PEARSON

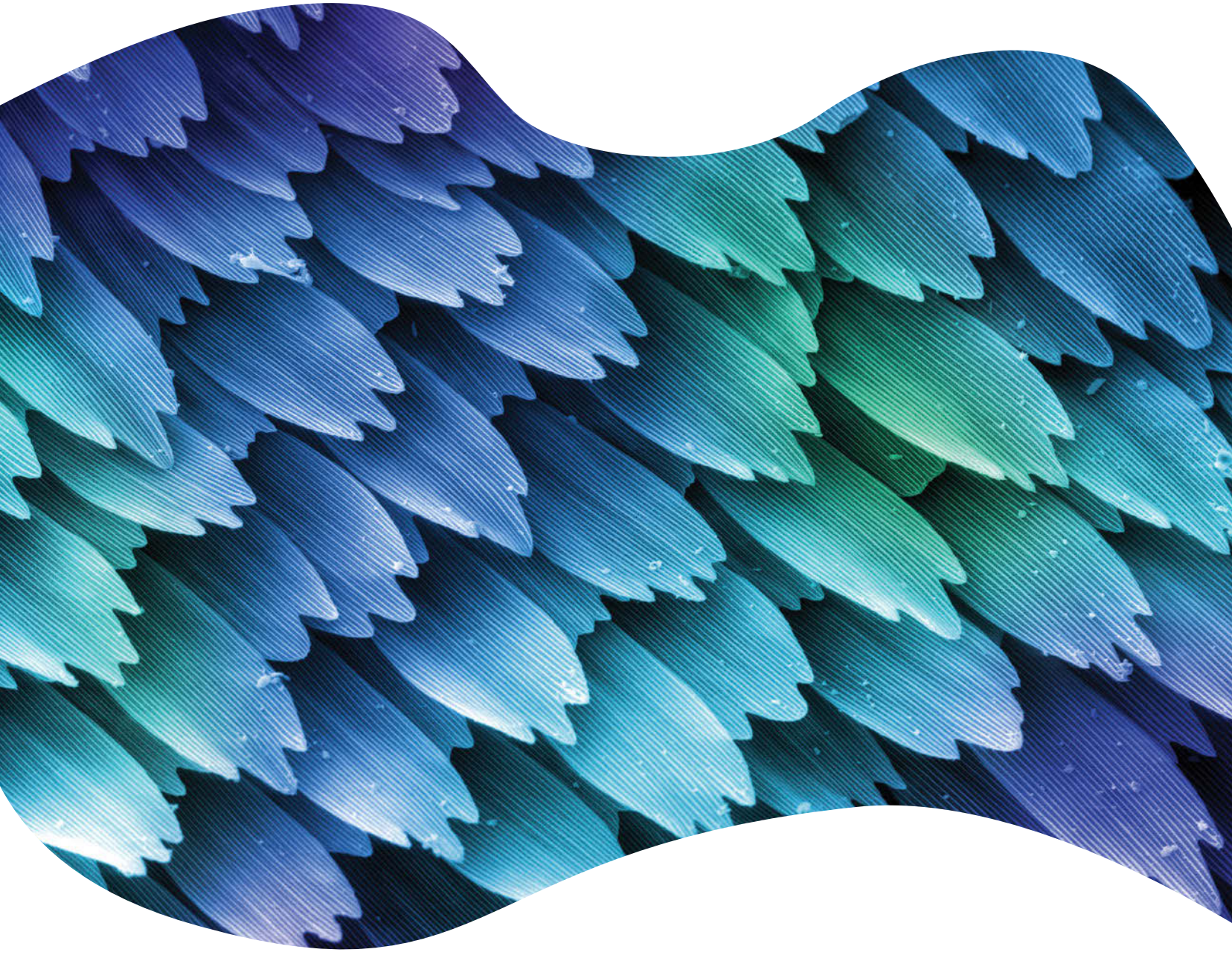
BIOLOGY

QUEENSLAND

STUDENT BOOK

11

UNITS 1 & 2



QCE 2019 SYLLABUS

PEARSON

BIOLOGY

QUEENSLAND

STUDENT BOOK

11

UNITS 1 & 2

Pearson Australia
(a division of Pearson Australia Group Pty Ltd)
707 Collins Street, Melbourne, Victoria 3008
PO Box 23360, Melbourne, Victoria 8012
www.pearson.com.au

First published 2019 by Pearson Australia
2022 2021 2020 2019
10 9 8 7 6 5 4 3 2 1

Lead Publisher: Alicia Brown
Project Manager: Michelle Thomas
Production Editor: Laura Pietrobon, Virginia O'Brien
Development Editor: Zoe Hamilton
Editor: Catherine Greenwood
Designer: Anne Donald
Rights & Permissions Editor: Lisa Woodland
Senior Publishing Services Analyst: Rob Curulli
Proofreader: Alexandra Cloud
Indexer: Ann Philpott
Illustrator: DiacriTech
Printed in China

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

ISBN: 978 1 4886 1953 3

Pearson Australia Group Pty Ltd ABN 40 004 245 943

Disclaimer
The selection of internet addresses (URLs) provided for this book was valid at the time of publication and was chosen as being appropriate for use as a secondary education research tool. However, due to the dynamic nature of the internet, some addresses may have changed, may have ceased to exist since publication, or may inadvertently link to sites with content that could be considered offensive or inappropriate. While the authors and publisher regret any inconvenience this may cause readers, no responsibility for any such changes or unforeseeable errors can be accepted by either the authors or the publisher. Some of the images used in *Pearson Biology 11 Queensland Student Book* might have associations with deceased Indigenous Australians. Please be aware that these images might cause sadness or distress in Aboriginal or Torres Strait Islander communities.

Practical activities
All practical activities, including the illustrations, are provided as a guide only and the accuracy of such information cannot be guaranteed. Teachers must assess the appropriateness of an activity and take into account the experience of their students and facilities available. Additionally, all practical activities should be trialled before they are attempted with students and a risk assessment must be completed. All care should be taken: appropriate protective clothing should be worn, the correct equipment used and appropriate preparation and clean up procedures followed whenever conducting any practical activity. Although all practical activities have been written with safety in mind, Pearson Australia and the authors do not accept any responsibility for the information contained in or relating to the practical activities, and are not liable for any loss and/or injury arising from or sustained as a result of conducting any of the practical activities described in this book.

PEARSON
BIOLOGY
QUEENSLAND

11

Writing and development team

We are grateful to the following people for their time and expertise in contributing to the Pearson Biology Unit 1 and 2 project.

Martin Hall
Senior Science Teacher
QCAA Syllabus Writer
(Biology Expert Writing Team)
Queensland Biology Series Consultant
Lead Author

Andrew Landroth
Senior Biology Teacher
QCAA District Panel (Biology)
Queensland Biology Associate Consultant
Author

Dr Troy Potter
Teacher, Exam Assessor (Biology)
Queensland Biology Subject Lead
Author

Anna Albert
Head of Science
Reviewer

Christina Bliss
Exam Assessor and Trial Exam Writer (Biology)
Teacher
Author

Nick Chandler
Head of Science
QCAA District Panel Chair
Reviewer

Samuel Fesuk
Head of Science
QCAA District Panel (Biology)
Author

Sylvia Hicks
Head of Faculty (Sciences)
QCAA Syllabus Writer (Biology Expert Writing Team)
QCAA District Panel (Biology)
Reviewer

Karen Paterson
Head of Science
QCAA District Panel
Reviewer

Juanita Jacobs
QCAA District Panel Chair,
Head of Senior Science, Expert Writing Team for Biology new syllabus, Chief Assessor for the QCAA endorsement trials for Biology
Author

Dr Harry Kanasa
Head of School of Education and Professional Studies,
Griffith University
Contributor

Margaret Riggs
Expert Teacher Group Leader in Biology for Brisbane Catholic Education
QCAA District Panel (Biology), Teacher
Author

Djaisi Robinson
Head of Science, Teacher
Author

Yvonne Sanders
Head of Science, Exam Assessor (Biology)
Queensland Skills & Assessment Book Author
Author

Donna Chapman
School Laboratory Technician
Safety Consultant

Penny Lee
School Laboratory Technician
Safety Consultant

Professor David F Treagust PhD FRSC FRSB FAERA
John Curtin Distinguished Professor
STEM Education Research Group
School of Education, Curtin University
Consultant and Reviewer

Dr Trish Weekes
Science Literacy Consultant
Teacher

The Publisher wishes to thank and acknowledge the following authors for their contribution in creating the original works of the series and longstanding dedication to Biology education:

Professor Pauline Ladiges AO FAA
Professorial Fellow, Botany
Australian Academy of Science
School of BioSciences, The University of Melbourne

Professor Barbara Evans
School of BioSciences, The University of Melbourne

Pearson wishes to acknowledge and thank the following individuals for their contribution to this series.

Contributing Authors
Krista Bayliss
Ian Bentley
Sally Cash
Caroline Cotton
Sarah Edwards
Neil van Herk
Samantha Hopley
Catherine Litchfield
Helen Silvester
Sue Siwinski

Pearson wishes to thank the following Queensland Biology teachers and biologists for their careful work in answer checking this series:
Narelle Cooley
Stacey Hollis
Kelly Merrin
Shar Sadeghi
Emma Wratten

Contents

ONLINE CHAPTER

Chapter 1 Biology Skills and Assessment toolkit

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

Unit 1: Cells and multicellular organisms

Topic 1: Cells as the basis of life

Topic 2: Multicellular organisms

Unit 2: Maintaining the internal environment

Topic 1: Homeostasis

Topic 2: Infectious disease

How to use this book

PEARSON BIOLOGY 11 UNITS 1 & 2 QUEENSLAND

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

Design

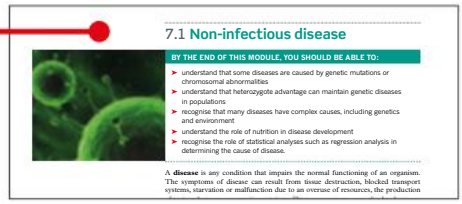
The best-practice literacy and instructional design supports all learners.
A simple to navigate, predictable design enables ease of use. The high-quality, relevant photos and illustrations assist the student understanding of the concepts.

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.

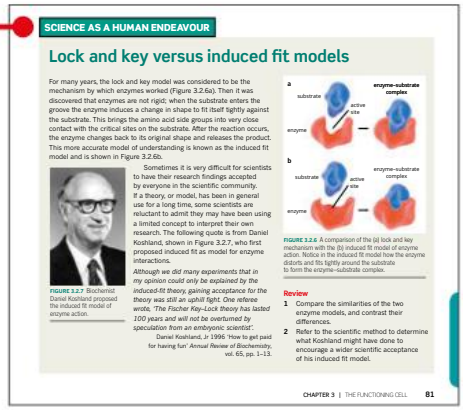
Module opener

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



Science as a Human Endeavour

The SHE feature provides an opportunity for students 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.



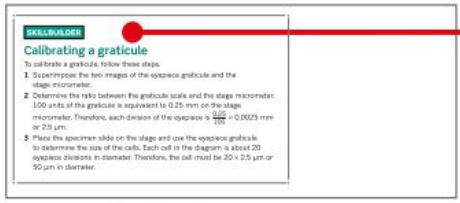
Highlight box

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 enhance student understanding of subject matter. Each Worked example is followed by a Try yourself task where students apply their learning to a mirrored problem.

Fully worked solutions to all Try yourself problems are available on *Pearson Biology 11 Queensland* Teacher Support.


SKILLBUILDER

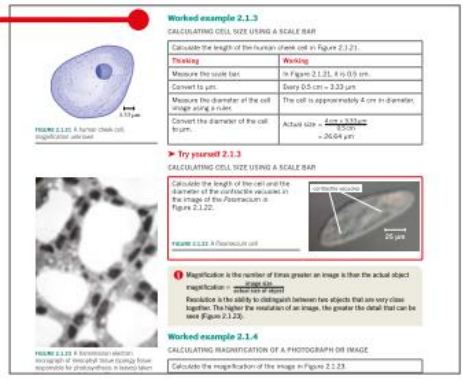
Calibrating a graticule

To calibrate a graticule, follow these steps.

1 Superimpose the two images of the eyepiece graticule and the stage micrometer.

2 Determine the ratio between the graticule scale and the stage micrometer. 100 units of the graticule is equivalent to 0.25 mm on the stage micrometer. Therefore, each division of the eyepiece is $\frac{0.25}{100} = 0.0025$ mm or 2.5 µm.

3 Place the specimen slide on the stage and use the eyepiece graticule to determine the size of the cells. Each cell in the diagram is about 20 eyepiece divisions in diameter. Therefore, the cell must be 20 × 2.5 µm or 50 µm in diameter.


Worked example 2.1.3

CALCULATING CELL SIZE USING A SCALE BAR

Calculate the length of the human cheek cell in Figure 2.1.21.

Thinking	Working
Measure the scale bar.	In Figure 2.1.21, it is 0.5 cm.
Convert to µm.	Every 0.5 cm = 3.33 µm
Measure the diameter of the cell image using a ruler.	The cell is approximately 4 cm in diameter.
Convert the diameter of the cell to µm.	Actual size = $\frac{4 \text{ cm} \times 3.33 \text{ µm}}{0.5 \text{ cm}}$ = 26.64 µm

Try yourself 2.1.3

CALCULATING CELL SIZE USING A SCALE BAR

Calculate the length of the cell and the diameter of the contractile vacuoles in the image of the *Paramecium* in Figure 2.1.22.

Magnification is the number of times greater an image is than the actual object magnification = $\frac{\text{image size}}{\text{actual size of object}}$

Resolution is the ability to distinguish between two objects that are very close together. The higher the resolution of an image, the greater the detail that can be seen (Figure 2.1.23).

Worked example 2.1.4

CALCULATING MAGNIFICATION OF A PHOTOGRAPH OR IMAGE

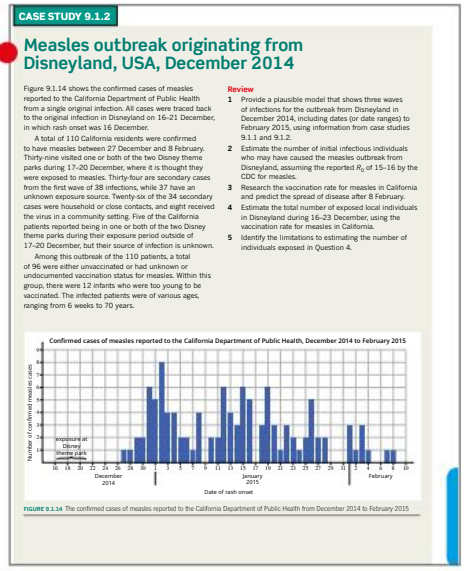
Calculate the magnification of the image in Figure 2.1.23.

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.

Case studies

Case studies provide opportunities to engage with current applications and research in biology and address essential syllabus objectives beyond typical learning and understanding conventions. Case studies develop skills in analysing, interpreting, evaluating, decision-making and predicting. Skills are modelled for students in the Case studies and then learning is applied in the Case study review.


CASE STUDY 9.1.2

Measles outbreak originating from Disneyland, USA, December 2014

Figure 9.1.14 shows the confirmed cases of measles reported to the California Department of Public Health from a single original infection. All cases were traced back to the original infection in Disneyland on 16–21 December, in which rash onset was 16 December.

A total of 110 California residents were confirmed to have measles between 27 December and 8 February. Thirty-nine visited one or both of the two Disney theme parks during 17–20 December, where it is thought they were exposed to measles. Thirty-four are secondary cases from the first wave of 38 infections, while 37 have an unknown exposure source. Twenty-six of the 34 secondary cases were household or close contacts, and eight received the virus in a community setting. Five of the California patients reported being in one or both of the two Disney theme parks during their exposure period outside of 17–20 December, but their source of infection is unknown.

Among this outbreak of the 110 patients, a total of 96 were either unvaccinated or had unknown or undocumented vaccination status for measles. Within this group, there were 12 infants who were too young to be vaccinated. The infected patients were of various ages, ranging from 6 weeks to 70 years.

Review

1 Provide a plausible model that shows three waves of infections for the outbreak from Disneyland in December 2014, including dates (or date ranges) to February 2015, using information from case studies 9.1.1 and 9.1.2.

2 Estimate the number of initial infectious individuals who may have caused the measles outbreak from Disneyland, assuming the reported R_0 of 15–16 by the CDC for measles.

3 Research the vaccination rate for measles in California and predict the spread of disease after 8 February.

4 Estimate the total number of exposed local individuals in Disneyland during 16–23 December, using the vaccination rate for measles in California.

5 Identify the limitations to estimating the number of individuals exposed in Question 4.

Confirmed cases of measles reported to the California Department of Public Health, December 2014 to February 2015

Number of confirmed measles cases

Exposure at Disney theme park

December 2014

January 2015

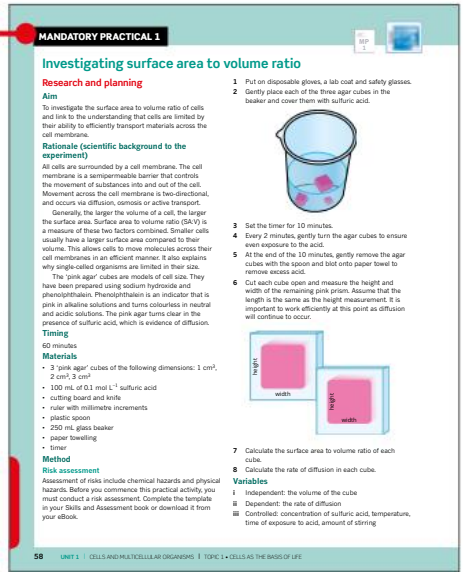
February

Date of rash onset

FIGURE 9.1.14 The confirmed cases of measles reported to the California Department of Public Health from December 2014 to February 2015

Mandatory practicals

The Student Book includes all mandatory practicals. Each practical has been trialled and tested to ensure it can be safely performed and yields effective results.


MANDATORY PRACTICAL 1

Investigating surface area to volume ratio

Research and planning

Aim

To investigate the surface area to volume ratio of cells and link to the understanding that cells are limited by their ability to efficiently transport materials across the cell membrane.

Rationale (scientific background to the experiment)

All cells are surrounded by a cell membrane. The cell membrane is a semipermeable barrier that controls the movement of substances into and out of the cell. Movement across the cell membrane is two-directional, and occurs via diffusion, osmosis or active transport.

Generally, the larger the volume of a cell, the larger the surface area. Surface area to volume ratio (SA:V) is a measure of these two factors combined. Smaller cells usually have a larger surface area compared to their volume. This allows cells to move molecules across their cell membranes in an efficient manner. It also explains why single-celled organisms are limited in their size.

The 'pink agar' cubes are models of cell size. They have been prepared using sodium hydroxide and phenolphthalein. Phenolphthalein is an indicator that is pink in alkaline solutions and turns colourless in neutral and acidic solutions. The pink agar turns clear in the presence of sulfuric acid, which is evidence of diffusion.

Timing

60 minutes

Materials

- 3 'pink agar' cubes of the following dimensions: 1 cm³, 2 cm³, 3 cm³
- 100 mL of 0.1 mol L^{-1} sulfuric acid
- cutting board and knife
- ruler with millimetre increments
- plastic spoon
- 250 mL glass beaker
- paper towelling
- timer

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 Put on disposable gloves, a lab coat and safety glasses.

2 Gently place each of the three agar cubes in the beaker and cover them with sulfuric acid.

3 Set the timer for 10 minutes.

4 Every 2 minutes, gently turn the agar cubes to ensure even exposure to the acid.

5 At the end of the 10 minutes, gently remove the agar cubes with the spoon and blot onto paper towel to remove excess acid.

6 Cut each cube open and measure the height and width of the remaining pink prism. Assume that the length is the same as the height measurement. It is important to work efficiently at this point as diffusion will continue to occur.

height

width

height

width

7 Calculate the surface area to volume ratio of each cube.

8 Calculate the rate of diffusion in each cube.

Variables

i Independent: the volume of the cube

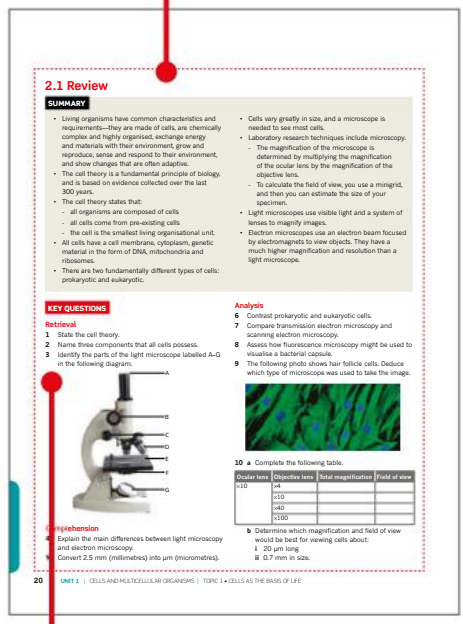
ii Dependent: the rate of diffusion

iii Controlled: concentration of sulfuric acid, temperature, time of exposure to acid, amount of stirring

58 UNIT 1 | CELLS AND MULTICELLULAR ORGANISMS | TOPIC 1 • CELLS AS THE BASIS OF LIFE

Module summary

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


2.1 Review

SUMMARY

- Living organisms have common characteristics and requirements—they are made of cells, are chemically complex and highly organised, exchange energy and materials with their environment, grow and reproduce, sense and respond to their environment, and show changes that are often adaptive.
- The cell theory is a fundamental principle of biology, and is based on evidence collected over the last 300 years.
- The cell theory states that:
  - all organisms are composed of cells
  - all cells come from pre-existing cells
  - the cell is the smallest living organisational unit.
- All cells have a cell membrane, cytoplasm, genetic material in the form of DNA, mitochondria and ribosomes.
- There are two fundamentally different types of cells: prokaryotic and eukaryotic.
- Cells vary greatly in size, and a microscope is needed to see most cells.
- Laboratory research techniques include microscopy.
  - The magnification of the microscope is determined by multiplying the magnification of the ocular lens by the magnification of the objective lens.
  - To calculate the field of view, you use a minigrid, and then you can estimate the size of your specimen.
- Light microscopes use visible light and a system of lenses to magnify images.
- Electron microscopes use an electron beam focused by electromagnets to view objects. They have a much higher magnification and resolution than a light microscope.

KEY QUESTIONS

Retrieval

1 State the cell theory.

2 Name three components that all cells possess.

3 Identify the parts of the light microscope labelled A–G in the following diagram.

Analysis

6 Contrast prokaryotic and eukaryotic cells.

7 Compare transmission electron microscopy and scanning electron microscopy.

8 Assess how fluorescence microscopy might be used to visualise a bacterial capsule.

9 The following photo shows hair follicle cells. Deduce which type of microscope was used to take the image.

10 a Complete the following table.

Ocular lens	Objective lens	Total magnification	Field of view
×10	×4		
	×10		
	×40		
	×100		

b Determine which magnification and field of view would be best for viewing cells about:

i 20 µm long

ii 0.7 mm in size.

Comprehension

4 Explain the main differences between light microscopy and electron microscopy.

5 Convert 2.5 mm (millimetres) into µm (micrometres).

20 UNIT 1 | CELLS AND MULTICELLULAR ORGANISMS | TOPIC 1 • CELLS AS THE BASIS OF LIFE

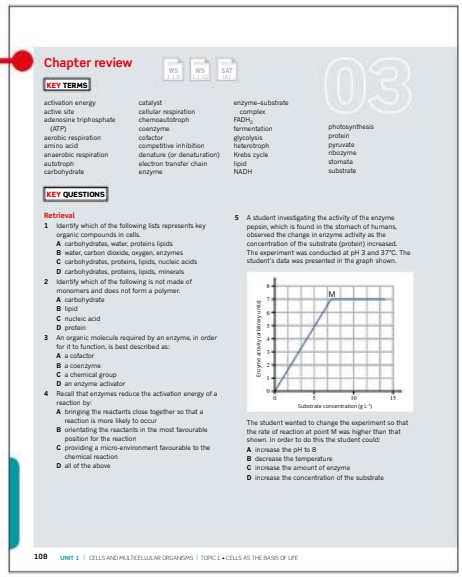
Module review

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

How to use this book

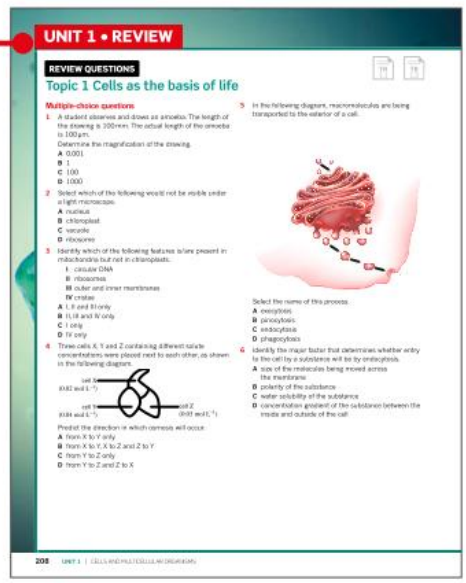
Chapter review

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



Unit review

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



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

Comprehensive answers and fully worked solutions for all Module review tasks, Try yourself, Science as a Human Endeavour, Case studies, Chapter reviews and Unit reviews are provided via the Teacher Reader+ eBook.

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 complementary **SPARKlab** alternative practical.

The ***Pearson Biology 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

Mandatory practical (MP)

MP 4

Practical activity (PA)

PA 3.2.1

Sample Assessment Task (SAT)

SAT IA1

Topic review (TR)

TR 1.2

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

Pearson Biology 11 Units 1 & 2 Queensland

Student Book

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

Skills and Assessment Book

The *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 exam-style Topic review sets.

Reader+ the next generation eBook

Pearson Reader+ lets you use your Student Book online or offline, anywhere and anytime, on any device. Pearson Reader+ retains the look and integrity of the printed book and includes extras such as videos, interactives and answers.

Teacher Support

Pearson Biology 11 Units 1 & 2 Queensland Teacher Support provides:

- complete answers, fully worked solutions or suggested answers to all *Student Book* and *Skills and Assessment Book* tasks
- mandatory practical expected results, common mistakes, suggested answers and full safety notes and risk assessments
- teaching, learning and assessment programs

Pearson

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

Understanding assessment instructions

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

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

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

The 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, summarised in the tables above and at right.

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 Biology Unit 1, Topic 1 showing the underlining of terms

Subject matter

Cell membrane

- describe the structure of the cell membrane (including protein channels, phospholipids, cholesterol and glycoproteins) based on the fluid mosaic phospholipid bilayer model
- describe how the cell membrane maintains relatively stable internal conditions via the passive movement (diffusion, osmosis) of some substances along a concentration gradient
- explain how the cell membrane maintains relatively stable internal conditions via the process of active transport of a named substance against a concentration gradient
- understand that endocytosis is a form of active transport that usually moves large polar molecules that cannot pass through the hydrophobic cell membrane into the cell
- recognise that phagocytosis is a form of endocytosis
- predict the direction of movement of materials across cell membranes based on factors such as concentration, physical and chemical nature of the materials
- explain how the size of a cell is limited by the relationship between surface area to volume ratio and the rate of diffusion
- Mandatory practical: Investigate the effect of surface area to volume ratio on cell size.

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

Module review—retrieval, comprehension and analysis

Chapter review—retrieval, comprehension, analysis and knowledge utilisation

Unit review—retrieval, comprehension, analysis and knowledge utilisation.

CHART A Cognitive processes, as arranged by Marzano and Kendall

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

Retrieval	Comprehension	Analysis	Knowledge utilisation
Level 1—basic level of thinking • Involves remembering, recalling, recognising and executing information.	**Level 2**—higher level of thinking than Retrieval • Involves understanding and identifying key information.	**Level 3**—more complex thinking than comprehension • Involves examination of information and the identification of 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 and associated verbs with sample questions and instructions

Cognitive processes, associated verbs and sample instructions and questions

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

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

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

continued over page

CHART B *continued*

Cognitive processes, associated verbs and sample instructions and questions			
Sample instruction and question	**Sample instruction and question**	**Sample instruction and question**	**Sample instruction and question**
Label a phospholipid in the diagram of a cell membrane. What is the structure of a cell membrane according to the fluid mosaic phospholipid bilayer model?	**Explain** the relationship between surface area and function of gaseous exchange surfaces. What relationship exists is there between surface area and the function of gaseous exchange surfaces?	**Determine**, using the data provided in the lung capacity schematic, which compartment is the alveoli and which is the capillaries. What can you deduce about gas exchange between alveoli and capillaries, based on the data provided?	**Predict**, using the data provided, which scenario would result in the greatest rate of gas exchange How will the rate of gas exchange be affected by the change in concentration in the data provided?

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 Chart B, 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 **b** **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** Occasionally a person is born without sweat glands, and cannot secrete water (sweat) onto their skin to lose heat and cool down. Two people are used for an experiment; one with and one without sweat glands. They were placed in warm, dry conditions and data collection included skin and mouth temperatures, and water loss through skin and urine. Which person was born without sweat glands? **Explain** your answer.
1 Underline the cognitive verb/s and identify a plausible thinking level for the verb.	'Which person, was born without sweat glands? Explain your answer.' **Explain** is found in the cognitive verb list for the **comprehension** thinking level.
2 Determine the scope, context of the question and its thinking level.	The scope of the question includes sweat concepts and understanding experimental data for two people under specific conditions. The context is analysing data from an experiment. This targets the **analysis** cognitive level.
3 Consider some cognitive actions from Chart B are required to complete the question	The question has depth and complexity. It asks for **analysis** of the data provided. It also requires a **judgement** to be made based on the analysed data.
4 Make sure you know the meaning of every word in the question or instruction.	**Explain** means to 'make an idea or situation plain or clear by describing it in more detail or revealing relevant facts; give an account of; provide additional information' *QCAA definition*.
5 Rephrase question or instruction in your own words, elaborating on all details required.	Rephrasing may be as another question or instruction. For example: 'Are there differences in the data between the two people that indicate one has sweat glands and one does not? If so, which person has the sweat glands and which doesn't? Then provide plain and clear details using the data to outline why one person was chosen over the other.'

ASSESSMENT TASKS AND COGNITIVE PROCESSES

Pearson Biology 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 questions under Retrieval, Comprehension and Analysis.

Chapter review questions cover these three levels as well 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 practice 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 the tasks, they are the underlying thinking levels necessary to complete the tasks. Hence the differences in the sizes of the ticks, with the largest tick indicating the focal cognitive thinking level.

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

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

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

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

	Retrieval	**Comprehension**	**Analysis**	**Knowledge utilisation**	
Short response: • multiple choice • single-word • sentences • calculating using algorithms	✔	✔	✔	✔	Short responses generally draw on factual subject matter in the retrieval and comprehension cognitive processes areas but may require analysis where calculations and data interpretation are involved.
Combination response: • short items requiring single-word, sentence or short paragraph responses • calculating using algorithms • interpreting graphs, tables or diagrams • responding to unseen data and/or stimulus • extended response (300–350 words or equivalent).	✔	✔	✔	✔	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

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

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
	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
	explain	make a statement or situation less confused or more comprehensible
	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)
	show	provide the relevant reasoning to support a response
	summarise	give a brief statement of a general theme or major point/s; present ideas and information in fewer words and in sequence
	symbolise	represent or identify by a symbol or symbols
	understand	perceive what is meant by something; grasp; be familiar with (e.g. an idea); construct meaning from messages, including oral, written and graphic communication
	use (models)	operate or put into effect; apply knowledge or rules to put theory into practice

Increasing complexity of thinking

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	judgment based on evidence (ACARA 2015c)
	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
	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
	determine	establish, conclude or ascertain after consideration, observation, investigation or calculation; decide or come to a resolution
	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
	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
	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
	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
	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

continued over page

continued

Increasing complexity of thinking

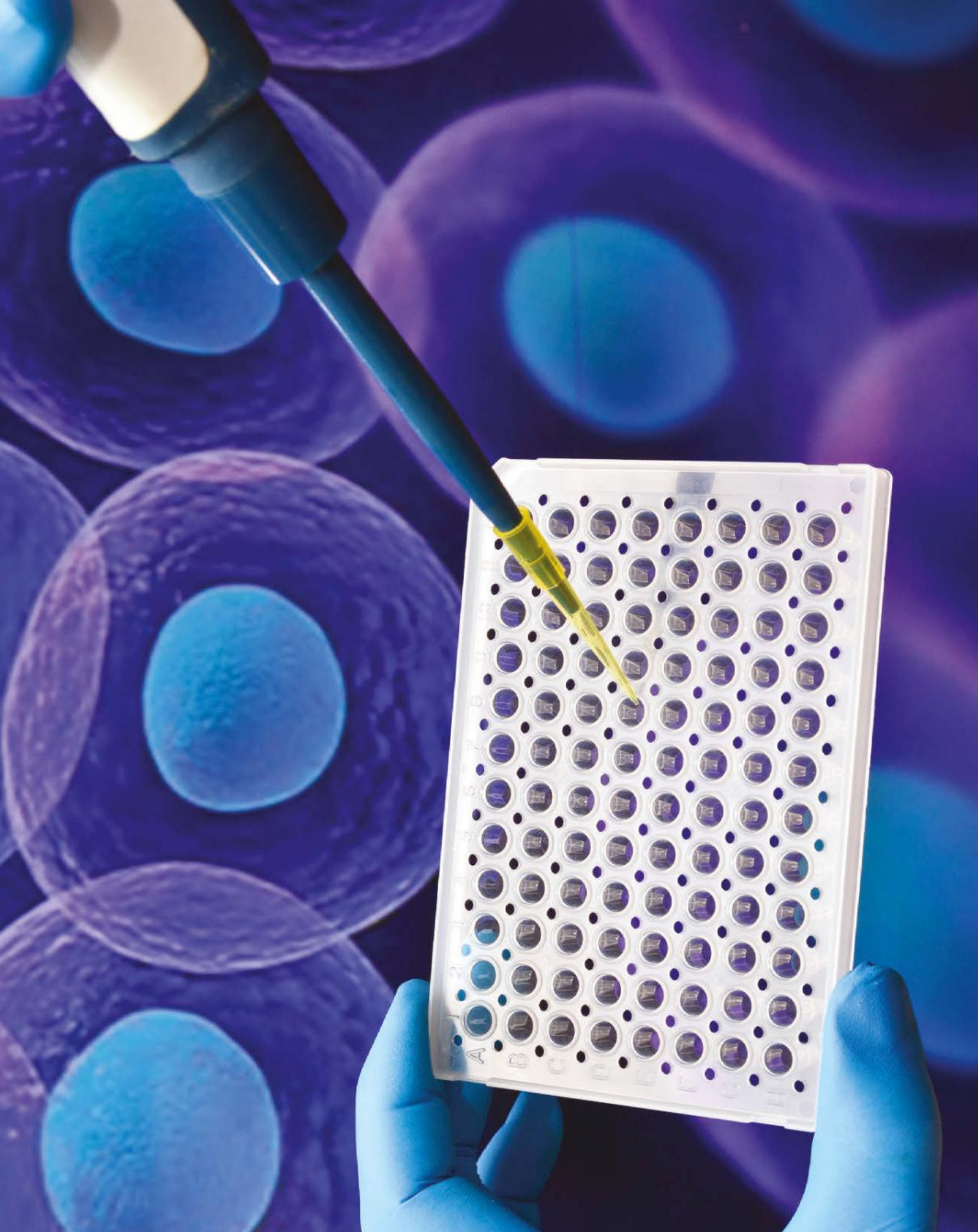
Level of thinking	Cognitive verb	Definition of cognitive verb
Analysis: **processes of matching, classifying, analysing errors, generalising, specifying** *(continued)*	interpret	use knowledge and understanding to recognise trends and draw conclusions from given information; make clear or explicit; elucidate 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

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
	conduct	direct an action or course; manage; organise; carry out
	conclude (conclusion)	a judgment based on evidence (ACARA 2015c)
	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
	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)
	decide	reach a resolution as a result of consideration; make a choice from a number of alternatives
	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

Increasing complexity of thinking

Knowledge utilisation: **processes of investigating, experimenting, decision-making, problem-solving** *(continued)*		
	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)	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
	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 Biology skills and assessment toolkit

This chapter provides important information and support in the study of the QCAA Biology General Senior Syllabus for Units 1 and 2.

