementary particles) and bosons by predicting that there will be a corresponding boson for every fermion, and vice versa. This could provide a way to unify the strong nuclear, electromagnetic and weak nuclear forces at very high energies, such as the conditions in the very start of the universe.

WS 4.3.2

WS 4.3.3

SCIENCE AS A HUMAN ENDEAVOUR

The Large Hadron Collider and the Higgs boson

There are properties of particles that were not explained by the original Standard Model. The W and Z bosons discussed in Module 13.3 have relatively large masses of around 80 and 90 GeV, about 100 times larger than a proton, which has a mass of around 938 MeV. But another boson, the photon, is massless. Why is this the case? Why do some particles have mass, and others don't?

The mass of particles cannot be predicted from the Standard Model you have learnt about so far; a new explanation is needed. This is where the Higgs field and the Higgs boson come in. When a particle passes through the Higgs field and interacts with it, it gets mass. The more strongly it interacts with the Higgs field, the more mass the particle has. You will already be familiar with the idea that fields are all around us, and that they can't be observed directly. This is the case with the Higgs field, but the Higgs field has a Higgs boson associated with it, which was predicted by Peter Higgs and his colleagues, and which could potentially be found. However, to search for it, a new type of particle collider was needed.

The Large Hadron Collider (LHC), at CERN on the border of France and Switzerland, was created to answer questions physicists still had about the Standard Model, in particular to test the prediction of the existence of the Higgs boson.

The LHC is the largest scientific instrument ever built: the tunnel has a circumference of 27 km with an average depth of 100 m below ground level (Figure 13.4.6). It is located underground for cost reasons, but this also has the extra benefit of shielding the accelerator from external radiation. Due to its groundbreaking work and enormous size, the LHC is probably the best-known particle accelerator outside of particle physics research. However, it is only the most recent and highest-energy accelerator in a series of accelerators and experiments at CERN. Together, the particle detectors working with the LHC allow specialised investigations at the leading edge of particle-physics research.

In 2012, the discovery of a candidate for the Higgs particle was announced—a particle had been found with a mass of 126 GeV, which was consistent with theoretical predictions (Figure 13.4.7 on page 376). On 10 December 2013, two of the original researchers, Peter Higgs and François Englert, were awarded the Nobel Prize in Physics for their work and prediction. The successful detection of the Higgs boson and subsequent determination of its mass was a major achievement of the LHC. However, physicists are not sure whether this is just an addition to the Standard Model, or if it suggests a new model of particle physics is needed.

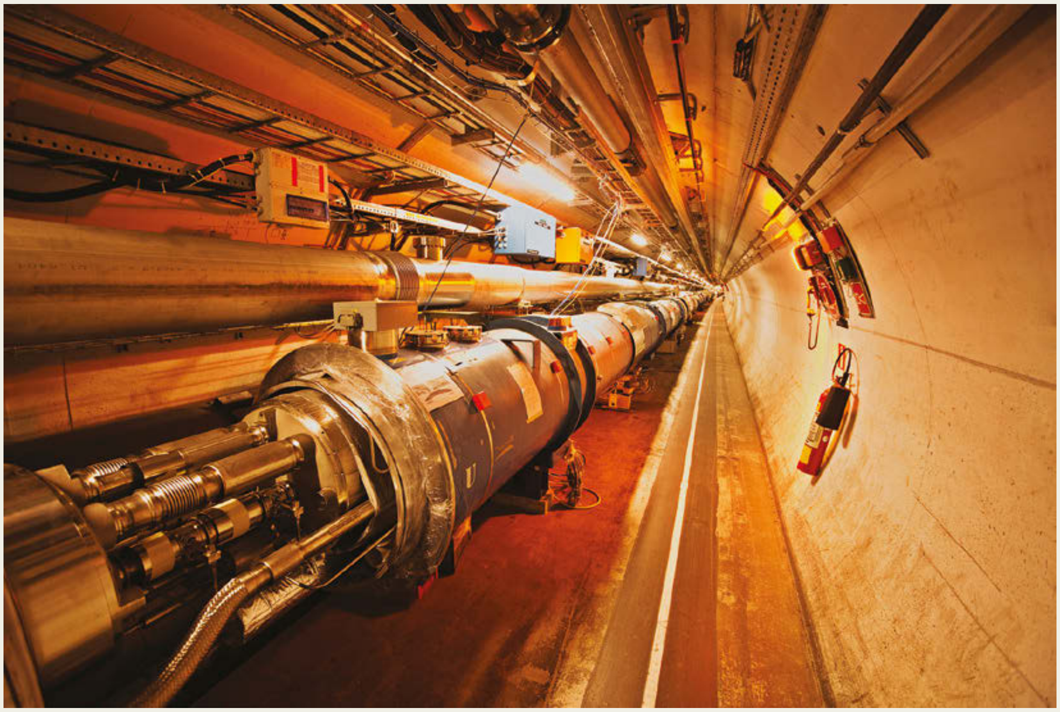


FIGURE 13.4.6 A section of the LHC's 27 km tunnel.

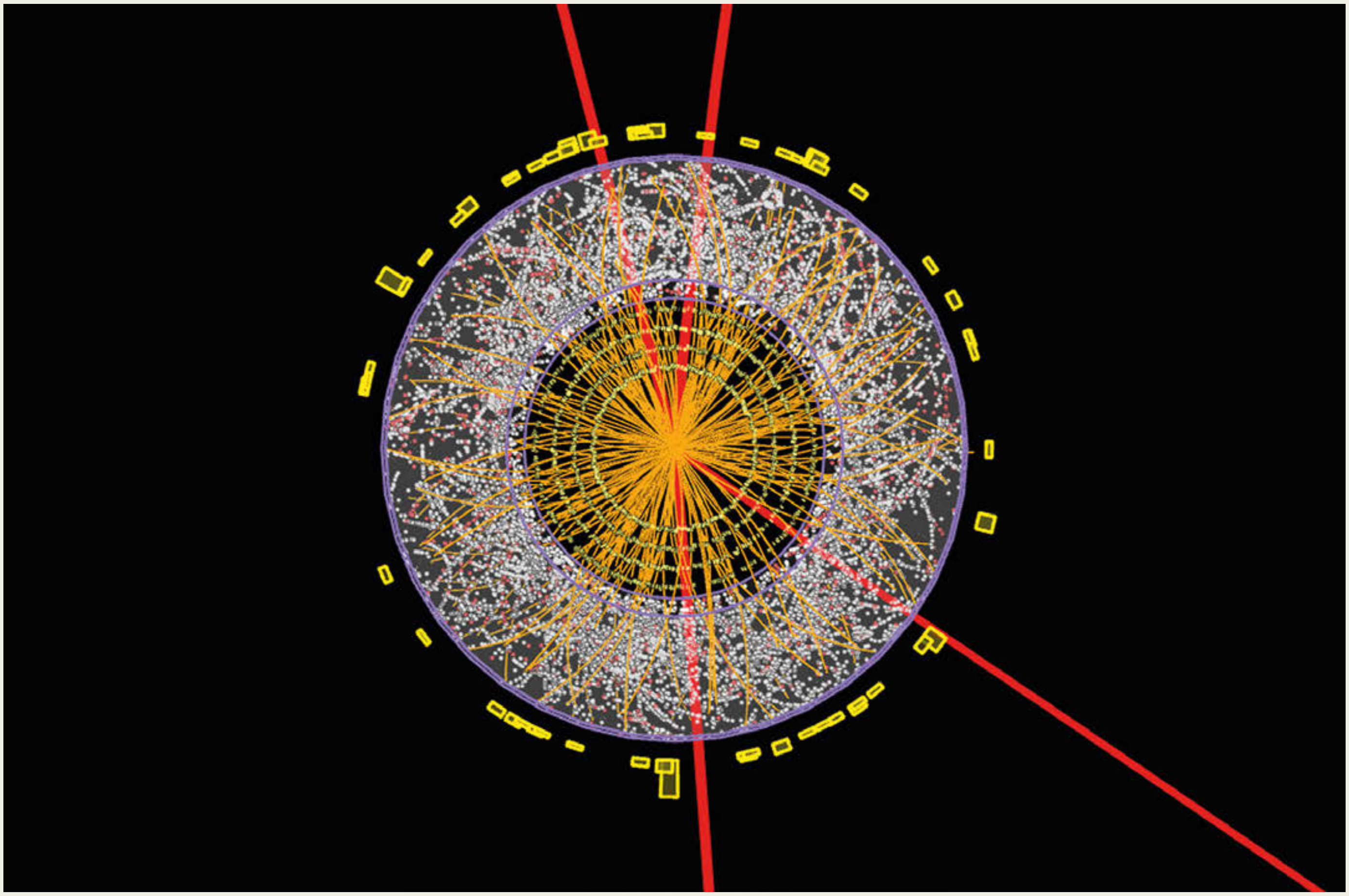


FIGURE 13.4.7 The image shows tracks of particles and measurements of their energies in the ATLAS detector at the LHC. The nature and energies of the particles produced are consistent with predictions of the formation of a Higgs boson.

Other goals of the LHC

The Standard Model is extremely successful in predicting the existence of particles and their behaviour. However, it is unable to answer questions about dark matter and why there is comparatively very little antimatter in the universe, among others. The main goal of the LHC is to add to the understanding of particle physics beyond the Standard Model. Some examples of other work being undertaken at the LHC, apart from the search for the Higgs boson, are given below.

- Gauge boson—the force-carrying particles studied earlier in this chapter—are used to explain forces being exerted on particles by fields. Scientists are seeking a unified theory for the four natural forces. The Standard Model links the weak nuclear force, the strong nuclear force and the electromagnetic force, but is unable to construct a similar theory for gravity. Supersymmetry—the existence of more massive particles than are currently known—could lead to a unified theory.
- Astronomical observations suggest that only 4% of all of the matter in the universe is visible. The LHC is searching for evidence of dark matter and dark energy, which are theorised to account for 23% and 73% of the remaining matter respectively.
- Matter and antimatter existed together in equal quantities at the time of the big bang but today, as far as we know, there is comparatively very little antimatter. Experiments at the LHC will attempt to determine why.
- Heavy ions such as lead colliding at high energies form hot, dense matter. The LHC will be used to investigate the state of matter called the quark–gluon plasma, which is theorised to have existed in the early universe.

Review

1. Describe whether the Higgs boson was found through experiment, theory or both.
2. The Standard Model does not explain several phenomena of the universe. State two areas of work that the LHC is undertaking to explain these phenomena.
3. Describe how the Higgs boson explains how particles get their mass.

13.4 Review

SUMMARY

- When a matter particle and its antimatter particle collide, they are completely annihilated and produce photons with the equivalent energy of the two particles, calculated by Einstein's mass–energy equation $E = mc^2$.
- In all particle interactions, quantities such as mass–energy, electromagnetic charge, lepton number and baryon number are conserved. These conservation laws put limits on the possible outcomes of any interaction or decay.
- Particle interactions can be illustrated using Feynman diagrams.
- Symmetry is an important feature of particle physics, helping physicists to predict what particle interactions are possible, and to predict the existence of new particles.

KEY QUESTIONS

Retrieval

1 In a particle interaction, the mass of the particles after the interaction is less than the mass of the particles before the interaction. State whether energy is conserved in this interaction, and if so describe where the difference in mass has gone.

2 Demonstrate that the following interactions are possible using conservation of electromagnetic charge, lepton and baryon number:

a $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

b $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

c $p + n \rightarrow 2p + e^- + \bar{\nu}_e$

Comprehension

3 Describe the similarities and differences between matter and antimatter particles.

4 Draw and label a Feynman diagram for each of the following interactions.

a electron–electron repulsion

b beta negative emission

Analysis

5 The rest mass energy of an electron or a positron is 0.511 MeV. Determine the minimum energy of the incident photon if a gamma ray photon interacts with an atomic nucleus and an electron–positron pair is produced.

Chapter review

SAT IA3 WS 4.3.4 WS 4.3.5

13

KEY TERMS

annihilation
antiparticle
baryon
baryon number
colour charge
elementary particle
fermion
Feynman diagram
gauge boson
gluon
hadron
lepton
lepton number
meson
neutrino
pair production
photon
quantum numbers
quark
Standard Model
W^+, W^- and Z^0
weak nuclear force

KEY QUESTIONS

Retrieval

1 State which quarks make up protons and neutrons.

2 Describe how the Standard Model explains three of the four fundamental forces. As part of your answer, identify the three forces and their associated particle(s). State which force is not explained by the Standard Model.

3 State whether an electron is a composite or a fundamental particle and whether it is a lepton or a hadron.

Comprehension

4 Draw a concept map to show the division of particles of the Standard Model.

5 Describe what happens in the process called pair production.

6 Archie is revising for his Year 12 physics exam and is confused over the term annihilation. Describe what this term means to help him revise.

7 A neutron in an evacuated container decays to produce a proton and two other particles. The proton is then attracted to an electron and becomes the nucleus of a hydrogen atom. The atom then slowly drifts to the base of the container.

List the four fundamental forces that have been involved in the sequence of events described above from first to last. If any were not involved then they should go last.

8 Explain how the proton gains a +1 charge from its constituent quarks and how a neutron gains a neutral charge from its constituent quarks.

Analysis

9 Compare the properties of quarks and leptons.

10 Pair production in particle physics usually refers to the production of an electron–positron pair from a photon. However, under certain circumstances the pair production of a muon–antimuon pair or a proton–antiproton pair is possible.

In one interaction, an electron and positron annihilate to produce a photon, from which a muon–antimuon pair is produced. Calculate the minimum energy of the photon that produced the muon–antimuon pair if the rest mass energy of a muon is 105.7 MeV.

11 Determine whether the following interaction is possible or not by considering the conservation of electromagnetic charge, lepton number and baryon number:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Knowledge utilisation

12 Determine why two photons are produced in an electron–positron annihilation reaction and not just one photon.

UNIT 4 • REVIEW

REVIEW QUESTIONS

Topic 1: Special relativity

TR 4.1 TR 4.2 TR 4.3

Multiple choice

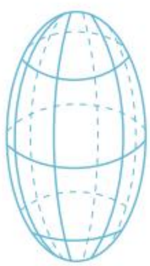
1 Select the option that best describes inertial frames of reference.

A Inertial frames move at a constant velocity.
B Inertial frames accelerate at a constant rate.
C Inertial frames change velocity at a constant rate.
D Inertial frames do not move relative to one another.

2 A sphere is approaching an observer at a speed of 0.8*c*.

Identify which sphere would be measured by the observer.

A



B

C

D

3 Identify the two postulates of special relativity from the following options.

A The speed of light in a vacuum is constant in all inertial reference frames and the laws of physics only hold at slow speeds.
B The speed of sound is constant in all inertial reference frames and mathematics cannot model observations made at large speeds.
C The laws of physics are the same in all inertial reference frames and all speeds are relative to the observer's reference frame.
D The laws of physics are the same in all inertial reference frames and the speed of light in a vacuum is constant in all inertial reference frames.

4 Select the statement that explains why no object can accelerate to travel at the speed of light.

A It would take infinite energy.
B The object would vanish into warp space.
C At such a high speed, the object would explode.
D Due to length contraction, the object would disappear.

5 Assume you are approaching a light beacon while travelling at half the speed of light (0.5c). Calculate what you would measure the speed of light from the beacon to be.

A 1.0*c*
B 1.5*c*
C 0.50*c*
D 0.75*c*

6 Identify the definition of 'simultaneity' in the context of special relativity.

A It is the ability to measure the time between two events.
B Two events can never be exactly simultaneous due to different frames of reference.
C Events occurring at the same time will be simultaneous in all reference frames as a consequence of the constant speed of light.
D Two events that occur at the same time in one reference frame may occur at different times in a different reference frame.

7 Identify the definition of 'rest mass'.

A It is the mass that has been converted to energy.
B It is the mass of an object measured in the same reference frame.
C It is the mass of an object measured in an inertial reference frame.
D It is the mass of an object measured when the absolute velocity is zero.

8 Identify which of the following statements concerning Einstein's equation $E = mc^2$ is correct.

A Mass is greater than energy.

B Energy and mass are equivalent.

C Mass and the speed of light are equivalent.

D Energy and the speed of light are equivalent.

9 An electron with a mass of 9.109×10^{-31} kg travels past an observer at a speed of 2.0×10^8 m s^{-1}. Identify the relativistic momentum of the electron.

A 2.4×10^{-22} kg m s^{-1}

B 1.8×10^{-22} kg m s^{-1}

C 1.4×10^{-22} kg m s^{-1}

D 3.2×10^{-22} kg m s^{-1}

10 Amy and George synchronise their watches on Earth. Amy remains on Earth while George takes a round trip to Pluto at near light speed. Determine whose watch will show the greater passage of time when they reunite.

A It is impossible to tell.

B Amy's watch (on Earth)

C George's watch (on the spaceship)

D Amy and George's watches are the same.

Short answer

1 **a** Galilean relativity states there is no absolute velocity; rather, all velocities are relative. Explain what this means, using an example. Use numerical values in your example.

b Explain how special relativity differs from Galilean relativity with respect to the speed of light.

2 The time t_0 and the length L_0 are referred to as the proper time and proper length. Explain what is meant by proper time and proper length, and illustrate with an example to compare them to relativistic length and relativistic time.

3 Two vehicles are some distance apart and are moving directly towards each other. Each vehicle is travelling at 20 m s^{-1} relative to the ground.

a Calculate at what speed each vehicle would see the other travel.

b As the two vehicles approach each other, a passenger in each car shines a torch towards the other car. Explain at what speed each car's occupant will see the light from the others' torch travel. Justify your answer.

4 Einstein's theory of special relativity is based on the principles that:

- the speed of light in a vacuum is an absolute constant and
- the laws of physics are the same in all inertial frames of reference.

Identify the apparent contradiction of accepting these two principles, and explain how Einstein's theory of special relativity resolves this apparent contradiction.

5 The mass of reactants is measured prior to undergoing a reaction in a nuclear reactor. The mass is measured again after the reaction has taken place. A mass defect of 800 g is noted. Calculate the amount of energy that has been emitted in this reaction.

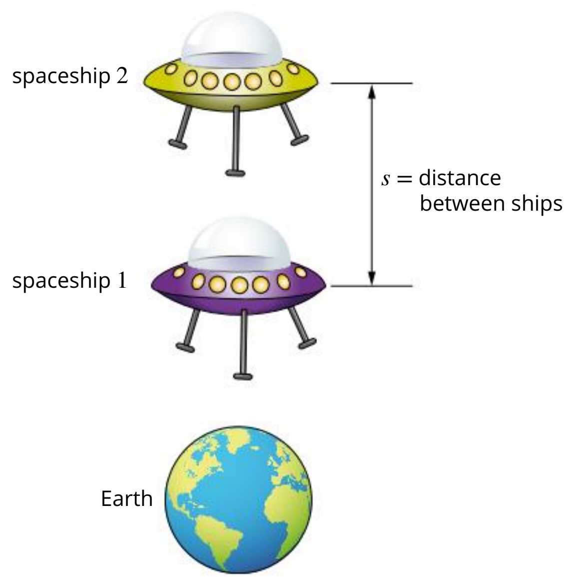
6 A meson of rest mass 2.4×10^{-28} kg travels at 0.85c. Calculate the amount of energy released if the meson decays completely to electromagnetic radiation at this speed.

7 **a** A comet is travelling away from Earth at a speed of 0.180c. A space probe that has been sent to observe the comet measures its long axis to be 3.20 km. Calculate the length the comet appears to be from Earth when the long axis is travelling away from the Earth.

b The comet is rotating on its axis such that the long axis is at times perpendicular to the observer on Earth. Calculate the length the comet will appear to have for an Earth observer when it is in this position.

8 The proper length of a spacecraft is 75 m. As it passes by a space station, its length is measured to be 60 m. Calculate the speed of the spacecraft relative to an observer on the space station.

9 Two spaceships are travelling side by side at the same high velocity towards the right. As they pass Earth, the captain of spaceship 1 sends a radio signal (hence it is travelling at c) to the captain of spaceship 2. The captain of spaceship 2 then sends a return signal. This situation is illustrated below.



The captains of the two spaceships record the time for the signals to pass between them as less than that recorded by an observer at the space command centre on Earth. Explain this apparent contradiction with the aid of a labelled diagram and a supporting description.

10 A space probe is sent to make observations of a planet orbiting a nearby star. The planet is 24.6 light-years from Earth and the probe is sent from Earth with a speed 0.820c. The probe carries an atomic clock that was synchronised with a similar clock on Earth at the start of the journey.

a Calculate how long the journey will take as measured by the clock on Earth.

b Calculate how long the journey will take as measured by the clock on the probe.

c Calculate the distance travelled to reach the planet, as determined from the space probe's frame of reference.

d On arrival at the planet, the space probe sends signals of its measurements back to Earth using various parts of the electromagnetic spectrum.

i Calculate the velocity at which the signals will travel, as determined from the probe's frame of reference.

ii Calculate the velocity at which the signals will travel, as determined from Earth's frame of reference.

iii Justify your answers to parts **i** and **ii**.

11 One of the pieces of evidence to support Einstein's special theory of relativity is the observation of the lifetimes of muons, which travel at speeds close to the speed of light.

a Calculate the lifetime of a muon travelling at 0.90*c*, assuming the lifetime of a muon at rest is 2.2×10^{-6} s.

b Calculate the lifetime of a muon as measured by an observer able to travel with the muon. Justify your answer.

c As the muon travels through the atmosphere, the observer travelling with the muon measures the height of a hill to be 200.0 m. Calculate the height of this hill as measured on Earth.

d Given the distance that muons need to travel and their short lifetimes, Newtonian physics predicts that muons, created high in the Earth's atmosphere, should not be able to reach the Earth's surface. This is not what is observed by scientists. Explain how it is possible for muons to strike the Earth's surface, given their short lifetimes and long distance to travel.

12 A rocket travels past the International Space Station (ISS) at a speed of 0.98c from left to right. The proper length of the ISS is 109 m. When the rocket passes the middle of the ISS, astronauts start stopwatches on both the rocket and the ISS.

a Calculate the length of the ISS according to an astronaut on the rocket.

b Two lamps are placed at either end of the ISS. An astronaut at the midpoint of the ISS observes the lamps to flash simultaneously at time = 0 s. Deduce which lamp flashed first, as determined by the astronaut on the rocket.

c The rocket turns on its engine and begins to decelerate at a constant rate. It comes to a stop and then begins to accelerate back towards the ISS at the same rate. Once the rocket reaches a velocity of 0.98*c*, it continues at a constant velocity towards the ISS. Determine which stopwatch measures the longest amount of time.

Topic 2: Quantum theory

Multiple choice

1 Identify which one or more of the following statements about light is true.

A Light has both momentum and energy.
B Light travels at a fixed speed in a vacuum.
C Light can exhibit both particle and wave properties.
D Light is an electromagnetic wave produced by an oscillating electric charge.

2 Select the statement that is true of Rutherford's model of the atom.

A The model explains atomic emission spectra.
B The atom carries a net negative charge.
C The atom has a cloud of protons and electrons.
D The atom has a positively charged nucleus surrounded by orbiting electrons.

3 Identify which of the following statements about Bohr's model of the atom is incorrect.

A It adopted quantum mechanical principles.
B It assumed that the inner electron orbits have the most energy.
C It could explain emission spectra for simple atoms like hydrogen.
D It had electrons orbiting a positive nucleus in a set of discrete orbits.

4 The surface temperature of the Earth is 15.0°C. The peak wavelength of Earth's black-body radiation is:

A 107 µm
B 10.7 mm
C 10.1 µm
D 101 µm

5 Select the correct description of a photon.

A A photon has no momentum.
B A photon has a rest mass of zero.
C Photons travel at a speed proportional to their frequency.
D A photon has a mass approximately equal to the mass of an electron.

6 Identify the energy of a photon with a wavelength of 6.45×10^{-7} m.

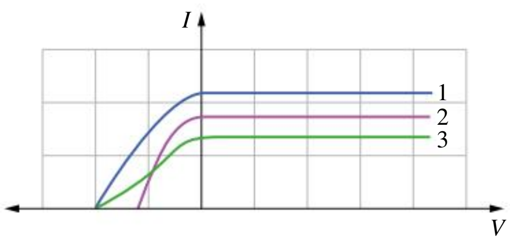
A 3.08×10^{-33} J
B 3.08×10^{-19} J
C 4.27×10^{-40} J
D 4.27×10^{-6} J

7 Identify the correct statement about the photoelectric effect.
- **A** The photoelectric effect is used as evidence to support the model of light as a transverse electromagnetic wave.
- **B** The minimum energy of a photon needed to eject an electron from a metal surface varies with the frequency of the incident light.
- **C** The kinetic energy of electrons ejected from a metal surface will increase as the intensity of light incident on the surface is increased.
- **D** For light above the required minimum frequency, an increase in the intensity of the incident light on a metal surface will increase the number of electrons ejected from its surface.

8 Select the maximum wavelength of light that a hydrogen atom will emit when an electron goes from the $n = 2$ energy level to the $n = 1$ energy level. The Rydberg constant for hydrogen is $1.097 \times 10^7\,m^{-1}$.
- **A** 0.274 nm
- **B** 121.5 nm
- **C** 0.0082 nm
- **D** 0.0022 nm

9 The following graph was collected during a photoelectric effect experiment. The graph shows the photocurrent measured as a function of potential difference applied.

Photocurrent measured as a function of potential difference applied



Select the correct statement.
- **A** Light 2 has less intensity than light 3.
- **B** Light 2 is a higher frequency than light 1.
- **C** Light 1 and light 3 are the same intensity but have different frequencies.
- **D** Light 1 and light 3 are the same frequency light but have different intensities.

10 Select the evidence that supports the particle theory of light.
- **A** photoelectric effect, polarisation of light
- **B** black-body radiation, photoelectric effect
- **C** Young's double-slit experiment, polarisation of light
- **D** Young's double-slit experiment, photoelectric effect

Short answer

1 Decide whether an atom will emit photons (light) of any energy when an electron falls from a higher energy level to a lower energy level. Explain your answer.

2 Explain why Newtonian (classical) laws of physics are not appropriate when describing what occurs at the subatomic level.

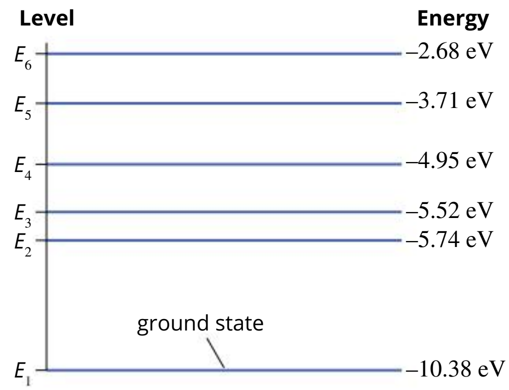
3 State two pieces of evidence that support the wave model of light. For one of these pieces of evidence, describe how it provides evidence for the wave nature of light. Diagrams may be used to assist your explanation.

4 Blue light and red light are both shone on a metal surface. Electrons were measured being emitted when the blue light was shone on the metal, but not when the red light was shone.
Define the terms 'threshold frequency' and 'work function' using this example.

5 Violet light of wavelength 390 nm is used in a photoelectric effect experiment. When violet light shines on a metal cathode, the stopping voltage measures 0.90 V. Calculate the velocity of the most energetic electrons that are emitted from the metal's surface.

6 Black-body radiation was originally described using a classical model. The peak wavelength was observed to decrease as the temperature increased. Paraphrase the two assumptions Planck made to describe the shape of the curve.

7 The diagram below shows some of the energy levels for a mercury atom.



- **a** The line emission spectrum for mercury has a prominent blue line at about 437 nm. Determine between which two energy levels an excited electron will transition to emit light of this wavelength.
- **b** Identify how many different lines could appear in an emission spectrum for mercury for an electron falling from energy level 4 to the ground state.

8 Explain the limitations of Rutherford's model of the atom and explain how Bohr's model overcame them.

9 In Young's double-slit experiment, photons of green light were fired at a double slit. A series of bright and dark lines were observed on a screen a few metres away.

a Explain which aspect of wave–particle duality this experiment shows.

b Explain how the dark and bright lines are produced.

10 In an experiment to determine the threshold frequency and work function for a particular metal, a researcher measured the kinetic energy of the electrons ejected from the metal's surface at a range of frequencies. The results are tabulated below.

Frequency ($\times 10^{15}$ Hz)	Kinetic energy of electron ($\times 10^{-19}$ J)
2.50	9.055
5.00	25.63
7.50	42.20
10.0	58.78
12.5	75.36

a Draw a graph of kinetic energy against frequency.

b Determine the threshold frequency for the metal from the graph.

c Determine the work function for the metal from the graph.

d Calculate the slope of the line.

e The researcher carries out the same experiment to determine the threshold frequency and work function for a second metal and graphs the kinetic energy against frequency. Predict the slope of the line for this second metal.

f Explain what evidence the effect studied in this experiment provides about the nature of electromagnetic radiation.

11 While working on cathode rays (high-energy electron beams) and their effects in 1895, Wilhelm Roentgen observed that when electrons that had been accelerated to a high speed in a vacuum tube struck the wall of the glass tube, fluorescent minerals some distance away would glow. It was known electrons travelled only a few centimetres in air, so Roentgen concluded that these effects were due to a new type of radiation he called 'X-radiation' or X-rays. Because these X-rays were not detectable by electric or magnetic fields, it was concluded that they were not charged particles.

About a month after Roentgen's discovery, J. J. Thomson observed that if the X-rays were passed through a gas, the gas became electrically conducting.

It was suggested the X-rays were a form of invisible light; but refraction, interference or diffraction patterns were not observed when the rays were used with ordinary optical instruments. It was noted that the diffraction gratings available at that time had a typical width in the order of 10^{-6} m. In about 1912, it was suggested that it would be possible to test if X-rays were a wave by directing them onto crystals. It had been estimated that atoms in a crystal were separated by about 10^{-10} m, so the crystal could act as a diffraction grating. Scattering of X-rays from crystals did show diffraction patterns, suggesting the wave-like nature of X-rays.

It was also observed that X-rays are produced when high-speed electrons strike a metal surface. But it was also shown that electrons are ejected from metals that are exposed to X-rays. The specific frequency of X-rays that causes the ejection of an electron is unique to each metal and more electrons are ejected with higher intensity X-rays of the required frequency.

a Explain why a mineral exposed to this new radiation would fluoresce, or glow.