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

Focus

The chapter focuses on providing support and guidance in:

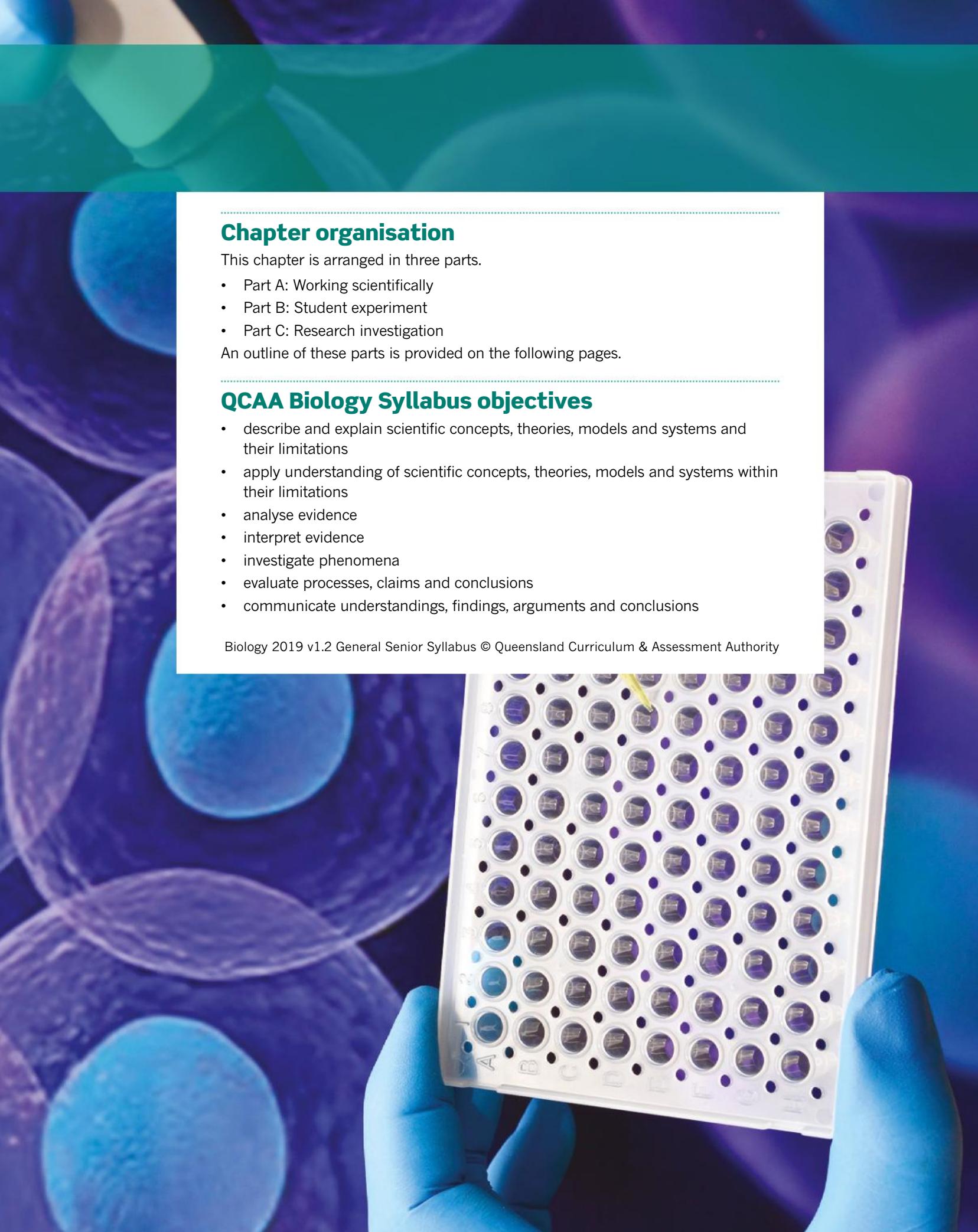
- Development and application of scientific skills
  - Mathematical and statistical processes used in Biology
  - SI units
  - Visual representations
  - Graphical representations
  - Measurement errors and uncertainty
- Responding to the assessment tasks
  - Preparation in skill development: understanding,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

Assessment

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

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

- Student experiment (Internal Assessment 1A2)
- Research investigation (Internal Assessment 1A3)



Chapter organisation

This chapter is arranged in three parts.

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

An outline of these parts is provided on the following pages.

QCAA Biology 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. It features many worked examples and opportunities to apply these examples yourself. These skills are engaged with throughout the course. Therefore, they are assessed, directly and indirectly, in assessment tasks and drawn on to analyse data in experiments and investigations. Engage with Part A in order to help prepare yourself with the skills you will draw on for 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 examination.

Refer to the following outline of *Part A: Working scientifically* to learn, revise or get some practice in the areas in which you need help.

Module	Look here for	eBook page
1.2 Orders of magnitude and estimation	• scientific notation • SI prefixes • transforming decimal notations to scientific notation • converting values from decimal to scientific notation • converting between scientific notation and scientific units • examples of calculations	e10 e13
1.3 Mathematical basics for biology	• examples of maths used in biology	e15
1.4 Units	• correct use of units • SI units • examples of correct and incorrect uses of units	e17
1.5 Uncertainties in measurement and error	• explanations of the terms 'uncertainty', 'error', 'accuracy', 'precision' • causes of errors • calculations with uncertainty and error • writing measurements with uncertainty and error values • writing measurement and calculations to the correct significant figure	e19 e21
1.6 Tables and graphing	• arranging and recording data in tables • converting data from tables to graphs • types of graphs: scatterplots, line graphs, bar and column graphs, pie charts • outliers • representing missing data on graphs	e27 e28
1.7 Statistics	• calculating mean, median, mode, range • statistical significance of standard deviation • regression, linear regression and *r*-values • statistical methods to analyse data sets, including Pearson coefficient and *t*-tests	e33

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

Part B: Student experiment

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

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

Engage with Part B for examples of how to modify, extend, refine or redirect the initial practical and write a research research question or hypothesis. Use the step-by-step guide to evaluate the quality of your hypothesis/question. Delve into particular sections of Part B, when needed, to reinforce your knowledge and understanding of scientific methodology. Refer to Part B for support on data types, data collection and analysis of data to draw valid conclusions. This includes how to identify errors in data, validity and relationships between data. Be guided in the write-up of your scientific report with support material on scientific writing style, and the structure of the report

Refer to the following outline of *Part B: Student experiment* to learn, revise or get some practice in the areas in which you need help.

Module	Look here for	eBook page
1.8 Research and planning	• types of variables • modify, refine, extend or redirect initial experiment • develop a research question or hypothesis • evaluate the research question or hypothesis • using a scientific journal to keep a record • validity and reliability • quantitative and qualitative data • nominal, ordinal, discrete and continuous data • risk assessments • chemical codes and symbols	e50 e52
1.9 Conducting and experimenting	• determine what data is relevant • determine what sufficient data is • collection of data • considerations for planning an experiment • precision of scientific instruments	e68
1.10 Results	• analysis of raw data • identifying errors; mistakes, systematic errors and random errors • analysing precision • analysing validity and theoretical relationships • interpreting results	e72
1.11 Communicating and writing a scientific report	• the sections of a report • scientific writing style • write a scientific report • acknowledging sources • addressing the ISMG	e77

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

Part C: Research investigation

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

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

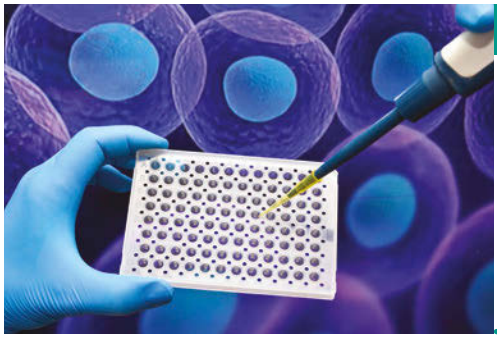
Engage with Part C to assist with writing your research question. Delve into the examples of claims, their analysis for context and elements, to guide you in developing your own research question. Be guided by the information about locating and evaluating suitable secondary sources for the research. 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 the report and provides details on the literature review format.

Refer to the following outline of *Part C: Research investigation* to learn, revise or get some practice in the areas in which you need help.

Module	Look here for	eBook page
1.12 Developing the research question from a claim	• analyse a claim • identify variables and measureable terms in the claim • examples of claims and questions developed from them • guidelines for developing a question • develop a research question • refining a research question	e86 e87
1.13 Finding and choosing suitable resources	• difference between primary and secondary sources • locating resources • determine reliability and validity of resources	e92
1.14 Research: taking and organising notes	• recording notes in a scientific journal • paraphrasing information • different ways to record information • recording data and results • recording information about sources	e99
1.15 Writing a report for the research investigation	• different ways to present the report • presenting the report as a literature review • features of a literature review • structure of the literature review	e104

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

1.1 Biological science



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

- understand that science provides a systematic approach for comprehending the world
- recognise that biology is the field of science that investigates living organisms and systems
- understand that biology comprises a range of divisions
- explain the difference between scientific models, theories, laws, principles and facts.

Biology is the study of living organisms and systems. This includes (but is not exclusive to) cells, multicellular organisms and the maintenance and regulation of their internal environments; genetics, reproduction and inheritance; biodiversity and the relationships between the living and non-living; and the continuation of life throughout time. An understanding of biology informs us about fundamental principles of the living world around us and can inform critical evaluation of personal and social issues, and technology.

THE SCIENCE OF BIOLOGY

Science is a human endeavour to understand the world around us and the known universe. It is one of many methods we use to develop knowledge. This knowledge is continually refined and redefined. Science follows a **methodology** to observe, test, measure, analyse and evaluate natural **phenomena** in a way that we can understand and construct meaning. There is no single **scientific method** that is applicable to experimentation, investigations and theoretical research (e.g. meta-analysis). However, the scientific method is a cyclical process, including observing natural phenomena, questioning, hypothesising and predicting, experimenting and gathering data, refining and altering all previous elements, and theorising (Figure 1.1.1).

Biology can explain how the structure and function of cells interrelate with environmental **variables** to exchange matter and energy.

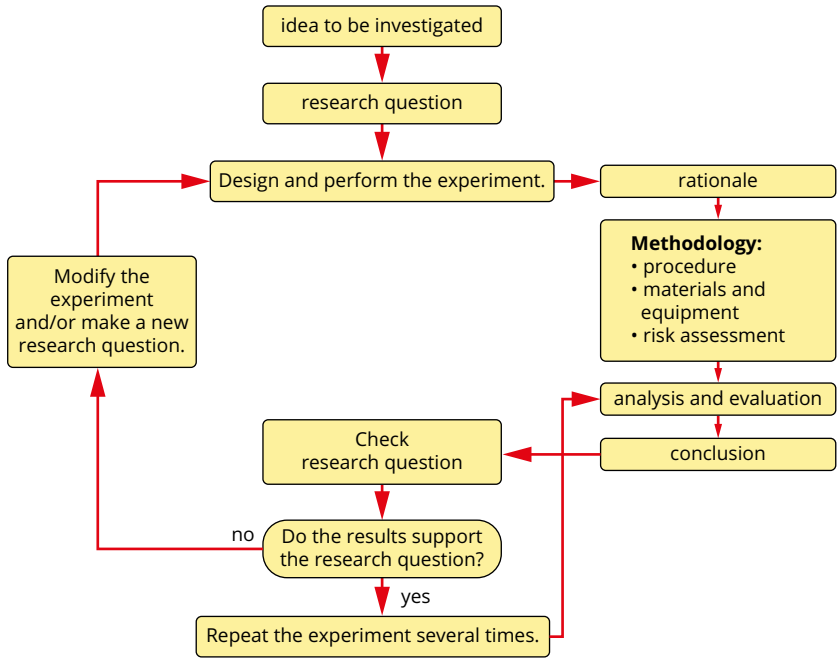


FIGURE 1.1.1 The processes involved in the scientific method. It is more of a cyclical process rather than a linear process.

Innovations through biological science

All scientific disciplines are expanding into new frontiers. The number of divisions and fields in biology is increasing and the relationship between disciplines is becoming more intertwined. Innovations include genetically modified crops, neurological implants such as the bionic eye providing vision to blind people, robotic-arm prosthetics controlled by thought, animal cloning, biofuels and tissue and organ growth for transplants from adult stem cells.

Innovations today are crossing traditional barriers between technology, chemistry, physics and biology. For example, apps on smart watches and phones use the user's biological **data** to provide personal information. Pacemakers and devices communicate using information technology. Artificial intelligence in apps and personal devices can detect personal health.

Divisions of biology

There are numerous divisions of biology (Figure 1.1.2), and as technology develops and scientific disciplines become increasingly transdisciplinary, the number of divisions grow.

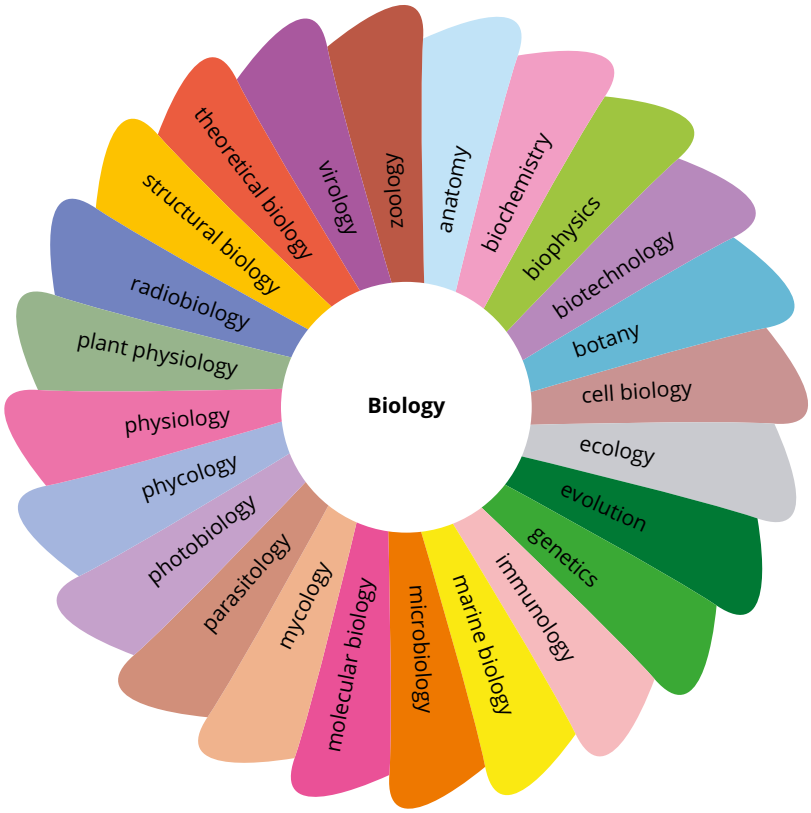


FIGURE 1.1.2 Some of the many divisions of biology

The role and work of a biologist

Biology is an expanding area. Trends suggest that careers in STEM (science, technology, engineering and mathematics) will increase, and that biology will be an essential part of STEM development.

A small list of examples of careers related to biology can be seen in Figure 1.1.3 on page e8.

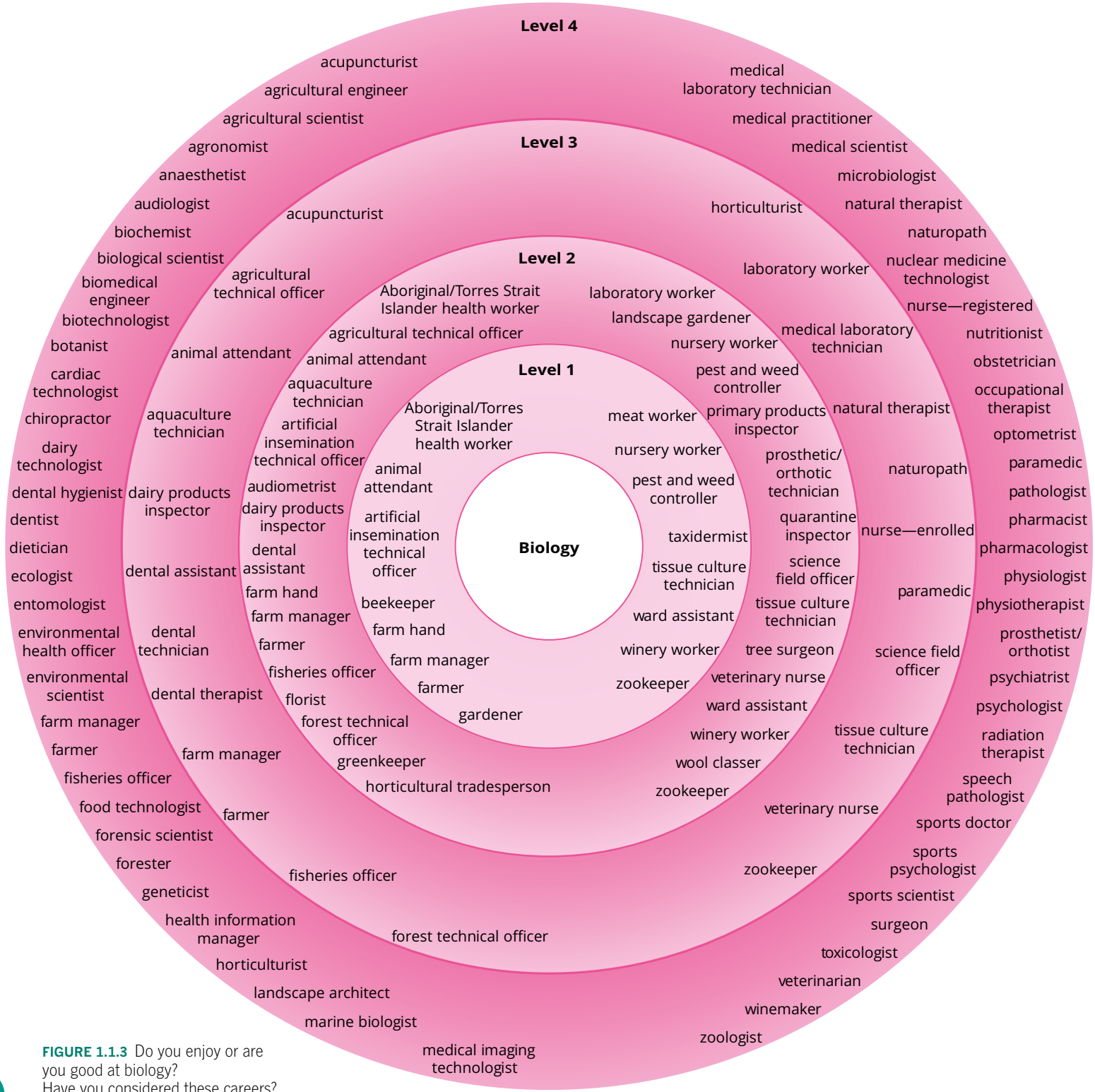


FIGURE 1.1.3 Do you enjoy or are you good at biology? Have you considered these careers? The levels relate to the level of education required for each career.

THE WORK OF SCIENTIFIC RESEARCH

The foundation of all sciences, including biology, is scientific research. Scientific research investigates the unknown to develop new understanding. To build evidence, it may take years and many experiments. In interpreting scientific evidence, scientists endeavour to establish **models**, **theories**, **laws**, principles and **facts**. These are illustrated in Figure 1.1.4. It is important to note that all these deductions change over time as knowledge develops.

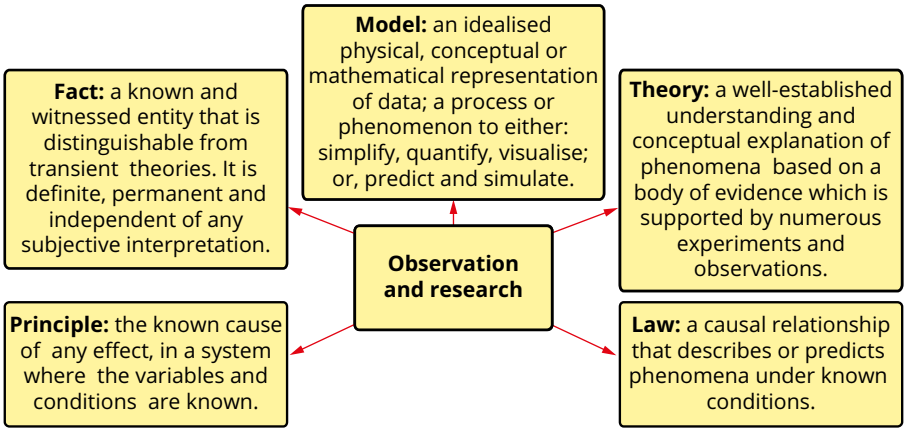


FIGURE 1.1.4 Scientific research and observations are used to develop facts, principles, laws, theories and models.

1.1 Review

SUMMARY

- Science is a systematic approach to developing knowledge through testable explanations and repeatable means.
- Biology is the study of living organisms and systems.
- There are numerous divisions of biology, and as technology improves and scientific disciplines become increasingly trans-disciplinary, the number of divisions grows.
- STEM (science, technology, engineering and mathematics) research, is a trans-disciplinary approach to scientific endeavours.
- Scientific evidence is used to formulate and establish models, theories, laws, principles and facts.
- A scientific model is an idealised representation of a process, a phenomenon or data.
- A scientific theory is a well-established understanding and conceptual explanation of phenomena based on a body of evidence.
- A scientific law is a causal relationship that describes or predicts phenomena under known conditions.
- A scientific principle is the known cause of any effect in a system where the variables and conditions are known.
- A scientific fact is a known and witnessed entity that is distinguishable from transient theories. Facts are definite, permanent and independent of any subjective interpretation.

KEY QUESTIONS

Retrieval

1 Define 'biology'.

2 Define 'STEM'.

Comprehension

3 Look at the careers model in Figure 1.1.3 and:

a provide two examples of careers in biology at Level 4.

b identify a biology career in a growing STEM area.

c identify a biology career in a traditional area.

Analysis

4 A student argued that a scientific theory becomes a scientific law if enough evidence is found to support the observed phenomenon. Explain whether or not you agree with the student.

PART A **WORKING SCIENTIFICALLY**

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

1.2 Orders of magnitude and estimation

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

- convert values from decimal notation to scientific notation, and vice versa
- convert values from scientific notation to scientific units, and vice versa
- solve biological calculations that have values in scientific notation or use scientific units.

SCIENTIFIC NOTATION

'Scientific notation', 'standard notation' and 'standard form' all have the same meaning.

In science, measurements are often written in **scientific notation**. Quantities are written as a number between one and ten and then multiplied by an appropriate power of ten.

Examples of some values written in scientific notation are:

6.022×10^{23} particles

$25.25\,\text{mL} = 2.525 \times 10^{-2}\,\text{L}$

$0.00302\,\text{mol} = 3.02 \times 10^{-3}\,\text{mol}$

Values given in scientific notation show the significant numbers and indicate the **precision** of measurement during experimentation by the instrument. See Module 1.5 for more details about significant figures.

SKILLBUILDER

Transforming decimal notation to scientific notation

Scientists use scientific notation to deal with very large and very small numbers. For example, instead of writing 0.000 000 035, scientists would write 3.5×10^{-8}.

A number in scientific notation (also called standard form or power of ten notation) is written as:

$$a \times 10^{n}$$

where

a is a number equal to or greater than 1 and less than 10; that is, $1 \leq a < 10$

n is an integer (a positive or negative whole number). n is the power that 10 is raised to and is called the index value.

To transform a very large or very small number into scientific notation:

- write the original number as a decimal number greater than or equal to 1 but less than 10
- multiply the decimal number by the appropriate power of 10.

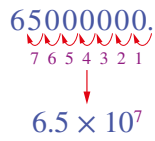
The index value is determined by counting the number of places the decimal point needs to be moved to form the original number again.

- If the decimal point has to move n places to the right, n will be a positive number. For example: $510 = 5.1 \times 10^{2}$.
- If the decimal point is moved n places to the left, n will be a negative number. For example: $0.051 = 5.1 \times 10^{-2}$.

This is shown in Figure 1.2.1.

You will notice from these examples that when large numbers are written in scientific notation, the 10 has a positive index value. Numbers less than 1 are written with 10 to a negative index.

a



b

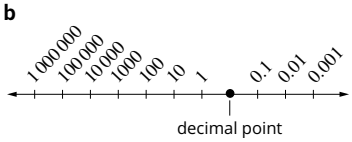


FIGURE 1.2.1 (a) The number of places the decimal moves becomes the power index. (b) Decimal place according to place value. (c) Common numbers in expanded form with their respective scientific notation.

c

Scientific notation	Number (expanded form)
1×10^{-9}	0.000 000 001
1×10^{-6}	0.000 00 1
1×10^{-3}	0.001
1×10^{-1}	0.1
1	1
1×10^{1}	10
1×10^{3}	1000
1×10^{6}	1 000 000
1×10^{9}	1 000 000 000

Worked example 1.2.1

CONVERTING TO SCIENTIFIC NOTATION

A typical virus is 0.000 000 020 m in diameter. How many individual viruses of this size can fit across a typical pinhead with a diameter of 1.5 mm?	
Thinking	**Working**
The size of a virus has too many digits for a calculator or will take an excessive time to calculate, so convert it to scientific notation.	
Move the decimal place to the final digit.	0.000,000,020 = 2.0
Count the number of places the decimal placed was moved.	8
Use the number of decimal places moved as the power index to multiply 10.	2.0×10^{8}
Determine whether the decimal has to be moved to the left or the right to form the original number.	left
Place a negative symbol (–) in front of the power index, 8.	2.0×10^{-8}
Convert 1.5 mm to m.	1.5 mm = 0.15 cm = 0.0015 m
Convert to scientific notation, using the same steps as above.	1.5×10^{-3} m
Calculate the number of individual viruses that can fit on a pinhead by dividing the pinhead diameter (1.5×10^{-3}) by the virus diameter (2.0×10^{-8}).	$\text{number} = \frac{1.5 \times 10^{-3}}{2.0 \times 10^{-8}}$ = 75 000

➤ Try yourself 1.2.1

CONVERTING TO SCIENTIFIC NOTATION

Escherichia coli is a common disease-causing bacterium. It averages approximately 0.000 002 m in length. Calculate how many *E. coli* bacteria could fit across a pinhead, if they were lined up length to length.

You should use scientific notation to express numbers. This involves using your calculator intelligently. Scientific and graphics calculators can be put into a mode that displays all numbers in scientific notation. It is useful when doing calculations to use this mode rather than frequently attempting to convert to scientific notation by counting digits on the calculator display.

Using scientific notation removes ambiguity about the precision of some measurements. For example, a measurement recorded as 240 g could be a measurement to the nearest gram (i.e. somewhere between 239.5 g and 240.5 g) or it could have been rounded up to the nearest 10 g. By writing this quantity as 2.40×10^{2} g, it makes the accuracy of the value clear (in this case three significant figures).

ORDERS OF MAGNITUDE AND PREFIXES

Scientists often work with very large or very small numbers. Physicists can measure astronomical distances between stars billions upon billions of kilometres away. Chemists can measure the number of atoms in solution to the millions or billions of molecules. Biologists measure the number of DNA bases in a genome in the millions or the size of biological molecules that are a millionth or a billionth of a metre. It is important to understand the numbers in scientific text and their order of magnitude and be able to convert them to other units.

Measurements can also be recorded using units that represent the order of magnitude. For example, 2.56×10^{-6} m can be written in scientific notation as it is already, or as 256 µm. The symbol µ represents the prefix micro, which means one-millionth of the measured unit. So when micro is placed in front of metre, it becomes micrometre, meaning one-millionth of a metre. Therefore, 256 µm becomes 256 millionths of a metre.

Table 1.2.1 lists some prefixes used in biology. Each prefix in Table 1.2.1 represents an order of magnitude and you should be familiar with both scientific notation and prefixes for units of measurement. You should also be able to interchange units by referring to Table 1.2.1.

TABLE 1.2.1 The 12 official SI prefixes used in biology

Prefix	Symbol	Multiplier	Description	Decimal	Example
tera	T	10^{12}	trillion	1 000 000 000 000	1 TByte hard drives are now common.
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 is 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 the Earth.
–	–	1	unit	1	–
deci	d	10^{-1}	tenth	0.1	1 dL is a common unit of measurement for blood when screening for health conditions.
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 mg in a gram.
micro	µ	10^{-6}	millionth	0.000 001	µg is the unit commonly used for medicine dosage.
nano	n	10^{-9}	billionth	0.000 000 001	The wavelength of yellow sodium streetlights is 550 nm.
pico	p	10^{-12}	trillionth	0.000 000 000 001	Blood concentrations of insulin are measured in picomoles (pmol).

SKILLBUILDER

Converting between units

In science you may often need to convert from one unit to another to complete a calculation. Knowing how to change between units is an important skill. Because some units of measurement are difficult to visualise, knowing the relative size of different units will help your understanding, and help you avoid errors in calculations. It is important to give a symbol the correct case (upper or lower case)—there is a big difference between 1 mm and 1 Mm.

For example, blood concentrations of insulin can be measured in picomoles (pmol). Some studies have measured the amount of insulin in blood after a meal of pasta to be approximately 40 pmol L^{-1}. To put 40 pmol L^{-1} into context, you can convert this value into a unit you can easily visualise, such as grams per litre (g L^{-1}).

To convert 40 pmol L^{-1} to mol L^{-1} (before converting to g L^{-1}), move the decimal 12 places to the left, so it becomes 0.000 000 000 04 mol L^{-1}. This can also be written as 4.0×10^{-11} mol L^{-1}.

One mole of insulin weighs 5800 g.

Therefore, 0.000 000 000 04 mol L^{-1} is equal to 232 ng L^{-1}.

So this is 0.000 000 232 g L^{-1} (or 2.32×10^{-7} g L^{-1}), which is very small indeed!

Worked example 1.2.2

CONVERTING BETWEEN UNITS

In some plants, the rate of photosynthesis is measured by measuring the change in atmospheric CO_2 in moles per m^2 of leaf area, per second (mol/m^2/s or mol m^{-2} s^{-1}). If a plant was measured to photosynthesise CO_2 at a rate of 25 µmol m^{-2} s^{-1}, calculate the number of moles of CO_2 this plant would photosynthesise per second and per hour.

Thinking	Working
To calculate moles per second, multiply 25 µmol by the multiplying factor for µ (micro).	$25 \times 0.000\,001 = 0.000\,025$ mol m^{-2} s^{-1}
To calculate moles per hour, multiply 0.000 025 mol m^{-2} s^{-1} by 3600 (because there are 3600 s in an hour).	$0.000\,025 \times 3600 = 0.09$ mol m^{-2} h^{-1}

➤ Try yourself 1.2.2

CONVERTING BETWEEN UNITS

The photosynthetic rate of CO_2 by a plant was measured to be 6.2 µmol m^{-2} s^{-1}. Calculate the number of moles of CO_2 that are photosynthesised per square metre per second.

Worked example 1.2.3

CONVERTING BETWEEN UNITS WITH MAGNITUDE

A bacterial culture contains 2×10^{11} cells/L. Determine the number of bacterial cells that would be transferred with 2 mL of bacterial culture. Provide the answer in scientific notation.

Thinking	Working
To convert cells/L to cells/mL, multiply 2×10^{11} by the multiplying factor for milli (m).	$2 \times 10^{11} \times 0.001 = 2 \times 10^{8}$
Multiply 2×10^{8} cells/mL by 2.	$2 \times 10^{8} \times 2 = 4 \times 10^{8}$ cells/mL

➤ Try yourself 1.2.3

CONVERTING BETWEEN UNITS WITH MAGNITUDE

Catalase in liver cells can convert 4×10^{7} molecules of hydrogen peroxide to oxygen and water per second. The activation energy of a catalysed reaction controlled by catalase is 6.58×10^{6} J mol^{-1}. Convert this to kJ mol^{-1}.

1.2 Review

SUMMARY

- 'Scientific notation', 'standard notation', 'power of ten notation' and 'standard form' all have the same meaning.
- A number in scientific notation is written as $a \times 10^{n}$, where:
  - a is a number greater than or equal to 1 and less than 10; that is, $1 \leq a < 10$
  - n is an integer (a positive or negative whole number). n is the power that 10 is raised to and is called the index value.
- A range of scientific symbols are used to represent 10^{n}.

KEY QUESTIONS

Retrieval

1 Recall the prefix and symbol for the following orders of magnitude.
- **a** 1 000 000 000
- **b** 0.000 001
- **c** 0.000 000 001

Comprehension

2 Convert the following to scientific notation.
- **a** 0.000 000 000 012
- **b** 0.000 45
- **c** 73 000 000 000 000 000

3 Convert the following to scientific notation.
- **a** 1.7 nm using m
- **b** 8.2 TW using W
- **c** 2.4 ML using L

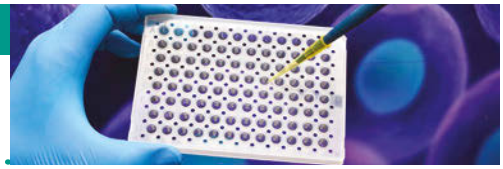
Analysis

4 The normal oxygen uptake in a human is 3.6×10^{-9} mol s^{-1} g^{-1}. Calculate how many moles of oxygen a 70 kg person would use in one hour.

5 Convert 121 000 into scientific notation.

6 Convert 60 700 grams to kilograms.

1.3 Mathematical basics for biology



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

- understand that the rules of mathematics apply for solving mathematical operations or calculations in biology.

Scientists use mathematics when working with data. The evidence can be quantified, measured and analysed. This is known as statistical analysis (a branch of mathematics).

When conducting mathematical operations or calculations, remember all the rules of mathematics apply. These include:

- order of operations
- rules for transposing formulas and working with fractions
- substitutions
- approximations.

EXAMPLES OF MATHEMATICAL BASICS IN BIOLOGY

Table 1.3.1 shows some examples of the use of mathematics in biology.

TABLE 1.3.1 Examples of mathematics in biology

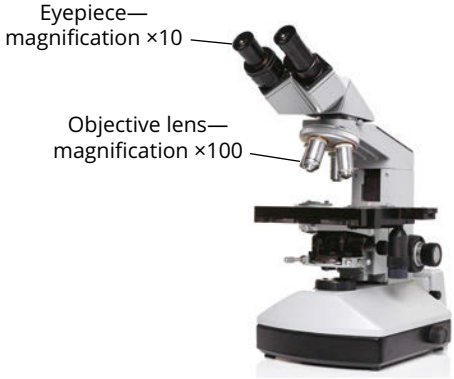
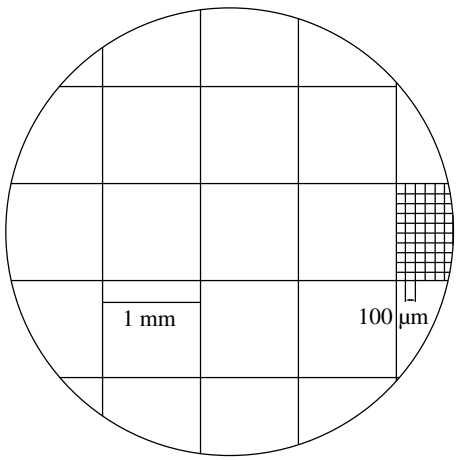
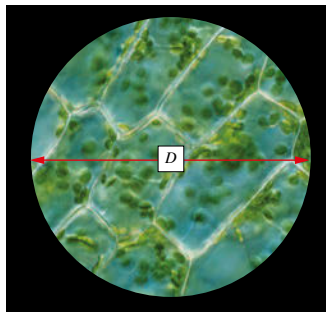
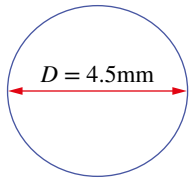
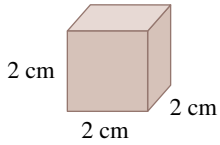
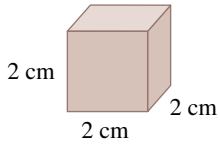
Calculating the magnification of a microscope	
	$M_t = M_e \times M_{ol}$ $= 10^1 \times 10^2$ $= 10^{1+2}$ $= 10^3$ M_t = total magnification M_e = eyepiece magnification M_{ol} = objective lens magnification
Calculating the field of view diameter from magnification x40	
	To determine the size of microbes or specimens under the microscope, you need to know the field of view diameter. The diameter for this field of view at magnification of ×40 is 4.6 mm. $D_b = \frac{M_a}{M_b} \times D_a$ D_a = original diameter D_b = new diameter M_a = original magnification M_b = new magnification To calculate the field of view diameter at ×400: $D_{\times 400} = \frac{M_{\times 40}}{M_{\times 400}} \times D_{\times 40}$ $= \frac{40}{400} \times 4.6$ $= 0.46$ mm

TABLE 1.3.1 continued

Calculating the size of a specimen in the microscopic field of view	
	To complete a comparative study, estimate organelle size, determine organelle density (or concentration) and sometimes calculate rates of cellular processes for cells, you need to know the size of a specimen. The field of view diameter at ×400 is 0.4 mm. $\text{Size (length)} = \frac{D}{\text{no. of specimens across } D}$ $= \frac{0.4\,\text{mm}}{2.5}$ $= 0.16\,\text{mm}$
Calculating the area of a microscopic field of view	
	When completing bacterial studies, including lawn cultures and colonies, it is too difficult to count the number of bacteria so you need the area of population. $A = \pi r^2$ $= \pi 2.25^2$ $= 15.896\ 25\,\text{mm}^2$ $= 15.9\,\text{mm}^2$ (considering significant figures, see Module 1.5)
Calculating the surface area (SA)	
	Dimensions of cells (or simulated cells) are required when determining a cell's capacity to undergo diffusion. SA = (length × length) × 6 sides = (2 cm × 2 cm) × 6 = $24\,\text{cm}^2$
Calculating the surface area to volume ratio (SA:V)	
	This is required to understand the relationship between cell size and rate of diffusion. This also helps to understand the structure and function relationship in cells. SA:V = (length × length) × 6 sides : length^3 = $2^2 \times 6 : 2^3$ = 24 : 8 = 3 : 1

1.3 Review

SUMMARY

- When conducting mathematical operations or calculations, remember all the rules of mathematics apply, including:
  - order of operations
  - rules for transposing formulas and working with fractions
  - substitutions
  - approximations.

KEY QUESTIONS

Retrieval

1 Name three ways that mathematics can assist in the study of biology.

Comprehension

2 Show the missing figures by completing the following table.

Ocular lens	Objective lens	Total magnification
×10	×4	
	×10	
	×40	
	×100	

Analysis

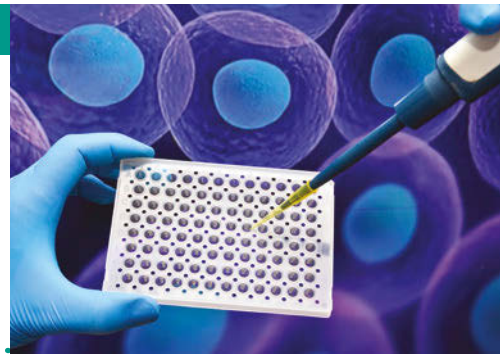
3 Calculate the field of view area of a microscope, for the following field of view diameters.
- **a** 1.4 mm
- **b** 445 µm

4 Calculate the surface area to volume ratio of a rectangle measuring 5 µm × 4 µm × 8 µm.

1.4 Units

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

- appreciate that biology uses the Standard International (SI) units
- recall some common SI units and symbols used in biology
- write measurements and communicate quantities using SI units
- understand that the SI prefixes are multipliers of powers of ten of the base units
- convert between various units of the same type, using SI and some non-SI units.