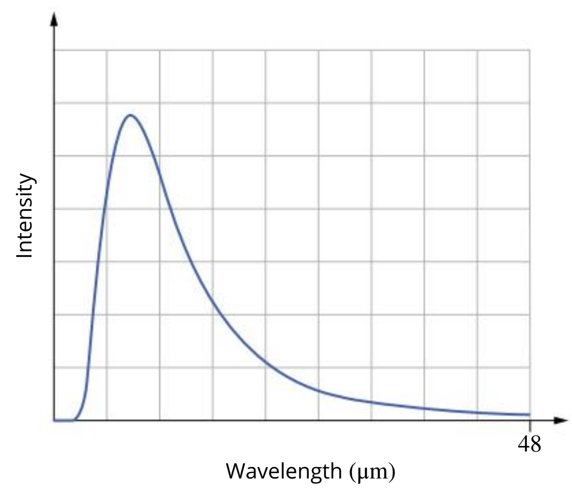
b Draw two conclusions about X-radiation, other than the one given in the information, that are based on the nature of the interaction of the X-radiation with electric and magnetic fields.

c Explain J. J. Thomson's observation about the behaviour of X-rays passing through a gas.

d Draw a conclusion about the nature of X-rays based on the observation of the effect of exposing metals to X-rays. State the name is given to this effect.

12 A heater is measured to emit radiation with a peak wavelength of 8.21 μm, as shown in the spectrum below.

Intensity versus wavelength for a heater



a Describe the type of radiation being emitted from the radiator, including in which part the greatest amount of energy is being emitted.

b Explain why the hot radiator is emitting radiation.

c Calculate the temperature of the radiator.

d Predict the change in radiation as the radiator increases in temperature.

e Explain why the black-body spectrum of radiation gives evidence for quantised electron energy levels.

Topic 3: The Standard Model

Multiple choice

1 Select the correct statement about elementary particles.
A They are always strange.
B They are neutral in charge.
C They are all quarks, with a charge of $\frac{1}{3}$ or $\frac{2}{3}$.
D They are the fundamental building blocks of matter.

2 Define an 'antiparticle' in relation to its pair.
A a particle with the same mass and electric charge, but opposite spin
B a particle with the same magnetic properties but opposite electric charge
C a particle with the same charge, but opposite magnetic properties and spin
D a particle with the same mass but opposite electric charge and quantum numbers

3 Identify the correct list of quark names.
A up, down, left, right, top, bottom
B top, bottom, up, down, over, under
C up, down, top, bottom, strange, charm
D up, down, left, right, bottom, strange, charm

4 Select the list that names only leptons.
A tau, muon, electron, tau neutrino
B tau, muon, electron, photon, proton
C electron, positron, neutrino, proton, neutron
D tau neutrino, muon neutrino, electron neutrino, gluon

5 Select the statement that correctly describes gauge bosons.
A Gauge bosons are massless particles.
B Gauge bosons include gluons and photons.
C Gauge bosons are always neutral in charge.
D Gauge bosons are the same as Higgs bosons.

6 Identify the statement that is not correct.
A Gluons do not interact with leptons.
B Quarks are not subjected to the strong nuclear force.
C Leptons are not subjected to the strong nuclear force.
D Quarks and leptons are both subjected to the electromagnetic force.

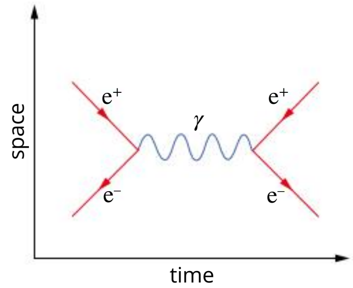
7 Identify one difference between baryons and mesons.
A Baryons are a subclass of leptons and mesons are a subclass of hadrons.
B Baryons are a subclass of hadrons and mesons are a subclass of leptons.
C Baryons are made up of a quark and an antiquark and mesons are made up of three quarks.
D Baryons are made up of three quarks and mesons are made up of a quark and an antiquark.

8 Select the correct statement about the baryon number of a particle.
A It is only conserved if the electric charge is conserved.
B It is only conserved if the initial baryon number is equal to 0.
C It is a conserved quantity that represents the net electric charge of the particles.
D It is a conserved quantity in which every quark has a baryon number of $+\frac{1}{3}$ and every antiquark has a baryon number of $-\frac{1}{3}$.

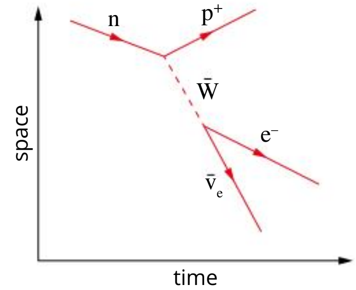
9 Select the correct statement about the lepton number of a particle.
A They come in six different flavours.
B The lepton number of an electron is –1.
C The lepton number of all baryons is zero.
D It is the measure of the number of leptons in a system.

10 Identify the Feynman diagram below that depicts an electron and positron interaction.

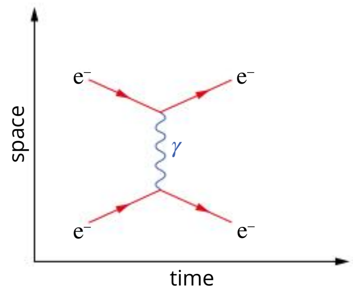
A



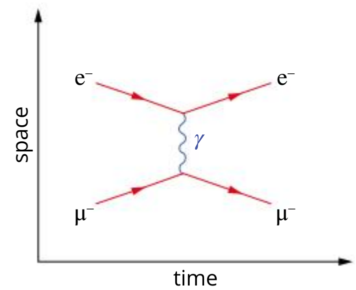
B



C



D



Short answer

1 a The Standard Model explains three of the four fundamental forces in terms of an exchange of force-carrying particles called gauge bosons. Complete the table below for the four forces. Gravity has been completed as an example, but it is not part of the Standard Model.

Force	Nature of force	Range over which force acts (m)	Force carrier (gauge bosons)
	causes radioactive decay	10^{-18}	W^+, W^- and Z^0
electromagnetic			
	holds the nucleus of atoms together and acts between quarks	$\sim 10^{-15}$	
gravity	a force of attraction between any two objects with mass	infinite	graviton (theoretical and unobserved)

b Rank these four fundamental forces in order of their strength from strongest to weakest.

2 It was observed in the 1930s that when a neutron decayed, a proton and an electron were produced. It was consistently observed that the energy of the electron was less than expected. To avoid the violation of two fundamental principles of physics, Wolfgang Pauli suggested that another particle, undetectable at the time, was produced during neutron decay. This particle was later discovered and is now called an antineutrino.

Name the two fundamental principles of physics that would have been violated if an antineutrino was not produced during neutron decay.

3 State which one or more of the fundamental forces (strong nuclear, weak nuclear, electromagnetic and gravity) act on the following particles:

a proton

b electron

c neutron

4 A neutron is composed of two down quarks and one up quark. The mass of a neutron is greater than the sum of the masses of its component quarks. Explain this discrepancy in mass.

5 Name the two groups of hadrons and explain why they are separated.

6 Explain how a proton gains a +1 charge from its constituent quarks and explain how a neutron gains a neutral charge from its constituent quarks.

7 Describe what is meant by symmetry in particle interactions, and explain the significance.

8 Before the development of the Standard Model, it was thought that forces were exerted on particles by fields. In the Standard Model, it is believed that forces are exerted by the exchange of other particles.

a State the name given to the particles that give rise to forces.

b Explain how the Standard Model accounts for the repulsion observed when two electrons approach each other.

9 Quarks are one of the two elementary particles in the Standard Model of particle physics. There are six types of quarks. Each quark has its own antiquark.

Table of quarks			
Name	**Quark symbol**	**Quark electrostatic charge**	**Antiquark symbol**
up	u	$+\frac{2}{3}e$	$\bar{u}$
down	d	$-\frac{1}{3}e$	$\bar{d}$
strange	s	$-\frac{1}{3}e$	$\bar{s}$
charm	c	$+\frac{2}{3}e$	$\bar{c}$
bottom	b	$-\frac{1}{3}e$	$\bar{b}$
top	t	$+\frac{2}{3}e$	$\bar{t}$

Baryons are made up of three quarks. The lambda baryon, Λ_0, is composed of an up, a down and a strange quark. It has a rest mass of 1.98×10^{-27} kg and mean lifetime of 2.63×10^{-10} s.

a Show that the Λ_0 baryon has neutral electromagnetic charge.

b Calculate how much energy will be released if a Λ_0 baryon travelling at 0.95*c* decays to electromagnetic radiation.

c Calculate the mean lifetime of a Λ_0 baryon when it is travelling at 0.95*c* as measured in a laboratory.

10 a Complete the table below by filling in the name of each lepton.

Lepton	Lepton symbol	Antilepton symbol
	e^-	e^+
	ν_e	$\bar{\nu}_e$
	μ^-	μ^+
	ν_μ	$\bar{\nu}_\mu$
	τ^-	τ^+
	ν_τ	$\bar{\nu}_\tau$

All leptons have a lepton number of +1 and antileptons have a lepton number of –1. For example, an electron has an electron lepton number of +1 and a positron has an electron lepton number of –1.

Use the information above to answer the following questions.

b Determine whether the following decay for a muon is possible. Explain your answer.

$\mu^- \rightarrow e^- + \nu_e$

c Assume a muon decays to a combination of three leptons and antileptons. Using conservation of lepton number, electromagnetic charge and energy, describe what particles the muon could decay into.

11 When describing the interactions between fundamental particles, Feynman diagrams are often used. Draw the following interactions of particles using Feynman diagrams. Explain the diagrams.

a electron and electron

b electron and positron

c a neutron decaying into a proton

12 During collisions different particle interactions are possible. Determine if the following interactions are possible using the conservation of baryon number.

a $\pi^+ + p^+ \rightarrow p^+ + p^+ + \bar{n}$

b $p^+ + p^+ \rightarrow p^+ + p^+ + n$

Baryon number and lepton number conservation can determine the type of particle that is missing in an interaction. Complete the following questions for the particle interaction given below. Justify your responses.

$p^+ + p^+ \rightarrow p^+ + p^+ + X$

where X is an unknown particle

c Identify X as a baryon or a meson.

d State the electric charge of X.

e State whether X is a lepton or not.

In the following particle reaction, two unknown particles are produced.

$p^+ + p^+ \rightarrow p^+ + p^+ + X + Y$

Complete the following questions. Justify your answers.

f Identify which particles X and Y could be.

g State the electric charge of X and Y.

h State whether either X or Y could be a lepton.

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
att	a	10^{-18}
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	µ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
deca	da	10
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

TABLE 3 Some physical constants

Description	Symbol	Value
charge of electron	e	-1.60×10^{-19} C
atomic mass unit	amu	1.66×10^{-27} kg
electron volt	eV	1.60×10^{-19} J
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	3×10^{8} m s^{-1}
Coulomb's law constant	k	8.99×10^{9} N m^2 C^{-2} This is equal to $\frac{1}{4\pi\varepsilon_0}$
magnetic constant (permeability of free space)	μ_0	$4\pi \times 10^{-7} = 1.257 \times 10^{-6}$ T A^{-1}m
permittivity of free space	ε_0	8.85×10^{-12} C^2 N^{-1} m^{-1}
Planck's constant	h	6.626×10^{-34} J s, or 4.14×10^{-15} eV s
Stefan–Boltzmann constant	σ	5.67×10^{-8} W m^{-2} K^{-4}
Rydberg constant	R	1.097×10^{7} m^{-1}
rest mass of the alpha particle	m_α	$6.644\,657\,2 \times 10^{-27}$ kg
gravitational constant	G	6.67×10^{-11} N m^2 kg^{-2}
Mean acceleration due to gravity on Earth	g	9.8 m s^{-2}
Wien's displacement constant	b	2.898×10^{-3} m K
speed of sound in air at 25°C	v_s	346 m s^{-1}
mass of Earth	m_E	5.97×10^{-24} kg

TABLE 4 Heating processes

Latent heat of fusion for water	$L_f = 3.34 \times 10^{5}$ J kg^{-1}
Latent heat of vaporisation for water	$L_v = 2.26 \times 10^{6}$ J kg^{-1}
Specific heat capacity of ice	$c_i = 2.05 \times 10^{3}$ J kg^{-1} K^{-1}
Specific heat capacity of steam	$c_s = 2.00 \times 10^{3}$ J kg^{-1} K^{-1}
Specific heat capacity of water	$c_w = 4.18 \times 10^{3}$ J kg^{-1} K^{-1}

Formulas

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	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$
power in a circuit	$P = VI$ $P = I^2R$ $P = \frac{V^2}{R}$
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	$p = mv$ $\Sigma mv_{before} = \Sigma mv_{after}$ $\Delta p = F\Delta t$
Newton's second law	$a = \frac{F_{net}}{m}$
work done	$W = Fs$ $W = \Delta E$
gravitational potential energy	$\Delta E_p = mg\Delta h$
kinetic energy	$E_k = \frac{1}{2}mv^2$
conservation of momentum in elastic collisions	$\sum \frac{1}{2}mv_{before}{}^2 = \sum \frac{1}{2}mv_{after}{}^2$

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	$v = \frac{2\pi r}{T}$
centripetal acceleration	$a_c = \frac{v^2}{r}$
centripetal force	$F_{net} = \frac{mv^2}{r}$
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	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$ $\frac{1}{4\pi\varepsilon_0} = \frac{8.99 \times 10^9\ \text{Nm}^2\,\text{c}^{-2}}{\text{C}^2} = k$
simplified Coulomb's law	$F = k\frac{Qq}{r^2}$
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	$B = \frac{\mu_0 I}{2\pi r}$
force on a charged particle	$F = qvB\sin\theta$
magnetic force on a current-carrying wire	$F = BIL\sin\theta$
induced EMF (in coils)	$\text{EMF} = -\frac{n\Delta(BA\perp)}{\Delta t}$ $\text{EMF} = -n\frac{\Delta\Phi}{\Delta t}$
magnetic flux	$\Phi = BA\cos\theta$
power in transformers	$I_p V_p = I_s V_s$
voltage in transformers	$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$
magnetic field inside a solenoid	$B = \mu_0 nI$

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

The answers to questions that involve calculations are given to the least number of significant figures as given in the question.
See page e26 in Chapter 1 for more details.