MEASUREMENT AND UNITS

Scientists use conventional ways of writing numerical measurements, such as using Standard International (SI) units. Use common or SI units when recording your evidence. Table 1.4.1 presents common quantities and SI units used in biology.

TABLE 1.4.1 Common quantities and SI units used in biology

Quantity	SI unit (symbol)	Common unit (symbol)
mass	kilogram (kg)	gram (g)
volume	litre (L)	millilitre (mL) decilitre (dL)
energy	joule (J)	kilojoule (kJ)
concentration	moles per litre (mol L^{-1})	grams per decilitre (g dL^{-1}) grams per 100 mL (g/100 mL))
per cent solution		weight per volume (w/v) weight per weight (w/w)
temperature	kelvin (K)	Celcius (°C)
time	second (s)	minute (min)

Correct use of unit symbols

Standard International (SI) units are recognised internationally. It is important to use symbols correctly to avoid ambiguity. Table 1.4.2 lists some important points to remember when writing units and recording measurements and numbers. Some examples of the use of symbols for derived units are listed in Table 1.4.3.

TABLE 1.4.3 Some examples of the use of symbols for derived units

Correct symbol	Incorrect symbol
g/dL g dL^{-1}	gm/dl gdL^{-1}
g/kg/day g kg^{-1} day^{-1}	gm/Kg/day g$kg^{-1}day^{-1}$

TABLE 1.4.2 Some examples of correct and incorrect use of symbols for derived units

Rule	Correct	Incorrect
Do not mix written numbers and symbols.	thirty grams 30 grams 30 g	thirty g
Do not put spaces between prefixes and unit symbols.	kg mL	k g m L
Use the correct case for symbols (upper or lower case).	1 mm 84 kg 5.2 mL	1 Mm 84 KG 5.2 ml
Do not put a full stop after SI units unless they are at the end of a sentence. The symbols for units are not abbreviations.	mL	m.L.

TABLE 1.4.2 continued

Rule	Correct	Incorrect
Only use upper-case letters for the symbols of the units that are named after people. The exception to this rule is 'L' for litre, where there may be confusion because 'l' looks like the numeral '1'.	J (the unit of energy is joule, named after James Joule)	
Units named after people can take the plural form by adding an 's' when used with numbers greater than one. Never do this with the unit symbols.	two kilojoules	2 kJs
Show the product of a number of units by separating the symbol for each unit with a space. The division or ratio of two or more units can be shown in fraction form, using a slash, or using negative indices.	kJ h kJ/s	kJhr kJs
When units are displayed with a negative exponent such as $g\,dL^{-1}$, the negative value of the exponent signifies the division of the units; that is, per unit. In this case, $g\,dL^{-1}$ is the same as g/dL, or grams per decilitre.	$kg\,s^{-1}$	kg/s^{-1}

1.4 Review

SUMMARY

- Scientists use conventional ways of writing numerical measurements such as using Standard International (SI) units.
- Common quantities and SI units used in biology include:

Quantity	SI unit (symbol)	Common unit (symbol)
mass	kilogram (kg)	gram (g)
volume	litre (L)	millilitre (mL) decilitre (dL)
energy	joule (J)	kilojoule (kJ)
concentration	moles per litre ($mol\,L^{-1}$)	grams per decilitre ($g\,dL^{-1}$) grams per 100 mL ($g\,100\,mL^{-1}$)
per cent solution		weight per volume (w/v) weight per weight (w/w)
temperature	kelvin (K)	Celcius (°C)
time	second (s)	minute (min)

- When units are displayed with a negative exponent, the negative value of the exponent signifies the division of the units. For example, $g\,mL^{-1}$ is the same as g/mL or grams per millilitre.
- When writing and recording measurements, remember:
  - always use numerals for numbers that are accompanied by a symbol
  - do not put spaces between prefixes and unit symbols
  - write the correct case for symbols (upper or lower case).

  For example, $g\,mL^{-1}$ is the same as g/mL or grams per millilitre.
- When writing and recording measurements, remember:
  - numbers and symbols should not be mixed
  - do not put spaces between prefixes and unit symbols
  - write the correct case for symbols (upper or lower case).

KEY QUESTIONS

Retrieval

1 Recall the Standard International unit of measurement, and the symbol, for:
- **a** time
- **b** temperature
- **c** mass

Comprehension

2 Explain why it is important that all society, not just the scientific community, need a systematic and consistent set of units for measurement.

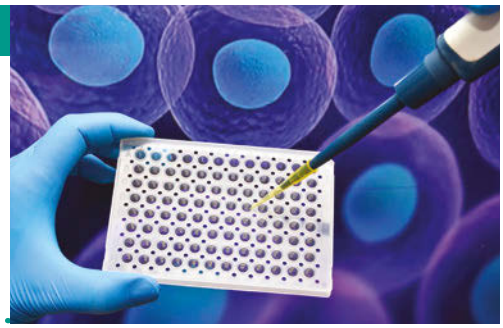
Analysis

3 Identify and correct any errors in the following measurements.
- **a** $23\,ml/g\,h^{-1}$
- **b** $79\,Kl\,s^{-1}$
- **c** four litres
- **d** 1.56 grams

1.5 Uncertainties in measurement and error

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

- explain the difference between accuracy and precision
- explain the difference between uncertainty and error
- calculate uncertainty and error values for measurements
- write measurements with uncertainty and error values
- use the correct number of significant figures
- perform calculations that contain uncertainty or error values.



All measurements are limited by the instrument being used and the observer. This limits the accuracy of the measurements and results. Instruments have a designed level of precision and cannot measure to less than the smallest increment of the device. The accuracy of measurements is also influenced by the observer's subjectivity. The observer's perspective, their current understanding and models of concepts, their exposure to previous **observations** and experience all influence their choice of variables to control and measure, the instruments to use, and the population to sample. Therefore, in science, it is impossible to measure the **true value** as all measurements include uncertainty and error.

Well-designed experiments can measure closer to the true value than others, and experimentation in closed systems enables more accurate and precise measurements. However, closed system measurements do not reflect true natural values.

All this results in **error** and **uncertainty** in the values measured or observed. Therefore, scientific results have some limitations. In science, measurements with uncertainty and errors are the norm and so results are always presented with a **range** (e.g. ±0.25), indicating the possible accuracy.

ACCURACY AND PRECISION

In science and statistics the terms 'accuracy' and 'precision' have very specific and different meanings.

- **Accuracy** is the ability to obtain the correct measurement. To obtain accurate results, you must minimise **systematic errors**.
- Precision is the ability to consistently obtain the same measurement. To obtain precise results, you must minimise **random errors**.

To understand more clearly the difference between accuracy and precision, think about throwing darts at a dartboard, as shown in Figure 1.5.1 on page e20. Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot. Measurements should be both precise and as accurate as you can make them.

Recording numerical data

When using instruments to measure, the number of significant figures (or digits) and decimal places you record is determined by the measurement with the instrument.

The precision depends on the scale, accuracy and precision of the instrument and technique you are using. The smallest increment on the instrument being used determines the digits being recorded and the significant figures. Examples are a measuring cylinder and a pipette. A cylinder with 1 mL increments can record data to the closest 1 mL, whereas a pipette (Figure 1.5.2 on page e20) with 0.1 mL increments can record data to the nearest 0.1 mL.

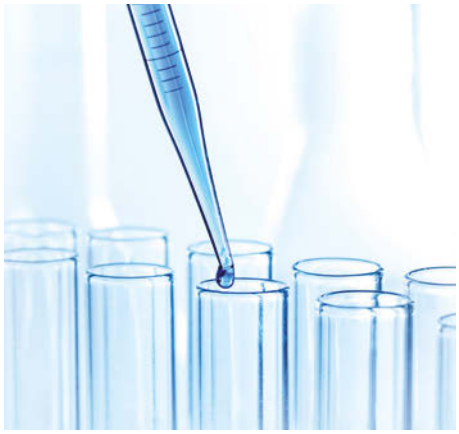


FIGURE 1.5.2 A 5 mL graduated pipette can measure volumes to an accuracy of one-tenth of a millilitre, or 5 mL ± 0.1 mL. The pipette has major divisions of 1 mL and minor divisions of 0.1 mL. You can estimate to 0.05 mL and record volumes to two decimal places; for example, 3.80 mL or 3.85 mL.

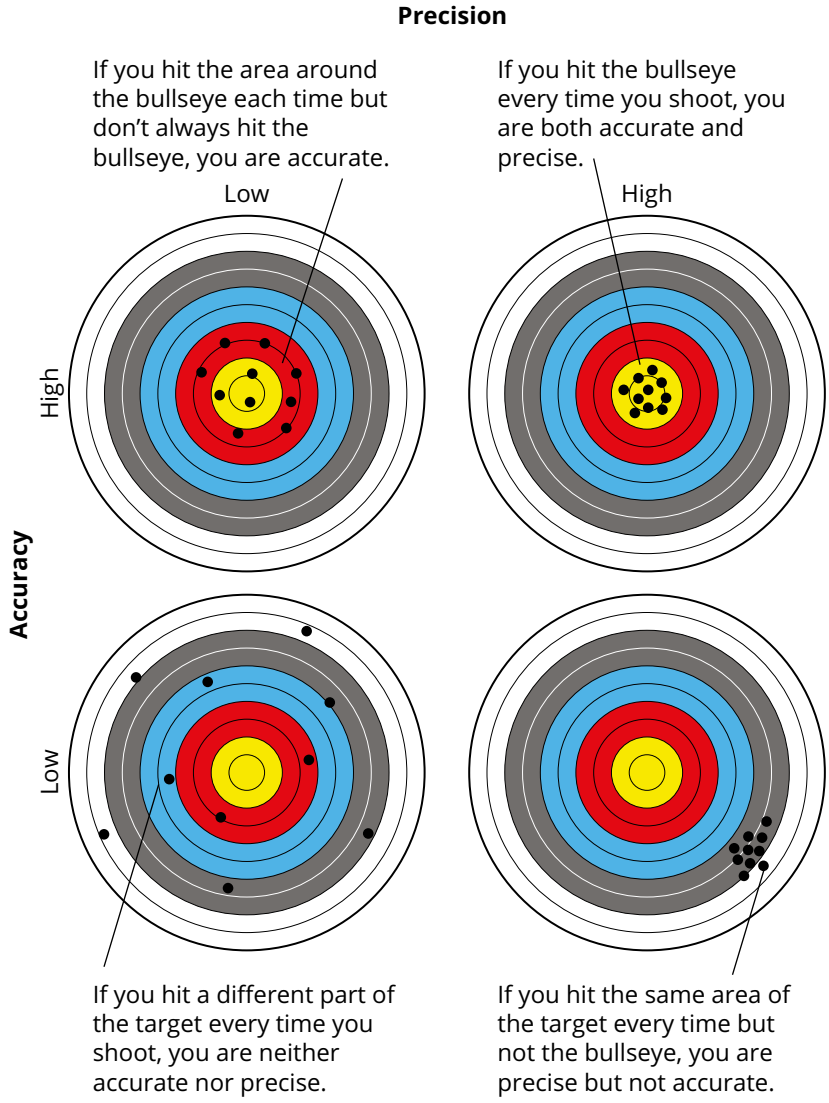


FIGURE 1.5.1 The difference between accuracy and precision

When you record **raw data** and report **processed data** (see Module 1.9), use the number of significant figures available from your equipment or observation. Using either a greater or a smaller number of significant figures can be misleading. For example, Table 1.5.1 shows measurements of five tissue samples taken with an electronic balance accurate to two decimal places. The data was entered into a spreadsheet to calculate the **mean**, which was displayed with four decimal places. You would record the mean as 20.83 g, not 20.8260 g, because two decimal places is the precision limit of the instrument. Recording 20.8260 g would be an example of false precision.

TABLE 1.5.1 An example of false precision in a data calculation

Sample	1	2	3	4	5	Mean
Mass (g)	20.13	20.62	21.22	20.99	21.17	20.8260

UNCERTAINTY AND ERROR

Uncertainty and errors arise from various sources. Uncertainty is a range of measurements in which the true value is thought to be. Because of variations in measurements, you can make an estimation to suggest where the true value should be found among the measurements (e.g. range). Uncertainty is one source of limitations.

Error is the difference between a measurement and the true value. This is *not* an indication of human error. It is due to an inability to achieve the true value. Error cannot be eliminated; therefore, it is important to understand and record the error and report it.

Two types of errors can occur—systematic error and random error. These are explained in Table 1.5.2.

TABLE 1.5.2 Systemic and random errors

Error	Definition	Cause	Example
systematic	An error in measurements caused by the design of a system (e.g. methodology) or an instrument (non-calibrated), which results in the measurements shifting in a systematic direction. The mean may be displaced or varied in a predictable way, affecting the accuracy of the measurement.	• Instrument **calibration** • Choice of instrument • Precision of instrument (increments) • Precision of instrument (sample rate—per second) • Sampling (the choice of population or representatives)	If a digital probe is used to measure the pH of various solutions after an enzyme reaction, and the probe was not calibrated before the experiment or between tests, then the measured pH values will all be shifted equivalently.
			If a person's pulse was counted for 20 s and then the measurement was multiplied by three to determine beats per minute, this methodology allows the heart rate to slow down over 20 s while the pulse is measured. The measured heart rate will shift downwards systematically and predictably.
random	An error that affects the measurement in an unpredictable way, which results in an even variation (fluctuation) in measurements above and below the expected true value. This affects the precision of the measurement.	• Estimation (measuring between increments) • Sampling (frequency, spread, increments) • Parallax • Instrument sensitivity • Noise	Using universal indicator to determine the pH of a solution, in which the pH must be estimated by the shade and colour of the paper (e.g. yellow/orange versus bright orange).
			Using a digital probe to measure gas pressure or heart rate to measure once per 2 seconds compared to a probe that measures 10 times per second.

Uncertainties and errors should always be calculated or measured and then reported. They then form part of the analysis and interpretation (see Module 1.10, Tables 1.10.1 and 1.10.2) as well as the evaluation of the investigation. Also, it is a good idea to consider uncertainty and error when planning experiments (see Modules 1.8 and 1.9).

Calculating uncertainty in measurement

When taking measurements, the goal is to get as close as possible to the 'true' or 'correct' value. For example, when using a measuring cylinder to measure the volume of a solution, the reading may be between two increments on the instrument. The uncertainty can be calculated or estimated and is often represented as a percentage or unit of measurement. If the uncertainty is described as ±1%, it means that the measurement is likely to be no more than 1% above or below the 'true' value.

When averaging repeat measurements, you should report the uncertainty alongside your average. Uncertainty represents a realistic range within which the true value is likely to be. One simple way to calculate the uncertainty is:

$$\text{uncertainty} = \pm \frac{(\text{maximum value} - \text{minimum value})}{2}$$

Worked example 1.5.1

CALCULATING UNCERTAINTY

An experiment was conducted to measure the length of time it takes to convert a substrate to a product in an enzymatic reaction. Three replications of the experiment produced the times 2.50, 3.48 and 2.81 s, the average time being 2.93 s. Calculate the uncertainty.

Thinking	Working
Write down the formula.	$\text{uncertainty} = \pm \frac{(\text{maximum value} - \text{minimum value})}{2}$
Insert the values then perform the calculation.	$\text{uncertainty} = \pm \frac{(3.48 - 2.50)}{2}$ $= \pm 0.49\,\text{s}$
Combine the measurement with the uncertainty.	$2.93\,\text{s} \pm 0.49\,\text{s}$

➤ Try yourself 1.5.1

CALCULATING UNCERTAINTY

Students measured the amount of oxygen produced by a plant over an hour. They performed the trial three times over three consecutive days. The results were 4.9, 5.5 and 5.2 mL. Calculate the uncertainty.

Another example of uncertainty is instrumental error or uncertainty in measurement. This is the precision of an instrument and is limited by the smallest increment the instrument can measure. The uncertainty of an instrument is half the smallest increment. This is known as **absolute uncertainty**. A simple way to calculate the absolute uncertainty of a measurement is:

$$\text{absolute uncertainty} = \pm \frac{\text{smallest increment}}{2}$$

Worked example 1.5.2

CALCULATING ABSOLUTE UNCERTAINTY FOR INSTRUMENTAL ERROR

The temperature during an experiment was measured using a glass thermometer and a digital thermometer. The temperature at peak enzyme activity was 32°C. The smallest increment on the glass thermometer was 1°C and the smallest measurable increment on the digital thermometer was 0.1°C. Calculate the absolute uncertainty of both instruments.

Thinking	Working
For the glass thermometer, write down the formula.	$\text{absolute uncertainty} = \pm \frac{\text{smallest increment}}{2}$
Insert the values and perform the calculation.	$\text{absolute uncertainty} = \pm \frac{1}{2}$ $= \pm 0.5$
Combine the measurement with the uncertainty.	32°C ± 0.5°C
For the digital thermometer, write down the formula.	$\text{absolute uncertainty} = \pm \frac{\text{smallest increment}}{2}$
Insert the values and perform the calculation.	$\text{absolute uncertainty} = \pm \frac{0.1}{2}$ $= \pm 0.05$
Combine the measurement with the uncertainty.	32°C ± 0.05°C

➤ Try yourself 1.5.2

CALCULATING ABSOLUTE UNCERTAINTY FOR INSTRUMENTAL ERROR

A student experiment measured the peak oxygen production of an indoor plant to be 7.3 mL in an hour at 42°C. Calculate the absolute uncertainty for the oxygen measurement.

Uncertainty can also be reported as a percentage of the measurement, which is known as **relative uncertainty**. To calculate the relative uncertainty, apply this formula:

$$\text{relative uncertainty} = \pm \left(\frac{\text{absolute uncertainty}}{\text{measurement}} \right) \times 100$$

Worked example 1.5.3

CALCULATING RELATIVE UNCERTAINTY FOR INSTRUMENTAL ERROR

A student experiment testing the effect of pH on enzyme activity measured the peak activity at a pH of 5.56, using a new digital sensor. The digital sensor reads to two decimal places. Calculate the relative uncertainty.

Thinking	Working
Write down the formula for relative uncertainty.	$\text{relative uncertainty} = \pm \left(\frac{\text{absolute uncertainty}}{\text{measurement}} \right) \times 100$
Insert the values and perform the calculation.	$\text{relative uncertainty} = \pm \left(\frac{0.005}{5.56} \right) \times 100$ $= \pm 0.09\%$
Combine the measurement and uncertainty.	pH 5.56 ± 0.09%

➤ Try yourself 1.5.3

CALCULATING RELATIVE UNCERTAINTY FOR INSTRUMENTAL ERROR

A student experiment testing the effect of pH on enzyme activity measured the peak activity at a pH of 5.6, using an old digital sensor. Calculate the relative uncertainty.

Significant figures

When measuring phenomena during experimentation, the precision of the instruments determines the number of significant figures and decimal places you record in the data.

Significant figures are the numbers that convey meaning and accuracy. The number of significant figures used depends on the scale of the instrument. Record data using the number of significant figures available, from the equipment or observation. Using either a greater or smaller number of significant figures can be misleading.

Significant figures are the exact digits observed when recording the results of an observation or experiment. For example, if the volume of O_2 gas produced and measured from a plant photosynthesising during a 6-hour experiment was 6.0 mL because exactly 6.0 mL was observed, then the measurement is 6.0 mL with two significant figures, not 6 mL.

SKILLBUILDER

Determining the significant figures of a measurement from an instrument

When conducting measurements for an experiment or undertaking the methodology, your recorded values must indicate the precision (increments) of the instrument. The plastic pipette in Figure 1.5.3 measures up to 5 mL and has 1 mL increments. Because the instrument measures in whole millilitre increments, the recorded value must be to a whole millilitre.

If you measured 2 mL with the pipette in Figure 1.5.3, then you should measure 2 mL, not 2.0 mL. This is because the measurement was not precise to one-tenth (0.1) of a millilitre. Therefore, using this instrument, the value is measured and recorded to one significant figure.

To determine how many significant figures there are in a measurement, follow these rules.

1. All non-zero digits are significant.
2. All zeros between non-zero digits are significant.
3. Trailing zeros (either decimal or not) if measured are significant.
4. Leading zeros are not significant (in numbers with decimals, they only inform where the decimal is placed).

Table 1.5.3 shows some examples of measurements and how many significant figures they have. Review the examples to learn more about significant figures.

TABLE 1.5.3 Measurements and significant figures

Measurement	Number of significant figures
15	2
3.5	2
3.50	3
0.037	2
1401	4

FIGURE 1.5.3 This 5 mL plastic pipette has 1 mL increments.

It is important to record the exact numbers measured during an experiment. This determines the significant figures, and later the accuracy and precision of the analysis. If you observe a zero, record it because it is the exact amount measured. This includes all zeros before and after decimal places.

Calculations with uncertainties

There are a few rules when conducting calculations with numbers (or measurements) that have uncertainties. It is important to record the correct uncertainty once all the calculations are complete so that you report the appropriate accuracy. Table 1.5.4 outlines the rules for undertaking calculations with data and its associated uncertainty.

Keep in mind that the rules for significant figures apply to all numerical reporting, including the uncertainties.

TABLE 1.5.4 Rules for calculations involving uncertainty

Calculation	Rule	Examples
addition and subtraction	Add the uncertainties.	$5.4 \pm 0.05 + 3.2 \pm 0.05 = 8.6 \pm 0.1$ $5.4 \pm 0.05 + 3.2 \pm 0.1 = 8.6 \pm 0.15$ $5.4 \pm 0.05 - 3.2 \pm 0.05 = 2.2 \pm 0.1$ $5.4 \pm 0.05 - 3.2 \pm 0.1 = 2.2 \pm 0.15$
multiplication and division	Add the relative uncertainties.	$3.0 \pm 0.05 \times 1.5 \pm 0.05$ $= 3.0 \pm 1.7\% \times 1.5 \pm 3.3\% = 4.5 \pm 5.0\%$ $3.0 \pm 0.05 \div 1.5 \pm 0.05$ $= 3.0 \pm 1.7\% \div 1.5 \pm 3.3\% = 2.0 \pm 5.0\%$
multiplying with a constant (absolute uncertainty)	Multiply the uncertainty.	$3.14 \times (4.1 \pm 0.05) = 12.9 \pm 0.16$
multiplying with a constant (relative uncertainty)	Maintain the uncertainty.	$3.14 \times (4.1 \pm 1.6\%) = 12.9 \pm 1.6\%$

Uncertainty due to nature

In nature, there are many sources of variation that make it impossible to measure the same value twice. Examples of variations in nature are shown in Figure 1.5.4. They include:

- genetic differences
  - variation in the genetic code
  - variation in the regulation of the code
- intracellular differences in molecular processes and capacity
- extracellular differences in the maintenance and relationships between cells, tissues, organs and systems
- differences in how organisms relate (intraspecies and interspecies relationships)
- various abiotic factors affecting biotic factors in habitats and ecosystems
- local, regional and global differences in ecological relationships.

There are a few terms used to describe the variations found naturally in biology, including 'genetic variation', 'biological variation' and 'natural variation'. Genetic variation is found in biological organisms and systems. Therefore, when the term 'natural variation' is used, it often refers to genetic variation. When reporting natural, biological or genetic variation, it is best to choose one term and use it consistently.

The difficulty with uncertainty due to nature is that the true value can never be known. Most biological experiments are open systems, so are influenced by many variables. Also, most biological experiments measure non-invasive or indirect results, making it difficult to achieve accuracy. Measuring a range of values is expected in biology; therefore, analysis and evaluation using uncertainty to acknowledge accuracy and precision is important when you interpret the results. Statistical analysis helps to analyse the data and range of measurements, and determine uncertainty (see Module 1.7).

FIGURE 1.5.4 (a) Close inspection of bees reveals variation in the shades of colour and banding. (b) The same species of plant can be affected by different pH values in the soil, displaying variation within a habitat. (c) Genetic variation within a family. (d) Genetic variation within plants shown by wrinkled peas (left) and round peas (right).

1.5 Review

SUMMARY

- Accuracy is the ability to obtain the correct measurement. To obtain accurate results, you must minimise systematic errors.
- Precision is the ability to consistently obtain the same measurement. To obtain precise results, you must minimise random errors.
- Uncertainty is a range of measurements from the experiment in which the true value is thought to be.
- Error is the difference between a measurement and the true value; this is not an indication of human error or maintaining scientific validity.
- Uncertainty and error values are presented as a range (e.g. ±0.25).
- A simple way to calculate uncertainty is:

$$\text{uncertainty} = \pm\frac{(\text{maximum value} - \text{minimum value})}{2}$$

- A simple way to calculate the absolute uncertainty is:

$$\text{absolute uncertainty} = \pm\frac{\text{smallest increment}}{2}$$

- A simple way to calculate the relative uncertainty is:

$$\text{relative uncertainty} = \pm\left(\frac{\text{absolute uncertainty}}{\text{measurement}}\right) \times 100$$

- The rules for calculations involving uncertainty are:

Calculation	Rule
Addition and subtraction	Add the uncertainties
Multiplication and division	Add the relative uncertainties
Multiplying with a constant (absolute uncertainty)	Multiply the uncertainty
Multiplying with a constant (relative uncertainty)	Maintain the uncertainty

- Significant figures are the numbers that convey meaning and precision. The number of significant figures used depends on the scale of the instrument.
- The rules governing significant figures are as follows.
  - All non-zero digits are significant.
  - All zeros between non-zero digits are significant.
  - Trailing zeros (either decimal or not) if measured are significant.
  - Leading zeros are not significant (in numbers with decimals, they only inform where the decimal is placed).

KEY QUESTIONS

Retrieval

1 Recall how values of uncertainty and error are presented.

Comprehension

2 Explain the difference between accuracy and precision.

3 Explain the difference between raw and processed data.

4 Identify the following scenarios as examples of random or systematic error.

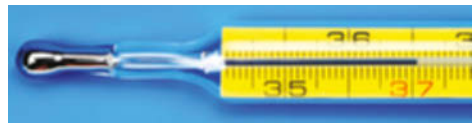
a You weigh the mass of a powder three times, using the same scales and get three different readings.

b The tape measure you are using to measure distance has been stretched.

c When electronic scales are zeroed, they read 0.05 g.

5 Determine the instrumental error in the following instrument.

6 Write the temperature measured by the thermometer including the instrumental error.



7 The pipette shown on the right is a 10 mL glass pipette with 0.1 mL increments. If exactly 2 mL was measured using this pipette, write the value of this measurement with the appropriate number of significant figures.

Analysis

8 Calculate the average and uncertainty of these two sets of data.

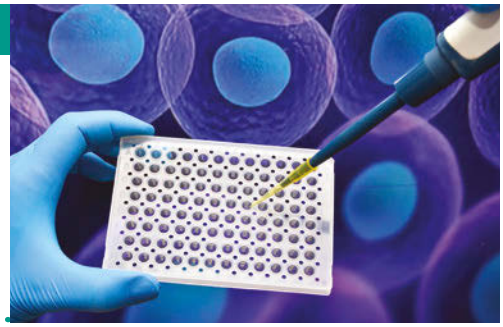
Data set A: 11.4, 10.9, 11.8, 10.6, 11.5, 11.1

Data set B: 25.3, 27.4, 22.0, 26.1, 28.4, 23.1

1.6 Tables and graphing

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

- create tables to record and organise data
- present data from tables into graphs
- distinguish between types of graphs
- select appropriate graphs to represent data
- represent missing data in graphs
- explain what an outlier is, and know how to represent outliers in graphs.



PRESENTING DATA IN TABLES

Tables record number values and allow you to organise your data. In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data in graph form than in table form.

Presenting raw data in tables

Tables organise data into rows and columns, and can vary in complexity according to the nature of your data. Tables can be used to organise raw data and processed data, or to summarise results.

The simplest form of a table is a two-column chart. The first column should contain the **independent variable** (the one you control) and the second column should contain the dependent variable (the one that may change in response to a change in the independent variable).

As you can see in Figure 1.6.1, tables should have the following features:

- a descriptive title, including table number
- column headings (including the units)
- aligned figures (align the decimal points)
- the independent variable placed in the left column
- the dependent variables placed in the right columns.

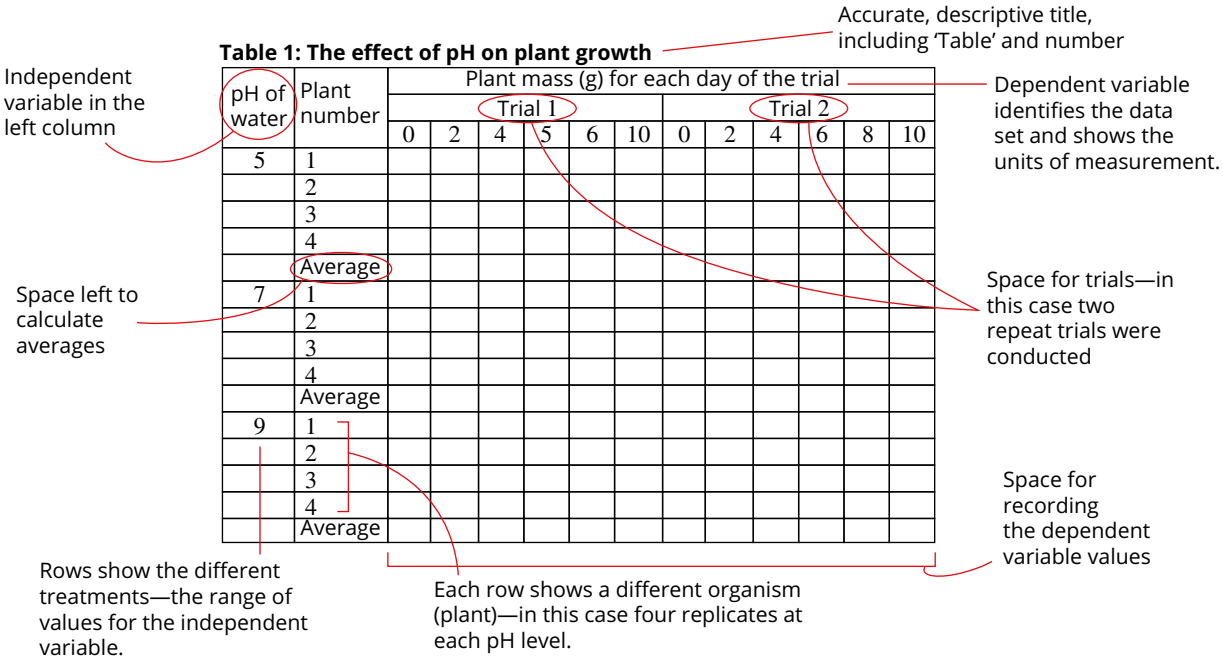


FIGURE 1.6.1 A model table and examples of features to be included in tables

Presenting processed data in tables

Table 1.6.1 shows the relationship between temperature and mean transpiration rate. It displays transpiration data in a processed format, because it displays the mean of several values for each temperature. The uncertainty is also displayed, which will be a requirement for assessments.

TABLE 1.6.1 Effect of temperature on mean transpiration rate, including uncertainty

Temperature (°C)	Mean transpiration rate ($mL\,g^{-1}\,h^{-1}$)
15	0.038 ± 0.002
25	0.043 ± 0.001
35	0.059 ± 0.001
45	0.074 ± 0.0015

PRESENTING DATA IN GRAPHS

Graphs are used to display relationships, trends and patterns between two variables with one proposed to be dependent on the other, as shown in Figure 1.6.2.

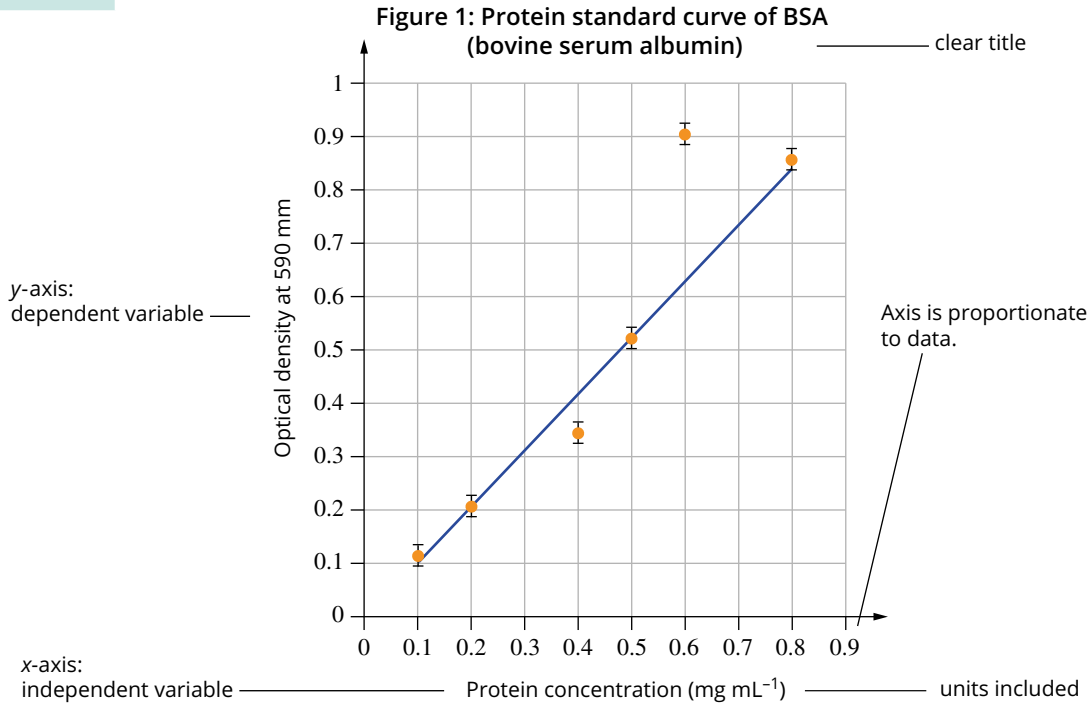


FIGURE 1.6.2 Examples of features to be included in graphs

There are several types of graphs, including line graphs, bar graphs and pie charts. The best one to use will depend on the nature of the data. General rules to follow when making a graph include the following.

- Keep the graph simple and uncluttered.
- Use a descriptive title, including figure number.
- Represent the independent variable on the *x*-axis and the dependent variable on the *y*-axis.
- Start each axis at zero.
- Match the length of the axes to the data.
- Clearly label axes with both the variable and the unit in which it is measured.
- Use small symbols such as circles or squares for data points.
- Use different symbols for different data sets.

Scatterplots and line graphs

Scatterplots are appropriate and often best for continuous and discrete data. They are used to show the relationship between two variables when one variable is dependent on the other.

The data is plotted on the graph as a series of points the data can be continuous or discrete (see Module 1.8). Each point should be drawn in pencil as a small circle or cross. Alternatively, you can use a computer program to generate your graphs.

A **line graph** is a good way of representing continuous quantitative data. In a line graph, the values are plotted as a series of points on the graph. A line can then be drawn from each point to the next, as shown in Figure 1.6.3. This line shows the change in data from one point to the next but does not predict the value of a point between the plotted data.

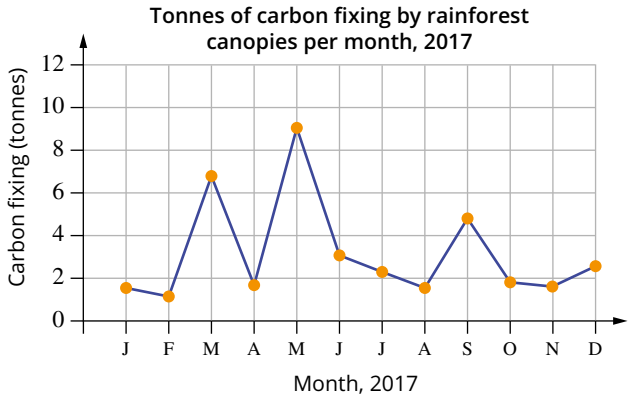


FIGURE 1.6.3 A line graph showing tonnes of carbon fixing by rainforest canopies per month, in 2017, with lines ruled from each point to the next

Alternatively, a single straight or curved line can be drawn that passes an equal distance between all data points, as shown in Figure 1.6.4. This is a **trend line** or a line of best fit. It is used to show the overall trend in the data, and can be used to predict values between the data points. A line of best fit usually does not pass through every data point. Its position can be estimated by eye (ensuring equal number of data points above and below the line but more accurate trend lines (used by scientists) can be acquired using programs to calculate the line mathematically from the data (see Module 1.7).