Chapter 2 Vectors and projectile motion

2.1 Vectors in two dimensions

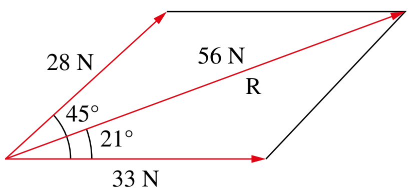
TY 2.1.1 50° clockwise from the rightwards direction

1 a full circle or true bearing, or a quadrant bearing
2 a direction and an angle
3 **a** down **b** south **c** right
d up **e** east
4 west
5 **a** **i** 225°T **ii** S45°W
b **i** 120°T **ii** S60°E
6 40° clockwise from the left direction

2.2 Adding vectors in two dimensions

TY 2.2.1 5.8 N, 31° north of east or N59°E

1 graphical solution
2 0 N
3



The resultant force is 56 N, 21° upwards.
4 31.0 N
5 227 km, S67.5°E

2.3 Subtracting vectors in one and two dimensions

TY 2.3.1 9.2 m s^{-1} N41°E

1 false
2 Change the sign (direction) of the first vector so that it is 20 km right and then add this to 17 km upwards.
3 32 N, N56°E
4 47.8 m s^{-1} upwards at 47.2° from the vertical
5 533 m s^{-1}, N49.6°W
6 59.4 m s^{-1}, due north-west
7 8.79 m s^{-1} west 53.3° north (N36.7°W)

2.4 Vector components

TY 2.4.1 1580 N down **TY 2.4.2** 32.6 km north 13.5° east

1 Pythagoras' theorem
2 25 m north
3 2298 N south
4 43.0 m east, 18.9 m south
5 109 000 N north and 208 000 N west
6 **a** 50.0 N south, 86.6 N east
b 60.0 N north, 0 N east
c 102.6 N E, 281.9 N S
d 1.50×10^5 N vertically, 2.60×10^5 horizontally
7 15.0 N horizontally, 26.0 N vertically
8 16 N at 51° above the horizontal

2.5 Projectile motion

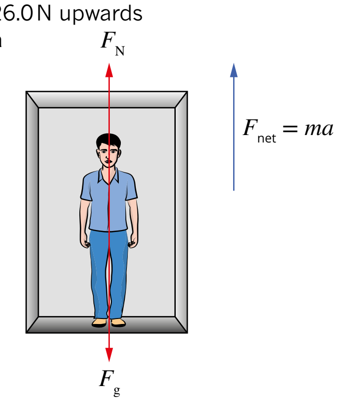
TY 2.5.1 **a** 2.5 s **b** 49.4 m **c** 31 m s^{-1} at 50° below the horizontal
TY 2.5.2 **a** 6.11 m s^{-1} horizontally to the right **b** 0.25 m **c** 0.44 s

1 remains constant
2 at the highest point of its trajectory
3 parabolic
4 **a** 1.30 m **b** –2 m s^{-1} **c** 2.23 m s^{-1}
5 **a** 1.0 s **b** 20 m **c** 9.8 m s^{-2}
d 21 m s^{-1} **e** 22 m s^{-1}
6 **a** 47 m s^{-1} **b** 58° below the horizontal
7 **a** 0.4 s **b** 1.54 m **c** 9.8 m s^{-2} downwards

Chapter 3 Inclined planes

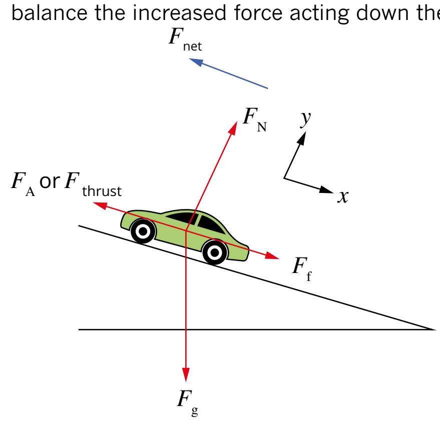
3.1 Inclined planes

TY 3.1.1 7990 N
TY 3.1.2 26.0 N upwards
TY 3.1.3 **a**



b 700 N upwards
TY 3.1.4 **a** 780 N perpendicular to the slope downwards
b 780 N perpendicular to the slope out of the plane
c 3.3 m s^{-2} down the slope
TY 3.1.5 4.2 m s^{-2}

1 $F_g = mg$
2 newton (N)
3 It is always straight down regardless of the angle of the inclined plane.
4 It is always at right angles to the surface on which the object is resting.
5 The normal force is the force acting on an object on a surface due to the surface itself pushing back on the object. If the object is not in contact with the surface, then the surface cannot push back on it and hence there is no normal force.
6 As the angle of the bridge increased, F_g remained constant, F_N decreased, but the frictional force acting on the tyres increased to balance the increased force acting down the incline.
7



8 32 000 N up the slope
9 tension = 8.9 N; force = 36 N up the incline

Chapter 4 Motion in a circle

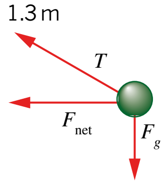
4.1 Circular motion

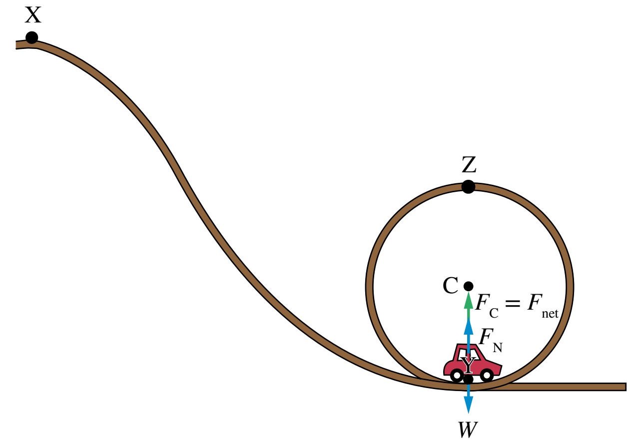
TY 4.1.1 **a** 120 Hz **b** 8.3×10^{-3} s **c** 67 m s^{-1} **d** 7.6 m s^{-1}
TY 4.1.2 **a** 1400 m **b** 9.0×10^2 m **c** 28 m s^{-1}
d 18 m s^{-1} from X to Y

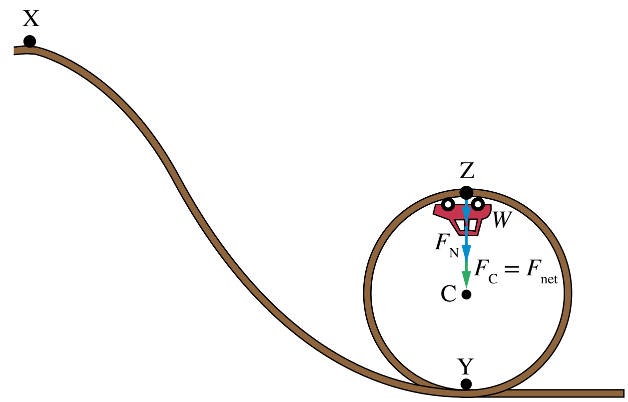
1 period (s), frequency (Hz), average speed (m s^{-1}), average velocity (m s^{-1})
2 the motion of an object moving around a circle with a constant speed

3 The average speed is the total distance travelled (i.e. the circumference) divided by the total time taken (i.e. the period). The average velocity is the total displacement divided by the period.
4 Period is the total time taken for one rotation (measured in seconds). Frequency is the inverse of the period, or how many rotations are completed in one second (measured in hertz, Hz).
5 Acceleration is defined as the change in velocity divided by time. Velocity is a vector so it requires magnitude and direction. Even if the magnitude is constant, if the direction of an object changes, then its velocity changes and hence it accelerates.
6 **a** 4.4×10^7 m **b** zero **c** 7.6×10^3 m s^{-1} **d** 0 m s^{-1}
7 3.09 m s^{-1} towards the north-west
8 The distance moved by an object in uniform circular motion is the circumference or part of the circumference of a circle. The displacement is the straight line length between the starting and finishing locations. The maximum displacement is when the start and finish are separated by 180°, which is the diameter of the circle or 2 radii. The distance covered after 180° is 3.14 radii. At every point on the circle's circumference the distance travelled will always be larger than the displacement, thus the average speed will always be greater than the average velocity.

4.2 Centripetal force

TY 4.2.1 **a** 3.0×10^4 m s^{-1}
b 6.0×10^{-3} m s^{-2} towards the Sun
c 3.6×10^{22} m s^{-2} towards the Sun
TY 4.2.2 **a** 1.3 m
b


c 2.6 N towards the pole
d 3.0 N along the cord towards the top of the pole
e 4.7 m s^{-1}
TY 4.2.3 6.0 times his weight, or 6.0 g
1 Centripetal acceleration acts directly towards the centre of the circle that the object is moving in.
2 Centripetal force also acts directly towards the centre of the circle that the object is moving in.
3 The net force must act at right angles to the object's velocity for the object to move in a circle.
4 Velocity is always at a tangent to the circle, that is, at right angles to the radius.
5 In order for an object to undergo uniform circular motion, the net force on the object must be towards the centre of the circle it is moving in, that is, at 90° to the velocity of the object. There can be many forces acting on an object, and Newton's second law states that the sum of the forces that act on an object directly is equal to the net force or $F = ma$. The centripetal force is the result of the forces that would act on the object directly if they were all reduced to one single force. If the direction of the net force is at 90° to the velocity of the object, then the object will accelerate towards the centre of the circle.
6 Once they let go of their projectile there is no longer any centripetal force acting, so the projectile will move with the same speed and direction it had at the instant the centripetal force was removed. Assuming that the projectiles do not curve, then the hammer and discus thrower must release their projectiles when the hand(s) holding the hammer or discus form a right angle to the arena. They do not want to release their projectile when their hand(s) are pointing directly at the arena, because the projectile will move off at right angles and hit the safety cage.
7 **a**


b


8 0.34% of the value of the acceleration due to Earth's gravity
9 2.32×10^7 m s^{-1}
10 1.5 km

Chapter 5 Gravity

5.1 Newton's law of universal gravitation

TY 5.1.1 The acceleration on Mars is 7.63 times greater than the acceleration of Phobos.
TY 5.1.2 1.5×10^{-7} N
TY 5.1.3 3.52×10^{22} N
TY 5.1.4 1.19×10^{25} m s^{-2}
TY 5.1.5 Both equations give the same result: 49 N.
TY 5.1.6 960 N upwards
1 The force of attraction between any two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.
2 the distance between the centres of the two objects
3 **a** The gravitational force between the two masses is doubled.
b The gravitational force between the two masses is one quarter of the original force.
c The gravitational force between the two masses is decreased by a factor of 16.
4 The Moon has a smaller mass than Earth and therefore experiences a larger acceleration from the same gravitational force.
5 **a** 1.63×10^{21} N towards each object
b 2.55×10^{-3} m s^{-2} towards the Sun
6 **a** 2.94×10^{16} N towards each planet
b 3.52×10^{24} m s^{-2} towards the Sun
c 0.000 000 835%
d 225 million km

7 On Earth, weight is the gravitational force acting on an object near the Earth's surface. Apparent weight is the contact force between the object and the Earth's surface. In many situations, these two forces are equal in magnitude but are in opposite directions, such as on any horizontal, non-accelerating surface. This is because apparent weight is a reaction force to the weight of an object resting on the ground. However, in a lift accelerating upwards, the apparent weight of an object would be greater than its weight, since an additional force is required to cause the object to accelerate upwards.

8 **a** 1.5×10^{-6} N towards each astronaut
b 1.0×10^{-8} m s^{-2} towards each other

9 **a** $g_{Mercury} = G\frac{M_{Mercury}}{r_{Mercury}^2}$
b The smaller radius of Mercury would have the effect of increasing the gravitational acceleration at the surface.
c The much smaller mass of the planet would have the effect of decreasing the gravitational acceleration at the surface.
d 3.69 m s^{-2} towards the surface of Mercury
e 277 N downwards, towards the surface of Mercury

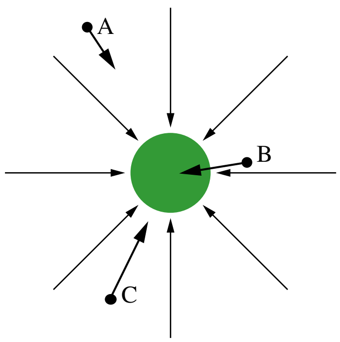
10 666 N downwards, towards the surface of Venus

11 **a** 550 N upwards **b** 490 N upwards

12 **a** 2.22×10^{17} N towards each planet
b 1.40×10^{21} N towards the Sun

5.2 Gravitational fields

TY 5.2.1 **a**



b The field is stronger at point B than at point A. Field at C is weaker than field at B, but stronger than the field at A.

TY 5.2.2 9.77 N kg^{-1} downwards **TY 5.2.3** 0.887 **TY 5.2.4** 3.1

1 units: m s^{-2}; $g_{average}$ = 9.8 m s^{-2}

2 Albert Einstein

3 Gravitational field lines from a single body always point towards the centre of mass of that body. Because Earth is so large, we can approximate these arrows as being parallel at the surface, within a small enough area.

4 The field at 1200 km is one-ninth of the field strength at 400 km.

5 9.73 N kg^{-1} downwards

6 **a** 5.68 N kg^{-1} **b** 1.49 N kg^{-1}
c 0.564 N kg^{-1} **d** 0.224 N kg^{-1}

7 **a** 8.22×10^{-4} N kg^{-1} **b** 1.19×10^{4}

8 **a** The very small radius of the neutron star would create an intensely strong gravitational field at its surface—much, much larger than that of our Sun.
b 2×10^{12} N kg^{-1} **c** 2×10^{11} **d** ≈ 5 000 000 km

9 **a** The gravitational field strength at the equator would be four times weaker than that at the poles.
b $G_{equator}$ = 2.03 N kg^{-1} which is four times weaker than at the poles

10 10 Earth radii

Chapter 6 Orbits

6.1 Kepler's laws of planetary motion

TY 6.1.1 3.08×10^{3} m s^{-1}

TY 6.1.2 **a** 6.70×10^{5} km **b** 1.90×10^{27} kg **c** 8.20 km s^{-1}

1 **1** The planets move in elliptical orbits with the Sun at one focus.
2 The line connecting a planet to the Sun sweeps out equal areas in equal intervals of time.
3 For every planet, the ratio of the of the average orbital radius, *r*, to the square of the period, *T*, is the same.

2 The aphelion is the point in a planet's orbit when it is furthest from the Sun and the perihelion is the point when it is closest to the Sun.

3 In order to sweep out equal areas in equal times, a planet must be travelling faster near the Sun than when further from it.

4 Equate the centripetal force of circular motion $\frac{4\pi^2 mr}{T^2}$ with Newton's force of universal gravitation $\frac{GMm}{r^2}$ and rearrange to get $\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$.

5 12 years

6 30.1 AU

7 0.0663 days

8 1.8 days

9 6.402×10^{20} kg

6.2 Satellites and their orbits

1 A satellite is an object that is in a stable orbit around a larger mass.

2 As a geostationary satellite has a period of 24 hours, its position in the sky will remain fixed. This means that a receiving dish can also be fixed, once it has been oriented in the direction of the satellite. In other words, the satellite dish does not need to be steerable.

3 The minimum time—0.24 s—is determined by the altitude of the geostationary satellite and the speed of the radio signal (*c*) in travelling from Earth to the satellite and back. Even though this time delay is small, it will still be noticeable.

4 ratio = $\frac{1}{4}$, orbital radius = 2.7×10^{7} m

Chapter 7 Electric fields

7.1 Coulomb's law

TY 7.1.1 6.32×10^{-4} N repulsion

TY 7.1.2 -6.35×10^{-10} C

TY 7.1.3 0.355 N at an angle of 82° below the horizontal

1 Coulomb's law describes the force exerted by electrostatically charged objects on other electrostatically charged objects. It says that the greater either of these charges is, the larger the force will be. Furthermore, the closer the two charges are, the greater the force and, conversely, the further apart they are, the smaller the force.

2 **a** the charges of the two particles (Q, q) and the distance between them (r)
b There is a linear dependence on the charge of the first particle, a linear dependence on the charge of the second particle, and an inverse squared dependence on the radial distance between the two particles.