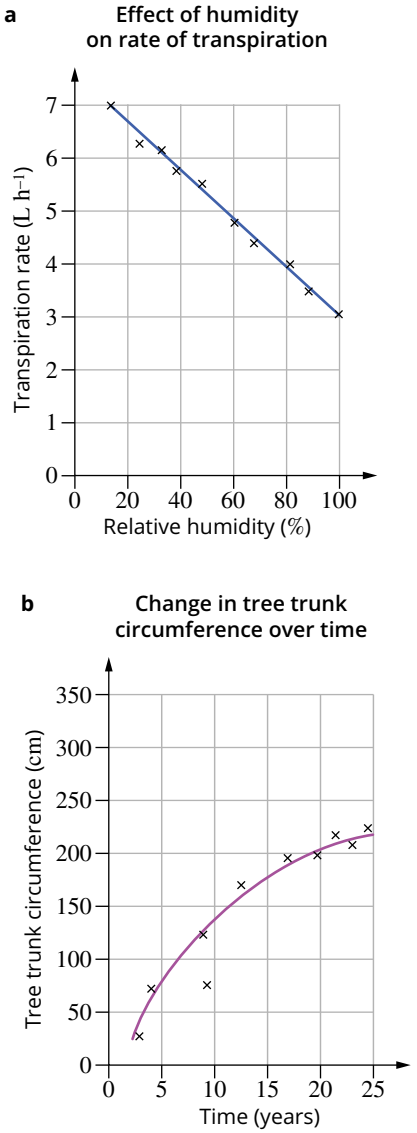


FIGURE 1.6.4 Scatterplot graphs showing (a) straight and (b) curved trend lines

Bar and column graphs

Bar and column graphs are used to show categories and discrete (discontinuous) data (see Module 1.8).

- A **column graph** shows the value of the dependent variable by the height of the column; the categories are labelled across the *x*-axis.
- A bar graph shows the value of the dependent variable by the length of the horizontal bar; the categories are labelled up the *y*-axis.

Bar and column graphs are commonly used when the independent variable is categorical rather than numerical, or when the numerical data is discrete. The bars or columns are always the same width and the same distance apart.

Bar and column graphs are very useful for graphing qualitative and discrete data, such as the number of base pairs and number of genes on each human chromosome (Figure 1.6.5). Note that two different vertical axes are used for the different data sets, which have very different scales.

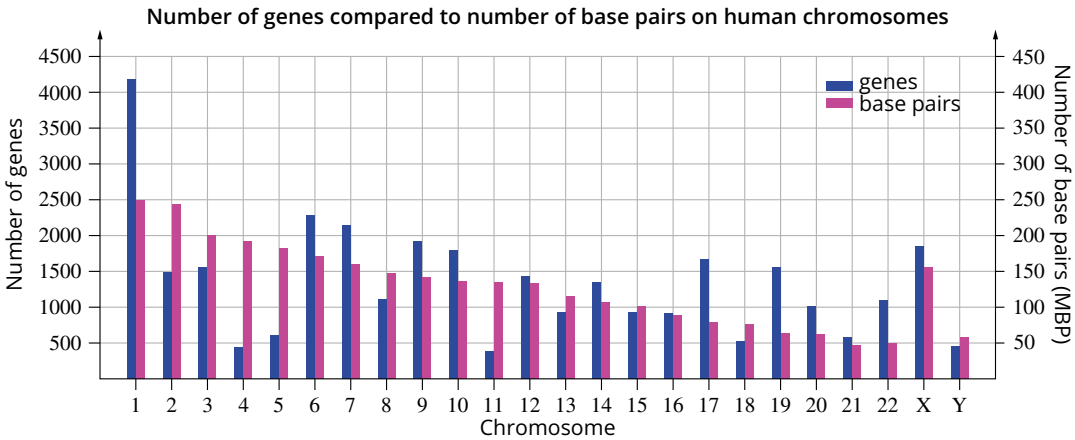


FIGURE 1.6.5 A column graph comparing the number of genes (blue, left axis) and the number of base pairs (pink, right axis) on human chromosomes

When the labels of the variables are long, horizontal bar graphs can be used. Bar graphs are also used when the data ranges are variable and overlapping, such as genome sizes, as shown in Figure 1.6.6.

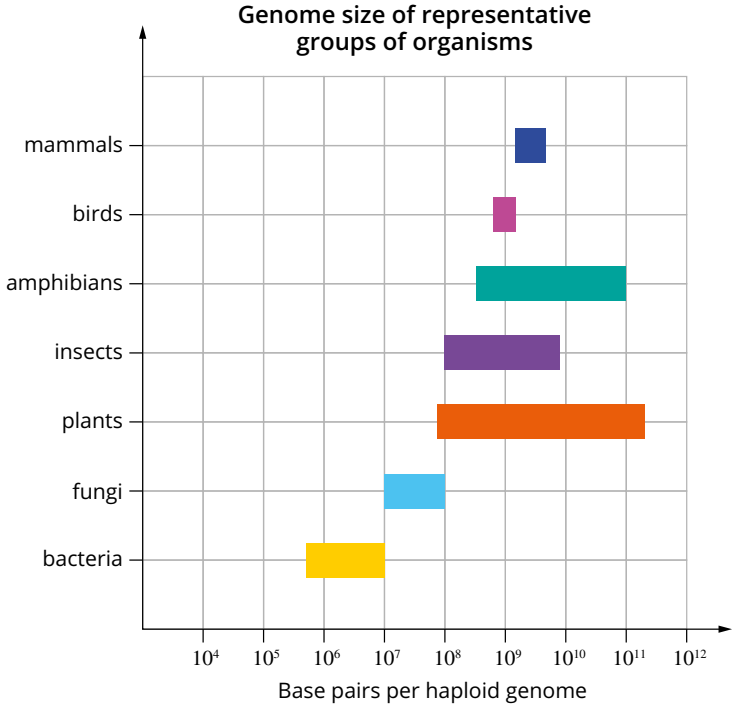


FIGURE 1.6.6 A horizontal bar graph comparing genome size of representative organisms from the different kingdoms of life

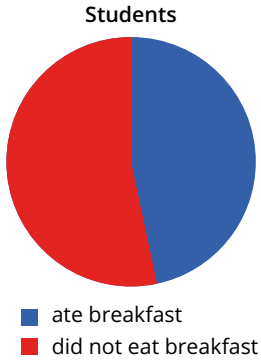


FIGURE 1.6.7 A pie chart presenting data on the breakfast habits of students

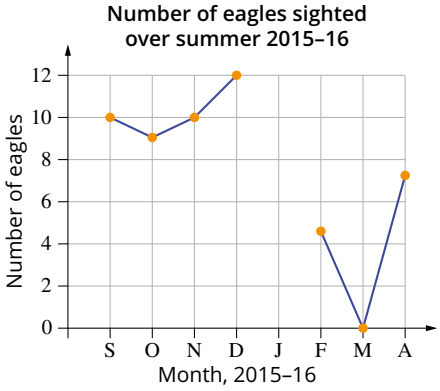


FIGURE 1.6.8 A line graph with missing data. This accurately represents the measurements taken during the methodology.

Pie charts

A **pie chart** is a way of presenting qualitative or discrete quantitative data (see Module 1.9, page e58). It shows each category of data as a proportion of the total data. The chart is a circle divided into sections according to the proportions of each category, like slices of a pie (Figure 1.6.7). Each category is coloured or shaded differently so that it can be clearly distinguished from the other categories. It is recommended to use pie charts only when there are few categories.

A circle is equal to 360°. To draw a pie chart, you must determine how many degrees are needed for each category. This can be done as follows:

1. Add the amounts in each category to find the total.
2. Divide 360° by the total (this will tell you how many degrees of the circle one value is worth).
3. Multiply the answer by the amount in the first category. Your answer will be in degrees that can then be marked for the first category using a protractor on the circle.
4. Repeat for each category.

Missing data

When you have missing data, leave a gap for it, as shown in Figure 1.6.8. Ensure that the axes are complete (do not skip values) and do not join the data points that have missing data points between them.

Anomalies and outliers

Sometimes one data point does not fit the trend and may be an error. This is called an **anomaly** or **outlier**. Outliers are often caused by a significant random error when measuring (see Module 1.5). Outliers are determined using statistical calculations (Module 1.7), and they cannot be determined using a trend line. If you have an anomaly or outlier in your results, include it in your graph but ignore it when drawing the line of best fit (Figure 1.6.9).

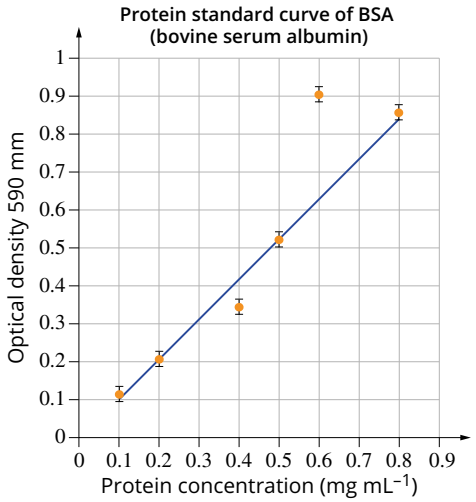


FIGURE 1.6.9 A line graph showing an anomaly or outlier, which has been ignored when adding the line of best fit

Error bars/whiskers

When graphically representing data and results, the uncertainty, error or range in data can be shown. When data is collected or measured, the precision or uncertainty is recorded as $\pm n$. This should be shown in the graph. Inserting error bars or whiskers onto the data points on a graph will display a range. This range can be the range in measurements, instrumental precision, uncertainty, error or standard deviation for example.

As you will recall from Module 1.5, uncertainty and error are a range in which the true value lies. A graph should indicate this. Choosing which range to indicate on the graph depends on the analysis and interpretation of data trying to be achieved in answering the research question or testing of a hypothesis. Module 1.7 explains various calculations that are useful for analysing and interpreting data. Module 1.7 will assist with choosing which range to indicate on a graph to demonstrate reliability or significance of results.

Distorting the truth

Poorly constructed graphs can distort the truth. For example, in Figure 1.6.10 you can see two figures that show the same data—the test results of two groups of students. One group of students did not eat breakfast before doing the test, and scored an average of 42 marks out of 50. The other group of students did eat breakfast and scored an average of 48 marks out of 50. Figure 2 distorts the difference in marks between the two groups by using a scale of only 40 to 50 marks on the *y*-axis. It is important to make sure the figures you create do not distort your data. You should also be wary of distorted data when interpreting figures in other publications.

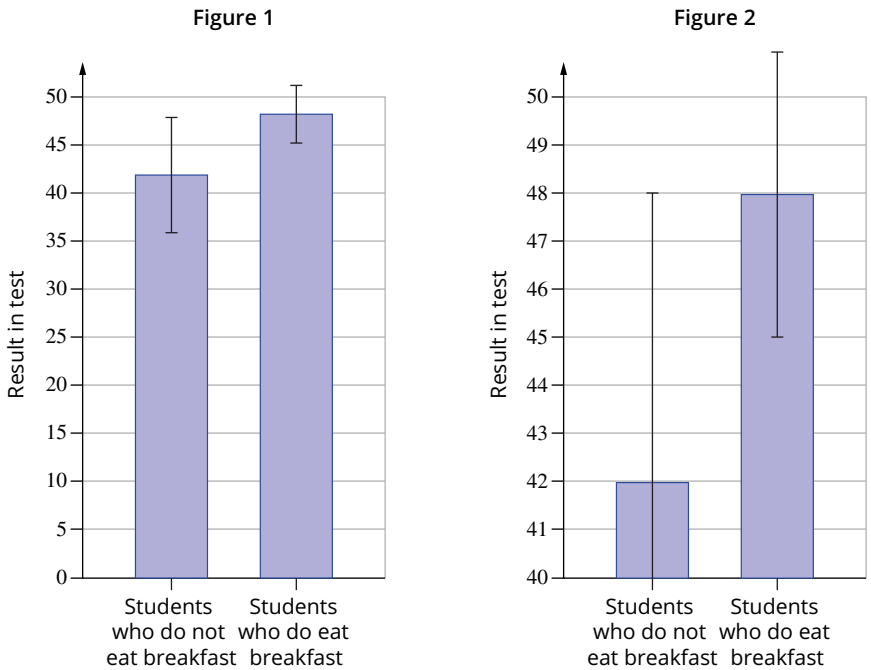


FIGURE 1.6.10 Figure 1 shows the difference between two groups of students' test results (marks out of 50) on the *y*-axis. Figure 2 shows the difference between the two groups within only a narrow range of marks on the *y*-axis, which distorts the difference and makes it appear larger than it really is.

1.6 Review

SUMMARY

- Tables and graphs are used to represent scientific data.
- In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data in graph form than in table form.
- Tables organise data into rows and columns, and can vary in complexity according to the nature of your data.
- Tables should have:
  - a descriptive title
  - column headings (including the units)
  - aligned figures (align the decimal points)
  - the independent variable placed in the left column
  - the dependent variable placed in the right column.
- Graphs are used to display relationships, trends and patterns between two variables with one proposed to be dependent on the other.
- There are several types of graphs, including line graphs, bar graphs and pie charts. The best one to use will depend on the nature of the data.
- Scatterplots are commonly used to display data in the form of a graph, and can be used to plot raw or processed data.
- A trend line (line of best fit) is used to show the overall trend in the data, and can be used to predict values between the data points.
- A line graph is a good way of representing continuous quantitative data.
- Bar and column graphs are used to show categories and discrete (discontinuous) data.
  - A column graph shows the value of the dependent variable by the height of the column; the categories are labelled across the *x*-axis.
  - A bar graph shows the value of the dependent variable by the length of the horizontal bar; the categories are labelled up the *y*-axis.
- A pie chart is a way of presenting qualitative or discrete quantitative data.
- Missing data is represented in graphs by leaving a gap.
- An outlier is a data point that does not fit the trend, and may be caused by an error.

KEY QUESTIONS

Retrieval

1 State the purpose of a trend line.

Comprehension

2 Describe why an anomaly or outlier, if known, is ignored when drawing a trend line.

Analysis

3 Annotate two self-drawn graphs, one illustrating an appropriate line of best fit and the other an inappropriate line graph.

4 Immunologists have measured the levels of antibodies in blood serum to gather background data on population responses to infection. They collected the following data on the concentration of two different types of antibody, IgG and IgA, from participants ranging in age from 6 months to 20 years (the antibody levels are listed in order of increasing age of subject):

Age of subject: 6 months, 1, 2, 4, 10, 20 years

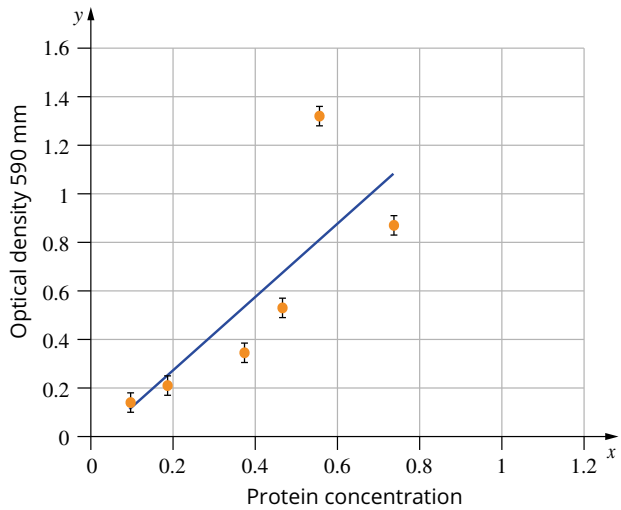
Concentration of IgG (mg/100 mL): 300, 600, 800, 1000, 1500, 1500

Concentration of IgA (mg/100 mL): 50, 100, 100, 150, 200, 400

a Prepare a data table.

b Prepare a graph of the data.

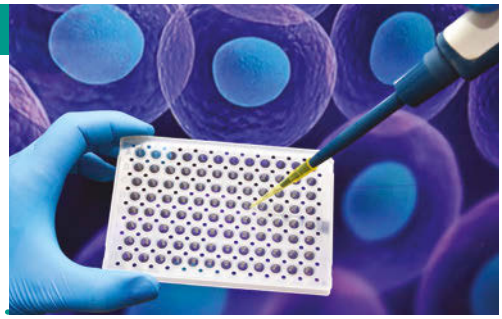
5 Determine at least four ways that the following graph could be improved.



1.7 Statistics

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

- explain and calculate the following features of data sets: range, mean, median and mode
- explain the statistical significance of standard deviation
- explain the meaning of regression, linear regression, *r*-values and R^2 values
- understand that various statistical methods are used to analyse data sets, including the Pearson coefficient and student *t*-tests.



One of the difficulties in the biological sciences is that direct measurements or measurements within a closed system are challenging to obtain. Therefore, there are various limitations and uncertainties in biology, commonly involving accuracy and precision (see Module 1.5) as well as errors related to reliability and validity (see Modules 1.8 and 1.9). To address this problem, biologists perform statistical analysis to help understand the quality of the measurements and their meaning.

Ways to achieve good-quality evidence through good scientific practice are outlined in Modules 1.8 and 1.9. This module will outline a basic understanding of common statistical analysis used in biology and ones relevant to the Queensland Biology syllabus.

RANGE

The range is the difference between the highest and lowest values in a data set. Table 1.7.1 shows the measurements taken for five different plants after treatment with a plant hormone.

TABLE 1.7.1 Plant height in a hormone treatment experiment

Treatment	Height (mm)					Mean (mm)	Range (mm)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5		
hormone-treated	158	378	320	377	363	319.2	378 – 158 = 220
untreated control	140	135	170	171	193	161.8	193 – 135 = 58

To determine the range for values in Table 1.7.1, you subtract the smallest value from the largest value. Notice how an abnormally large or abnormally small value in the data set makes the variability appear high.

If one value appears vastly different, such as plant 1 in the hormone-treated group, another statistical analysis may be used to determine whether it is an outlier. An outlier is a value that lies outside (is much smaller or larger than) most of the other values in a set of data. To determine if a value lies outside most other values, it must be statistically calculated. This illustrates the importance of observation during experiments and recording all details in a journal as the experiment is conducted. The range outlines the total variation in measured results. No other analysis or interpretation can be applied.

MEASURES OF CENTRAL TENDENCY

Measures of central tendency are single values that allow you to describe the central position in a set of data. Measures of central tendency are sometimes also called measures of central location. The mean, median and mode are all measures of central tendency.

TABLE 1.7.2 When to use the different measures of central tendency

Type of data	Mean	Median	Mode
nominal (qualitative)	✓	×	×
ordinal (qualitative)	✓	✓	maybe
discrete or continuous (quantitative)	✓	✓	✓

TABLE 1.7.3 Measured resting heart rate (beats per minute) for males and females

Resting heart rate (bpm)	
Female	**Male**
77	69
78	68
72	71
73	72
76	71
74	68
Mean 75	Mean 70

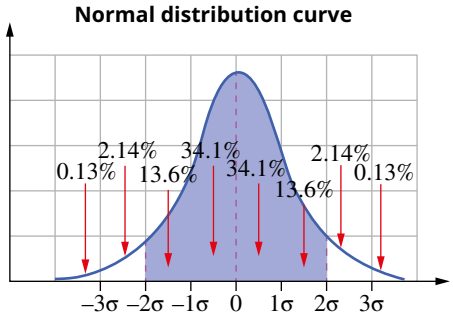


FIGURE 1.7.1 A normal distribution curve showing how far each standard deviation (σ) is from the mean (0).

Consider the data set 3, 5, 7, 8, 8, 8, 10.

- The mean, $\bar{x}$, is the average of a data set. It is calculated by dividing the sum of the values by the number of values.

  $$\bar{x} = \frac{\Sigma x_1 + x_2 + x_3 \ldots}{n}$$

  where Σ = sum of $x_1 + x_2 + x_3$ = measurement$_1$ + measurement$_2$ + measurement$_3$, n = total number of measurements

  In this case, the mean is $(3 + 5 + 7 + 8 + 8 + 8 + 10) \div 7 = 7$.
- The **median** is the 'middle' value in an ordered list of values, which in this case is the fourth value, which is 8.
- The **mode** is the value that occurs most often in a list of values, which in this case is 8. This measure is particularly useful for describing qualitative or discrete data.

The appropriate measure of central tendency to use depends on the type of data you are working with (Table 1.7.2).

Graphically representing the data using central tendency provides a clear and succinct display of results. As there are many measured values and results in raw data, the data can be difficult to analyse and interpret. It is much easier and less complicated to interpret processed data compared to raw data. An interpretation can be surmised by comparing three values (representing many results) (e.g. three means), rather than 15 separate individual results in the raw data.

However, it is important to note that statistical calculations do not produce the true value; they produce a single value (or smaller number of values) that are meant to represent many. As can be seen in Table 1.7.3, the two means are processed values for five measurements. The measured values for heart rate have been averaged using the mean.

STANDARD DEVIATION

Standard deviation specifically estimates the spread of data in a population or set of values. It calculates the spread or dispersion of data and its distance from the mean.

The standard deviation calculation assumes that the data being used is from a set in which a normal curve (or normal distribution) exists. A normal distribution of data forms a 'bell' curve or a normal curve as seen in Figure 1.7.1. A normal curve on a graph has:

- approximately 68.2% of all the measurements (data) within 1 standard deviation (1σ) of the mean; that is, 34.1% above the mean and 34.1% below the mean
- approximately 27.2% of all the data between the first and second standard deviation (between 1σ and 2σ); that is, 13.6% above 1σ and 13.6% below 1σ
- approximately 4.2% of all data between the second and third standard deviation (between 2σ and 3σ); that is, 2.14% above 2σ and 2.14% below 2σ
- the final 0.2% above and below 3σ, 0.13% on either side.

When using standard deviation to analyse data, it is important to understand what has been calculated. If a measured phenomenon is expected to be equivalent from one test to another, then it would be expected that all measurements would be very close to the mean, except for unusual results such as an error. Using standard deviation, you could decide that all accurate measurements should be within two standard deviations (2σ) of the mean. Therefore, any measurement outside (greater than) 2σ from the mean would be considered as an outlier (measurements that have a value outside of the expected calculation).

If standard deviation was used for a set of data in which variation is expected, it could be used to demonstrate the variation. If the heights of all the females in a Year 11 Biology class were measured, the results could look like those in Table 1.7.4. A standard deviation could be used to estimate where individuals fit into the assumed normal curve for the height of adult females in Australia.

Using the formula to calculate standard deviation (SD):

$$SD = \sqrt{\frac{\sum(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_3 - \bar{x})^2}{n - 1}}$$

where $\sum$ = sum of

x_1 = measurement$_1$

$\bar{x}$ = mean

$n - 1$ = number of measurements – 1

The standard deviation for the set of data is ±8.5 cm. Student 4 at 180.6 cm is more than 2σ away from the mean (Figure 1.7.2). Therefore, it can be said that this student is estimated to be in the top 3% of the adult female population for height. This is not an outlier because variation is expected, so standard deviation was used to understand the variance of female students in the class.

TABLE 1.7.4 Height of female students in a Year 12 Biology class

Sample	Height (cm)
student 1	164.5
student 2	156.7
student 3	172.2
student 4	180.6
student 5	163.4
student 6	158.8
student 7	153.9
student 8	150.7
student 9	160.4
student 10	156.8
mean	161.8

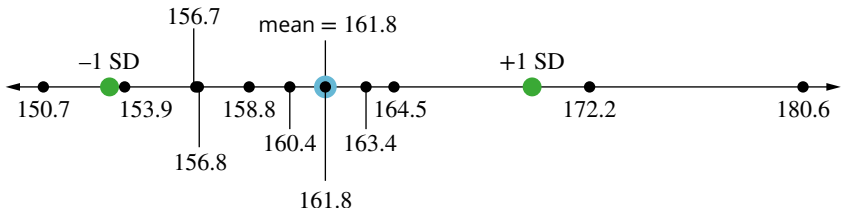


FIGURE 1.7.2 This image plots the heights of the students from Table 1.7.4. The mean is represented by the blue dot; one standard deviation from the mean is represented by the two green dots.

Worked example 1.7.1

CALCULATING THE MEAN AND STANDARD DEVIATION

The heights of a group of students were measured, and are listed below. Calculate the mean and standard deviation for student height:

160 cm, 158 cm, 123 cm, 145 cm

Thinking	Working
Write the formula for the mean.	$\bar{x} = \frac{\sum x_1 + x_2 + x_3 \ldots}{n}$
Insert the values and perform the calculation.	$\bar{x} = \frac{160 + 158 + 123 + 145}{4}$ $= 146.5\,\text{cm}$
Write down the formula for standard deviation.	$SD = \sqrt{\frac{\sum(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_n - \bar{x})^2}{n - 1}}$
Insert the values and perform the calculation.	$SD = \sqrt{\frac{\sum(160 - 146.5)^2 + (153 - 146.5)^2 + (123 - 146.5)^2 + (145 - 146.5)^2}{4 - 1}}$ $= \sqrt{\frac{\sum 182.25 + 132.25 + 552.25 + 2.25}{3}}$ $= 17\,\text{cm}$

➤ Try yourself 1.7.1

CALCULATING THE MEAN AND STANDARD DEVIATION

The following data was collected for the amount of offspring mice had. Calculate the mean litter size and standard deviation.

Litter sizes: 2, 14, 6, 8, 9, 11, 5, 6

REGRESSION

Regression is the term used to state that the independent variable causes the result in the dependent variable during an experiment. Some relationships between variables are causal, meaning that there is a cause and effect relationship.

There are numerous statistical calculations that estimate the causal relationship between variables.

- Some calculations indicate how directly an independent variable causes the dependent variable result. This attempts to show the strength of the relationship.
- Other statistical calculations for regression consider the variation in results and attempt to predict the effect the independent variable has on the dependent.

In biology, due to the open system nature of experiments, not all relationships are direct or straightforward. Often there are many variables that influence the dependent variable and it is helpful to try and predict how much of an effect the independent variable has on the dependent variable while other variables are also influential.

Pearson correlation coefficient

Linear regression is a calculation that estimates a direct **linear relationship** between the independent and dependent variables. It assumes a direct causal relationship. When used, a straight line (trend line of best fit) can be drawn on a graph using all the data points (results) and an *r* value is displayed.

The *r* value calculated will be between −1 and 1, and can be anywhere in between; for example, the *r* value could be –0.92, –0.78, –0.13, 0, 0.24, 0.81 etc. A positive *r* value means that the independent variable causes an increase in the dependent value (Figure 1.7.3). A negative *r* value means that the independent variable causes a decrease in the dependent value (Figure 1.7.1). The *r* values of −1 and 1 mean the relationship is perfectly correlated and therefore 100% causal, *r* values of –0.91 or 0.91 means the correlation between the variables is strong at 91%, and values of –0.13 or 0.13 would be due to a weak relationship that is 13% correlated. A value of 0 means there is no relationship. Remember that the negative and positive values refer to the type of relationship (positive refers to an increasing relationship and negative to indicate a decreasing relationship).

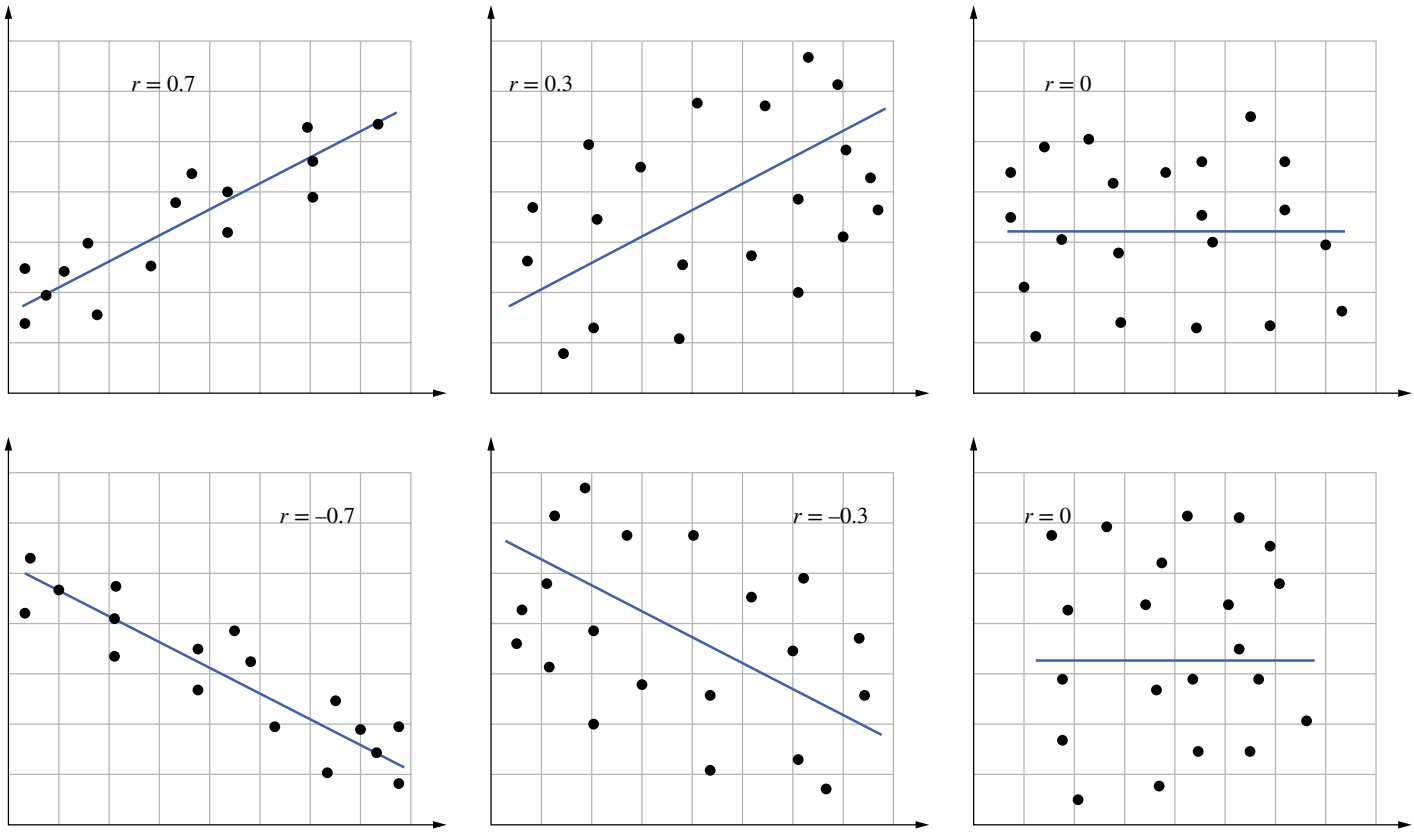


FIGURE 1.7.3 Scatterplot graphs demonstrating the line of best fit produced by the Pearson correlation coefficient with their associated *r* value

The **Pearson correlation coefficient** calculates the strength of the relationship; hence, the *r* value is an indicator of how strongly the dependent variable is related to the independent variable. If the relationship is strong and no errors occurred during experimentation, then it would be expected that the experimental data (results) would be plotted near the trend line (the *x* and *y* intercepts) with an *r* value above 0.8 or between −0.8 and −1.0. Many different disciplines of science have different interpretations of the *r* value. Some interpret values of 0.5 to 1.0 or −0.5 to −1.0 to be strong, while others require values above 0.75, or from −0.75 to −1.0, to be considered strong. The closer the value is to 0, the weaker the relationship is.

Along with establishing how strong the direct relationship is, you can also make a forecast and extrapolate information. **Extrapolation** is when a trend or pattern is shown on a graph and you predict beyond what the graph is showing, by continuing the trend or pattern beyond what was measured. This is done so that you can estimate what the result would be if further testing were done.

The Pearson correlation coefficient can use either processed or raw data in its calculation. Raw data is best because the result of the calculation is a more accurate representation of the relationship. However, it is important to note that the calculation assumes that outliers have been removed. This would have to be achieved using a different statistical calculation first.

Examples of using the Pearson correlation coefficient to analyse data are shown in Tables 1.7.5 and 1.7.6. One experiment tested the effect of exercise intensity on heart rate while the other tested the effect of temperature above 45°C on the rate of photosynthesis.

The *r* value for the Pearson correlation coefficient was calculated using the formula:

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

where n = the number of samples (measurements)

x = dependent variable value on the x axis

y = independent variable value on the y axis

Completing statistical calculations is time consuming and due to multiple inputs can easily result in errors. Most statistical calculations can be done easily using software programs such as Excel.

Coefficient of determination (R^2)

Consider two groups of students conducting the same experiment, the effect of exercise on heart rate from Table 1.7.5. One group uses a finger on the pulse to count the heart rate over 10 s and multiplies the result by 6 to calculate the beats per minute (bpm). The second group uses a digital heart rate monitor. Figure 1.7.4 and Figure 1.7.5 (on page e38) show the results in a scatterplot graph for both groups.

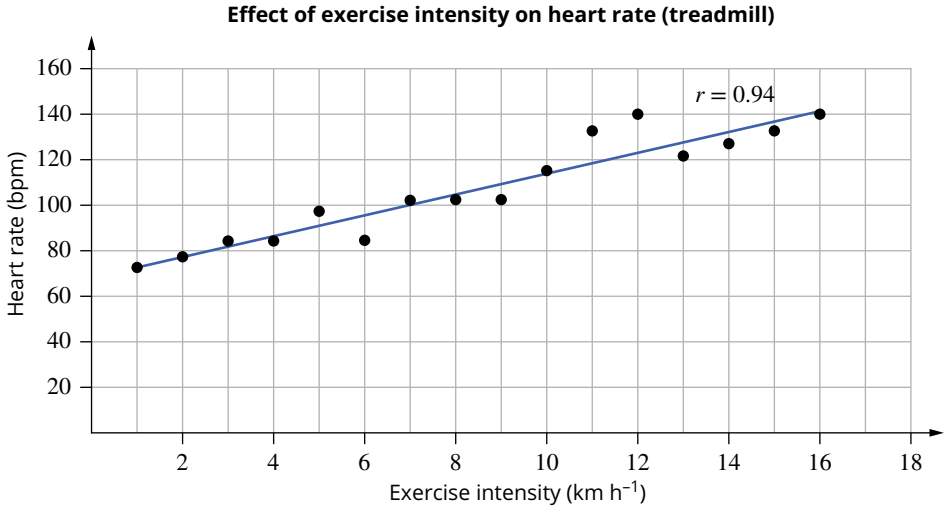


FIGURE 1.7.4 Graphed results for group 1 using a finger on the pulse to count the heart rate. Linear regression was used to establish a line of best fit.

TABLE 1.7.5 The effect of exercise intensity on heart rate using a treadmill

Exercise intensity (km h^{-1})	Heart rate (bpm)
rest	70
1	75
2	80
3	86
4	91
5	95
6	99
7	104
8	110
9	116
10	120
11	125
12	131
13	136
14	141
15	145
***r* value**	**1.00**

TABLE 1.7.6 The effect of temperature (45°C and above) on the rate of photosynthesis

Temp. (°C)	Rate of photosynthesis ($CO_2\ m^{-2}\ s^{-1}$)
45	55
47	52
49	45
51	40
53	20
55	10
***r* value**	**−0.96**

Even though both groups conducted the same experiment, the data is different. Group 1 has an r value of 0.94 and group 2 has an r value of 1.00. As can be seen in the graphs (Figures 1.7.3 and 1.7.4), the linear trend line (calculated by the Pearson correlation coefficient) is very similar with a similar slope. So even though the raw data is different between the groups, the trend line is very similar.

The **coefficient of determination** (R^2) can calculate a value that indicates the predictability between the variables based on how much the results vary. The coefficient of determination produces a value that is an estimate as to how well you can predict the dependent variable based on the change in the independent variable. In doing this, it considers the variations in the results. In the example in Figure 1.7.4, the data of group 1 does not follow the linear trend line exactly and therefore as the exercise intensity (the independent variable) changes consistently, the heart rate (dependent variable) does not always change consistently with it. Sometimes the heart rate changes by 5, sometimes by 2 or even by 10 or more. The coefficient of determination (R^2) will estimate the predictability in the measured results due to the variation.

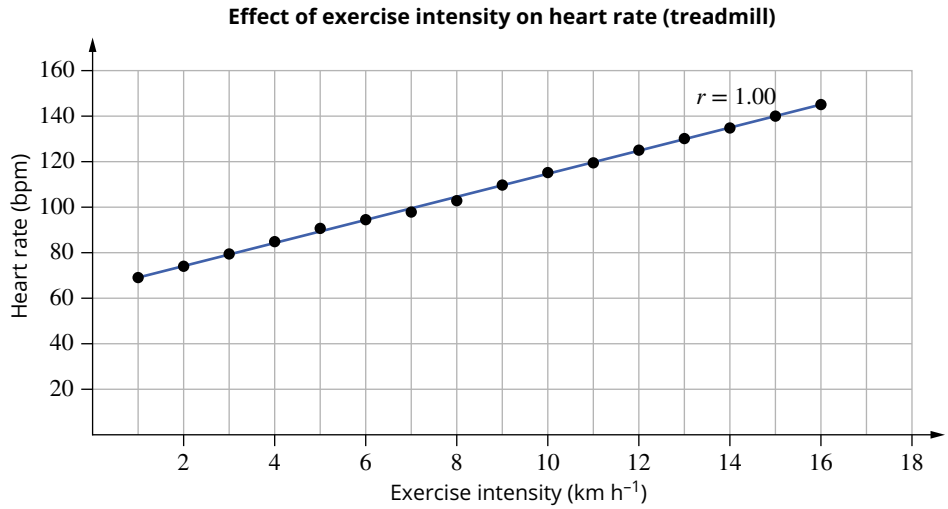


FIGURE 1.7.5 Graphed results for group 2 using the digital heart rate monitor. Linear regression was used to establish a line of best fit.

The coefficient of determination produces a value between 0 and 1. If the value is 0, it is unable to predict the change in the dependent variable from the independent variable. If the value is 1, then it can predict the change in the dependent variable 100% of the time without error. Any other number between 0 and 1 is considered a percentage. For example, 0.76 means that the coefficient of determination can predict 76% of the dependent variable results due to the independent variable. It is interpreted as 76% of the variation in the dependent variable can be explained by the independent variable.

Figures 1.7.6 and 1.7.7 show the results from the two class groups testing the effect of exercise intensity on heart rate, and the coefficient of determination has been calculated and displayed on the graph as the R^2 value.