3 **a** *double* and *repel* **b** *quadruple* and *repel*
c *double* and *attract* **d** *quadruple* and *repel*

4 zero

5 zero

6 -8.2×10^{-8} N

7 36.9 N

8 2.1×10^{-28} N at 45°

7.2 Electric fields

TY 7.2.1 5.62×10^{-4} N C^{-1}

TY 7.2.2 8.0×10^{5} N C^{-1} to the right

1 **a** true **b** false **c** false **d** true
e true **f** false **g** false

2 It decreases with an inverse square relationship.

3 The force is opposite to the direction of the electric field in which the charge is placed.

4 The charged particle will change velocity and/or direction.

5 1.25×10^{-2} N

6 1.4 mC

7 5.72×10^{11} ms^{-2}

7.3 Electrical potential energy

TY 7.3.1 2.16×10^{-18} J; work is done on the field

1 It is the difference in potential energy stored in an electric field when a charge is placed at a particular point in that field compared to when that charge is an infinite distance away from the source of the field.

2 It is the energy available to an object because of its position relative to other objects or its position within a field.

3 When a charge is accelerated by a force due to an electric field, work is done on the charge by the field. When a charge is moved through a field against the direction of the force acting on it, work is done on the field by the charge.

4 **a** by the field **b** no work **c** on the field
d no work **e** on the field **f** by the field

5 **a** 1.09×10^{-19} J **b** on the field

6 300 V

7 1200 V

Chapter 8 Magnetic fields

8.1 Magnets

1 *permanent magnets* (materials that hold magnetic properties over a long period of time), *temporary magnets* (materials that temporarily gain magnetic properties when exposed to a strong enough magnetic field) and *electromagnets* (magnetic fields produced by running an electric current through a coil of wire).

2 non-contact force

3 towards Earth's geographic north

4 All magnets are dipolar.

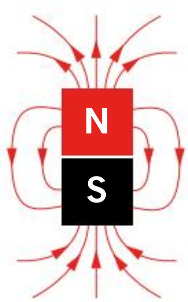
5 The object is attracted to and repelled by the magnet.

6 **a** *F* decreases **b** *a* decreases **c** *a* and *F* increase

8.2 Magnetic field diagrams

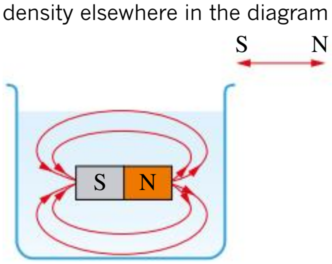
1 It indicates the direction of the force that would act on a single north pole at that point.

2



3 by the density of its field lines at a particular point relative to the density elsewhere in the diagram

4



5 in the east direction

6 west

7 zero field

8.3 Creating magnetic fields

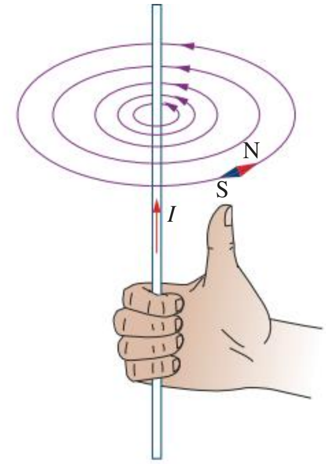
TY 8.3.1 The magnetic field direction is perpendicular to the wire. As the current travels along the wire, the magnetic field runs anticlockwise around the wire.

TY 8.3.2 1.9×10^{-8} T

1 crosses = directed into the page; dots = directed out of the page

2 A charged particle induces an electric field by virtue of having charge. It generates a magnetic field whenever it is in motion.

3



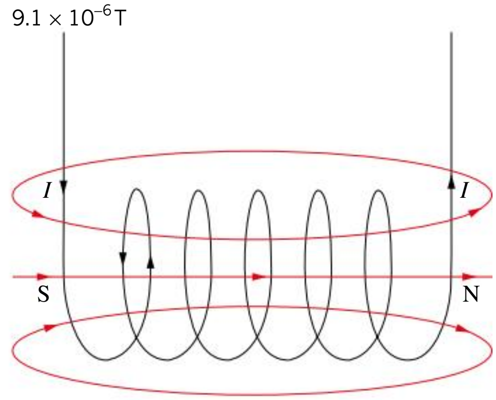
4 **a** $\frac{1}{2}B$ **b** $3B$

5 1.9×10^{-5} T

6 3.0 A

8.4 Solenoids

TY 8.4.1 **a** 9.1×10^{-6} T
b



1 a single wire coiled up with an electric current running through it

2 inserting a piece of iron through the coil, increasing the current through the coil or increasing the number of turns per metre in the coil

3 linear relationship

4 A

5 The solenoids will repel each other.

6 south-west

7 2.15×10^{-5} T

8 0.15 A

9 2.0×10^{4} loops per metre

8.5 Magnetic force on a current-carrying wire

TY 8.5.1 2.5×10^{-3} N

TY 8.5.2 vertically downwards

TY 8.5.3 **a** 0 N
b 1.0×10^{-3} N out from Santa's house as you are looking at it

TY 8.5.4 1.3×10^{-5} N

1 The direction of the current and the magnetic field. Point your thumb in the direction of the current and curl your fingers in the direction of the magnetic field. Your palm will be facing in the direction of the magnetic force.

2 **a** 0° or 180° **b** 90° or 270°

3 no force, hence no direction of force

4 into the page

5 **a** no change **b** no change

6 0.4 N

7 2.0×10^{-4} N north

8 **a** 0.18 N downwards **b** no change

9 0.56 N out of the page

8.6 Motors

1 when the force is applied at right angles to the axis of rotation
2 1.0×10^{-2} N into the page
3 1.0×10^{-2} N out of the page
4 0 N
5 anticlockwise
6 The direction of the current does not affect the magnitude of the torque, only its direction.
7 0.10 N
8 anticlockwise
9 All three actions cause the coil to rotate faster.

8.7 Magnetic force on a single charge

TY 8.7.1 inwards
TY 8.7.2 4.8×10^{-22} N
TY 8.7.3 2.6×10^{-14} N
TY 8.7.4 **a** 1.3×10^{5} V m^{-1} **b** 9.4×10^{7} m s^{-1} **c** 1.8×10^{-3} m

1 $F = qvB$
where
q is the electric charge of the particle, in coulombs
v is the velocity at which the particle is travelling, in m s^{-1}
B is the strength of the magnetic field in which the particle is travelling, in tesla.
2 0 N
3 radius is doubled
4 It continues in a straight line with the same speed.
5 $v\cos\theta$ is the component of velocity that is parallel to the field, but this contributes nothing to the force acting on the particle.
6 **a** south
b the arc of a circle while the particle is inside the field, and a straight line when it is outside the field
c constant
d A
e particles with no charge
7 Charged particles experience a force from the magnetic field which constantly accelerates the particle. This force is always perpendicular to the magnetic field, causing the net force to be towards the centre of a circle.
8 vertically downwards
9 1.6×10^{-24} N
10 1.7×10^{-24} N downwards
11 0 N
12 4.7×10^{-4} T
13 4.8×10^{-17} N south
14 The magnitude becomes $2F$ and the direction of the force is north.
15 4.8×10^{-19} C

Chapter 9 Electromagnetic induction

9.1 Magnetic flux

TY 9.1.1 8.0×10^{-5} Wb
TY 9.1.2 3.2×10^{-2} Wb

1 magnetic field strength
2 at right angles to the field or parallel to the normal to the area
3 between the normal to the plane of the loop and the magnetic field
4 0 Wb
5 1.3×10^{-5} Wb
6 **a** 3.2×10^{-6} Wb
b decreases from 3.2×10^{-6} Wb to 0 after one quarter of a turn, increases to 3.2×10^{-6} Wb through the opposite side of the loop after half a turn, decreases to 0 again after three quarters of a turn and returns to 3.2×10^{-6} Wb after a full turn
c The changes in flux are the same whether the magnetic field or the loop is rotated. The flux decreases from 3.2×10^{-6} Wb to zero after a quarter turn, then it increases again to its original value through the opposite side of the loop, as the magnetic field continues to rotate through to 180°. This occurs because in the initial position the field and loop are perpendicular and the flux is a maximum. As the field rotates through 90° the plane of the field and the loop are parallel, so $\theta = 90°$, cos 90° is zero and the flux is zero. As the angle changes from $\theta = 90°$ to zero, the value of the flux increases up to the original value when the field and the loop are again positioned at right angles.
7 **a** 35° **b** 55°

9.2 Electromotive force

TY 9.2.1 A non-dangerous EMF of just 0.70 V would develop.

1. The current is turned on or off.
2 A current in the second coil will only be induced when there is a changing magnetic flux cutting through this coil from the first coil. The first coil has a current flowing through it, which creates a magnetic field. However, this field is constant once the current is flowing and so there is no changing flux and no current induced in the second coil.
3 **a** a deflection
b deflection returns to zero
c a deflection opposite to that noticed at **a**
4 There is a change in magnetic flux and thus an EMF is induced while the coil is moving.
5 1.4×10^{-2} V
6 0.84 m s^{-1}
7 0.10 m
8 0 V
9 **a** 0.50 V
b decreases and gradually drops to zero
10 0.50 m s^{-1}
11 **a** The force on positive charges in the field is reversed.
b The induced charge would move out of the page, back into the page, out of the page, back into the page, and continue likewise for the duration of the oscillation.

9.3 Faraday's law

TY 9.3.1 **a** 5.0×10^{-4} Wb **b** 5.0×10^{-3} V
TY 9.3.2 1.0×10^{3} turns

1 volts (V)
2 changing the area of the coil, the strength of the field or the angle of the flux threading the loop
3 1.2×10^{-6} Wb
4 None
5 3.0×10^{-5} V
6 **a** As the falling magnet enters the coil, the flux through the coil changes rapidly. This change in flux creates a positive EMF as seen on the trace. When the magnet falls out of the coil, the coil experiences an opposite change in flux. As a result, an EMF is created that is opposite in direction to the original pulse.
b The magnet falls faster as it accelerates downwards, therefore the velocity is greater when the magnet leaves the coil than when it enters the coil. As a result, the flux through the coil changes more quickly as the magnet exits the coil, producing a greater induced EMF.
7 0.010 m^{2}
8 4.00×10^{-3} V
9 2.00 V
10 6.0×10^{-3} V
11 Abigail must induce an EMF of 1.0 V in the wire by somehow changing the magnetic flux through the coil at an appropriate rate. This can be achieved by changing the strength of the magnetic field or the area of the coil. The magnetic field can be changed by changing the position of the magnet relative to the coil. The area can be changed by changing the shape of the coil or by rotating the coil relative to the magnetic field.

9.4 Lenz's law and its applications

TY 9.4.1 clockwise when viewed from above
TY 9.4.2 **i** Y to X **ii** no current flow **iii** X to Y
TY 9.4.3 anticlockwise
TY 9.4.4 anticlockwise

1 It indicates the direction of the induced EMF.
2 increases to the left

3 right-hand grip rule

4 **a** zero flux **b** upwards **c** upwards
d downwards **e** clockwise

5 **a** zero flux **b** into the loop
c out of the loop **d** anticlockwise

6 anticlockwise

7 When a conductor moves through a magnetic field, a circular current, called an eddy current, is induced inside the conductor. The conductor experiences a magnetic force due to $F = BIL$. By the right-hand rule, this force acts in the opposite direction to the motion of the conductor and slows its motion down.

8 **a** out of the page **b** out of the page

9 **a** anticlockwise
b strength of the magnet, speed of the magnet, area or diameter of the ring, orientation of the ring, type of copper making up the ring and resistance of the current in the coil

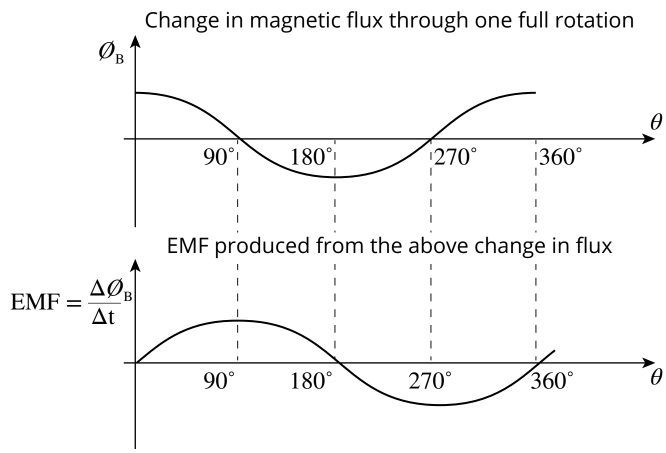
9.5 Electric power generators

1 Relative motion between a coil and a magnetic field induces an EMF in a coil.

2 maximum

3 90° and 270°

4

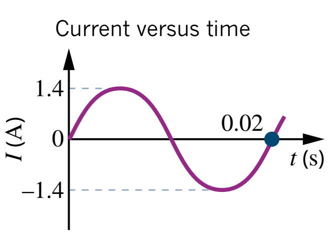


5

Component	Description	Function
armature	coils of wire wound around an iron core	a current is induced within the structure as it rotates inside a magnetic field
carbon brushes	carbon-based blocks	maintain electrical connection between the rotating slip rings and the output circuit
slip rings	metal rings that rotate with the armature	draw induced current from the armature to the output circuit

6 **a** 8.0 V **b** 8.0 V

7



8 60 W

9.6 Transformers

TY 9.6.1 4000 turns
TY 9.6.2 0.013 A
TY 9.6.3 3 W
TY 9.6.4 0.36 MW

1 a device for increasing or decreasing AC voltage

2 a soft iron coil

3 100%

4 $\frac{V_p}{V_s} = \frac{n_p}{n_s}$

5 AC current supplied to a primary coil sets up a change in magnetic flux in the secondary coil. This change in flux induces an EMF in the second coil.

6 **a** in the iron core
b It is constructed of laminations, or thin plates of iron, that are electrically insulated from each other.

7 To induce an EMF in the secondary coil, the magnetic flux must be changing. Only AC voltage produces an alternating current that creates a changing magnetic flux.

8

n_1	n_2	Step-up or step-down transformer
1	50	step-up
10	200	step-up
20	1	step-down
1000	25	step-down

9 **a** $P_1 = P_2$ **b** $\frac{I_2}{I_1} = \frac{n_1}{n_2}$

10 **a** 80 V **b** 16 W **c** 0.20 A

11 **a** 40 turns **b** 0.10 A **c** 24 W **d** 0 V

12 40.0 MW

13 Statement A is incorrect because the V in the formula refers to the voltage drop in the transmission lines, not to the voltage being transmitted in the line. Statement B is correct, as the greater the current in the transmission line, the greater the power loss.

14 5630 V

9.7 Electromagnetic radiation

TY 9.7.1 5.00×10^{14} Hz

1 electric and magnetic fields

2 Light waves can travel through a vacuum.

3 90°

4 ultraviolet light

5 from shortest to longest wavelength: X-rays, visible light, infrared radiation, FM radio waves

6 390–780 nm

7 A changing magnetic field produces a changing electric field which in turn produces a changing magnetic field and so on so that the wave, once formed, will continue to travel.

8 Mechanical waves such as sound waves and water waves require a medium in which to travel, so scientists thought that since light reaches Earth from the Sun, there must be a medium between Earth and Sun. They called this the aether.

9 shorter

10 increases

11 microwaves

12 **a** electrons
b An alternating current signal causes the electrons to oscillate.

13 Its frequency is altered.

14 The frequency of the microwaves matches the resonant frequency of water molecules. This makes the water molecules vibrate quickly, increasing their kinetic energy and heating them up. This heat cooks the remainder of the food through the processes of conduction and convection.