In Figure 1.7.7 the heart rate was able to be predicted 99% of the time without error from the exercise intensity. This suggests that very little influenced the relationship between the variables; there is little chance that other variables or biological processes influenced the results; there is little chance the methodology (including error, **bias** or instrumental precision) influenced the results. This means the results are highly reliable.

Figure 1.7.6 shows that the heart rate could be predicted from the exercise intensity 89% of the time. This also suggests little influenced the causal relationship between the independent and dependent variable. However, the R^2 value is lower than group 2, meaning the results are less predictable due to more variation. Compared to group 2, group 1 had variables that influence their results. This could be due to other biological variables and processes, the methodology, error, bias or

instrumental precision. If the only difference in this example was the instrument to measure the heart rate, then we can conclude that using a finger on the pulse to count rate heart is less reliable (causes more variation).

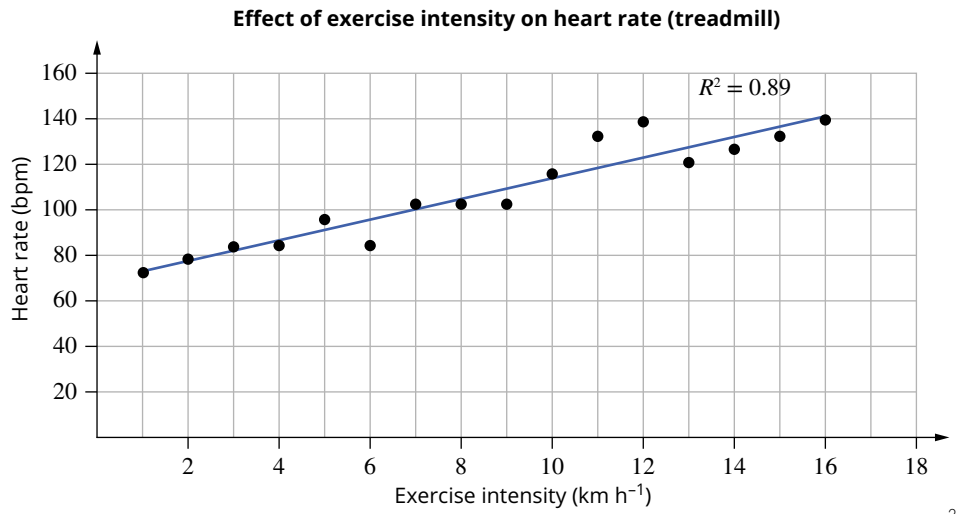


FIGURE 1.7.6 Graphed results for group 1 using a finger on the pulse to count the heart rate with an R^2 value of 0.89 between exercise intensity and heart rate

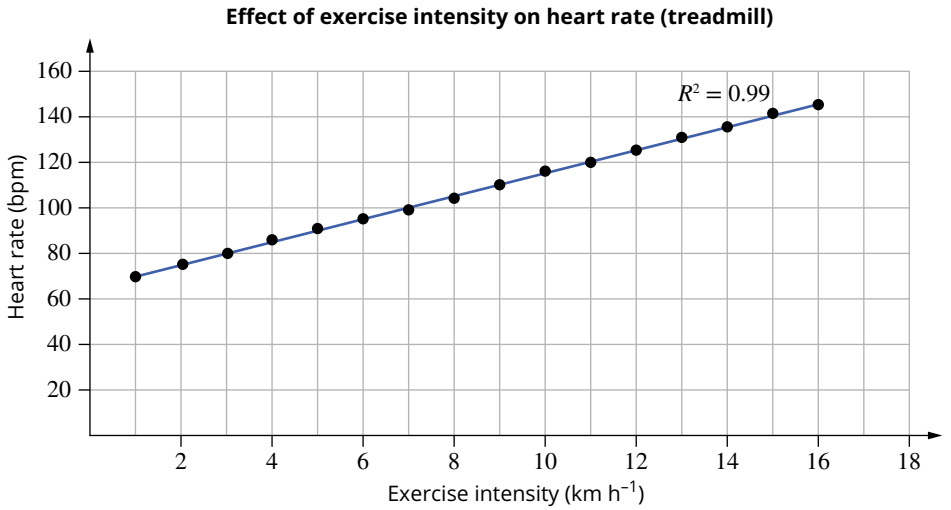


FIGURE 1.7.7 Graphed results for group 2 using the digital heart rate monitor with an R^2 value of 0.99 between exercise intensity and heart rate

In experiments, there could be a number of reasons for the R^2 value to not be above 90% or close to 100%, and not all reasons should be considered due to poor results or deficiencies in the experimentation. A scientist may be trying to establish that no relationship exists and therefore would hope to produce a low R^2 value. Or they may be trying to establish that a relationship exists but it is not known how strong or direct the relationship may be and therefore an R^2 value between 0.50 and 0.90 would be valuable.

The formula to calculate the R^2 value (coefficient of determination) is:

$$R^2 = \left(\frac{1}{N} = \frac{\sum[(x_i - \bar{x}) \times (y_i - \bar{y})]}{(\sigma_x \times \sigma_y)^2}\right)$$

where N = number of measurements (values)
x_i = x value (independent variable)
$\bar{x}$ = mean for x value (independent variable)
y_i = y value (dependent variable)
$\bar{y}$ = mean for y value (dependent variable)
σ_x = standard deviation of x
σ_y = standard deviation of y

Computer software and apps have formulas to conduct statistical calculations, making it easier to perform such analysis. Also, fewer errors are made when calculations are conducted using software.

Pearson correlation coefficient versus coefficient of determination

Both statistical calculations produce a trend line of best fit and both analyse only a linear relationship. Table 1.7.7 summarises the two statistical analytical tools.

TABLE 1.7.7 Summary of the two statistical analytical tools

	Pearson correlation coefficient	Coefficient of determination
Calculates	How closely variables are related (correlated)	How predictable the change in the dependent variable is due to the independent variable
Result	r value = –1.00 to 1.00	R^2 value = 0 to 1.00
Meaning	The closeness of the relationship is given a value and whether the independent variable positively or negatively influences the dependent variable.	Provides a value that indicates the variation that always occurs in experimentation and influences the results and the validity or reliability of the data.
Interpretation	The strength of the relationship (correlation) is due to a causal relationship either directly or indirectly.	The higher the value, the less variation in the data, therefore the more reliable or valid the data.

An analysis of Figure 1.7.8 using the r and R^2 values could be interpreted as: the r value of 0.97 shows a strong relationship between the length of time in days and the length of a leaf (cm). The relationship between time and leaf length is causal. The R^2 value of 0.93 is high, with 93% of the increase in leaf length being predictable from the change in time. Even though the biological processes of leaf length due to growth is a result of many variables, such as photosynthesis, cellular respiration, nutrient access and supply, the predictability of leaf length (cm) due to time (days) is high. In this experiment, very few variables influenced the results more so than time. This could mean that the biological processes are closely related to time. Or, as there is little variation in the data from the linear trend line, the results are highly reliable.

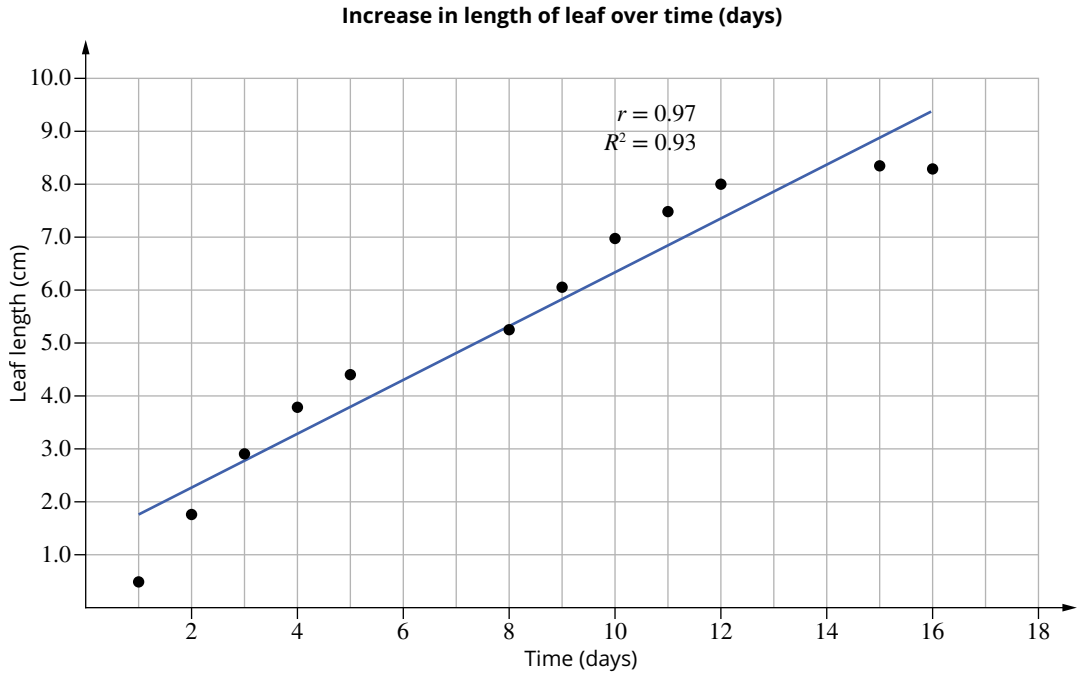


FIGURE 1.7.8 Scatter plot showing the length of a leaf over a number of days with the r value of 0.97 and R^2 value of 0.93 displayed.

Spearman rank correlation

The Spearman rank correlation is another calculation that determines a trend line, however it is able to be used for non-linear regression relationships, as seen in Figure 1.7.9. This calculation estimates the strength and direction of a non-linear relationship between two variables in a single direction. The results of ±–1.0 to ±1.0 are interpreted the same as the Pearson correlation coefficient (Figure 1.7.10).

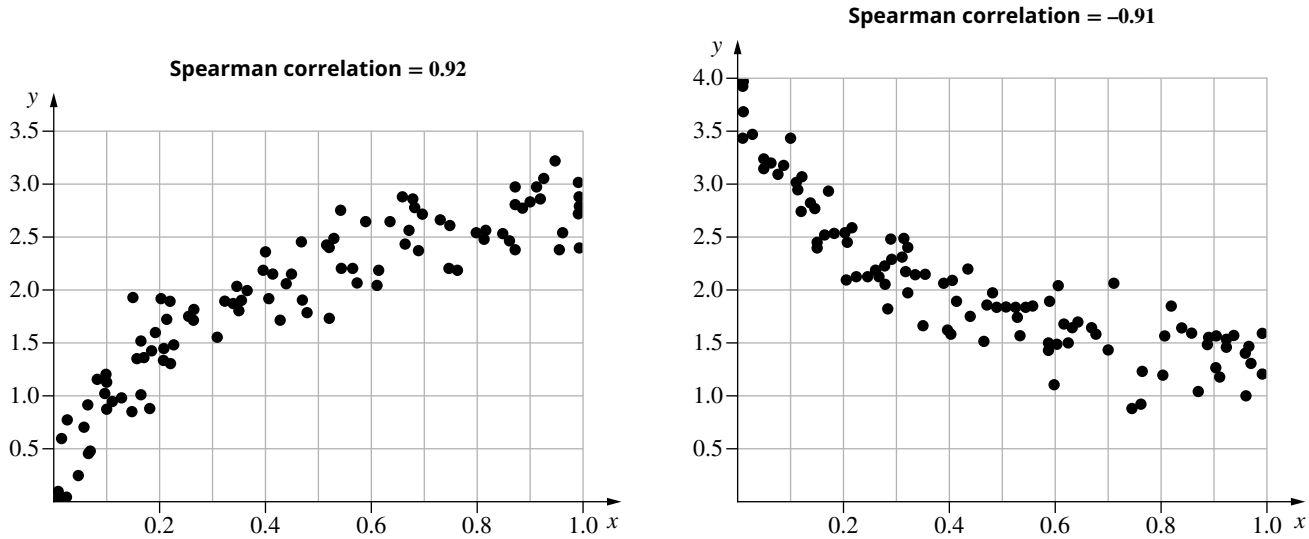


FIGURE 1.7.9 The data in these graphs follows a non-linear pattern, and using the Spearman correlation, the graph on the left has a 0.92 (positive) correlation, meaning as the independent *x* variable increases, so does the dependent *y* (in a non-linear fashion). The graph on the right shows a negative correlation, meaning as *x* increases, *y* decreases in a non-linear pattern.

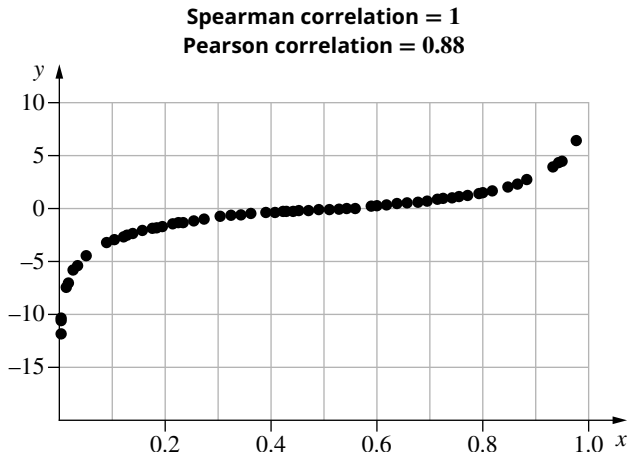


FIGURE 1.7.10 An example of how the Spearman rank correlation explains the pattern in the data more precisely than the Pearson correlation coefficient. Therefore, the relationship is non-linear.

STUDENT *t*-TEST

The **student *t*-test** (also known as the *t*-test) compares two means to determine if there is a difference between them. More specifically, the *t*-test is used for a null hypothesis (a hypothesis that no change or difference will be seen in the results) and estimates the probability that the difference between the means is due to natural variation or by chance. As the null hypothesis assumes no change between a set of results when the independent variable is changed, the *t*-test assumes the null hypothesis is true and that any variation between the sets is due to natural variation, and not the independent variable.

The calculation for the student *t*-test produces a *t*-value between 0 and 1.00 and is a percentage. For example, a *t*-value of 0.04 is 4% and a *t*-value of 0.82 is 82%. A *t*-value below 0.05 means that there is less than 5% chance (probability) that the difference between the means of two sets of data is due to natural variation. You would therefore reject the null hypothesis; you would reject that there is no difference between the two means (therefore, the sets of results are significantly different). A *t*-value of 0.43 means that there is a 43% probability that natural variation or chance caused the difference between the means. The calculation of *t*-values above 0.05 do not provide a strong enough estimation to reject the null hypothesis, so no significant difference between the means would be the conclusion.

One of the unique features of the student *t*-test is that it can be used for small **sample sizes**, although it is limited to being used for samples (data sets or sample groups) that are related.

There are two types of student *t*-tests, unpaired and paired (Table 1.7.8). An unpaired student *t*-test compares the means and data sets from two different samples. A paired student *t*-test compares the means and data sets of the same sample tested twice, before and after changing the independent variables.

TABLE 1.7.8 Examples of unpaired and paired student *t*-tests

Unpaired student *t*-test	Paired student *t*-test
comparing the mean heights of the high school swim team and the athletics team	comparing the mean height of the 14-year-old boys in the athletics team one year, with their mean height a year later
comparing the mean chloroplast counts of a sample of *Elodea* from one pond and another sample from another pond	comparing the mean chloroplast count of a sample of *Elodea* from fresh water, with the same sample after being treated with salt for 2 weeks
comparing the mean white blood cell counts of a sample of people exposed to the flu in Brisbane and a sample from Townsville	comparing the mean white blood cell count of a sample population in Brisbane, and then the same sample population 2 months later

It is best to use software such as Excel, IBM SPSS Statistics® or your graphics calculator to calculate the *t*-value.

Worked example 1.7.2

USING THE STUDENT *t*-TEST TO COMPARE THE MEAN NUMBER OF CHLOROPLASTS IN TWO DIFFERENT *ELODEA* PLANTS, ONE GROWN IN NATURAL LIGHT AND THE OTHER GROWN IN THE SHADE

An experiment was conducted to test if sunlight has an effect on the number of chloroplasts found in the cells of *Elodea* plants. A null hypothesis was developed, that there would be no difference in the number of chloroplasts between plants grown in natural light and those grown in shade. Calculate the *t*-value to determine if the null hypothesis is supported or not.

Thinking

Record the raw data from the experiment and place it into Excel.

Working

Plant	No. of chloroplasts per cell	
	Natural daylight	Shade
A	13	11
B	15	13
C	16	15
D	23	14
E	18	12
F	19	16

Thinking

Calculate the mean, using Excel 'insert function'.

Working

Plant	No. of chloroplasts per cell	
	Natural daylight	Shade
A	13	11
B	15	13
C	16	15
D	23	14
E	18	12
F	19	16
Mean	17	14

Thinking

Summarise the results.

Working

The mean number of chloroplasts for *Elodea* plants grown in natural light is 17, while the mean for plants grown in the shade is 14. There is a difference in the means but it is not known if it is significant. Both groups include variation: *Elodea* grown in natural light have a range of 10, while those grown in shade have a range of 5.

Thinking

Choose the *t*-test in Excel 'insert formula'. Select sample 1 (plant A results), then sample 2 (plant B results). Choose 2 tail, and then 2 again for the type of *t*-test.

Working

Plant	No. of chloroplasts per cell	
	Natural daylight	Shade
A	13	11
B	15	13
C	16	15
D	23	14
E	18	12
F	19	16
Mean	17	14
t-value	0.04	

Thinking

Summarise the results of the *t*-test

Working

There is a 4% chance that the difference between the means and data sets is due to natural variation. Therefore, the difference in the mean number of chloroplasts is significant. The hypothesis is not supported, and therefore rejected.

➤ Try yourself 1.7.2

USING THE STUDENT *t*-TEST TO COMPARE THE MEAN NUMBER OF CHLOROPLASTS IN TWO DIFFERENT ELODEA PLANTS, ONE GROWN IN NATURAL LIGHT AND THE OTHER GROWN IN RED LIGHT

An experiment was conducted to test if the colour of light has an effect on the number of chloroplasts found in the cells of *Elodea* plants. One group of plants was grown in sunlight while the other group was grown under red light.

Sunlight results: 14, 18, 19, 21, 24, 19

Red light results: 13, 14, 15, 15, 17, 17

A null hypothesis was developed, that there would be no difference in the number of chloroplasts between plants grown in natural light and those grown in red light. Calculate the *t*-value to determine if the null hypothesis is supported or not.

Worked example 1.7.3

USING THE STUDENT *t*-TEST TO COMPARE THE MEAN NUMBER OF CHLOROPLASTS IN *ELODEA* PLANTS BEFORE AND AFTER EXPOSURE TO SALT

An experiment was conducted to test if placing *Elodea* in salt water for 2 days would affect the number of chloroplasts found in the cells of *Elodea* plants. A null hypothesis was developed, that there would be no difference in the number of chloroplasts between the plants in fresh water and the plants in salt water. Calculate the *t*-value to determine if the null hypothesis is supported or not.

Thinking	Working
Record the raw data from the experiment and place it into Excel.	

Plant	No. of chloroplasts per cell	
	Fresh water	Salt water
A	13	12
B	15	13
C	16	16
D	23	17
E	18	18
F	19	16

Calculate the mean, using Excel 'insert function'.

Plant	No. of chloroplasts per cell	
	Fresh water	Salt water
A	13	12
B	15	13
C	16	16
D	23	17
E	18	18
F	19	16
Mean	17	15

Summarise the results.

The mean number of chloroplasts for *Elodea* plants grown in fresh water is 17, while the mean for plants placed in salt water is 15. There is a difference in the means but it is not known if it is significant. Both groups include variation, *Elodea* grown in fresh water have a range of 10, while those grown in shade have a range of 6.

Choose the *t*-test in the Excel 'insert formula'. Select sample 1 (plant A results), then sample 2 (plant B results). Choose 2 tail, and then 1 for the type of *t*-test.	

Plant	No. of chloroplasts per cell	
	Fresh water	Salt water
A	13	12
B	15	13
C	16	16
D	23	17
E	18	18
F	19	16
Mean	17	15
t-value	0.08	

Summarise the results of the *t*-test.	There is an 8% chance that the difference in the means is due to natural variation. Even though a notable difference exists between the two tests, it cannot be interpreted as significant as it is above 5% (0.05) and may not be due to the exposure to salt water. The hypothesis is supported.

➤ Try yourself 1.7.3

USING THE STUDENT *t*-TEST TO COMPARE THE MEAN NUMBER OF CHLOROPLASTS IN *ELODEA* PLANTS BEFORE AND AFTER EXPOSURE TO BLUE LIGHT

An experiment was conducted to test if placing *Elodea* under blue light for 2 days after being grown in natural light would affect the number of chloroplasts found in the cells of *Elodea* plants.

Blue night results: 22, 19, 21, 21, 24, 16

Natural light results: 23, 18, 20, 21, 24, 19

A null hypothesis was developed, that there would be no difference in the number of chloroplasts after exposure to blue light. Calculate the *t*-value to determine if the null hypothesis is supported or not.

1.7 Review

SUMMARY

- The range is the difference between the highest and lowest values in a data set.
- The mean, $\bar{x}$, is the average of a data set. It is calculated from the formula:

  $$\bar{x} = \frac{\Sigma x_1 + x_2 + x_3 \ldots}{n}$$

  where Σ = sum of $x_1 + x_2 + x_3$ = measurement$_1$ + measurement$_2$ + measurement$_3$, n = total number of measurements
- The median is the 'middle' value in an ordered list of values.
- The mode is the value that occurs most often in a data set. The mode is particularly useful for describing qualitative or discrete data.
- Standard deviation is a measure of the spread or dispersion of data and its distance from the mean.
- Regression is the term used to state that the independent variable causes the result in the dependent variable during an experiment.
- Linear regression is a calculation that estimates a direct linear relationship between the independent and dependent variables.
- *r* values (Pearson correlation coefficients) indicate the degree of correlation between variables.
- *r* values are between –1 and 1.
- A positive *r* value means that a positive relationship exists between the variables, that is the independent variable causes an increase in the dependent value.
- A negative *r* value means that the independent variable causes a decrease in the dependent value.

1.7 Review *continued*

- The closer the *r* value is to 1 or –1, the stronger the correlation between variables.
  - *r* values of –1 and 1 mean the relationship is 100% correlated
  - *r* values of –0.91 or 0.91 mean the correlation between the variables is strong (91%)
  - *r* values of –0.13 or 0.13 are due to a weak relationship (13%)
  - An *r* value of 0 means there is no relationship.
- The coefficient of determination estimates how well you can predict the dependent variable based on the change in the independent variable.
- The coefficient of determination produces an R^2 value between 0 and 1.
- The closer R^2 is to 0 the less predictable the dependent result is based on the independent value. The closer the R^2 is to 1 the more predictable the dependent result is based on the independent value.
- The Spearman rank correlation determines a non-linear trend line and the strength of non-linear relationships, in a single direction.
- The Spearman rank correlation produces a value equivalent to the Pearson correlation coefficient and is interpreted in the same way.
- The student *t*-test assumes that any variation between the sets is natural and is not due to the independent variable.
- Student *t*-test values are interpreted as a percentage chance, for example, 0.42 is a 42% chance.
- Student *t*-test values less than 0.05 are significant and are caused by the independent variable.

KEY QUESTIONS

Retrieval

1 Define 'outlier'.

Comprehension

2 Describe what the standard deviation informs scientists about a data set.

3 Describe what the student *t*-test informs scientists about in a data set.

Analysis

4 For the data set below, calculate and record the:

a range

b median

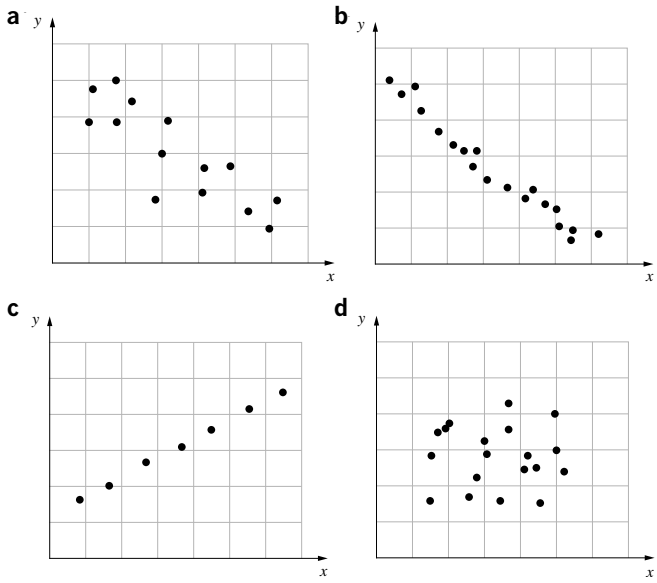
c mode

d mean and uncertainty.

Data: 21, 28, 19, 19, 25, 24, 20

5 Select the appropriate *r* value from the list below for the following graphs.

r values: –0.90, –0.50, 0.00, 0.50, 1.00



PART B STUDENT EXPERIMENT

The QCAA requires students to complete a student experiment in Unit 3 Biology. In preparation for Unit 3, teachers may choose to assign a similar assessment task in Units 1 or 2, as preparation for Unit 3.

The student experiment assessment task requires students to research a question or hypothesis. Students use research conventions to investigate the question or hypothesis by collecting, analysing and synthesising primary data. The experiment requires students to locate and use information beyond the scope of their knowledge and what they have been given.

The student experiment requires students to undertake the full scientific method. The Queensland Biology syllabus states that this process begins with a practical conducted during class, either a mandatory or a 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 a hypothesis for the student experiment.

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

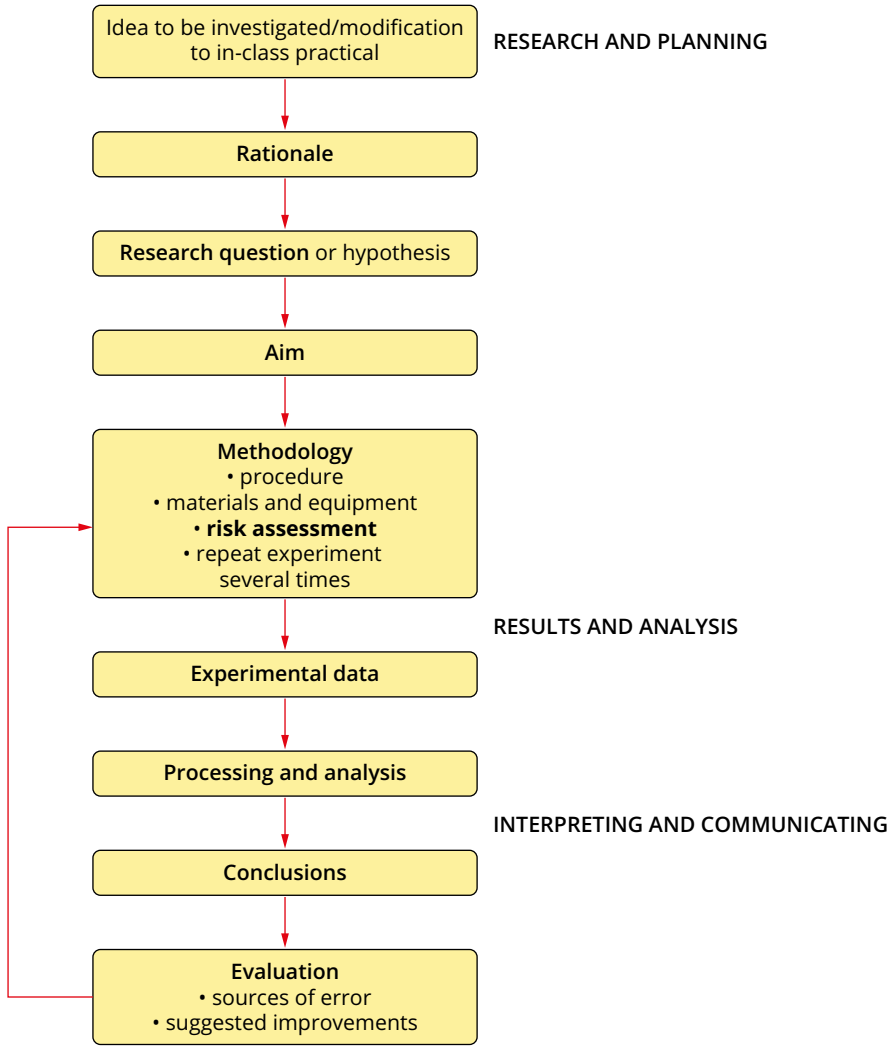
A summary of the ISMG student experiment (IA2) is provided below. The summary includes the objectives and marking for this summative internal assessment.

The student experiment may be presented in:

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

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

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



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

The ISMG has:

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

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

In order to be awarded a mark of 5 or 6 for this criterion, you need to show 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 that will be assessed. Student work must demonstrate these objectives. The definition of the objectives is in the syllabus glossary. How they will be assessed is described by the characteristics listed in the 'Key features' section below.

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

Objectives of assessment task

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

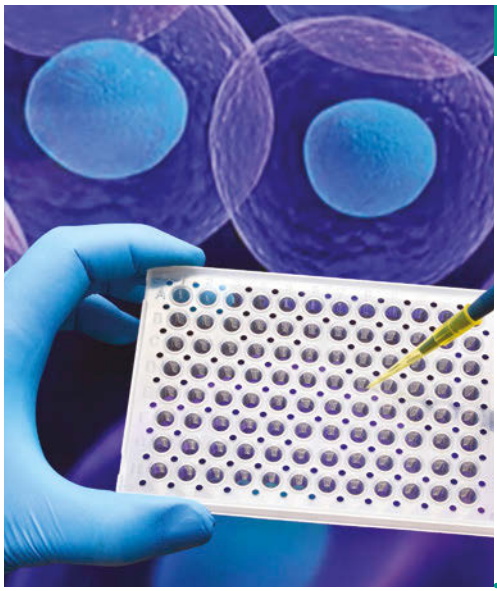
Key features that distinguish between marking levels:	Marks
• Processing relevant data correctly to demonstrate the appropriate application of algorithms and representations of data • Thoroughly identifying relevant relationships, trends, patterns to demonstrate systematic and effective analysis of evidence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

Performance level

Performance mark
The performance indicator describes requirements to achieve marks.

In the modules that follow, you will find a guide to a scientific method (Modules 1.8–1.10) followed by an outline on producing a scientific report (Module 1.11).

1.8 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 research questions and hypotheses
- use a scientific journal to record experiments and experimental data
- plan, evaluate and refine scientific experiments
- explain what validity and reliability mean in relation to experimentation
- explain the difference between, and identify, qualitative and quantitative data
- characterise qualitative data as either nominal or ordinal
- characterise quantitative data as either discrete or continuous
- explain the difference between replication and repeat trials
- conduct risk assessments for planned experiments
- recognise common chemical GHS codes and symbols.

All scientific work begins with research and planning. This includes understanding the relationship between **controlled variables** or **measured variables** as well as the independent and **dependent variable**. 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 and is your personal all-encompassing document. 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 OR HYPOTHESIS

Identifying an experiment for the student experiment requires you to modify, refine, extend or redirect a practical undertaken in class. Therefore, the experiment will be similar to the class practical but altered to investigate something slightly different, as shown in Figure 1.8.1.

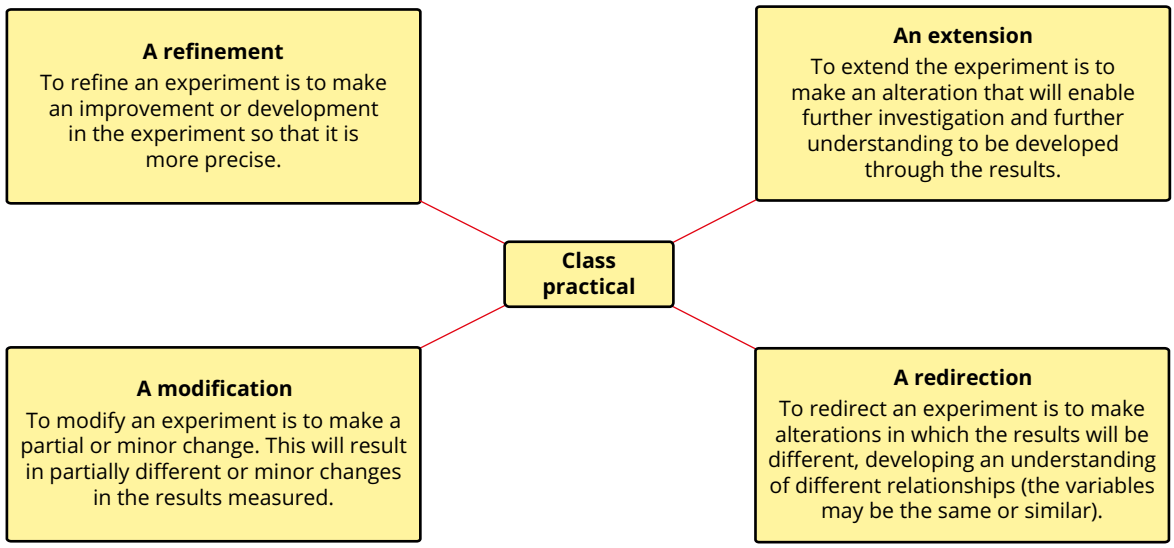


FIGURE 1.8.1 Chart showing possible changes to a class practical when developing a student experiment

Identifying an experiment

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

- Start with an observation or topic about 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 1.8.1 shows examples of modifying, refining, extending or redirecting practicals into a topic of interest for a student experiment.

TABLE 1.8.1 Some ideas for changes to class practicals

Class practical	Modification, refinement, extension or redirection	Student experiment idea
Investigate the effect of surface area to volume ratio on cell size (1 cm cube compared with a 2 cm cube).	modification and refinement	Investigate the effect of surface area to volume ratio on cell shape—25 mL volume cells of various shapes.
	extension	Further investigate the effect of surface area to volume ratio on cell size—maintain the same shape, 3 cm, 4 cm and 5 cm cubes.
Use a light microscope to observe prepared slides of cells in plants and animals to identify nucleus, cytoplasm, cell wall, chloroplasts and cell membrane. Calculation of total magnification and field of view is required.	extension	Prepare wet mount slides to observe microorganisms, comparing and contrasting cellular structures and sizes of microorganisms.
	redirection	Use a high-powered light microscope to study different layers of plant cells in a leaf to observe chloroplast concentration.
	redirection	Use a light microscope to observe the chloroplast concentration in various plants.
Investigate the effect of temperature on the rate of reaction of an enzyme.	extension	Investigate the effect of temperature on the rate of reaction of an enzyme with various substrate concentrations.

The Queensland Biology syllabus requires the student experiment report to justify the alteration of the methodology from the class practical. This is addressed in the section 'Refining the methodology' (page e65).

When altering the class practical to identify a student experiment, it is best to think of a single variable that may influence the outcome (independent variable). This may require some research. The more variables that are changed (including measured and controlled variables), the more research is 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.

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, by measuring the results. There are four categories of variables, as shown in Figure 1.8.2 on page e52. 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). If both the independent and dependent variable are altered, then the data between the class practical and student experiment is not comparable.

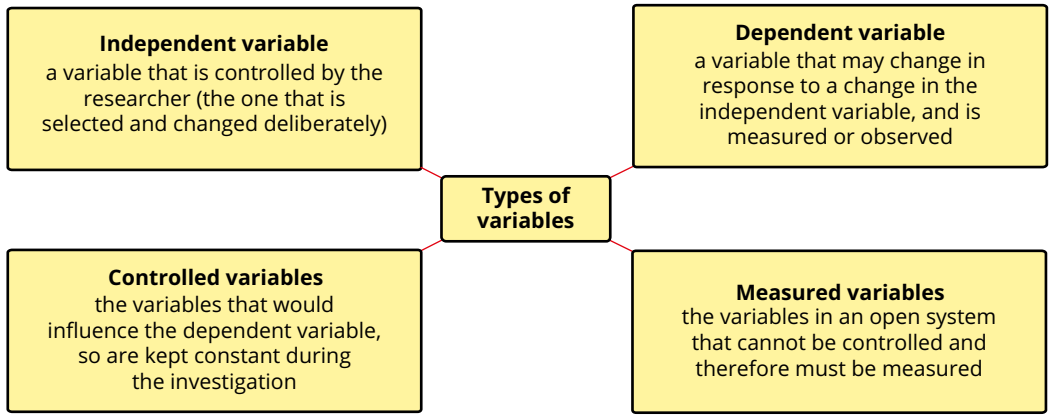


FIGURE 1.8.2 The four types of variables in experiments

Developing a research question

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

The question determines the experiment, and the experiment is testing the question. A research question should:

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

Consider the example in Figure 1.8.3.

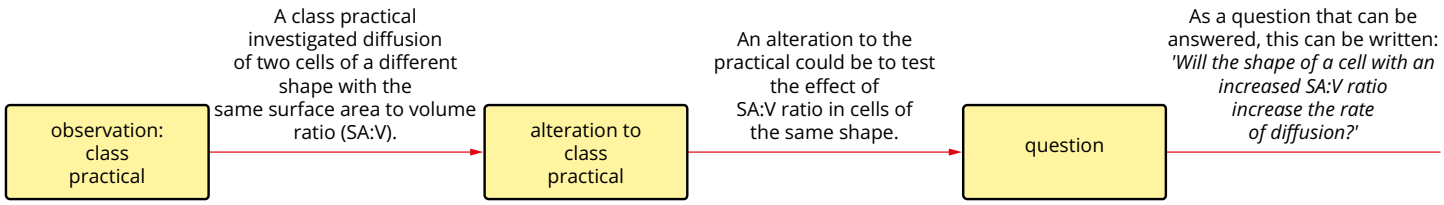


FIGURE 1.8.3 The process from class observation of a practical, to altering the practical and developing a possible question

Background research for the student experiment would follow to refine the question. The research could include:

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

Figure 1.8.4 demonstrates the process of question refinement and the resultant question that will guide the student experiment.

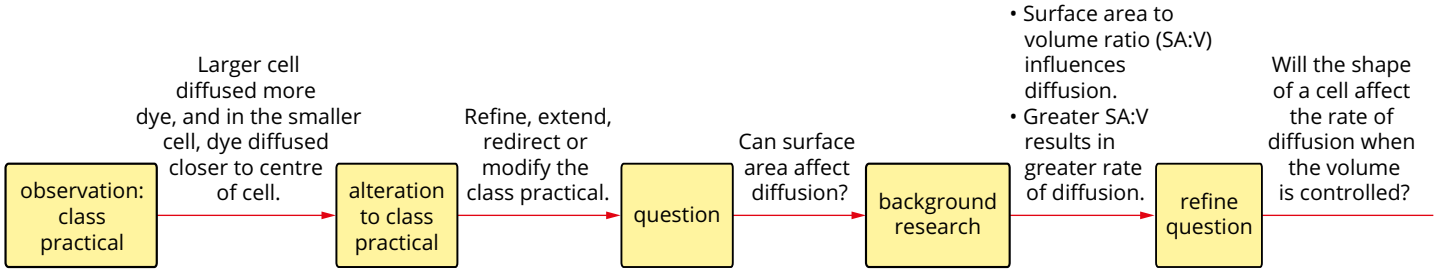
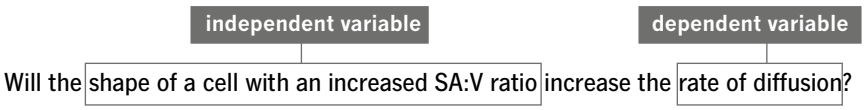


FIGURE 1.8.4 Refining the question

The structure of a research question

All research questions should state the independent and the dependent variables. The question should ask if the independent variable will affect the dependent variable. The research question must specifically outline variables in a way that is measureable; this also allows the question to be answered.

Consider the following example:



As the research question is constructed, it should:

- include measurable variables—the independent and dependent variables
- have a guiding word, such as *what*, *why*, *would* 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 specific task can be determined.

Table 1.8.2 gives examples of constructed research questions.

TABLE 1.8.2 How to interpret an inquiry question

Guiding word	Example research questions	What are you being asked to do? What are the command verbs?
what	• *What* difference does surface area make to diffusion?	• Identify and describe specific evidence, reasons and examples from a variety of possibilities. *Identify* and *describe*.
will	• *Will* natural antibiotics be more effective than synthetic antibiotics?	• Identify and describe, giving reasons for effectiveness. *Identify* and *describe*.
how	• *How* does the volume of cells of the same shape affect diffusion? • *How* does substrate concentration affect enzyme activity? • *How* do different wavelengths influence the number of chloroplasts in plant cells?	• Identify and describe in detail a process or mechanism. Give examples using evidence and reasons. *Identify* and *describe*.
why	• *Why* do cells in different layers of a plant leaf have different concentrations of chloroplasts? • *Why* is the relationship between enzyme activity and temperature non-linear?	• Explain in detail the causes, reasons, mechanisms and evidence for. *Identify* and *explain*.
would	• *Would* salinity affect prokaryotes and eukaryotes equivalently?	• Evaluate. Justify, giving reasons for and against (using evidence and comparisons). *Evaluate* and *justify*.
is/are	• *Are* all prokaryotic cells smaller than eukaryotic cells? • *Is* the cell wall of bacteria different from one species to another?	• Evaluate. Justify, giving reasons and evidence. *Evaluate* and *justify*.
on what basis	• *On what basis* is the substrate–enzyme complex a limiting factor in enzyme activity?	• Evaluate. Justify, using reasons and evidence. *Evaluate* and *justify*.
can	• *Can* enzyme concentration increase the rate of enzyme activity?	• Evaluate and assess. Is it possible? Give reasons, suggesting possible alternatives. *Evaluate*, *assess*, *justify* and *create*.
do/does	• *Does* surface area or volume affect the rate of diffusion?	• Evaluate. Justify using reasons and evidence for and against. *Evaluate*, *assess* and *justify*.
should	• *Should* hands be washed with plain soap or antibacterial soap? • *Should* hands be washed to reduce cross-contamination?	• Evaluate advantages and disadvantages, implications and limitations. Make a judgement. *Evaluate*, *assess*, *justify* and *create*.

Formulating a hypothesis

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

The student experiment does not necessarily require a hypothesis and it is not always appropriate or beneficial. A hypothesis, if it is suitable, requires the controlled 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. With more stringent controls, it may be possible for errors and uncertainties to be reduced. The interpretation of results may be more straightforward (though not always).

Scientists use **literature reviews** and background research to develop an understanding of an observation and then infer a reason for their observation. Their **inference** is then tested by 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 developing a question. Steps for formulating a hypothesis are shown in Figure 1.8.5.

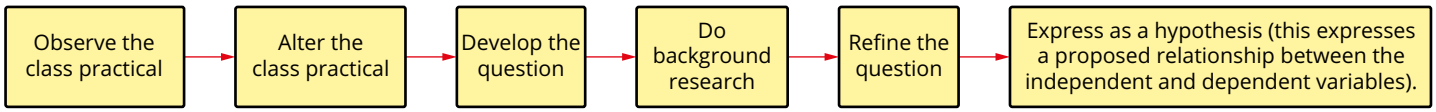
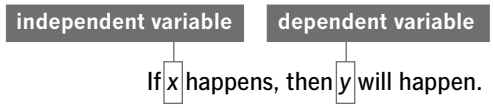
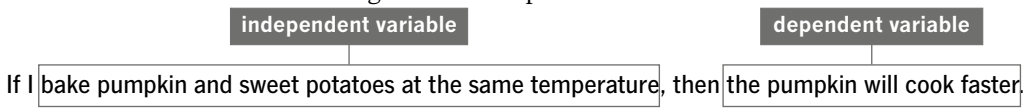


FIGURE 1.8.5 Process for formulating a hypothesis

To formulate a hypothesis, write it in terms of the dependent and independent variables:



Consider the following at this example.



The 'if' part of the hypothesis refers to the independent variable—the variable you alter in the experiment. 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 previous hypothesis could also be worded in the following ways:

- Example 1: Pumpkin will cook faster than sweet potatoes when they are cooked at the same temperature.
- Example 2: When cooked at the same temperature, pumpkin will cook faster than sweet potatoes.

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

Benefits of a hypothesis include:

- methodology guidance: provides specific limitations and guidance (due to the proposed relationship) directing the planning of the experiment
- methodology guidance: suggests specific variables to control and measure
- results: offers guidance in an analysis (processing data to determine if the proposed relationship exists)

- results analysis is specific: gives direction for the display of results to be specific to the hypothesised relationship between the variables
- evaluation is specific: directs what should be considered for adjustments in the methodology to improve or extend the experiment.

EVALUATING YOUR RESEARCH QUESTION OR HYPOTHESIS

The quality of the research question or hypothesis is vital to the quality of the response that can be written (in the student experiment report, the data analysis, evaluation and conclusion).

Once you have developed a research question or hypothesis, stop to evaluate it before progressing. Follow the prompts in Figure 1.8.6 to refine and improve the research question or hypothesis.

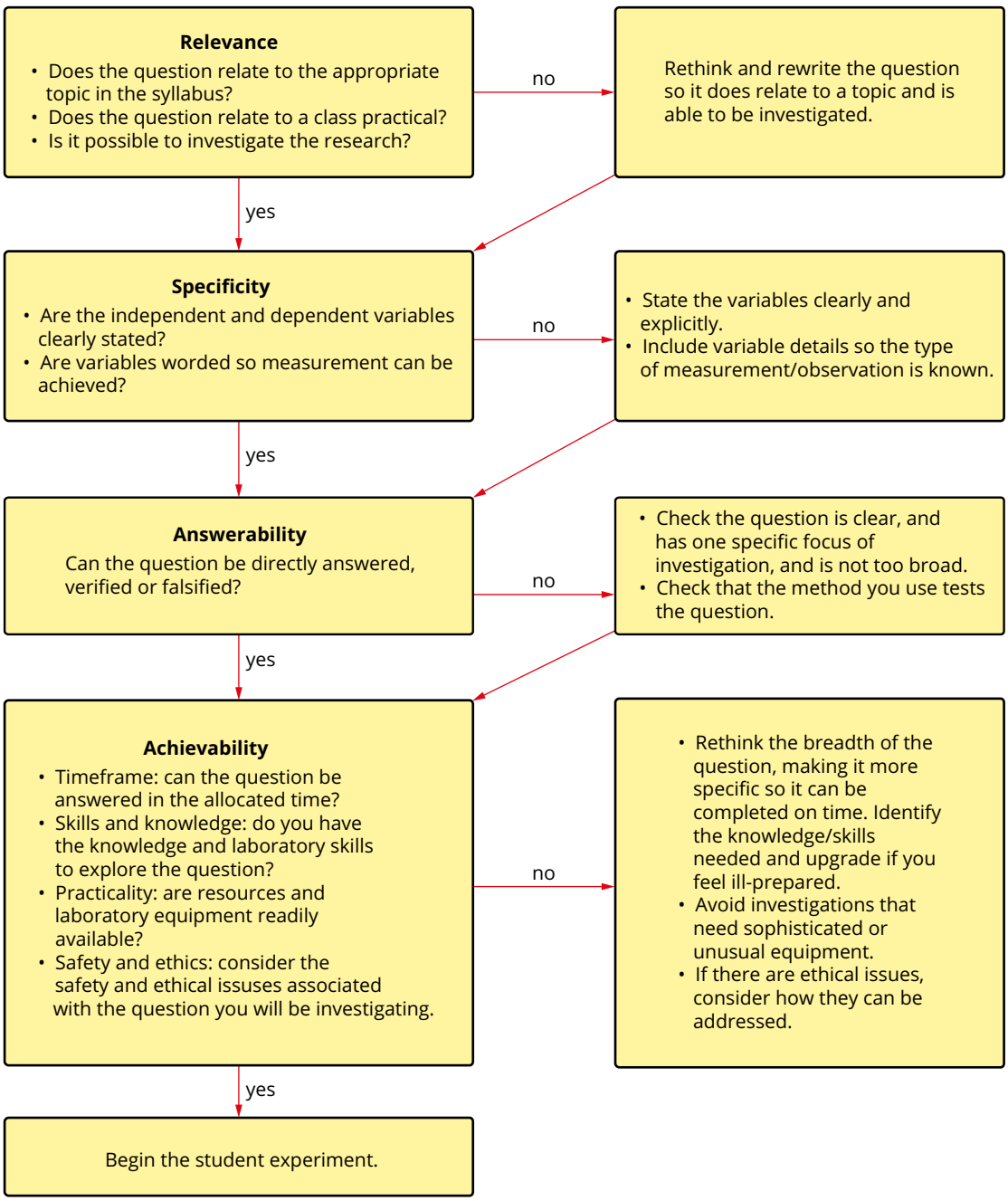


FIGURE 1.8.6 A chart summarising steps to evaluate the student experiment research question or hypothesis.

Examples of hypotheses and research questions

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

Hypothesis: As the intensity of exercise increases, the heart rate will increase linearly.

Research question: Is the relationship between exercise intensity and heart rate linear?

Hypothesis: The degree of wilting in plant leaves will increase as room temperature increases from 25°C to 55°C.

Research question: Will wilting of plant leaves occur when room temperature increases from 25°C to 55°C?

Hypothesis: A 20% tea tree oil solution will result in a zone of inhibition greater than control (water) on agar plates with *E. coli* lawn culture.

Research question: Does 20% tea tree oil have antibacterial properties?

DEVELOPING THE RATIONALE

Once you have decided upon a hypothesis or question, you should provide a rationale. The rationale is where you explain the scientific concepts appropriate to the research question

Researching relevant scientific information

The student experiment in the Biology syllabus requires students to:

- research what is currently known about the relationship between the dependent and independent variable
- develop 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) states that in the research and planning students are required to demonstrate:

- a rationale for the experiment that demonstrates consideration
- methodological modifications that have been justified
- a methodology that collects data that is pertinent to, and adequate to test the research question, with deliberate design.

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

- explicitly justify the modifications to the methodology (alterations to the class practical)
- explain how the methodology will enable the research question to be answered through the collection of the data
- inform risk, ethical and environmental management. This relates to identifying how the risks associated with the experiment will be mitigated through personal protective equipment or specific features of the methodology. The ethical and environmental issues could relate to the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes or the Animal Ethics Committee for each use of '**animals**' or type of use of 'animals'.

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

There is so much information to record during a student experiment that it would be best to keep it all in a single document. Scientists always document all their ideas, questions, background research and literature reviews, methodology drafts and revisions, results, refinements etc. in a single document. It is called the **scientific journal**.

Taking notes and recording your thoughts in the scientific journal keeps a record of all information that arises during the process of the scientific method. It is unknown how vital some information will become throughout the process until it is complete and summarised into the scientific report. This information will be used in a rationale for the experiment; to explicitly justify the modifications to the methodology (alterations to the class practical); provide a reason for collecting data and to inform risk, and ethical and environmental management. It is also expected to inform the interpretation of the evidence (results) and conclusion.

The purpose of researching background scientific information in the scientific method is to develop understanding and knowledge. This information 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. Background research is essential to achieve 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

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

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

The methodology of your experiment is a specific step-by-step procedure. However, in the final scientific report, the methodology 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 hypothesis or research question
- the certainty that something observed in your experiment was the result of your experimental conditions and not another cause that you did not consider; in other words, whether the independent variable influenced the dependent variable in the way you have concluded and by keeping all other variables constant (except those being measured)
- the degree or scope to which your findings can be generalised to the wider population from which your sample is taken (the chosen samples represent the general population), or to a different population, place or time.

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 that 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 versus qualitative), and that each will be measured, collected or controlled appropriately.

Data can be either qualitative or quantitative. **Qualitative data** is descriptive and unmeasurable and uses descriptions or adjectives to record observations. **Quantitative data** is empirically measurable and uses instruments to record observations as numbers with units.

Qualitative and quantitative data have further subsets in each category (Figure 1.8.7).

Qualitative data—can be observed but not measured

They can only be sorted into groups or categories such as flower colour or leaf shape.

Quantitative data—can be measured.

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

Nominal data

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

Example 1: the gram positive or gram negative bacteria, and sex (male or female)

Example 2: genotypes—AA, Aa or aa

Discrete data

Variables consist of only integer numerical values, not fractions.

Example 1: the number of nucleotides in a sequence of DNA

Example 2: the number of students with dark brown eyes

Ordinal data

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

Example 1: a person's Body Mass Index (BMI), and order of flowers opening

Example 2: perceived exertion from 1 to 10 in an aerobic endurance test

Continuous data

Variables allow for any numerical value within a given range.

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

Example 2: time to reach peak enzyme activity or peak photosynthetic rate, temperature, pH, height

FIGURE 1.8.7 Qualitative and quantitative variables

Measurement of temperature requires an instrument and provides quantitative data. It is not appropriate to record qualitative data for temperature (e.g. cold, warm or hot) (Figure 1.8.8).

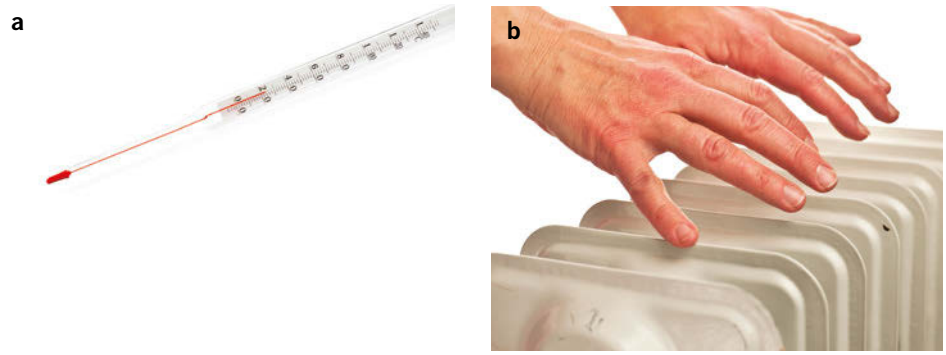


FIGURE 1.8.8 (a) A thermometer or a wireless temperature sensor will measure temperature empirically and provides quantitative data that can be analysed statistically. Processing empirical data can produce discrete, explicit and comparative analysis. (b) Feeling heat radiating from a heater is an example of qualitative data; it is based on personal observation. Qualitative data cannot be statistically analysed.

Depending on the experiment, it may be appropriate to record the qualitative observation (e.g. colour of algae), or perhaps measuring the quantitative results of wavelength (e.g. light emitted from a light source (Figures 1.8.9 and 1.8.10).

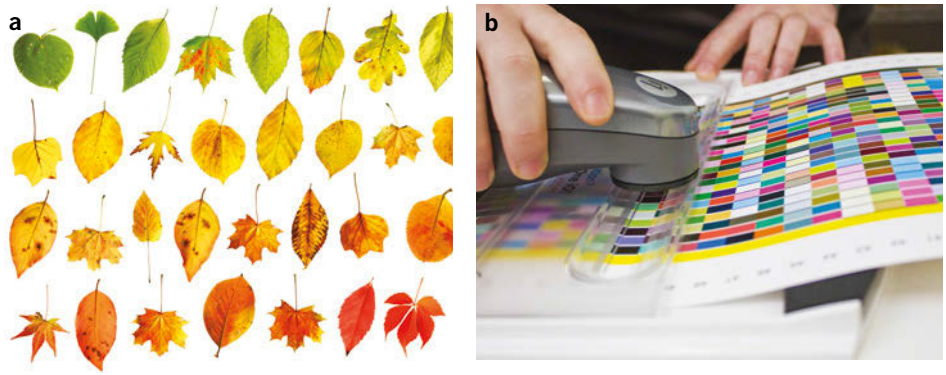


FIGURE 1.8.9 (a) When recording the colour of leaves using qualitative data, a reference image like this one helps to record good qualitative data. (b) Colour can also be measured using a spectrophotometer, which measures the wavelength emitted or reflected by the object. This would produce quantitative data.

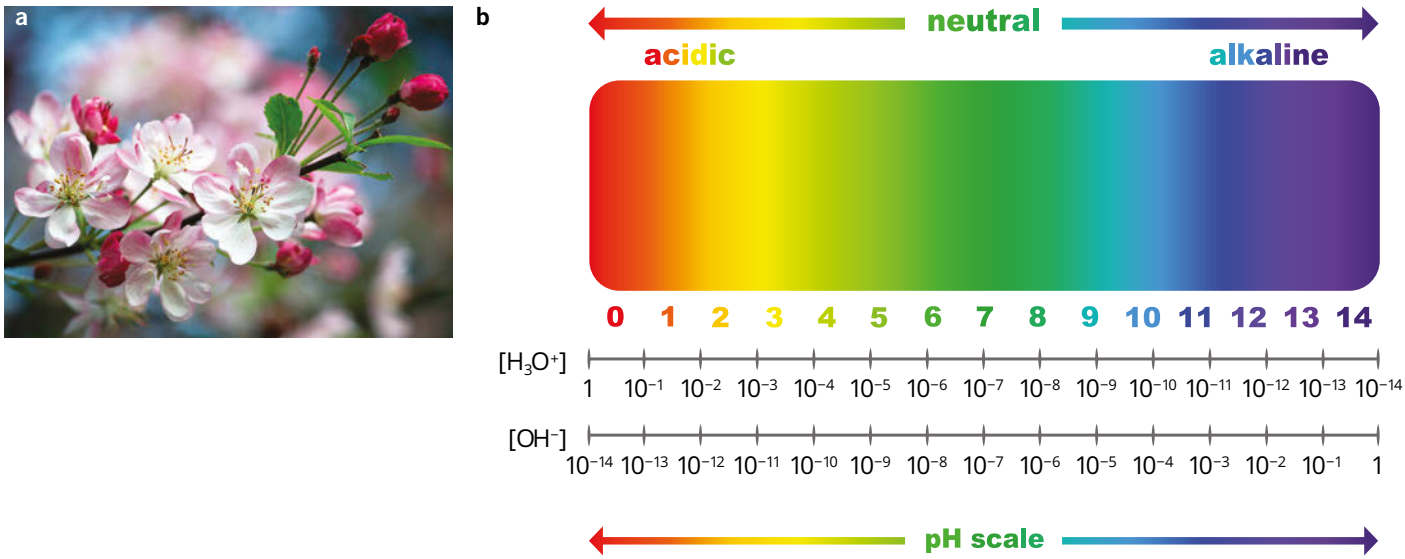


FIGURE 1.8.10 (a) Recording the order in which flowers open is an example of an **ordinal variable** that is qualitative data. (b) The pH scale can be measured numerically (empirically) on a continuous scale from 1 to 14. This is an example of a **continuous variable** that is quantitative data.

Controls

Controlling as many variables as possible to determine what has influenced the results provides more accurate and precise data.

It is difficult—sometimes impossible—to eliminate all variables that might affect the outcome of an experiment. Such variables in biology include time of day, temperature, amount of light, season, and level of noise. To overcome this set up a second group within the experiment (called a **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 hypothesis.

Randomisation

Random selection of your sample reduces selection bias and improves validity. Selection bias occurs when the sample does not reflect the wider population. For example, if you were scoring phenotypes in large trials of genetically modified crop plants, it is more valid to choose locations at random throughout the plot than one in which you choose only the edges of the plot. Random selection encourages the collection of data or evidence from samples that will more likely include the true value (see Module 1.5). Random selection of samples should result in samples that reflect natural variation.

If the experiment is an investigation of an open system, for example an ecological relationship within a natural habitat, the random selection of samples are required to test if the inferred relationship may exist in nature. If the experiment is in a closed system and controlled, the controlled variables need to reflect natural conditions as much as possible to minimise selection bias of conditions and influencing the relationship between the tested variables.

Reliability

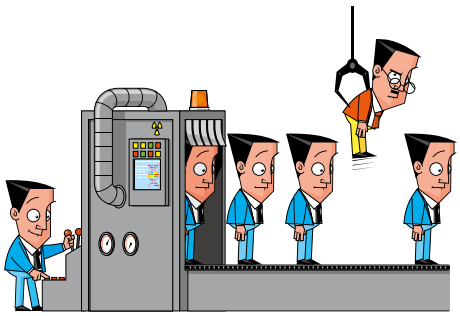


FIGURE 1.8.11 If you can reproduce your results, then they are reliable.

Reliability refers to the notion that if the experiment is repeated many times, the results obtained should be equivalent. Reliability (repeatability) is the ability to obtain the same results if an experiment is repeated (Figure 1.8.11). The closer the results to the true value, the more reliable they are. Because a single measurement or experimental result will 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 and uncertainties in measurement)
- include replicate (several) 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 aids with repeatability and therefore reliability and affects the:

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

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 (see Module 1.5).

Sourcing appropriate equipment and materials

You will need to decide on the materials, technology and instrumentation that will be used to carry out your experiment or investigation. It is important to find the right balance between items that are easily accessible and those that will obtain accurate and precise results. When conducting your investigation, you will need to record in your journal the precision of the chosen instrumentation's precision and how this affects the accuracy and validity of your results. This will form part of your scientific report.

ELECTRONIC DATA ACQUISITION IN SCHOOLS

Data collection has advanced since 20 years ago, when discrete measurements were recorded with manual tools and human readings over short periods of time. Now you can connect independent sensors to any device, which enables simple and highly effective electronic data acquisition over extensive periods of time, from any location.

Data acquisition can be achieved through sensors, or probes, recording data to a standalone device, computer, tablet or even a phone (Figure 1.8.12). The software generally graphs the data and performs the uncertainty propagation automatically. This specialised software allows for many analysis functions not found in standard spreadsheets. Many smart watches (Figure 1.8.13) and apps in phones include digital sensors that can be accessed and used for some class practicals and experiments.

FIGURE 1.8.12 Data acquisition software produces real-time graphs that can be downloaded or printed.

FIGURE 1.8.13 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 directly to a computing device. There are a variety of sensors, probes and instruments that can measure different phenomena on a single device. Some examples of data acquisition devices are shown in Figure 1.8.14.

Often, one of the measurements is time; the user decides what the other measurement (or variable) is by selecting the type of sensor, or probe, to use. Probes can measure temperature, distance, water content, electrical quantities, concentration of gases in air, loudness of sound or the amount of pollutants in the environment and many more phenomena.

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

FIGURE 1.8.14 (a) Sensors connected to computing devices such as phones and tablets are readily used in the field. (b) Many different probes and sensors can attach to a single device, such as those being used for water quality measurements here. (c) They can be very precise and measure multiple times per second, such as the frequency and amplitude of air vibrations in sound. (d) They are usually easy to use and produce results immediately for example, providing the temperature of skin upon contact.

FIGURE 1.8.15 A close-up view of a direct drive kart steering wheel and **data logger**

FIGURE 1.8.16 When planning an investigation, you need to identify, assess and control hazards.

The rate at which measurements are recorded is called the sample rate or capture rate. For example, the data capture rate can be varied from as short a time as every 1×10^{-5} s through to once an hour, depending on what the operator needs. Probes and electronic data acquisition have extensive applications throughout many industries. They provide informative feedback to manufacturers during the assembly of vehicles and also many devices (especially electronics) for quality control and assurance. They are also used for diagnostic testing of equipment in aeroplanes, commercial air-conditioners and office equipment, such as photocopiers, and in cars to provide data on speed (Figure 1.8.15), oil and engine operation.

RISK ASSESSMENT

While 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 we do involves risk. **Risk assessments** identify, assess and control hazards. A risk assessment should be performed for any situation, whether in the laboratory or in the field, that could harm people or animals. Always identify the risks and control them to keep everyone safe (Figure 1.8.16).

To identify risks, think about the following:

- the activity that you will be carrying out
- where in the environment you will be working, for example, in a laboratory, school grounds, or a natural environment
- how you will use any equipment, chemicals, organisms or parts of organisms that you will be handling
- what clothing you should wear, for example, laboratory (lab) coat and goggles.

The hierarchy of risk controls is shown in Figure 1.8.17. 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 the risk from the scientific investigation.

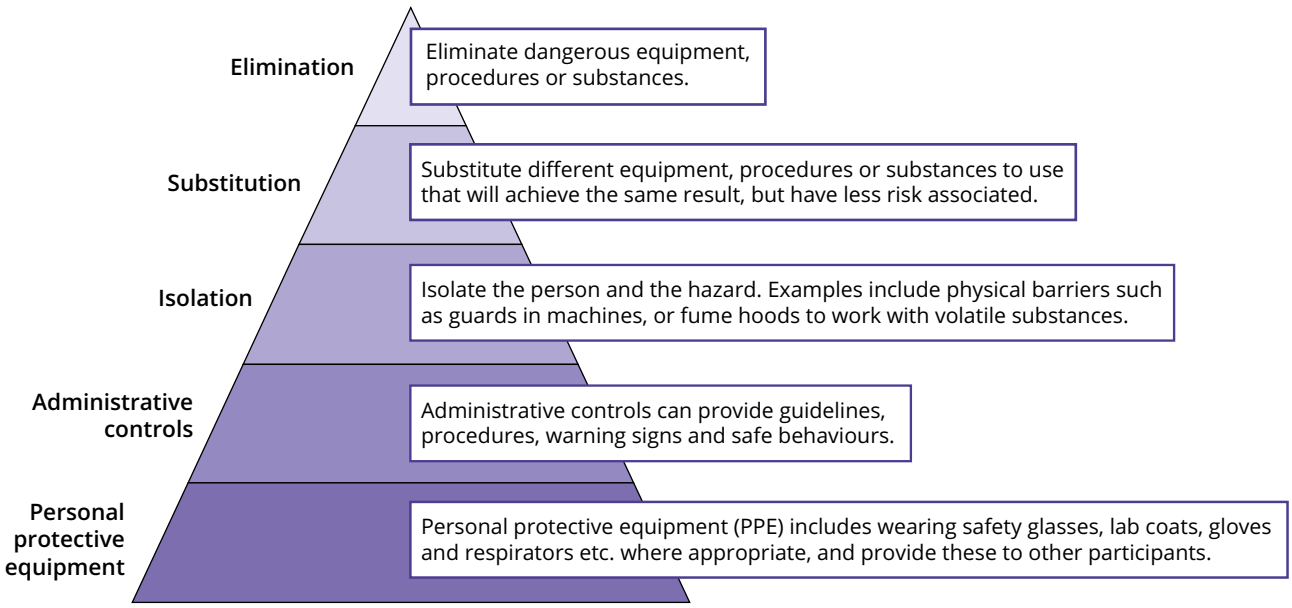


FIGURE 1.8.17 The hierarchy for risk control is shown in this pyramid, marked from bottom to top in order of increasing importance.

Personal protective equipment

Everyone who works in a laboratory wears PPE to help keep them safe. PPE includes:

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

Some PPE is shown in Figure 1.8.18.

FIGURE 1.8.18 PPE includes protective eye wear, lab coats and gloves.

Chemical codes

The chemicals at school or the hardware shop have a warning symbol on the label. These are **chemical (HAZCHEM) codes**. In 2017, the Globally Harmonised System of Classification and Labelling of Chemicals (GHS) was introduced in Australia for use in workplaces, including school laboratories. Some common pictogram codes and their meanings are shown in Table 1.8.3.

Safety data sheets

Each chemical substance has an accompanying document called a **safety data sheet (SDS)** (Figure 1.8.19 on page e64). An SDS contains important safety and first-aid information about each chemical you commonly use in the laboratory. If the products of a reaction are toxic to the environment, you must pour your waste into a special container (not down the sink).

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

TABLE 1.8.3 Some common codes and their meanings

Symbol	Meaning
	Corrosive: can dissolve or eat away at substances, including tissues such as your skin or airways
	Acute toxicity: can cause injury or death if ingested, inhaled or absorbed
	Health hazards: cause discomfort, pain or itchiness
	Flammable: is flammable
	Chronic health hazard: including any biological harm; for example, cancer, allergy, breathing difficulties

a

RISK ASSESSMENT

Bacteria in yoghurt

[redacted]

Written by: Mr Smith **Commenced on:** 25 Jul 2017 **Expires:** 25 Oct 2018

Classes for which experiment is required

Teacher: Mr Smith **Year Group:** 11 Biology

Room	Period	Date
L1	1	Mon 1/1/18

Items to be prepared by laboratory technician

Wire inoculating loops 10
Milk nutrient agar plates 20
Plain home brand yoghurt 10x 3mL in test tubes/microtubules with lid
Tape for sealing agar plates
Permanent markers (black) 10
Box of matches 10 OR spark lighters 10
Incubator set at 25 degrees
Spray bottles of 70% ethanol 5

Procedure or reference, including variations

Senior Biology

Equipment to be used

adhesive tape

Potential hazards
Do not tape over mouth or nose, or use as a restraint.

box of matches

Potential hazards
Box burns violently if ignited.

Standard handling procedures
Keep dry. Used matches should never be returned to the box. Count boxes out and in.

bunsen burner

Potential hazards
Roaring flame is very hot and can cause severe burns. Rapid passage of hand through fully luminous flame usually does not result in a burn. Roaring bunsen burner may "burn back" at low gas flow, with flame emerging from air holes in base; this makes the base of the burner hot to touch and liable to cause burns. Gas from gas tap or from end of rubber tube burns with large luminous flame, likely to cause burns. Rubber hose is easily melted by flame from burner, e.g. if burner knocked over, resulting in fire from burn hole in tube. Ensure hair is tied back, so does not catch alight.

Standard handling procedures
Inspect and clean the jet and base of bunsen burners regularly. Inspect and replace tube whenever any sign of wear or damage is noticed. Use only hoses of the correct size to ensure a comfortable fit on both bunsen burner and gas tap.

hand sanitiser

incubator

Potential hazards
Possible source of electrical shock if not wired correctly. Possible ignition source.

Standard handling procedures
Check for electrical safety each time before use. Test and tag at regular intervals.

inoculation loop

Potential hazards
Loop will be hot following flame sterilization and may cause burns. When flaming the loop, ensure the loop is held at a downwards angle to reduce the amount of microbial aerosols created.

Standard handling procedures
Ensure no flammable liquids near flame during sterilization. Ensure loop is flame sterilized before and after use. Do not inoculate unknown organisms since they may be pathogenic.

marker pen

Potential hazards
Inhaling the contents may be harmful due to the volatile

Standard handling procedures
Recap tightly after use. Do not allow students to inhale

b

solvents. Flammable. fumes.

test tube, small (~75 x 8 mm), soda glass

Potential hazards
Breakage of test tubes. Cuts from chipped test-tube rims. Melts at red heat in roaring bunsen flame (sodium fusion test) and shatters when dropped into water; use gauze to protect against flying glass fragments.

Standard handling procedures
Inspect and discard any damaged test tubes. Sweep up broken glass with brush and dustpan; do not use fingers.

Chemicals to be used and produced

agar, solid

Class: nc PG: none **(K-12)** Users: (1,2,3,4,5,6) CAS: 9002-18-0

GHS data: Not classified as a hazardous chemical.

Potential hazards
Low toxicity.

ethanol 5-13 M (24-70% wt/wt) (ethyl alcohol) $CH_3CH_2OH_{(aq)}$

Class: 3 PG: III **7-12** Users: 1,2,3,4,5 UN: 1170 CAS: 64-17-5

GHS data:

DANGER

Flammable liquid and vapour
Causes eye irritation

Potential hazards
FLAMMABLE. Liquid irritates eyes. Prolonged contact with skin causes irritation. Low toxicity. Higher concentrations form violently explosive mixtures with nitric acid and other oxidising agents. Reaction of 70% wt/wt ethanol with acidified dichromate solution is highly exothermic. Potassium reacts explosively with aqueous ethanol.

Standard handling procedures
70% wt/wt ethanol is the optimum concentration for killing bacteria and is often used as a sterilizing liquid. Ethanol is a controlled substance, not usually available in schools. Aqueous methylated spirits is the usual substitute in schools.

Living organisms to be used

bacteria

Potential hazards
Possibility of infection during experiments with unknown bacteria. Some bacteria are highly pathogenic.

Standard handling procedures
Some school authorities ban the culturing of unknown micro-organisms in experiments, due to the possibility of culturing pathogens. Many school authorities do not permit sub-culturing of bacteria from wild cultures. Your school authority may allow commercially obtained pure strains of non pathogenic bacteria to be subcultured from one plate to another, provided the appropriate safeguards are followed. Risk group 1 organisms, as described in AS/NZS 2243.3:2010, are generally regarded as suitable for supervised school experiments. Check the policy of your school authority.

yoghurt

Potential hazards
ALLERGY ALERT. Some individuals are allergic to dairy products. Do not eat in Science laboratory, due to the possibility of chemical contamination.

Standard handling procedures
Store in refrigerator for maximum of 1 week or until expiry date.

Others

Students will wear safety glasses throughout the procedure.
spark lighters - overuse will damage flint; caution to be issued.
milk allergies - will not be ingested; caution students with allergies.

Knowledge

I have read and understood the potential hazards and standard handling procedures of all the equipment, chemicals and living organisms.
I have read and understood the (Material) Safety Data Sheets for all chemicals used and produced.
I have copies of the (Material) Safety Data Sheets of all the chemicals available in or near the laboratory.

FIGURE 1.8.19 Two pages from a risk assessment for a bacterial experiment that uses the safety data sheet (SDS) to alert the reader to any potential hazards, including appropriate measures to reduce risk of harm.

Ethical considerations

When planning an investigation, you should identify possible ethical considerations and evaluate their necessity or ways to reduce or mitigate them. **Ethics** is a set of moral principles by which your actions can be judged as right or wrong. Every society or group of people has its own principles or rules of conduct. Scientists have to obtain approval from an ethics committee and follow ethical guidelines when conducting research that involves animals, including, and especially, humans.

Ethical issues could include the following.

- How can this affect wider society?
- Does one party benefit over another; for example, one 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 anyone from gaining their basic needs?
- How can this impact on future ethical decisions or issues?
- Does the research cause damage to the environment?
- Does the research cause harm to other living things?
- In reality, school biology investigations will generally have minor ethical issues, if any, but you should consider these in your planning.