15 **a** 4.57×10^{14} Hz **b** 5.09×10^{14} Hz
c 6.17×10^{14} Hz **d** 7.56×10^{14} Hz

16 0.07%

17 500 nm

18 4.3 m

19 1.50×10^{18} Hz

20 0.122 m

Chapter 10 Special relativity

10.1 Einstein and relativity

TY 10.1.1 **a** $5\,\text{m s}^{-1}$ **b** $4\,\text{m s}^{-1}$

1 They are observed at the surface of Earth many kilometres away from where they should have decayed. This indicates that when they travel very fast, muons last longer.

2 In the car's reference frame: you, the driver, seats, a dog, McDonald's wrappers, shoes etc. Not in the car's reference frame: the road, other cars, pedestrians, houses, Earth etc.

3 *very short, μs, very similar to, should not, do.*

4 **a** $370\,\text{m s}^{-1}$ **b** $300\,\text{m s}^{-1}$ **c** $360\,\text{m s}^{-1}$ **d** $340\,\text{m s}^{-1}$

5 **a** $15\,\text{m s}^{-1}$ backwards **b** 3.0 mm backwards **c** 0.20 s

6 **a** 0.10 s **b** $50.0\,\text{m s}^{-1}$ in all frames **c** 1.0 m
d $50.0\,\text{m s}^{-1}$ **e** 0.08 s

10.2 Frames of reference

1 Physicists believed that all waves—including light—had to travel in a medium. So just as air is the medium for sound, they invented the aether as the medium for light.

2 Some examples: an aircraft in steady flight and a car driving up a hill of constant slope at a steady velocity.

3 Some examples: an aircraft accelerating while taking off and a car going around a curve.

4 zero

5 One possibility: a hanging pendulum in the spaceship will move from its normal vertical position when the spaceship accelerates.

6 **a** You and the ball are in the same reference frame that is moving at a constant velocity, so there is no motion backwards or forwards.
b You are now in a non-inertial reference frame, so there will be some relative velocity between you and the ball. The ball has some forwards velocity, but you have now stopped.

7 Max's sister is in circular motion so she is in a non-inertial reference frame. Thus she sees the ball curve. Max sees the ball move in a straight line, as the ball is in his inertial reference frame.

10.3 Postulates of relativity

1 Time is not constant in all frames of reference.

2 both

3 Answers will vary but should include a moving object, with something stationary in it, and someone outside the object. The stationary object inside the moving object should see light hit a barrier in all directions at the same time. However, the observer will notice the light hitting the barrier in the direction opposite the movement first.

4 The speed of the ball is greater for Jana than it is for Tom. The speed of the sound is greater forwards than it is backwards for Jana, while for Tom it is the same forwards and backwards. The speed of light is the same for Jana and Tom.

5

	Similarities	Differences
Newton	All observers, regardless of whether they are moving or not, are equivalent when it comes to their description of the world around them.	Space and time are constant, uniform and straight.
Einstein	All inertial frames are equivalent, the observer's motion (with constant velocity) is irrelevant, and that all laws of physics have the same form in all inertial frames.	Neither space nor time are fixed and unchangeable.

6 Incorrect. The ray of light is the fish, the aether is the water, and the other fish moving downstream represent Earth.

10.4 Simultaneity

1 Space and time are interdependent.

2 $3 \times 10^{8}\,\text{m s}^{-1}$

3 Stephen is in a different frame of reference to Barry. Stephen will see the light source from the left moving towards him, whereas the light source from the right is alongside him, and so this light source will take longer to catch up to Barry.

4 Answers will vary. An example is a person sitting in the middle of a plane travelling at close to the speed of light and sending flashes of light simultaneously towards the front and back of the plane. If a stationary observer on the ground could see this light, they will see the flash of light strike the back of the plane first, whereas the person on the plane will see the flashes of light strike the front and back at the same time.

10.5 Time dilation

TY 10.5.1 520 s

1 *light, oscillation, time, constant.*

2 The time measured at rest with respect to the event being timed, or where measurements are made in the same location in space.

3 The slowing effect is well below what we can detect, as the speed of the equator is only about $460\,\text{m s}^{-1}$ (about 1.5 millionths of c).

4 (1) Time dilation is only detectable with objects moving at close to the speed of light. (2) Even if we go at speeds high enough to bring about a large slowing down of local time, we wouldn't notice it because our body clocks would also be running just as slowly.

5 1.29 s

6 48.2 s

7 2.20 s

8 1.15 s

9 **a** 1.00 m **b** $3.33 \times 10^{-9}\,\text{s}$ **c** $d = ct_c$
d $7.65 \times 10^{-9}\,\text{s}$ **e** 2.29

10 **a** $1.74 \times 10^{-5}\,\text{s}$
b non-relativistic = 655 m; relativistic = 5180 m

11 $2.93 \times 10^{-11}\,\text{s}$

10.6 Length contraction

TY 10.6.1 3.90 m

TY 10.6.2 20.5 m

1 Proper length is the distance between two points whose positions are measured by an observer at rest with respect to those points.

2 Width and height are not affected as they are at right angles to the direction of motion, so a stationary observer will see a moving object with a contracted length.

3 0.812 m

4 3.37 m

5 **a** $2.71 \times 10^{8}\,\text{m s}^{-1}$ **b** 0.643 m

6 It is proper time, t_0, because the observer can hold a stopwatch in one location and start it when the front of the carriage is in line with the watch and stop it when the back of the carriage is in line with it; i.e. her stopwatch is in her own stationary reference frame regardless of what the observer is timing.

7 **a** $2.598 \times 10^{8}\,\text{m s}^{-1}$ **b** 0.5

8 23.5 m

9 **a** 1.20 m **b** 2.75 m

10.7 Mass in relativity

TY 10.7.1 $2.92 \times 10^{-30}\,\text{kg}$

1 In circular accelerating devices, as the velocity of the charged particle increases, the radius of its path also increases, but to a much greater degree than expected. If the charge q and the magnetic field B do not change, then the only explanation for the extra increase in radius is that the mass of the particle must have increased.

2 Its mass would approach infinity.

3 The relativistic mass is the increase in inertial mass due to the speed of the object approaching the speed of light. The more the speed of an object increases, the more difficult any further acceleration becomes. This is due to the inertial mass increasing, not the mass itself increasing.

4 26 kg

5 93.9 kg

10.8 Relativistic momentum and mass—energy equivalence

TY 10.8.1 **a** 1.56×10^{-21} kg m s^{-1} **b** $0.997c$

TY 10.8.2 **a** 4.81×10^{-12} J **b** 5.34×10^{-29} kg

1 Impulse can be found from the mass and the change in velocity by using $\Delta p = p_{final} - p_{initial}$. Alternatively, it can be calculated from the force and the time for which it acts, i.e. impulse = $\Delta p = mv - mu = m\Delta v = F\Delta t$.
2 As objects approach the speed of light, their mass gets larger and larger and they become more and more difficult to accelerate.
3 $E_k = \frac{1}{2}pv$
4 The greater the impulse, the greater the increase in momentum. At speeds near that of light, this can be interpreted as an increase in the mass of the object, and so the velocity only increases a very small amount.
5 9.53×10^{5} kg m s^{-1}
6 9.64×10^{-18} kg m s^{-1}
7 1.594×10^{-23} kg m s^{-1}
8 9.00×10^{16} J
9 4.466×10^{-26} kg

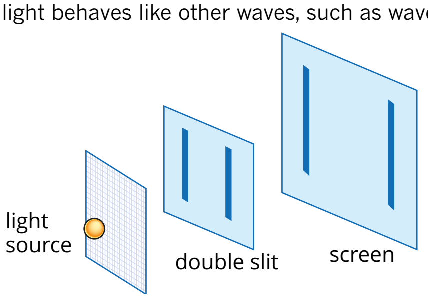
10.9 Apparent paradoxes

1 Crews A and B will see each other normally as there is no relative velocity between them. They will both see C and the Earthlings moving in slow motion, as Earth has a high relative velocity.
2 The remaining twin ages faster during both the acceleration and deceleration phases because the twin who travels experiences non-inertial frames of reference when accelerating and decelerating. This is when the travelling twin sees the twin at home ageing rapidly.
3 In your frame of reference time proceeds normally. Your heart rate would appear normal. As Mars is moving at a high speed relative to you, people on Mars appear to be in slow motion, as time for them, as seen by you, will be dilated.
4 Some examples are:
- If you went back to the time before your parents were born and shot your grandfather, you wouldn't have existed in the first place to pull the trigger.
- A mathematician travels into the future to steal a maths theorem that could change the world. The professor then gives the theorem to a student, who ends up being the student the professor stole the theorem from. It becomes a constant loop.
- What happens if you perform an action that eliminates your reason for travelling back in time?

Chapter 11 Quantum physics

11.1 Light as a wave

1 A pattern of alternating bright and dark lines was observed.
2 Laser light is monochromatic (of only one colour and therefore only one wavelength) and therefore the bright and dark fringes are equally spaced and seen more clearly. Light of many wavelengths, as emanating from a torch, will have fringes that overlap, making them much harder to differentiate.
3 By showing diffraction fringes, the experiment demonstrated that light behaves like other waves, such as waves in water.
4



5 A light wave is a continual motion of an oscillating electric and magnetic field, i.e. successive crest – trough – crest – trough, with the spacing between crests and troughs equal. Since the crest and trough spacings are equal and continuous, there will be an equal spacing of bright – dark – bright – dark fringes seen on a screen.
6 Fringes are not just formed when a crest meets a crest or a crest meets a trough. The whole wave will interfere with another wave which may slightly be out of phase, i.e. a crest meets part of a wave that is not at the crest, but between a crest and a trough. When this happens the intensity of the resulting addition of waves is not quite maximum.
7 The distance that two interfering waves have to travel from the slits to the screen is increasing. Since the intensity of a wave decreases as the distance from its source increases, the intensity of fringes further away from the central axis must decrease.
8 At the time, Newton's particle model of light was the dominant view of scientists. Scientists accepted that light was a stream of particles. However, Young's experiment—proving that light behaved like a wave—required scientists to rethink their view.

11.2 Black-body radiation

TY 11.2.1 30 000 K

TY 11.2.2 9.66×10^{-6} m

1 $\lambda_{max}T = 2.898 \times 10^{-3}$ m K where λ_{max} is the peak wavelength of the emitted radiation in metres (m) and T is the surface temperature of the object in kelvin (K).
2 infrared region
3 3623 K
4 4140 K
5 311 nm

11.3 Quantisation of energy

TY 11.3.1 1.5 eV

1 The energy of a single photon is very small and the joule is too large a unit to be convenient for measuring it.
2 a single quantum of light or any other electromagnetic radiation
3 The Planck equation explains the energy of a single photon, an individual quantum of energy. The energy is found by multiplying the frequency of the electromagnetic energy by Planck's constant.
4 1.60×10^{-6} J
5 **a** 3.80×10^{-19} J **b** 2.38 eV
6 **a** 3.03×10^{-19} J **b** 3.37×10^{-19} J **c** 4.09×10^{-19} J **d** 5.01×10^{-19} J

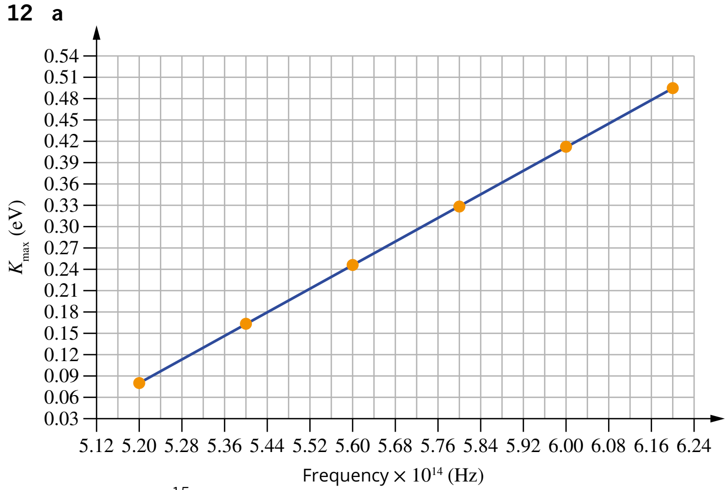
11.4 The photoelectric effect

TY 11.4.1 4.97 eV

TY 11.4.2 2.0 eV

1 false
2 electron volt (or joule)
3 The photoelectric effect leads to the ejection of negatively charged electrons from the initially neutral metal, leaving the metal with a net positive charge.
4 **a** False. When the intensity of light shining on the surface of the metal increases, the photocurrent increases provided that the frequency of the incident light is above the threshold frequency of the metal.
b False. When light of the same intensity but of different frequencies are used, the higher frequency light has a higher stopping voltage. However, it produces the same maximum current as the lower frequency light.
5 **a** true
b False. The stopping voltage is reached when the applied potential is equal to the energy of the most energetic photoelectrons divided by the charge on the photoelectrons.
c true
d true
6 Rb = 2.1 eV, Sr = 2.5 eV, Mg = 3.4 V, W = 4.5 eV
7 **a** 4.1 eV **b** 4.6 eV **c** 6.2 eV
8 8.84×10^{14} Hz

9 0.066 eV
10 0.255 eV
11 1.68 eV
12 a



b 4.1×10^{-15} eV s
c approximately 5.0×10^{14} Hz
d No. The frequency of red light is below the threshold frequency for rubidium.

Chapter 12 The atom

12.1 Rutherford's model

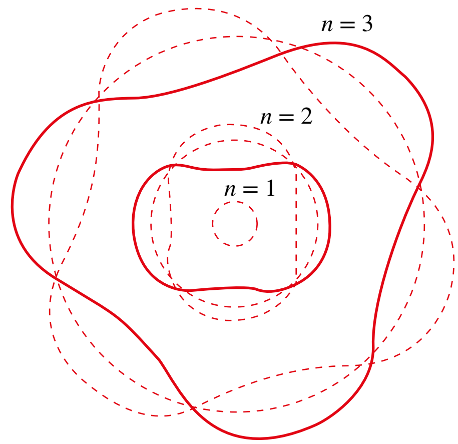
1 Most of the atom is empty space. The nucleus contains all of the positive charges in the atom, and is surrounded by an equal number of negatively charged electrons. The atom is about 10^{-10} m in diameter, and the nucleus is around 10^{-15} m diameter.
2 It doesn't explain why electrons don't spiral into the nucleus, why electrons don't emit energy continuously and the existence of emission spectra.
3 They were expecting the alpha particles to pass straight through the foil. Thomson's plum pudding model had the positive charge spread through the whole atom, so they expected that any repulsion would be spread evenly and have no effect.
4 An alpha particle is positive, and like charges repel.
5 127 m
6 1×10^{-7} m (to one significant figure)
7 The nucleus was larger in radius.

12.2 Bohr's model

TY 12.2.1 energy = 6.72×10^{-20} J and wavelength = 2.95×10^{-6} m
1 the electrostatic force (or electromagnetic force)
2 The energy given describes how well the electron is bound, and decreases from the energy of an unbound electron at 0 eV.
3 3.0×10^{-6} m
4 12.75 eV
5 4.0×10^{-19} J
6 It could not predict the higher-energy orbits of multi-electron atoms, the continuous emission spectrum of solids, and the intensity (brightness) of the spectral lines.

12.3 Particles as a wave

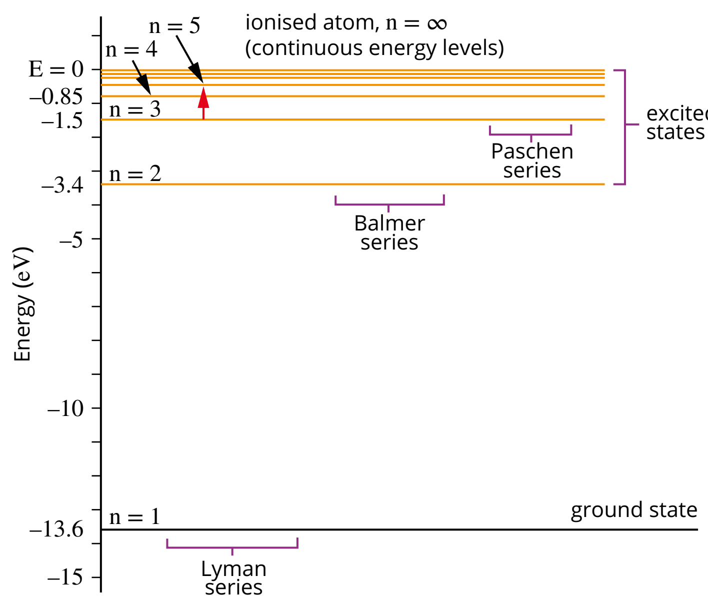
TY 12.3.1 5.7×10^{-13} m
TY 12.3.2 1.0×10^{-36} m
TY 12.3.3 0.17 nm
TY 12.3.4 1.5×10^{-27} kg m s^{-1}
TY 12.3.5 2.12×10^{-10} m
1 Since light, which had long been considered to be a wave, sometimes exhibited particle-like properties, then perhaps matter, which was considered to be made up of particles, might sometimes demonstrate wave-like properties.
2 They bombarded a nickel sample with a beam of electrons and observed a diffraction pattern formed by the electrons scattered from the lattice structure of the nickel.
3



4 The wavelength of a cricket ball is so small that its wave-like behaviour could not be seen by the cricket player.
5 7.3×10^{-10} m
6 1.8×10^{5} m s^{-1}
7 a 3.5×10^{-11} m
b 2.1×10^{7} m s^{-1}
8 $\lambda = \frac{h}{\sqrt{2qVm}}$
9 1.44×10^{-19} J
10 4.8×10^{-10} m

12.4 Atomic spectra

TY 12.4.1



TY 12.4.2 93.76 nm
TY 12.4.3 $n = 4$
TY 12.4.4 A photon of 6.7 eV will be absorbed, a photon of 9.0 eV cannot be absorbed and a photon of 11.0 eV will ionise the mercury atom.
1 It typically consists of a series of spaced coloured lines on a black background.
2 The different coloured lines in the emission spectrum correspond to the possible electron transitions between energy levels within the atom.
3 The electrons in a sample become excited when it is heated or an electric current flows through it. As the electrons return to their ground state, a photon is emitted.
4 horizontal lines

5 The photon energy will not be random. It will be exactly equal to the energy difference between the initial and final energy levels of the electron.
6 White light is passed through a cold dilute sample of a gas or solution. The atoms will absorb the characteristic wavelengths, leaving dark lines in the spectrum.
7 Electron transitions between energy levels in sodium atoms produce photons of the wavelength of orange light.
8 The atom is gaining energy by transitioning to a higher energy level. To gain energy, the atom absorbs a photon, so this is an absorption transition.
9 **a** $n = 1$
b $n = \infty$
c $n = 2, 3, 4$ and so on for integer values of n
10 energy = 10.2 eV; wavelength = 121.5 nm
11 **a** The atom is put in the first excited state.
b No light is absorbed.
c The atom absorbs the photon and is ionised.
12 9.7×10^{-8} m
13 from $n = 1$ to $n = 2$
14 –0.54 eVs
15 from $n = 6$ to $n = 2$
16 They all have only one electron and so behave as dictated by the Bohr model and the full Rydberg equation.
17 30.39 nm

12.5 The wave–particle dual nature of light

1 Young's double-slit interference, diffraction and polarisation of light
2 the photoelectric effect and Compton scattering
3 **a** wave **b** particle **c** wave
4 Optical microscopes can only create a clear image of structures of similar size or larger than the wavelength of light. Electrons can have a smaller wavelength (dependent on their speed) than a beam of light and so an electron microscope can create images with finer details.
5 **a** In the particle model, the energy of the incident photons is set by their frequency according to $E = hf$. Each incident photon interacts with only one electron; therefore, the energy of the emitted electrons will depend only on the frequency of the incident light. Electron energy was not altered by altering the intensity because this only varies the number of photons, not their energy. Therefore, the energy of the emitted electrons is not affected, only the number emitted.
b The wave model predicts that altering the intensity of the light produces waves of greater amplitude. Hence, the wavefronts should deliver more energy to the electrons and, therefore, the emerging electrons should have higher energy. This is not observed.
6 By de Broglie's equation, wavelength is inversely proportional to velocity. So as the velocity of an electron increases, its wavelength decreases. Thus faster electrons in an electron microscope give better image resolution than slower electrons.
7 3.80×10^{-11} m

Chapter 13 The Standard Model

13.1 The Standard Model of particle physics

1 gravity
2 **a** gauge bosons
c quarks and leptons
3 leptons
4 the positron
5 They have the same properties as their matter equivalents, but opposite charge and quantum numbers.
6 Protons and neutrons have similar mass, but protons carry a positive charge and neutrons carry no charge. The antimatter particle for a proton has a negative charge and is called an antiproton.
7 an antiproton and a positron

13.2 Quarks and leptons

TY 31.2.1 a $-1e$
b charge = $-\frac{1}{3}e$; colour = blue; types = down, strange or bottom
1 Leptons are fundamental particles and interact via the weak nuclear force. Leptons are not made of quarks. Hadrons are comprised of quarks and interact via the strong nuclear force.
2 **a** uud
b udd
c $u\bar{d}$
d $\bar{u}\bar{u}\bar{d}$
3 Leptons: electron, electron neutrino, muon, muon neutrino, tau, tau neutrino. Antimatter equivalents: positron, electron antineutrino, antimuon, muon antineutrino, antitau, tau antineutrino
4 the weak nuclear and electromagnetic forces
5 Particles have a total colour charge of white. Quarks combine so that their colour charge makes white: either red + green + blue or antired + antigreen + antiblue for baryons, or red + antired, blue + antiblue or green + antigreen for mesons. A quark by itself cannot have a total colour charge of white, as there are no quarks with the colour charge white.
6 Baryons are made of three quarks or three antiquarks and have a baryon number of 1. Mesons are made of two quarks (a quark–antiquark pair) and have a baryon number of 0.
7 Electrons, muons and taus carry a charge of –1, neutrinos carry no charge and lepton antiparticles carry a charge of +1.
8 Quarks have a baryon number of $+\frac{1}{3}$ and antiquarks a baryon number of $-\frac{1}{3}$. A proton, being made up of three quarks (uud), has a baryon number of 1, which indicates that it is a baryon. A pion-plus is made up of a quark and an antiquark ($u\bar{d}$). It thus has a baryon number of 0, indicating that it is not a baryon.
9 **a** $+1e$ **b** 0 **c** $+1e$
10 George is correct. An antiproton is $\bar{u}\bar{u}\bar{d}$. The antiparticle of an antiup quark is an up quark, and the antiparticle of an antidown quark is a down quark. Therefore the antiparticle of an antiproton is uud. This is a proton. A positron does not contain quarks.

13.3 Gauge bosons

1 a force-mediating particle
2 The ball represents the exchange particle or gauge boson.
3 strong nuclear (gluon), electromagnetic (photon), weak nuclear (W^+, W^- and Z^0), and gravity
4 The Standard Model concerns subatomic particles of very small mass, so the effects of gravity are negligible compared to the other forces they experience.
5 The photon and Z^0 particles are their own antiparticles as they are electrically neutral. The antiparticle of W^- is W^+.

13.4 Particle interactions

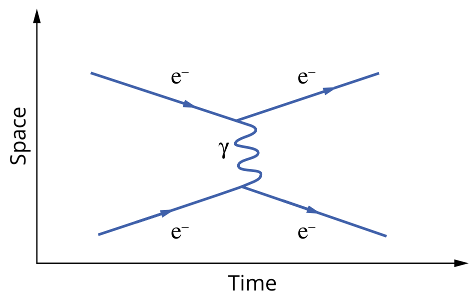
TY 13.4.1 0.178 MeV
TY 13.4.2 Lepton number is not conserved, so this interaction cannot happen.
1 Energy is conserved in this reaction. Using mass–energy equivalence, the difference in mass is equivalent to the kinetic energy of the particles after the interaction.
2 **a** Electromagnetic charge: (+1) = (+1) + 0 + 0; therefore charge is conserved.
Lepton numbers: muon lepton number: (+1) = 0 + 0 + (+1); electron lepton number: (0) = (–1) + (+1) + (0); therefore lepton numbers are conserved.
Baryon number: 0 = 0 + 0 + 0; therefore baryon number is conserved.

b Electromagnetic charge: (–1) = (–1) + 0 + 0; therefore charge is conserved.
Lepton numbers: muon lepton number: (+1) = 0 + 0 + (+1); electron lepton number: (0) = (+1) + (–1) + (0); therefore lepton numbers are conserved.
Baryon number: 0 = 0 + 0 + 0; therefore baryon number is conserved.

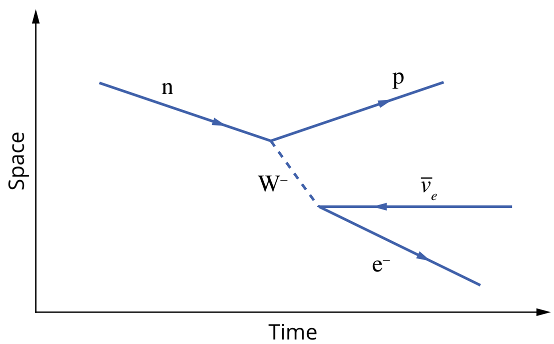
c Electromagnetic charge: (+1) + 0 = (+2) + (–1) + (0); therefore charge is conserved.
Lepton number: 0 + 0 = 0 + (–1) + (+1); electron lepton number: (0) + (0) = (0) + (+1) + (–1); therefore lepton numbers are conserved.
Baryon number: (1) + (+1) = (+2) + 0 + 0; therefore baryon number is conserved.

3 Matter and antimatter particles have the same mass. They also have the same magnitude electric charge and quantum numbers, but with opposite signs.

4 **a**



b



5 1.022MeV

Fully worked solutions to the Module review questions and Try yourself activities are available on the Reader+ eBook. Your teacher has a set of fully worked solutions for all questions in the Student Book.

Glossary

A

absolute measurement uncertainty an estimate of the dispersion of the measurement result; the range of values around the measurement result that is most likely to include the true value

absorption spectrum spectrum containing dark lines in the positions of the wavelengths that are absorbed by a gas as light passes through it. This is related to the emission spectrum of the gas

acceleration the rate at which an object's velocity changes (symbol, a; SI unit m/s^2)

acceleration due to gravity the rate at which a falling object will accelerate in a gravitational field. Equivalent to the gravitational field strength. Measured in m s^{-2}

accuracy the condition or quality of being true, correct or exact; freedom from error or defect; precision or exactness; correctness; in science, the extent to which a measurement result represents the quantity it purports to measure; an accurate measurement result includes an estimate of the true value and an estimate of the uncertainty

aether an invisible, massless, rigid substance that was proposed as the medium in which light waves propagate. There is no experimental evidence for the existence of the aether

alternating current (AC) an electric current typically used in power supplies that reverses direction many times per second

alternator an electric generator that produces alternating current (AC)

altitude height above ground level

angle the difference between the directions of two lines

annihilation the process in which matter is completely converted into energy. This is not a chemical process in which matter in one form is converted to matter in another form, as in burning

anomaly something that deviates from what is standard, normal or expected

antiparticle a particle with the same mass and opposite charge and/or spin to a corresponding particle, for example positron and electron

aphelion the point in a planet's orbit where it is closest to the Sun

apparent weight the force due to gravity, or the contact force (normal reaction force) between an object and the Earth's surface

applied force a force acting on an object that is usually in the same direction as the motion. It is usually from an engine or motor

armature a revolving structure in an electric motor or generator, wound with the coils that carry the current. It rotates within a magnetic field to induce an EMF

artificial satellite a human-made device placed in orbit around Earth or any other body

atomic clock a clock with an accuracy of 1 second in 1.4 million years, and the ability to measure time to an incredible number of decimal places

average speed the rate of change of distance calculated by the formula average speed $= \frac{\text{distance}}{\text{time}}$

average velocity the rate of change of displacement calculated by the formula average velocity $= \frac{\text{displacement}}{\text{time}}$

B

baryon number a strictly conserved additive quantum number of a system defined by $B = \frac{1}{2}(n_q - n_{\bar{q}})$, where n_q is the number of quarks and $n_{\bar{q}}$ is the number of antiquarks

baryons a composite subatomic particles made up of three quarks

black body a body that does not reflect any radiation. It does not necessarily have to be black; for instance, the Sun can be modelled as a black body

brushes devices that transfer the current in the rotating coil to a stationary external circuit by pressing against the split ring communicator or the slip rings

C

cathode ray tube (CRT) a vacuum tube in which electrons are released from a negative terminal, or hot cathode, and accelerated towards a positive terminal, or anode. The beam of electrons is collimated (narrowed) as it passes through a slit, and releases light when it hits a fluorescent screen

centripetal acceleration the acceleration experienced by any object moving in a circular path directed towards the centre of motion (symbol, a_c; SI unit is m/s^2)

centripetal force the force acting on an object travelling in a circle that constantly either pulls or pushes the object in towards the centre of motion (symbol, F_{net}; SI unit is N)

claim an assertion made without any accompanying evidence to support it

classical physics a name for non-quantum physics or events happening at non-relativistic speeds

coefficient a number by which a variable is multiplied in an algebraic equation

coherent waves that are in phase i.e. at the same stage at the same time

colour charge a property of quarks. Quarks can have a red, green or blue colour charge; antiquarks can have an antired, antiblue or antigreen colour charge. The colour charge of hadrons (particles made of quarks) must always be white; for example as red + blue + green or red + antired

commutator part of an electric motor that allows current to be reversed, enabling the coil to keep rotating due to magnetic force

component the proportion of a vector that can be considered to be acting in a particular direction

Compton scattering the inelastic scattering of a photon by an electron, demonstrating light has momentum

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

continuous spectrum spectrum of light in which every wavelength is produced. Also known as broadband radiation

Coulomb force the force exerted by two or more electrostatically charged particles on each other

Coulomb's law a law stating that like electric charges repel and opposite electric charges attract, with a force proportional to the product of the electric charges and inversely proportional to the square of the distance between them, expressed by the formula $F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$

D

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

dipolar having two poles, both a north and south, like a bar magnet

dipole a magnetic dipole has both a north and south pole. Magnetic poles only exist as dipoles

direct current a continuous electric current that flows in one direction only, without substantial variation in magnitude. Batteries are a source of direct current. Abbreviated to DC

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)

drag air resistance, or the retarding force that an object experiences when moving through a gas or a liquid

E

electric field strength the intensity of an electric field at a particular location

electric fields regions around an electrically charged particle or object within which a force would be exerted on other electrically charged particles or objects

electrical potential the work required (per unit charge) to move a positive point charge from infinity to a place in the electric field (units J C^{-1})

electromagnet a magnet consisting of an iron core wound with a coil of wire, through which a current is passed. The core only becomes magnetised when current is flowing

electromagnetic induction the production of an electromotive force (EMF) or voltage across an electrical conductor due to its dynamic interaction with a magnetic field