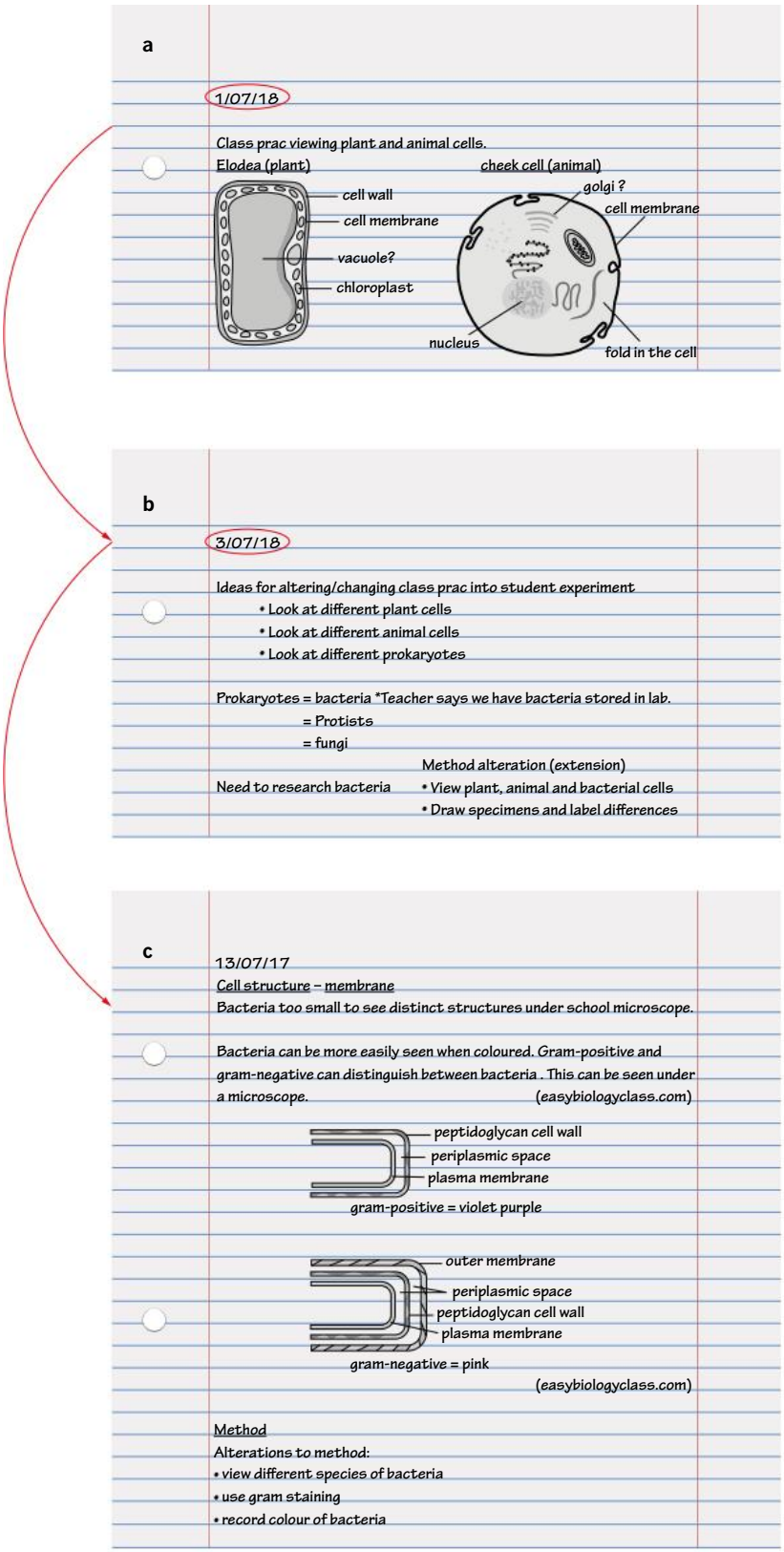


FIGURE 1.8.20 Demonstrating the alteration and refinement of a class practical into a student experiment in a student's journal. (a) The observations from the class practical. (b) The recordings of ideas and possible alterations to the class practical, developing a student experiment. (c) The refinement of the student's idea for the experiment, basing the refinement on research.

Scientific research involving humans or animals must be approved by an ethics committee before it can commence. All research involving animals in Australia must comply with the *Australian Code of Practice for the Care and Use of Animals for Scientific Purposes*. However, there might still be public concern about some types of research. The use of live animals in research (e.g. for testing the safety of pharmaceutical products) is also an issue for many people.

Refining the methodology

As the planning of the methodology is not linear, refinement may occur several times (due to further background research, refining the research question or as variables become understood). Scientists will employ an experimental methodology that has been refined many times over several years.

Record all refinements in the journal. The following may help with refining the methodology.

- Record everything.
- Be prepared to make changes and refinements to the plan and methodology.
- Note any difficulties encountered and the ways they were overcome. 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 1.8.20 shows a student journal demonstrating basic developments and refinements in their methodology.

If the expected data is not obtained, do not worry. As long as the data can be critically and objectively evaluated, the limitations of the investigation can be identified and further investigations proposed, the work is worthwhile. The syllabus requires an evaluation and a suggested improvement to the methodology or experiment in the scientific report. In the scientific report, you will have to justify your modification.

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.

1.8 Review

SUMMARY

- An independent variable is a variable that is controlled by the researcher (the variable that is selected and changed).
- 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 have the following characteristics:
  - include measurable variables (the independent and dependent variable)
  - have a guiding word, such as *who*, *what*, *why* or *will*
  - be phrased so that a definitive answer can be developed
  - be able to link the guiding word to command verbs (such as *identify*, *describe*, *compare*, *contrast*, *distinguish*, *analyse*, *evaluate* or *create*) so that a task can be determined.
- A simple way to formulate a hypothesis is to link the independent and dependent variables using the following sentence structure.
  - If (independent variable) happens, then (dependent variable) will happen.
- A scientific journal is a document scientists use to record all their ideas, questions, background research and literature reviews, methodology drafts and revisions, results and refinements related to an experiment.
- Validity refers to whether an experiment or investigation is in fact testing the set research question or hypothesis.
- Data can either be qualitative or quantitative.
- Qualitative data is descriptive and unmeasurable and uses descriptions or adjectives to record observations.
- Qualitative data can be characterised as either:
  - nominal, when the order of data is not important
  - ordinal, when the ordering of data is important.
- Quantitative data is empirically measurable and uses instruments to record observations.
- Quantitative data can be characterised as either:
  - discrete, when data can only be recorded as particular numerical values
  - continuous, when data is not restricted to particular numerical values, but occurs within a given range.
- Reliability refers to the notion that if the experiment is repeated many times, the results obtained should be consistent.
- Reliability is improved by:
  - replication, having multiple samples within an experiment
  - repeat trials, repeating the experimental test.
- Risk assessments identify, assess and control hazards.
- HAZCHEM pictograms are warning images used to identify hazardous substances.

KEY QUESTIONS

Retrieval

1 **a** State the meaning of the term 'variable'.

b Copy and complete the table with definitions of the types of variables.

Independent variable	Controlled variables	Dependent variable

Comprehension

2 Write each of the following inferences as a hypothesis that could be tested using grass in an experiment. Use the terms 'If... then ...' or 'when/will'.

a This grass receives the rain run-off from the path when it rains.

b The concrete path insulates the grass roots from the heat and cold.

c People do not walk on this part of the grass.

d The soil under the path remains moist while the other soil dries out.

3 Write a hypothesis to test whether:
- **a** carrot seeds or tomato seeds germinate quicker
- **b** sourdough, multigrain or white bread goes mouldy the quickest
- **c** Trigg the dog likes dry food or fresh food better.

4 Identify whether the following pieces of information about a cup of coffee are qualitative or quantitative.

Information	Qualitative	Quantitative
cost $3.95		
robust aroma		
coffee temperature 82°C		
cup height 9 cm		
frothy appearance		
volume 180 mL		
strong taste		
white cup		

5 Identify the independent, dependent and controlled variables that would be needed to investigate each of the following hypotheses.
- **a** An increase in temperature will lead to an increase in the rate of transpiration in plants.
- **b** If there is no light, there will be no photosynthesis in the leaves of a plant.
- **c** If a cup of hot chocolate has a lid on it, then it will stay hot for a longer period of time.
- **d** Because thin candles have less wax to burn, they will burn faster than thick candles.

6 Explain the reasons for having SDS for the chemicals used in the laboratory.

7 Determine the appropriate course of action if you spilled a chemical substance on yourself with the following label.

Analysis

8 Identify the difference between quantitative and qualitative data.

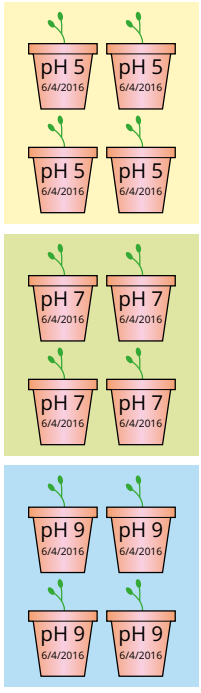
9 Select the best hypothesis, and explain why the other options are not good hypotheses.
- **A** If light and temperature increase, the rate of photosynthesis increases.
- **B** Transpiration is affected by temperature.
- **C** Light is related to the rate of photosynthesis.
- **D** Multigrain bread will show mould faster than white bread.

10 Consider the seedling growth investigation below.
- **a** State the independent variable for the experiment.
- **b** State the dependent variable for the experiment.
- **c** List the controlled variables stated in the procedure.
- **d** Explain the importance of controlling all variables except the dependent variable.
- **e** Identify three variables that could be used to modify this experiment and describe a modification for each variable.
- **f** Write a research question for each variable used to modify the experiment in part **e**.
- **g** Refine each research question from part **f**.

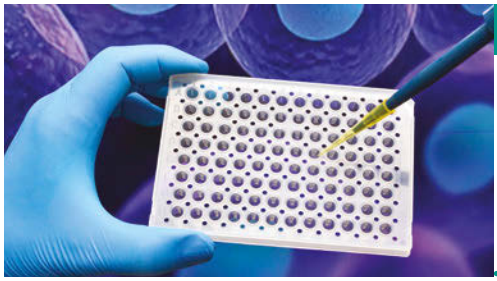
Purpose
To investigate the effect of pH on seedling growth.

Hypothesis
If the soil pH is increased, then seedling growth will increase.

Procedure
1 Germinate twenty pea seeds on damp cotton wool and choose twelve with a height of about 12 mm.
2 Plant a seedling in each of twelve pots of the same size. For each pot, use 80 g of quality potting mix, and water with 10 mL of tap water. Safety note: ensure that gloves and a mask are worn when handling potting mix, as it may contain harmful microbes.
3 Label each pot with the pH treatment the soil will receive: four pots at pH 5, four pots at pH 7 and four pots at pH 9.
4 Weigh each pot to the nearest 0.1 g. Draw up a data table and record the results for each pot in the column for day 0.
5 Reweigh the seedlings in their pots 2 days later. Record the results for each pot in the column for day 2.
6 Immediately after weighing, give each plant 10 mL of water at the appropriate pH according to the label on the pot.
7 Repeat steps 5 and 6 every 2 days for the next 10 days.
8 Keep plants in the same position where light is available to maintain lighting conditions.
9 Repeat steps 1–8 twice to reduce the chance of variability between trials.



1.9 Conducting and experimenting



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

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

Now that you know about the variables involved and you have planned your experiment methodology, you can conduct the experiment. Experiments rarely run according to the precise 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. If experimentation is in an open system such as an ecological investigation or survey, some variables to be measured (e.g. temperature, time, date, weather conditions and any other biotic and abiotic factors of influence) cannot be controlled in the methodology. Other people must be able to repeat your results under the same conditions. Therefore, all variables must be measured.

Ensure you choose instruments with appropriate precision, remembering that the instruments determine the significant figures and the accuracy and reliability of your results. The more precise the instrument, the more accurate the measurement and the more reliable the data is.

TABLE 1.9.1 Examples of rudimentary compared to improved experimental testing

Rudimentary (basic) set-up		
Agar cells used to test effect of SA:V on diffusion prepared by hand	Estimating temperature of a liquid by hand	Measuring time with a 5-minute sand timer
		
Improved set-up		
Agar cells used to test effect of SA:V on diffusion prepared by butter knife using a ruler	Measuring temperature with a digital thermometer (sensor) with known precision and uncertainty	Measuring time with a digital timer with known precision and uncertainty
		

Possible considerations when conducting an experiment

Depending on what your experiment is testing, there are several aspects of the experiment that should be included in the planning. These include:

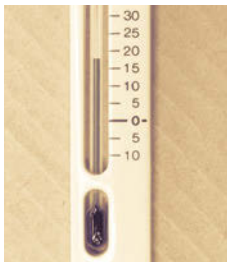
- equipment
- instruments
- safety precautions
- time (preparation, testing)
- complexity of testing
- chemical concentrations and volumes
- sequential order of activities to complete testing.

Equipment

The choice of equipment and instrumentation will influence the reliability of your experiment. Where possible, use equipment rather than human means to conduct experiments. Some examples are shown in Table 1.9.1.

When conducting the experiment, it is recommended to use the most precise instruments available. With higher precision instruments, there is less chance of error and lower uncertainty in the measurement. Table 1.9.2 demonstrates the benefits of greater precision instruments by reducing uncertainty.

TABLE 1.9.2 The difference in precision between instruments

Lower precision instrument		
Glass thermometer with a precision of ±2.5°C 	Measuring beaker with a precision of ±5 mL 	Microscope of magnification ×400 
Higher precision instrument		
Digital laser thermometer with a precision of ±0.05°C 	Measuring cylinder with a precision of ±0.25 mL 	Microscope of magnification ×1000 

Safety precautions

Always use safe procedures. The use of common sense is essential. For example, all glass 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.

COLLECTING SUFFICIENT AND RELEVANT DATA

It is important that the instruments and methodology used enable you to measure and collect the data needed. The data must be relevant to the variables in the research question or hypothesis. Also enough data and enough sampling is required when collecting or measuring data. Otherwise, the analysis and interpretation of the data will not be reliable or valid in relation to the research question or hypothesis.

Collecting sufficient data

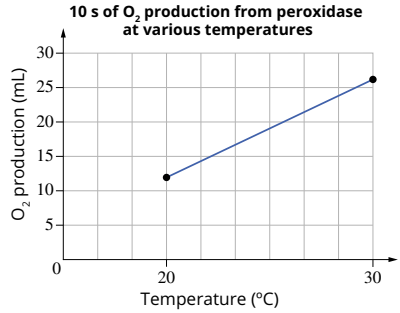
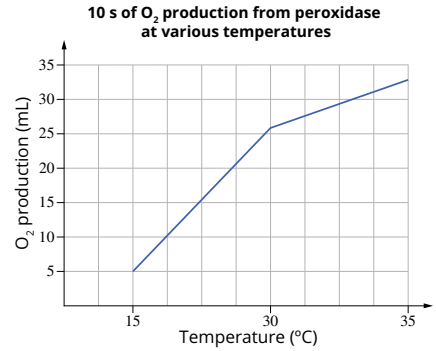
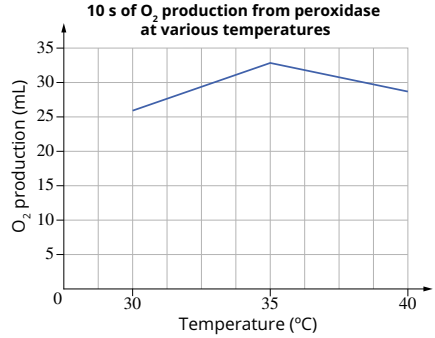
The term 'sufficient' is defined by the Queensland Biology syllabus as 'enough or adequate for the purpose'.

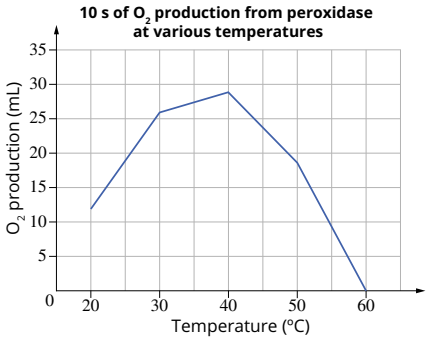
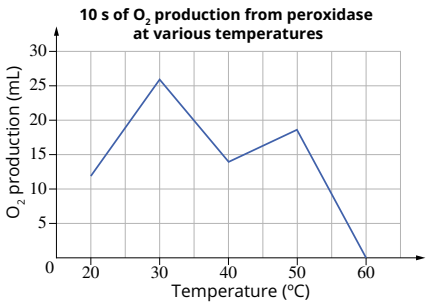
You need to collect enough data to substantiate whether or not a relationship exists between the variables. This includes collecting an appropriate number of replicates and an appropriate number of individual samples (also known as observational or collection points). It is also important that you collect data around interesting points in your range, such as any parts of a graph where the curve is changing direction.

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 1.9.3 outlines examples of sample size and their effect on the results of an experiment and the resultant interpretation. The example results are from an experiment into the effect of temperature on enzyme activity.

TABLE 1.9.3 Examples of sample size and their effect on the results of an experiment

Example of analysed data		Effect of sample size on analysis
	A line graph with two sample points.	With only two individual sample points, these results suggest an inappropriate linear relationship between temperature and enzyme activity—that enzyme activity increases with temperature.
	A line graph with three sample points using an uneven scale.	The spread between the chosen individual sample points is inappropriate for this experiment because they should be evenly spread. This example produces results with an incorrect relationship between temperature and enzyme activity—that enzyme activity increases and then plateaus as temperature increases.
	A line graph showing limited sample points.	The chosen number of individual sample points is somewhat appropriate. This may be sufficient, but the true relationship is not displayed. The next example of displayed results provides more validity for the relationship.

	A line graph with appropriate number and distribution of sample points.	The number of individual sample points here best demonstrates the relationship between the variables.
	A line graph based on data that had no replicates.	These results are due to only a single measurement for each individual sample point (temperature) without any replicates. In this example, the 40°C measurement was an error, but without replicates errors will influence the results.

Collecting relevant data

The variables to be measured or collected must be directly related to the proposed independent–dependent variable relationship. Additional variables can be measured or collected that are indirectly related to the hypothesised relationship, if the background research shows it could be beneficial in the analysis or interpretation of the relationship. If you do not have any background research relating a variable to the research question or hypothesis, then it is not relevant, and therefore is not to be measured or collected.

1.9 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 collected and measured data must be relevant to the proposed relationship in the research question or hypothesis.
- Equipment used during an experiment should enable you to collect and measure relevant data to address the research question or hypothesis.

KEY QUESTIONS

Retrieval

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

Comprehension

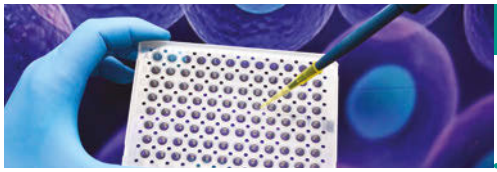
2 Explain how the precision of equipment can impact scientific conclusions.

Analysis

3 A student recorded the following data below to test the hypothesis, 'Does an increase in temperature increase the rate of germination of radish seeds?' Assess whether sufficient and relevant data was collected to address the research question.

Temperature (°C)	Light present?	Number of seeds planted	Number of seeds germinated	Seed colour	Seed shape	Colour of germinated leaves
0	yes	10	0	brown	spherical	yellow
	no	10	0	brown	spherical	green
10	yes	10	6	brown	spherical	green
	no	10	5	brown	spherical	yellow

1.10 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.

You must record all measurements and observations made during the experiment (in the journal). This is the raw data. Choosing not to record certain measurements or observations (raw data) is invalid, shows bias and is scientifically fraudulent. Unusual and unexpected measurements and observations may be due to valid relationships between variables that are unknown to the scientist. This cannot be determined until the raw data is processed, analysed and interpreted.

The results, after analysis, need to show whether or not a relationship exists between the variables in the research question. To achieve this, the results need to be presented appropriately. Being able to present results appropriately depends on appropriate measurement, observation and recordings (e.g. quantitative or qualitative). Make sure you plan this before conducting the experiment.

After you have analysed the raw data, you represent the data, using mathematical and scientific conventions, in tables, graphs, schematics or diagrams. Refer to Module 1.6 for specific guidance on producing quality and appropriate graphs and Module 1.11 for details regarding representing results.

FIGURE 1.10.1 It is important to read the bottom of the meniscus at eye level in order to avoid parallax error. This student is showing how to use a piece of white card (or a tile) to improve the contrast between the solution and the scale.

ANALYSING

Analysing the raw data enables processing in many ways to search for relationships between variables and trends or patterns in the data, uncertainties and errors, outliers and results of significance. This will produce processed data.

There are a number of ways of presenting data, including tables, graphs, flow charts and diagrams. The best way to visualise the data depends on the nature of the data. More information on these different formats is provided in Module 1.6. In this section, you will learn how to discuss your investigation and draw evidence-based conclusions in relation to your research question.

It is important that when you are analysing data, you do not selectively process it to demonstrate what you want to see. Such bias will result in using analysis tools (e.g. statistics) inappropriately and erroneously and will result in invalid conclusions and academic fraud. Quality scientific analysis processes the raw data as it is and is open to any result, including any relationship, trend or pattern revealed as a result of the investigation.

IDENTIFYING ERRORS

Most practical investigations have errors associated with them. For example, parallax error can occur when reading a burette measurement (Figure 1.10.1). As shown in Figure 1.10.2, there are many different types of errors that can occur.

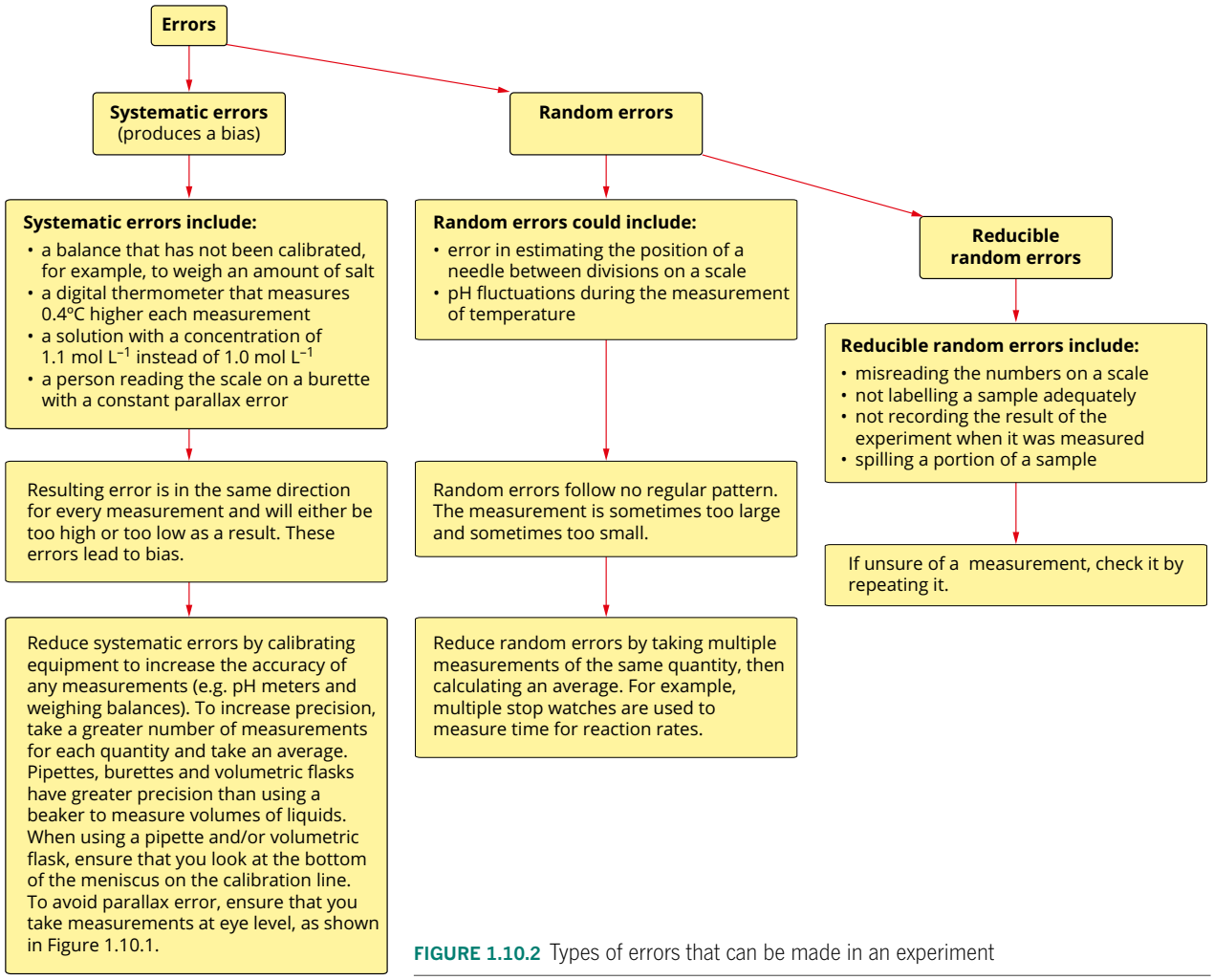


FIGURE 1.10.2 Types of errors that can be made in an experiment

Analysing precision

Understanding the uncertainty and precision is vital to any analysis of data. In biology there is always variation in measurements. You need to determine how much variation is due to natural biological variation and how much is due to the measurements and instruments.

Always display the precision and uncertainty of the instruments as a range of data next to the results (e.g. measurement ± *x*. See Module 1.5 for more explanation). If you perform calculations with the results, then you must do the appropriate calculations with the uncertainties (see Module 1.5). When the total uncertainty is known, it can be established if variation in the data is due to the instrument or the variables being tested.

If the measurements between samples or tests fall within the uncertainty range of the instrument (Table 1.10.1), then the variation in results could simply be due to the instrument. If the difference between the measured results is greater than the uncertainty range, then the variation in the results is not due to the instrument and is due to other variables.

Table 1.10.1 shows the resting arterial blood oxygen measurements of several recreational athletes, and there is variation between the measured results. The arterial blood oxygen content between athletes 1 and 2 has a difference of 0.4 mL L^{-1}. The uncertainty in measurement due to the accuracy of the instrument is ± 0.5 mL L^{-1}, therefore the difference between athlete 1 and 2 is within instrumental uncertainty. The difference between athletes 1 and 2 may be due to the instrument and not biological reasons. As this cannot be determined with certainty, it must be interpreted that there is no biological difference between athletes 1 and 2.

TABLE 1.10.1 The resting arterial blood oxygen levels in several recreational athletes

Sample	Total arterial oxygen (mL L^{-1})
athlete 1	206.3 ± 0.5
athlete 2	205.9 ± 0.5
athlete 3	206.8 ± 0.5
athlete 4	208.2 ± 0.5
athlete 5	199.5 ± 0.5
athlete 6	199.8 ± 0.5
mean	204.4 ± 0.5

The difference between athletes 3 and 4 is greater than the uncertainty range of the instrument. Therefore, you can be certain the difference is due to reasons other than the instrument. If the methodology controlled the extraneous variables appropriately and nothing unforeseen influenced the results, then you can interpret the difference between the athletes to be due to biological reasons related to the experiment rather than instrumental uncertainty.

It is important to understand the accuracy and precision of the instruments because 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 measurement and the greatest
- central tendency (e.g. mean) with instrumental uncertainty, which outlines the potential variation in instrumental measurements due to the instrument's design or increments.

For more information about analysing data, see Module 1.7.

Analysing validity and theoretical relationships

You must process the results and data to look for trends, patterns or differences. Some of the first processes in analysing data is to use statistical calculations to determine the true values, uncertainties, errors and significance of the measurements. Once you understand the quality of the data, then you can analyse the validity in relation to established theoretical concepts.

Table 1.10.2 shows the difference in arterial blood oxygen between males and females. The mean male and female arterial blood oxygen content has a difference of 7.0 mL L^{-1}, which is greater than the instrumental uncertainty and therefore is due to biological differences (barring methodological issues or unforeseen variables). Because the difference in results has been established as being due to experimental variables and not the instrument, processing the data using statistics can help analyse and ascertain which variable is the cause of the difference.

TABLE 1.10.2 The resting arterial blood oxygen levels in several recreational male and female athletes

Sample	Total arterial oxygen (mL L^{-1})	
	Male	Female
athlete 1	206.3 ± 0.5	196.5 ± 0.5
athlete 2	205.9 ± 0.5	196.8 ± 0.5
athlete 3	206.8 ± 0.5	198.7 ± 0.5
athlete 4	208.2 ± 0.5	195.9 ± 0.5
athlete 5	199.5 ± 0.5	193.4 ± 0.5
athlete 6	199.8 ± 0.5	203.3 ± 0.5
mean	204.4 ± 0.5	197.4 ± 0.5

It becomes important during the processing and analysis of the data to know which methods or statistics to use. No scientist knows how to use all statistical calculations; they use or have a resource that outlines the purpose and function of each statistical calculation and refer to this every time they process their results and data. Module 1.5 outlines many common useful statistical calculations to process and analyse data. Refer to this module every time you are processing the results of your class practicals or student experiments.

The results in Table 1.10.2 require statistical analysis to investigate the biological difference between males and females. The mean alone is not scientifically considered a significant difference. Further statistical analysis can determine if a significant difference exists, indicating if there is a valid biological difference between them. Without any further statistical calculations, the following is a list of plausible explanations for why a difference in arterial blood content could have been observed between males and females.

- Background research outlines that female blood oxygen levels are typically lower than males.
- The sample of males and females chosen may not represent the typical population, therefore:
  - there could be sample bias in the results due to the selection criteria used to choose the volunteer athletes, causing systematic error
  - there could be sample bias due to the type of people who volunteered, causing random error
  - one group, either male or female, could all be of a higher athletic standard; for example, the recreational male athletes could be general gym users while the recreational females athletes could be from a team of netballers

- some recreational athletes could exercise two times a week or others could exercise five times a week, resulting in uncontrolled biological variables that influence the results.

- The health of the volunteers may not all be equivalent.
- The body size and morphology may be vastly different.

Statistical calculations only perform functions with literal numbers; the calculation does not know where the numbers come from or what they represent. Therefore, analysing is a combination of processing numbers and the experimenter placing those numbers into a context. It is also vitally important to record observations during the experiment so that when analysing, the correct context can be given to the processed data with as little bias as possible.

In the example in Table 1.10.2, if all variables were controlled and observations made during the experiment confirmed that the experiment went to plan, then statistical processing can be applied to the measured data. In this case, the *t*-value can be calculated as shown in Table 1.10.3, which shows that the independent variable (gender) affects the dependent variable (arterial blood oxygen content).

Table 1.10.3 shows that for the comparison between the male and female means, the *t*-value is 0.01. This means that there is a 1% chance that the difference in the means is due to natural or biological variation (in the typical population and assuming that males and females are the same). Therefore, there is a 99% chance that this difference is not typical and must be related to or due to the independent variable, gender.

Statistical 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 an outlier in your data if one is found (see Module 1.6). This can then be used to suggest improvements in the methodology to remove such measurements.

If the results follow the established theoretical relationship, then there are a few ways to analyse the theoretical relationship between variables (see Module 1.7). These are the:

- Pearson correlation coefficient—to determine if a linear relationship exists (that the variables correlate), the direction and how strong the linear relationship is
- coefficient of determination—estimates the predictability in the measured results due to the change in the independent variable
- Spearman rank correlation—determines if a non-linear relationship exists in a single direction
- student *t*-test—determines if there is a difference between two means beyond natural variation (normal distribution).

TABLE 1.10.3 Resting arterial blood oxygen levels in several recreational male and female athletes

Sample	Total arterial oxygen ($mL\ L^{-1}$)	
	Male	Female
athlete 1	206.3 ± 0.5	196.5 ± 0.5
athlete 2	205.9 ± 0.5	196.8 ± 0.5
athlete 3	206.8 ± 0.5	198.7 ± 0.5
athlete 4	208.2 ± 0.5	195.9 ± 0.5
athlete 5	199.5 ± 0.5	193.4 ± 0.5
athlete 6	199.8 ± 0.5	203.3 ± 0.5
mean	204.4 ± 0.5	197.4 ± 0.5
t-value	0.01	

INTERPRETING

Once the results have been processed and analysed, you 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, errors, anomalies and relationships. Interpreting is placing this understanding into words and providing an in-depth explanation of what the numbers mean. 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. Therefore, the interpretation is always an inference. In addition, the interpretation of results in the scientific report should always be concise.

It is important to interpret only 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, instrumental precision and statistical analysis (e.g. r values or R^2 values, student t-test). For example, if you have not determined statistical significance, do not state that the results are significant. If an outlier has not been determined by statistical calculations, do not state a result or measurement is an outlier.
- When the results do not follow expectations, interpret them as such. You still need to relate the results to theory, and so you may need to do further research in order 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 observation provides a clue or a basis for what concepts or relationships need to be further researched. Further research will provide the theory to offer a plausibility (infer a reason) for the results. When the results are not as expected, it is important that you use statistical analysis to establish that the results did not follow expectations, rather than just stating because it 'looks' like it.

Once the interpretation is complete in your journal, you can write the scientific report, summarising all the scientific work and method used for the experiment.

1.10 Review

SUMMARY

- Raw data includes the measurements and observations made during an experiment.
- Processed data is derived from processing and manipulating raw data.
- Processed data enables trends, patterns and differences to be identified.
- If the measurements between samples or tests fall within the uncertainty range of the instrument, then the variation in results could simply be due to the instrument.
- Interpretations of data attempt to explain the observed results.

KEY QUESTIONS

Retrieval

1 State the two types of data.

2 Define 'systematic error'.

3 Describe random error.

Comprehension

4 Use a graphic organiser to summarise what is involved in:

a processing of data

b interpreting data.

Analysis

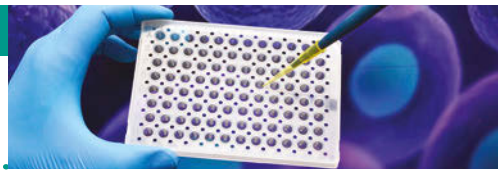
5 A group of subjects was given a drug believed to lower blood pressure. Analyse the data below to determine if it can be concluded the drug lowers blood pressure.

Sample	Systolic blood pressure (mmHg)	
	Before drug administration	After drug administration
subject 1	120 ± 2	118 ± 2
subject 2	121 ± 2	117 ± 2
subject 3	119 ± 2	116 ± 2
subject 4	118 ± 2	116 ± 2
subject 5	140 ± 2	136 ± 2
subject 6	130 ± 2	127 ± 2
mean	125 ± 2	122 ± 2

1.11 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.



To write a scientific report, you need to follow some general conventions. Even though there are many ways to present a report, it must follow a scientific genre and meet the requirements of the Queensland Biology syllabus. This module will provide a guide to writing an appropriate scientific report.

> **Your journal should contain all the information required to complete your scientific report for the student experiment. After all, it is a report, and reports summarise research and information gathered on a topic. The scientific report does not require much time to complete when reporting from a comprehensive journal.**

SCIENTIFIC WRITING AND LITERACY

Scientists use words (the agreed scientific language and terms) that have specific meanings, which may differ from the understanding of the term in common language. This allows a common understanding of words across all languages, to convey scientific meaning. Table 1.11.1 provides some examples of the differences in the understanding of words in common language and in scientific language (even if it is slight).

TABLE 1.11.1 A comparison of common and scientific language

Term	Common language meaning	Scientific language meaning	Difference in meaning
sample	A representative part or a single item from a larger whole or group, especially when presented for inspection or shown as evidence of quality	The specifically chosen physical representatives 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, although inspection is carried out through testing. In common language, 'sample' can be used generically while 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 which 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 the report is written using scientific language and conventions. Your report should be fluent and concise. Carefully plan all parts of the report:

- introduction
- summary of altered methodology
- results
- analysis and interpretation
- evaluation and conclusion
- suggested improvements.

Writing fluently and concisely

The report should be brief and comprehensive, so only use the words required to communicate your information. Writing a concise report avoids repetition and helps remain within the required word count or length. Use scientific language as it allows you to communicate details and knowledge in fewer words. Table 1.11.2 demonstrates communication of the same concept in a few different ways. Being fluent and concise will significantly influence the word count of the report and the quality of the writing.

TABLE 1.11.2 Communicating concepts in various ways

Concept	Communication	Commentary of communication
outlining the basic details of a virus	Viruses are small molecules that use cells to reproduce.	This is fluent and concise. However, it lacks scientific terms or language to convey in-depth understanding.
	Viruses are tiny little objects made up of numerous parts that infect cells. They cannot reproduce themselves so need other cells to replicate them, using their own (host cells) components. Inside a virus, you will find genetic molecules such as DNA and RNA. These are surrounded by a capsule or envelope called a capsid. Therefore, viruses are tiny and need other cells to replicate/reproduce.	This is fluent, but not concise. There is repetition (e.g. 'tiny' and 'little', which have the same meaning, and 'reproduce', which is stated twice). It also uses many words without using scientific terms to provide detail and understanding. This may be useful language in the journal when learning about a topic, but not in the scientific report.
	Viruses are obligate, intracellular parasites. They are composed of genetic material enclosed in a capsid and cannot replicate outside of cells.	This is fluent and concise. In-depth understanding is communicated through scientific terms, which enable much information to be conveyed in fewer words.

Writing in a scientific genre

There are a number of genres or styles of scientific communication, including literature review, empirical essay and poster presentation. This module 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** is written to scientific conventions, including format and language.

Reporting

Using headings in scientific reports is essential. There are international conventions for scientific report writing; however, they are specific to the journal publication. There is no single convention for scientific report writing. Table 1.11.3 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 it can be seen some subheadings are suitable for more than one section; however, each scientific report will only use each heading and sub-heading once. It is best to ask your teacher about the headings they prefer and ask how to align your scientific report and its headings to the syllabus.

TABLE 1.11.3 Scientific report sections, headings and information

Scientific report sections	Common title alternatives	Expected information within the section
title	–	A specific statement that outlines the expected relationship between independent and dependent variable. Or a question asking about the relationship between the independent and dependent variable.
abstract	–	A summary of the entire experiment/investigation in a single paragraph outlining the main information for each section: background information, method, results, analysis and conclusion. Usually includes 1–3 sentences per section, usually less rather than more.
introduction	• background information • background research • literature review • rationale	Information already known or inferred from previous experimentation and scientific literature specific to the research question or hypothesis. Explains the current scientific knowledge about the relationship between the independent and dependent variable and any other variables that may alter the relationship. Must also refer to the original experiment and justify the modification that was made.
methodology • sampling technique • preparation • experiment	• procedure • modifications to methodology	An outline of the exact details, including specific details about instruments, equipment models and precision, techniques employed and all information so other scientists can repeat the experiment. 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	• processed data • analysis • interpretation	The type of data presented is unique to specific journal publications. However, in general, all the data, observations and results need to be presented to explain the interpretation and conclusion. The results must show all the required information to answer the research question or hypothesis.
conclusion • analysis • interpretation • discussion • evaluation	• interpretation • discussion • evaluation • sources of error • suggestion for improvements/ modifications	An explanation of the results, including quality of experimentation (accuracy, precision, validity and reliability of the methodology), relating the results to current scientific understanding (theory). The strength of the relationship between the experimental evidence (data, observations or results) is to be stated.
references	–	A list of all sources used in the scientific report

Scientific writing

The report is written for a scientific audience, so it is important to use appropriate scientific language and conventions. This contrasts with English writing used in everyday situations.