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 (EM) spectrum the range of all possible frequencies of electromagnetic radiation. The visible spectrum is just one small part of the electromagnetic spectrum

electromotive force a difference in potential that tends to give rise to an electric current, also written as *emf*

electron gun a device for producing a narrow stream of electrons from a heated cathode

electron volt a unit of energy equal to the work done on an electron in accelerating it through an electrical potential difference of 1 volt (unit, eV)

elementary particle a particle whose substructure is unknown

ellipse can be likened to a flattened circle

emission spectrum a set of specific wavelengths emitted by an atom or molecule that is unique to the atom or molecule

energy level diagram a diagram that represents the energy levels occupied by electrons in any particular atom

energy levels the orbital levels in which electrons orbiting the nucleus of an atom can remain stable

error bars graphical representations on graphs to show the variability of data and thus indicate the uncertainty in a measurement

ethics moral principles governing people's behaviour

extend in science, to extend an experiment is to modify the methodology to overcome limitations of the scope or applicability of the data

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

F

Faraday's law a law stating that when the magnetic flux linking a circuit changes, an electromotive force (*emf*) is induced in the circuit proportional to the rate of change of the flux linkage

fermion an elementary particle that makes up atoms, e.g. quarks and electrons, or composite particles, such as protons and neutrons. Bosons are elementary particles that are not fermions

ferromagnetic materials materials that experience more magnetism than other materials; they are permanent magnets that can be easily magnetised

Feynman diagram a graphical representation of particle interactions showing time along the horizontal axis and space along the vertical axis. The axis may be reversed, however not in this syllabus

field a position in space where susceptible objects experience (are affected by) a force or acquire potential energy as they are 'worked' into that position; gravitational fields affect the mass of an object; electric fields affect electrically charged objects; magnetic fields affect ferromagnetic objects; electromagnetic fields affect electric charge carriers in matter

field lines a pictorial representation of the strength and direction of a field. The lines designate the direction of the field, while their density represents its relative strength

focus each ellipse has two focus points. The sun is at one focus of every planet's orbit; there is nothing at the other 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

frame of reference the abstract coordinate system that defines location of the observer

free-body diagram a diagram that shows only the forces directly acting on a single object

freefall an object is said to be in freefall if the only force acting on it is its weight, i.e. the force of gravity. Any object in outer space is in freefall, as is a rock dropped from a height on Earth before air resistance acts on it

frequency equal to the number of waves that move past a given point in one second (symbol, f; SI unit, Hz)

frictional force a force that acts on an object to oppose its motion

G

gamma ray high-energy electromagnetic radiation ejected from the nucleus of a radioactive nuclide

gauge boson carrier or exchange particles that govern particle interaction and the mediation of the four fundamental forces; there are four gauge bosons in the Standard Model: the gluon, photon, Z boson and W boson

***Gedanken* experiments** hypotheses and theories considered for the purpose of thinking about the experiment's consequences. (*Gedanken* is a German word for 'thought'.)

generator an electric device that converts kinetic energy into direct current (DC) electricity. Usually a coil is rotated, causing it to cut across a magnetic field

geocentric an orbit that is centred on Earth. The geocentric model of the universe described every heavenly body as moving around Earth

gluon an elementary particle that acts as an exchange particle for the strong nuclear force between quarks, similar to the exchange of photons in the electromagnetic force between two charged particles. Gluons carry the colour charge of the strong interaction. They can be considered to be the fundamental exchange particle underlying the strong interaction between protons and neutrons in a nucleus

gravimeter sensitive instrument use by geologists to detect small variations in gravitational field strength

gravitational constant the universal constant, $G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$

gravitational field strength the net force per unit mass at a particular point in the gravitational field

gravitational fields the region of space surrounding a body in which another body experiences a force of gravitational attraction

gravitational force the force applied on a mass by a gravitational field

H

hadron a composite particle that contains quarks held together by the strong force. Hadrons are subdivided into two families: baryons (e.g. the proton and neutron) and mesons (e.g. the pion and kaon)

heliocentric an orbit that is centred on the Sun. The heliocentric model of the universe describes the planets as moving around the Sun rather than Earth

hypothesis in science, a tentative explanation for an observed phenomenon, expressed as a precise and unambiguous statement that can be supported or refuted by experiment

I

ideal transformer a transformer that is 100% efficient and in which the input power and the output power are equal. Real transformers are close to being ideal

inclined plane a flat surface at an angle to the horizontal that acts as an aid to lifting or lowering a massive object

induced current electric current produced by changing a magnetic flux in the region of a conductor or by moving the conductor in a magnetic field

inertial frame of reference any frame of reference with respect to which the acceleration of the object of observation remains zero

inertial mass the mass measured by its resistance to changes in motion

infrared a non-visible section of the electromagnetic spectrum with wavelengths longer than those of visible light

interference the combination of two or more waves to form a resultant wave

inverse square law a physical law in which some quantity (e.g. gravitational force) is inversely proportional to distance squared

ionisation the process by which an atom or molecule acquires a negative or positive charge by gaining or losing electrons

L

length contraction an observer at rest relative to a moving object would observe the moving object to be shorter along the dimension of motion

Lenz's law states that the direction of an induced electric current always opposes the change in the circuit or the magnetic field that produces it

lepton number a conserved quantum number defined by $L = n_l - n_{\bar{l}}$, where n_l is the number of leptons and $n_{\bar{l}}$ is the number of antileptons

leptons particles that are governed by the weak nuclear force and, since they have charge, are also influenced by electromagnetism; there are six leptons in the Standard Model: electron, electron neutrino, muon, muon neutrino, tau and tau neutrino

line of best fit a straight line that best represents scatter-plot data but does not necessarily pass through all points

Lorentz factor the factor, γ, by which time, length and relativistic mass change for an object while that object is moving: $\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$

Lorentz force force acting on a charged particle in a magnetic field

M

magnetic describes a material having properties of magnetism

magnetic domain a region in the material where the magnetic field is aligned

magnetic field a region of space near a magnet, electric current or moving electrically charged particle in which a magnetic force acts on any other magnet, electric current or moving electrically charged particle

magnetic field lines visual representation of the magnetic field, used to show the direction of a magnetic field in diagrams

magnetic flux a measurement of the total magnetic field that passes through a given area; a measure of the number of magnetic field lines passing through the given area (symbol, Φ; SI unit, Wb)

magnetic flux density the strength of a magnetic field or the number of magnetic field lines per unit area (symbol, B; SI unit, Wb/m^2 or T)

magnetic force the force exerted by a magnet on a moving, charged particle

magnetic pole a region at the end of a magnet at which the field of the magnet is most intense. Field lines flow from the north pole to the south pole

magnetism a physical phenomenon caused by magnets, that results in a field that attracts or repels other magnetic materials

major axis the major axis of an ellipse is a line that passes through both foci. It is the greatest distance between two points on an elliptical orbit

medium a physical substance, such as air or water, through which a mechanical wave is propagated

mesons subatomic particles composed of one quark and one antiquark

microwaves a form of electromagnetic radiation with a typical wavelength of 0.03 m

modify change the form or qualities of; make partial or minor changes to something

muon a high-velocity unstable subatomic particle. It is a lepton similar to the electron but with a heavier mass

N

natural satellite an object or body in orbit around another, typically larger, body. The term is often used to differentiate such bodies from artificial satellites

neutrino an almost massless, neutral particle released during some nuclear reactions

Newton's law of universal gravitation the force of attraction between each pair of point particles that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them

non-inertial frame of reference a frame of reference in which a body does not seem to be acting in accordance with inertia, i.e. it is undergoing acceleration

normal force the force acting along an imaginary line drawn perpendicular to the surface

nuclear magnetic resonance (NMR) a phenomenon whereby nuclei in a magnetic field absorb and re-emit electromagnetic radiation

O

outlier a value that 'lies outside' (i.e. is much smaller or larger than) most of the other values in a set of data

P

pair production the creation of a particle and its antiparticle. This is commonly the result of two photons interacting or a photon interacting with an atomic nucleus

perihelion the point in a planet's orbit where it is furthest from the Sun

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)

permanent magnet material that holds magnetic properties over a long period of time, or indefinitely; e.g. the magnets on your refrigerator

permeability of a vacuum a constant, $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T\,m\,A^{-1}}$, representing the proportionality that exists between magnetic flux density and magnetic field strength in the medium

perpendicular at right angles (90°) to

photocurrent current caused by the flow of photoelectrons during the photoelectric effect

photoelectric effect the spontaneous emission of electrons from the surface of some metals if light of the appropriate wavelength is shone on their surface

photoelectron an electron released from an atom due to the photoelectric effect

photon a quantum of all forms of electromagnetic radiation; a gauge boson responsible for mediating the electromagnetic force

point charge an ideal situation in which all of the charge on an object is considered to be concentrated at a single point. The point size is negligible in relation to the distance between it and another point charge

polarised describes nuclei whose intrinsic magnetic fields are aligned with an external magnetic field

pole the end of a magnet is referred to as a magnetic pole

postulates of special relativity the first postulate states that the laws of physics are the same in all inertial [i.e. non-accelerated] frames of reference; the second postulate states that the speed of light in a vacuum has the same value c in all inertial frames of reference

potential difference the difference in the electric potential between two points in an electric field. This can be used to calculate the work that will be done on a charged particle moving through this field (unit, V)

projectile an object that is fired, kicked, thrown or otherwise moving under the influence of a gravitational field

proper length the length measured in the frame of reference in which the object is at rest

proper time the time between two events that occur at the same point in space

Pythagoras' theorem states that in a right-angled triangle the square of the hypotenuse is equal to the sum of the squares of the two other sides. Given by $c^2 = a^2 + b^2$

Q

qualitative data information that is not numerical in nature

quantitative data numerical information

quantum the name given to a defined (small) amount of energy. Each quantum has an energy proportional to its frequency according to the equation $E = hf$

quantum numbers a set of numbers that describe the specific locations and states of a particle

quarks subatomic particles governed by the strong nuclear force that constitute hadrons; there are six quarks in the Standard Model: the up, down, charm, strange, top and bottom quark

R

radio waves a form of electromagnetic radiation, with a typical wavelength of 3 m

random error uncontrollable effects of the measurement equipment, procedure and environment on a measurement result; the magnitude of random error for a measurement result can be estimated by finding the spread of values around the average of independent, repeated measurements of the quantity

raw data unprocessed and/or unanalysed data; data that has been collected without any additional processing

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

relativistic length the length measured in the frame of reference in which the object is in motion (symbol, L; SI unit, m)

relativistic mass the mass of an object when measured in the frame of reference in which the object is in motion (symbol, γm_0)

relativistic momentum the momentum of an object when measured in the frame of reference in which the object is in motion (symbol, p_v; SI unit, N s)

relativistic time interval the time interval measured in the frame of reference in which the object is in motion (symbol, t; SI unit, s)

resolve to find the component of a vector in each of two directions (e.g. horizontal and vertical or north and east)

resonant frequency frequency with which nuclei in the polarised state absorb and re-emit electromagnetic radiation

rest mass the mass of an object when measured in the same reference frame as the observer

retrograde motion a planet will generally seem to move in a steady direction across the background of distant stars. However, some planets occasionally move for a short time in the opposite direction. This is called retrograde motion

right-hand grip rule method for determining the direction of the magnetic field around a current-carrying wire by curling the fingers of the right hand around the wire with the thumb pointing in the direction of the current (and vice versa)

right-hand slap rule method for determining the direction of the magnetic force acting on a current-carrying wire by pointing the thumb of the right hand in the direction of the current and the fingers in the direction of the magnetic field. The direction of the force is outwards from the palm

risk assessment evaluations performed to identify, assess and control hazards in a systematic way that is consistent, relevant and applicable to all school activities; requirements for risk assessments related to particular activities will be determined by jurisdictions, schools or teachers as appropriate

S

satellite object in a stable orbit around a central body. Could be natural, like a planet, or artificial, like a communications satellite

semi-major axis half the length of the major axis of an ellipse

simultaneity the relation between two events assumed to happen at the same time in a frame of reference

simultaneous events occurring at the same time

slip rings components of alternators (AC generators) that allow a constant electrical connection to be made between the rotating armature and the static external circuit through which the generated alternating current flows

solenoid coil of many turns of wire that can be used as an electromagnet

spacetime a term used to describe the situation in which the three-dimensional space coordinate system (x, y, z) is linked to the one-dimensional time system

Standard Model a mathematical description of all known particles and three of the forces acting on them. It is currently the most successful theory for predicting the behaviour and properties of the particles that exist in nature

standing wave waves with stationary vibration patterns formed due to the superposition of waves with particular frequencies

step-down transformer device that decreases the secondary voltage compared to the primary voltage

step-up transformer device that increases the secondary voltage compared to the primary voltage

stopping voltage the applied voltage required to stop all photoelectrons from reaching the collector electrode. For a particular frequency of incident light on a particular metal, the stopping voltage is a constant

systematic errors an error that is affected by the accuracy of a measurement process that causes readings to deviate from the accepted value by a consistent amount each time a measurement is made

T

temporary magnet material, such as soft iron, that will temporarily gain magnetic properties when exposed to a strong magnetic field

tension a force that acts along a string or wire that supports a massive object. The direction of this force is away from the object but along the string or wire

threshold frequency the minimum frequency of a photon that can eject an electron from a surface

time dilation the difference of elapsed time between two events as measured by observers moving relative to each other

transformer a device that transfers an alternating current from one circuit to one or more other circuits, usually with an increase (step-up transformer), or decrease (step-down transformer) in voltage. The input goes to a primary coil; the output is taken from a secondary coil or windings linked by induction to a primary coil

transit a transit takes place when an object such as a planet passes between the Sun (or any other star) and Earth

U

ultraviolet a non-visible section of the electromagnetic spectrum with wavelengths shorter than those of visible light

uniform circular motion the motion of an object travelling at a constant speed in a circle

V

variable in science, a factor that can be changed, kept the same or measured in an investigation, e.g. time, distance, light, temperature

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 $\underline{a}$

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

visible light light that can be seen by human eyes. It is part of the electromagnetic spectrum, with wavelengths between about 400 and 800 nm

W

W^+, W^- and Z^0 the gauge bosons that mediate the weak nuclear force

wave a phenomenon by which energy is moved from place to place due to vibrations. Sound and water waves require material to carry them, but light waves do not

wave–particle duality light exhibits both wave and particle behaviour

weak nuclear force one of the four fundamental forces; the weak nuclear force is responsible for radioactive decay and is mediated by W and Z bosons

weight force due to gravity that acts on any mass in a gravitational field (symbol, F_g or W; unit, N)

work function the minimum energy required to remove an electron from a solid (symbol, W; SI unit, J)

X

X-rays a form of electromagnetic radiation with a typical wavelength of 10^{-10} m

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1	1 **H** hydrogen 1.01					Atomic number **Symbol** Name Relative atomic mass												2 **He** helium 4.00
2	3 **Li** lithium 6.94	4 **Be** beryllium 9.01											5 **B** boron 10.81	6 **C** carbon 12.01	7 **N** nitrogen 14.01	8 **O** oxygen 16.00	9 **F** fluorine 19.00	10 **Ne** neon 20.18
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*Values in brackets are for the isotopes with the longest half-life.