The student experiment report should have paragraphs, with each paragraph explaining only one idea. The first sentence (topic sentence) of the paragraph introduces the topic. Following sentences provide the details of the idea. The final sentence concludes the idea. Each sentence should flow on to the next, slowly building the details of the explanation. The report should be brief and comprehensive, so you should only use the words required to communicate and use language that conveys detailed understanding.

Reports should be written in:

- past tense because the experiment was conducted in the past
- third person, passive voice and impersonal verbs—science uses this language convention (Table 1.11.4 on page e80)
- scientific language—the terms used are specific to concepts, models and theories
- objective, unbiased language—avoid subjective and emotional or persuasive writing (Table 1.11.5 on page e80)
- concise language—avoid unnecessary repetition and express ideas. Scientific language allows more details, knowledge and understanding to be communicated in fewer words. Use shorter sentences that are less wordy. Table 1.11.6 on page e80 shows some examples of more concise wording.

TABLE 1.11.4 Examples of first-person and third-person narrative

First person	Third person
I put 50 g of marble chips in a conical flask and then added 10 mL of 2 mol L^{-1} hydrochloric acid.	First, 50 g of marble chips were weighed and then placed into the conical flask; then 10 mL of 2 mol L^{-1} hydrochloric acid was added.
After I observed the reaction, I found that ...	After the reaction was completed, the results showed ...
My colleagues and I found ...	Researchers found ...

TABLE 1.11.5 Examples of persuasive writing versus scientific writing styles

Persuasive writing	Scientific writing
Use of biased and subjective language • The results are extremely bad, atrocious, wonderful ... • This is terrible because ... • This produced a disgusting odour. • Health crisis	**Use of unbiased and objective language** • The results showed ... • The implications of these results suggest ... • The results imply ... • This produced a pungent odour. • Health issue
Use of exaggeration • The object weighed a colossal amount, like an elephant.	**Use of non-emotive language** • The object weighed 256 kg.
Use of everyday or colloquial language • The bacteria passed away. • The results don't ... • The researchers had a sneaking suspicion ...	**Use of formal language** • The bacteria died. • The results do not ... • The researchers predicted/hypothesised/theorised ...

TABLE 1.11.6 Examples of wordy and concise language

Verbose language	Concise example
Due to the fact that ...	Because ...
Smith undertook an investigation into ...	Smith investigated ...
It is possible that the cause could be ...	The cause may be ...
End result ...	Result ...
In the event that ...	If ...
Shorter in length ...	Shorter ...

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 and informative title
- labels, captions or descriptions, units of measurement, uncertainty
- numbering; for example, Figure 1, Figure 2, 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 bar charts and line graphs illustrate relationships between variables well. Tables and graphs will communicate in-depth information concisely. More information on tables and graphs can be found in Module 1.6.

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 few hours or a day or two after you have completed it. When reading your own work, read it carefully, 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

The student experiment does not require a bibliography; a **reference list** is sufficient. A bibliography is a list of all the sources you used during the research to develop understanding (including information in the journal), even if the information was not used directly or explicitly in the scientific report. A reference list only lists the sources used and cited (referenced in the text) in the scientific report.

All the quotations, documents, publications and ideas used in your scientific report need to be listed in the references and acknowledgements. In order to avoid plagiarism and to ensure you properly credit other people for their work, you must complete this accurately. References and acknowledgements also give credibility to your study and allow the audience to locate information sources should they wish to study it further.

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; for example, at the end of a sentence or following a diagram. If you quote directly from a source, enclose the text in quotation marks. Referencing will ensure you give credit to the original author and it will enable the reader to find the original source.

Referencing

List your sources at the end of the report in alphabetical order (by author last name or organisation name).

Compile your references in a separate document as you conduct the student experiment. The APA (American Psychological Association) style is currently the most commonly used referencing style.

In-text citations

Each time you write about the findings of other people or organisations, you need to include an in-text citation and provide 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 date in brackets (author, date).

The following examples show the use of in-text citation and the reference list entry in APA Style.

- *In-text citations:* two options for including in the sentence are:
  - It was reported that in testing of five pro-oxidant additives added to commonly manufactured polymers, none resulted in significant biodegradation after three years (Selke et al., 2015).
  - Selke et al. (2015) reported that in testing of five pro-oxidant additives added to commonly manufactured polymers, none resulted in significant biodegradation after three years.
- *Reference list:* the example above would be:
  - Selke, S., Auras, R., Nguyen, T.A., Aguirre, E.C., Cheruvathur, R., & Liu, Y. (2015). Evaluation of biodegradation—promoting additives for plastics. *Environmental Science & Technology, 49*(6), 3769–3777.

ADDRESSING THE SYLLABUS ISMG

Your final scientific report must address all the characteristics in the performance level descriptors of the student experiment ISMG. Before you begin the scientific report, plan the sections and titles and then assign the ISMG characteristics to each section. As outlined earlier, there is no single convention for the scientific report, and the student experiment ISMG characteristics will fit into any scientific report style. You will just need to decide where after discussing this with your teacher.

Word limits or word count guides can be assigned to each section. Apply a larger word count to the sections requiring explanations such as the rationale, discussion/conclusion and perhaps the analysis (depending on the convention chosen). This word allocation will act as a guide, but is flexible. Make sure your response does not exceed the word limit prescribed by the assessment specifications.

When you edit your completed report, assess whether it includes all the evidence in the four criteria (Research and planning, Analysis of evidence, Interpretation and evaluation, Communication) that make up the ISMG (IA2). These are the words that follow 'demonstrated by …'.

1.11 Review

SUMMARY

- A scientific report has the following features:
  - title—a specific statement that outlines the expected relationship between independent and dependent variable.
  - abstract—a single-paragraph summary of the entire experiment/investigation.
  - introduction—an explanation of the current scientific knowledge about the relationship between the independent and dependent variable (demonstrating application of understanding) and any other variables that may alter the relationship (considered rationale)
  - method—an outline of the exact details of the experiment, including specific details about instruments, equipment models and precision, techniques employed and all information required for others to repeat the same results. Should include both the original and modified elements of the experiment. Detail of the methodology must enable sufficient data to be collected.
  - results—the relevant data, observations and results relating to the experiment.
  - conclusion—an explanation of the results, including quality of experimentation. The explanation is related to current scientific understanding. The strength of the relationship between the experimental evidence is stated.
  - 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** methodology
- **b** conclusion

2 Recall in which section of a scientific report you would find processed data.

Comprehension

3 Explain when it is appropriate to use a:
- **a** bibliography
- **b** reference list

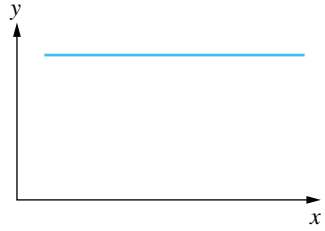
Analysis

4 **a** Determine which graph could show a change in transpiration as temperature changes.

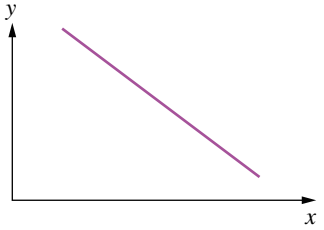
b Conclude which graph illustrates the following observation.

You are growing a bacterial culture on agar and make observations from days 3–6 in which the results seem to indicate a plateau in the number of colonies.

A



B



5 A scientist designed and conducted an experiment to test the following hypothesis.

Could an increased consumption of fast food cause a decrease in the function of the liver in people?

- **a** The discussion section of the scientist's report included comments on the accuracy, precision, reliability and validity of the investigation. Read each of the following statements and determine whether they relate to precision, reliability or validity.
  - **i** Only teenage boys were tested.
  - **ii** Six boys were tested.
- **b** The scientist then extended the fast food study to 50 teenage boys in the experimental group and 50 teenage boys in the control group. In the experimental group, all 50 subjects gained body mass. The scientist concluded that all the subjects gained weight as a result of the experiment. Deduce whether or not this conclusion is valid. Explain why or why not.
- **c** Provide recommendations to improve the validity and reliability of this investigation.

PART C RESEARCH INVESTIGATION

The QCAA requires students to complete a research investigation in Unit 4 Biology. In preparation for Unit 3, teachers may choose to assign a similar assessment task in Units 1 or 2, as preparation for Unit 3.

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

The research investigation requires you to gather secondary evidence on a research question. The QCAA Syllabus states that 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, and websites of governments, universities, independent research bodies or science and technology manufacturers.

The student experiment constitutes 20% of the total assessment in Unit 4 Biology.

A summary of the objectives and marking for the summative internal assessment research investigation IA3 (Unit 4) is provided below.

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.

Criteria	Assessment objectives	Demonstrated by	Marks
research and planning	• Apply understanding • Perform an investigation	• a considered rationale showing how the research question was developed from the claim • a research question that is specific and relevant • a collection of sufficient and relevant sources	6
analysis and interpretation	• Analyse the evidence sourced during the research. • Interpret the research evidence.	• detailed and careful coverage of relevant trends, patterns and relationships • detailed and careful coverage of the evidence 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 quality • extension of the 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 instrument-specific marking guide (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 ISMG are outlined below and shown for the Research and planning criterion. The table is an interpretation of assessment criteria. Just as with the student experiment, the ISMG is organised into:

- 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 two-mark range
- performance level descriptor.

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

Criterion: Research and planning

Objectives of assessment task

2 apply understanding of ... to develop research questions
5 investigate ... through research

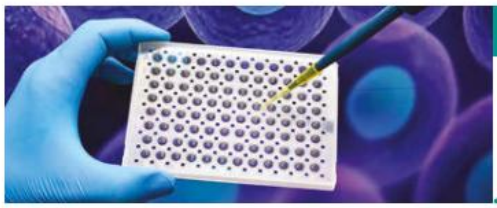
Key features that distinguish between marking levels:	Marks
• Applying an understanding of the subject matter in an informed way that demonstrates development of the research question from the claim • Applying an understanding of the subject matter in an informed way, that demonstrates careful consideration of the rationale for the question • Development of a research question that is specific and relevant from effective and efficient investigations • Using sufficient resources that are relevant in and effective and efficient investigation	5–6
• Applying an understanding of the subject matter in an adequate way that demonstrates links from the claim to the research question • Applying an understanding of the subject matter in an adequate way that demonstrates a reasonable rationale for the question • Development of a research question that is relevant from an effective investigation • Using resources that are relevant to an effective investigation	3–4
• Applying an understanding of the subject matter in a rudimentary way that demonstrates a weak rationale between the research question and the claim • Development of an inappropriate research question from an ineffective investigation • Using irrelevant and insufficient resources in an ineffective investigation	1–2
• Descriptors not addressed	0

Performance level

Examples of performance characteristics

Performance mark The performance indicator describes requirements to achieve marks.

1.12 Developing the research question from a claim



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

- analyse a claim to identify scientific concepts, variables and measureable terms within a claim
- develop a research question or hypothesis from a claim.

The research question should specifically address one of the concepts associated with the claim. It should clearly state the relevant variables. All the research conducted for the research investigation will be directly related to the research question. Therefore, the process begins with the claim and understanding the concepts it addresses.

UNDERSTANDING THE CLAIM

The Queensland Biology 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. The assertion has to be in isolation from any justification using data, research, evidence or reason from known information to support it. (Figure 1.12.1). Your teacher will provide you with a number of possible research claims. Your task will be to develop a research question based on one of these claims. Your research question will focus your investigation, making it necessary to gather evidence so that you can evaluate the claim.

FIGURE 1.12.1 An 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 the following:

- known scientific concepts
- variables
- measurable terms
- ideas related to concepts
- a term that is stated 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 characteristic 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 1.12.1 outlines an example of analysing and categorising elements of a claim.

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

TABLE 1.12.1 Three examples of analysing and classifying elements of a claim

Example 1		
Claim	Still, it's important to water your potted plants 3–4 times per week because the soil is likely to dry out more quickly.	**Classifying elements of the claim** Water • known scientific concepts—cellular and homeostatic processes use water (e.g. temperature, hydration, cellular respiration and photosynthesis) • variable in many concepts (plant growth, temperature, homeostasis, cellular respiration and photosynthesis) • measurable • water influences soil drying Water cycle • known scientific concept • measurable • related to concepts (plant growth, temperature, homeostasis, cellular respiration and photosynthesis) Soil drying • variable in plant growth and cellular respiration and photosynthesis • measurable • related to plant growth, cellular respiration and photosynthesis concepts Plants causing soil to dry more quickly • variables in growth, water cycle, cellular respiration and photosynthesis • measurable • related to growth, water cycle, cellular respiration and photosynthesis concepts
Source and context of claim	An article from the Iowa public radio website in reference to potting flowering plants in a container compared to traditional gardening in a garden bed	
Elements of the claim	• Water • Water cycle (3–4 times/week) • Soil drying • Plants causing soil to dry more quickly	
Example 2		
Claim	Purple rice could combat cancer, diabetes and heart disease but experts say it's too difficult to produce.	**Classifying elements of the claim** Purple rice • variable related to pigment and contents of rice • concept related to genetically modified organisms, nutrients, digestion and nutritional value • influences diabetes Diabetes • known scientific concept in disease, hormonal imbalance and homeostasis • measurable term (type I or II, blood insulin or blood sugar levels) • influenced by purple rice Combat diabetes • measurable term (blood insulin and sugar levels) • related to homeostasis, hormonal and disease concepts
Source and context of claim	A newspaper article in *The Sun* quotes Chinese researchers that genetically engineered rice can combat diabetes (and other diseases)	
Elements of the claim	• Purple rice • Diabetes • Combat diabetes • Difficult to produce	
Example 3		
Claim	... he is vaccine-injured ...	**Classifying elements of the claim** Vaccines • a known scientific concept Injury • a measurable term Immunisation and immunity • ideas related to vaccine concept
Source and context of claim	A *Daily Telegraph* newspaper article outlining a parent's claim regarding their son	
Elements of the claim	• Vaccines • Injury • Immunisation and immunity • Vaccine causes injury	

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.

After extrapolating and expanding the claim further into possible scientific elements, you can use each of these elements to form a question (Table 1.12.2). It is best to formulate a number of questions and write them all down in your journal. Each question must specify a dependent variable and enable a response that will evaluate the validity or the reliability of the claim.

This necessitates forming questions and using the elements of the claim in the phrasing of the research question. To complete this task, you will need to have an understanding of the dependent and independent variables in the elements of the claim. The claim may identify a dependent variable or independent variable; if not, they will be elsewhere in the material.

Some guidelines to help form a question are:

- finding a dependent variable or refining it by rephrasing the variable into something measurable
- choosing an element of the claim to become the independent variable, or identifying it in the material
- phrasing a question to ask if the independent variable will influence, cause or correlate with the dependent variable
- writing a few different questions. Usually the questions improve as you write more, which allows the formulation of a more developed research question.

Read through Table 1.12.2 to see examples of questions formed from the elements of the claims from Table 1.12.1.

TABLE 1.12.2 Three examples of formulated questions from a claim

Example 1	
Claim	Still, it's important to water your potted plants 3–4 times per week because the soil is likely to dry out more quickly.
Elements of the claim	**Water** Known concepts—cellular and homeostatic processes use water (e.g. temperature, hydration, cellular respiration and photosynthesis)
Formulated questions	• **A** Can plant homeostasis affect water in soil? • **B** Can plant photosynthesis affect the soil? • **C** Can the temperature of soil affect plant homeostasis?

Example 2	
Claim	Purple rice could combat cancer, diabetes and heart disease but experts say it's too difficult to produce.
Elements of the claim	**Purple rice** Variable related to pigment and contents of rice
Formulated questions	• **A** Can the pigments causing the purple colour of rice help diabetes? • **B** Are the nutrients causing the purple colour of rice related to insulin?

Example 3	
Claim	... he is vaccine-injured ...
Elements of the claim	**Immunisation and immunity** Are ideas related to vaccine concepts
Formulated questions	• **A** Can immunisation cause injuries? • **B** Can the immunity gained from vaccines cause injury?

REFINING THE RESEARCH QUESTION

As you conduct research into the concepts of the independent and dependent variables, new information will likely refine the question.

The process of developing a research question is often cyclical (Figure 1.12.2).

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.

The research question and the development of the research question from the claim using research, scientific concepts, knowledge and understanding is related to ISMG characteristics:

- **a carefully and deliberately constructed rationale identifying an easy to understand development of the claim from the research question**
- **a research question that is clear, and applicable and pertinent to the methodology**
- **selection of adequate, applicable and pertinent resources.**

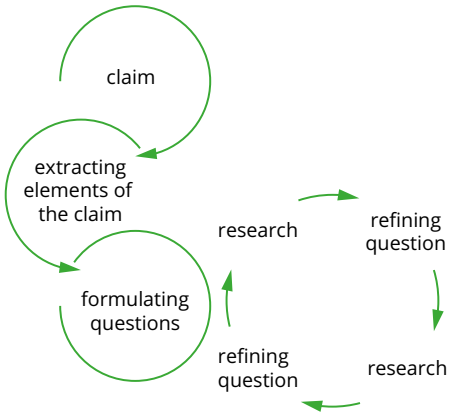


FIGURE 1.12.2 A diagram of a common process for developing a research question. This cycle can be repeated as many times as necessary until a scientist is satisfied with the investigation question.

During the research, continue to record your findings in your journal and make note of any ideas that may arise related to the questions. As you develop your knowledge and understanding about the variables, refine the research question to be more specific.

The goal is to develop the research question to a point in which exact data or evidence can be found regarding the variables in the question. Hence, it will develop into a research question when evidence from research can answer the question. Table 1.12.3 compares formulated research questions that were refined.

TABLE 1.12.3 Development of the original formulated questions into research questions

Example 1			
Claim	Still, it's important to water your potted plants 3–4 times per week because the soil is likely to dry out more quickly.		
Formulated questions	• **A** Can plant homeostasis affect water in soil?	• **B** Can plant photosynthesis affect the soil?	• **C** Can the temperature of soil affect plant homeostasis?
Refined research question	• **A** Can plant thermal homeostasis increase water loss from soil?	• **B** Can plant photosynthesis decrease the amount of water in soil?	• **C** Can the temperature of soil affect rate of plant transpiration?

Example 2		
Claim	Purple rice could combat cancer, diabetes and heart disease but experts say it's too difficult to produce.	
Formulated questions	• **A** Can the pigments causing the purple colour of rice help diabetes?	• **B** Are the nutrients causing the purple colour of rice related to insulin?
Refined research question	• **A** Can the pigments causing the purple colour of rice reverse type 2 diabetes?	• **B** Will purple rice affect the insulin response after a meal differently to normal rice?

Example 3		
Claim	... he is vaccine-injured ...	
Formulated questions	• **A** Can immunisation cause injuries?	• **B** Can the immunity gained form vaccines cause injury?
Refined research question	• **A** Can immunisation cause permanent neurological disorders?	• **B** Can the immunity gained from vaccines cause an allergy?

In your research investigation report, your recorded research in the journal will be used to write the considered rationale for the research question, displaying its clear development from the claim. Your research investigation report will outline its step-by-step development, justifying the steps that occurred in developing the research question using scientific concepts, knowledge and understanding.

The Syllabus glossary definition for 'specific' (required by the research investigation ISMG) is 'clearly defined or identified; precise and clear in making statements or issuing instructions; explicit'. The glossary defines 'relevant' as 'bearing upon or connected with the matter in hand; to purpose; applicable and pertinent; having a direct bearing on'.

Therefore, a specific research question must explicitly identify the dependent and independent variables. The research question must be connected to the considered rationale and the topic of study.

1.12 Review

SUMMARY

- A claim is an assertion made without any accompanying evidence to support it.
- Research questions and hypotheses can be developed from claims by identifying the underlying scientific concepts and variables of a claim.

KEY QUESTIONS

Retrieval

1 Define 'claim'.

2 State what a research question should explicitly identify.

Comprehension

3 Outline why a research question is refined.

4 Explain how refining a research question is related to finding evidence.

Analysis

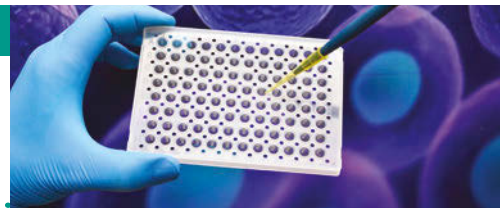
5 Formulate a question and then a hypothesis for the following claims.
- **a** Red wine stops cancer.
- **b** Chocolate kills dogs.
- **c** Global warming will kill domestic cats.

6 Specify how research and understanding will enable the research question to be relevant to the ISMG.

1.13 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 you gather scientific evidence for the research investigation, source it from reputable publications including:

- scientific journals: research papers and scientific reviews
- scientific articles written by organisations who apply scientific research to their industry
- commercial articles such as science magazines, newspapers and also websites.

Your research investigation report must include a reference list of cited resources. The resources used should be sufficient and relevant. The Biology syllabus defines sufficient as 'enough or adequate for the purpose', and relevant as 'bearing upon or connected with the matter in hand; to the purpose; pertinent; applicable and pertinent; has direct bearing on'. Figure 1.13.1 points out the features of sources deemed 'sufficient' and 'relevant'.

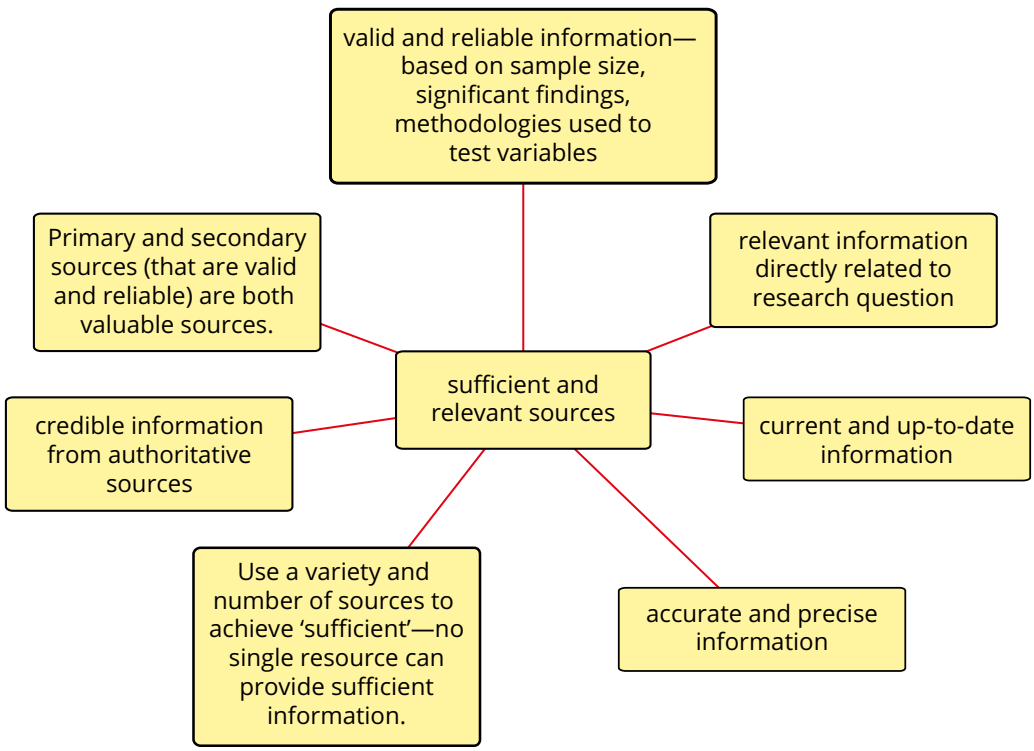


FIGURE 1.13.1 Features of sources suitable for the research investigation

SOURCING INFORMATION

Consider whether the information you use is from a primary or secondary source.

Primary and secondary sources

Table 1.13.1 summarises the characteristics of primary and secondary sources. Sometimes the same type of resource may be classified as both primary and secondary, depending on when and by whom it was written. For example, a scientist's journal article on a clinical trial of treatments for teenage obesity is a **primary source**, while a general magazine article about teenage obesity, written by a journalist and referring to the scientific study, is a **secondary source**.

TABLE 1.13.1 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

A primary source is written by the observer/witness of an event or the scientist who conducted the research. The information has only been processed by the original observer, so it is the least biased of all available sources of information. However, even primary sources may be biased, because the observer or researcher had to make choices related to the observation, control of variables, use of instruments and choices for processing data.

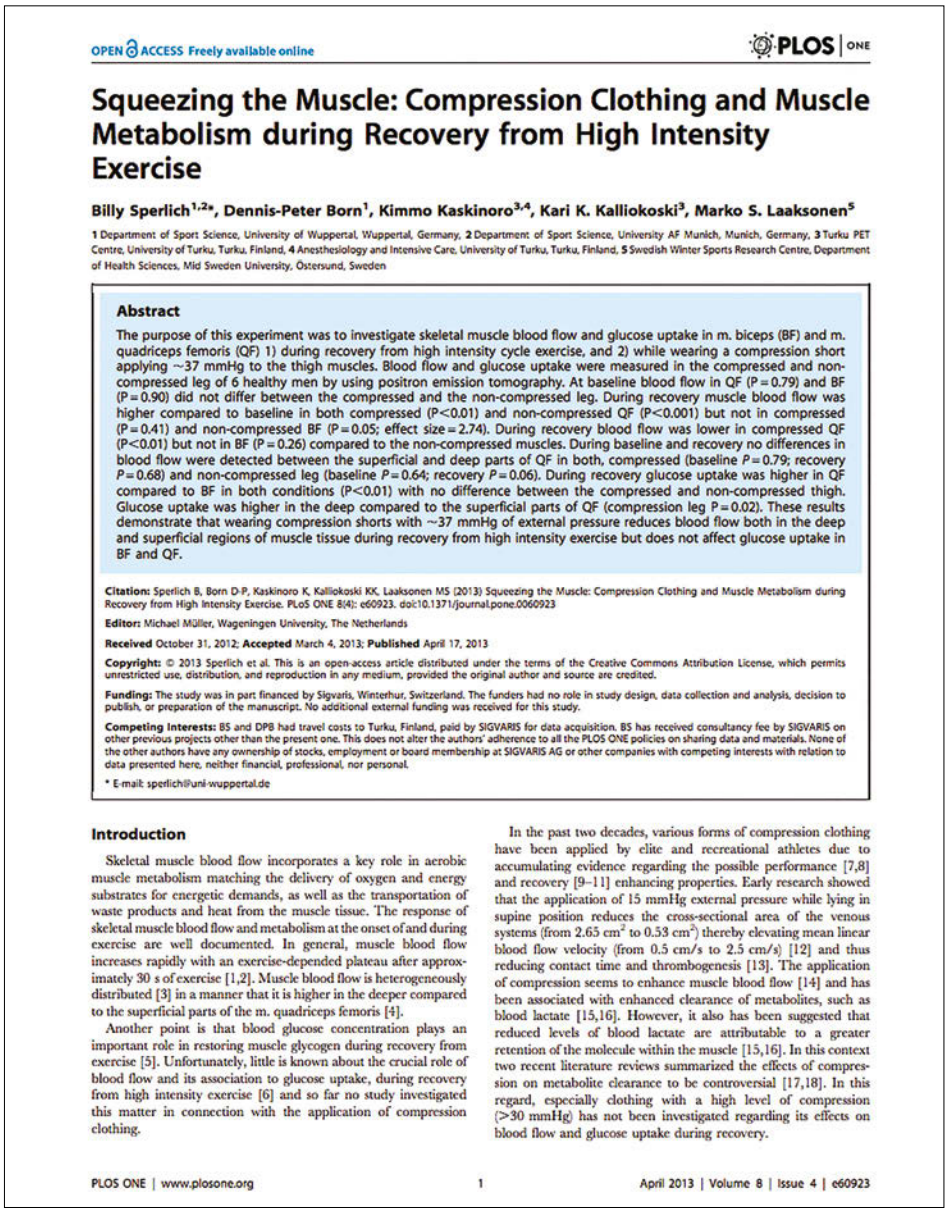
Secondary sources of information are not eye-witness accounts but interpretations of events by other people. As second-hand information, their accuracy and reliability may be reduced, and events may be interpreted through the writer's perception and bias. You should aim to use a wide range of data sources when using **secondary data**, to cross-check for accuracy, reliability and validity of information.

When searching for information and evidence, follow these guidelines.

1. Determine if it is a primary or secondary resource.
2. Confirm it is valid.
   - **a** Check that it contains information that is specifically related to the claim.
   - **b** Check that the evidence and information is pertinent to the variables in the research question.
3. Assess its reliability.
   - **a** Is it current/recent information?
   - **b** Is it up to date in its understanding of relationships?
   - **c** Is the evidence equivalent to other sources?
   - **d** Check its credibility—consider who the author is, their qualifications and expertise.
   - **e** Evaluate the methodology, including what variables were controlled or measured.

Articles in scientific journals

Peer-reviewed scientific journals are excellent sources of information. Journals are collections of scientific reports written by scientists who conducted research. The reports and articles in scientific journals are published primary sources, meaning they are the results of the experiments (Figure 1.13.2).



OPEN ACCESS Freely available online

PLOS ONE

Squeezing the Muscle: Compression Clothing and Muscle Metabolism during Recovery from High Intensity Exercise

Billy Sperlich[1,2]*, Dennis-Peter Born[1], Kimmo Kaskinoro[3,4], Kari K. Kalliokoski[3], Marko S. Laaksonen[5]

1 Department of Sport Science, University of Wuppertal, Wuppertal, Germany, 2 Department of Sport Science, University AF Munich, Munich, Germany, 3 Turku PET Centre, University of Turku, Turku, Finland, 4 Anesthesiology and Intensive Care, University of Turku, Turku, Finland, 5 Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Östersund, Sweden

Abstract

The purpose of this experiment was to investigate skeletal muscle blood flow and glucose uptake in m. biceps (BF) and m. quadriceps femoris (QF) 1) during recovery from high intensity cycle exercise, and 2) while wearing a compression short applying ~37 mmHg to the thigh muscles. Blood flow and glucose uptake were measured in the compressed and non-compressed leg of 6 healthy men by using positron emission tomography. At baseline blood flow in QF ($P = 0.79$) and BF ($P = 0.90$) did not differ between the compressed and the non-compressed leg. During recovery muscle blood flow was higher compared to baseline in both compressed ($P<0.01$) and non-compressed QF ($P<0.001$) but not in compressed ($P = 0.41$) and non-compressed BF ($P = 0.05$; effect size = 2.74). During recovery blood flow was lower in compressed QF ($P<0.01$) but not in BF ($P = 0.26$) compared to the non-compressed muscles. During baseline and recovery no differences in blood flow were detected between the superficial and deep parts of QF in both, compressed (baseline $P = 0.79$; recovery $P = 0.68$) and non-compressed leg (baseline $P = 0.64$; recovery $P = 0.06$). During recovery glucose uptake was higher in QF compared to BF in both conditions ($P<0.01$) with no difference between the compressed and non-compressed thigh. Glucose uptake was higher in the deep compared to the superficial parts of QF (compression leg $P = 0.02$). These results demonstrate that wearing compression shorts with ~37 mmHg of external pressure reduces blood flow both in the deep and superficial regions of muscle tissue during recovery from high intensity exercise but does not affect glucose uptake in BF and QF.

Citation: Sperlich B, Born D-P, Kaskinoro K, Kalliokoski KK, Laaksonen MS (2013) Squeezing the Muscle: Compression Clothing and Muscle Metabolism during Recovery from High Intensity Exercise. PLoS ONE 8(4): e60923. doi:10.1371/journal.pone.0060923

Editor: Michael Müller, Wageningen University, The Netherlands

Received October 31, 2012; **Accepted** March 4, 2013; **Published** April 17, 2013

Funding: The study was in part financed by Sigvaris, Winterhur, Switzerland. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. No additional external funding was received for this study.

Competing Interests: BS and DPB had travel costs to Turku, Finland, paid by SIGVARIS for data acquisition. BS has received consultancy fee by SIGVARIS on other previous projects other than the present one. This does not alter the authors' adherence to all the PLOS ONE policies on sharing data and materials. None of the other authors have any ownership of stocks, employment or board membership at SIGVARIS AG or other companies with competing interests with relation to data presented here, neither financial, professional, nor personal.

* E-mail: sperlich@uni-wuppertal.de

Introduction

Skeletal muscle blood flow incorporates a key role in aerobic muscle metabolism matching the delivery of oxygen and energy substrates for energetic demands, as well as the transportation of waste products and heat from the muscle tissue. The response of skeletal muscle blood flow and metabolism at the onset of and during exercise are well documented. In general, muscle blood flow increases rapidly with an exercise-depended plateau after approximately 30 s of exercise [1,2]. Muscle blood flow is heterogeneously distributed [3] in a manner that it is higher in the deeper compared to the superficial parts of the m. quadriceps femoris [4].

Another point is that blood glucose concentration plays an important role in restoring muscle glycogen during recovery from exercise [5]. Unfortunately, little is known about the crucial role of blood flow and its association to glucose uptake, during recovery from high intensity exercise [6] and so far no study investigated this matter in connection with the application of compression clothing.

In the past two decades, various forms of compression clothing have been applied by elite and recreational athletes due to accumulating evidence regarding the possible performance [7,8] and recovery [9–11] enhancing properties. Early research showed that the application of 15 mmHg external pressure while lying in supine position reduces the cross-sectional area of the venous systems (from 2.65 cm^2 to 0.53 cm^2) thereby elevating mean linear blood flow velocity (from 0.5 cm/s to 2.5 cm/s) [12] and thus reducing contact time and thrombogenesis [13]. The application of compression seems to enhance muscle blood flow [14] and has been associated with enhanced clearance of metabolites, such as blood lactate [15,16]. However, it also has been suggested that reduced levels of blood lactate are attributable to a greater retention of the molecule within the muscle [15,16]. In this context two recent literature reviews summarized the effects of compression on metabolite clearance to be controversial [17,18]. In this regard, especially clothing with a high level of compression (>30 mmHg) has not been investigated regarding its effects on blood flow and glucose uptake during recovery.

FIGURE 1.13.2 An extract of an article in a scientific journal, of a research report written by scientists. It follows a strict structure: an appropriate title; the names of the authors; an abstract; and the report, which includes introduction, method, results, analysis, conclusion and reference list.

You may find it difficult to access scientific journals because many journals require subscriptions or financial membership. However, some journals are free. Figure 1.13.3 on page e94 provides ideas for accessing scientific journals.

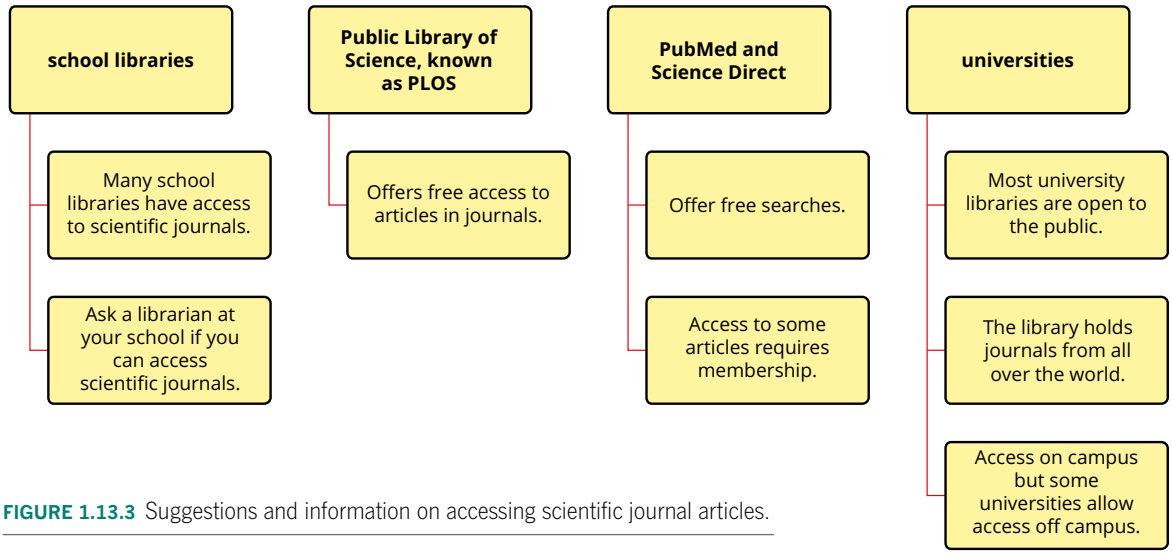


FIGURE 1.13.3 Suggestions and information on accessing scientific journal articles.

Table 1.13.2 outlines some advantages and disadvantages of sourcing and using articles in scientific journals for the research investigation.

TABLE 1.13.2 Advantages and disadvantages of using scientific articles for the research investigation

Advantages	Disadvantages
• written by experts • authoritative information (peer-reviewed) • most current information • logical, organised layout • content is relevant to the topic • contain an abstract that summarises all information in the article (if you don't find the information in the abstract, the article is not relevant) • primary source	• information is complex and challenging to understand—complex language and advanced processing and analysis of data • requires an understanding of scientific language and numeracy to understand • may be time-consuming to read and analyse • well-established concepts do not have recent published articles • may be difficult to locate

Books and physical publications

Secondary sources such as good science magazines and books are valuable sources of secondary information.

The first source you should use is your textbook. The language and concepts are presented specifically for high school students. In addition, the textbook addresses the syllabus objectives. Non-fiction books and magazines will probably be commonly used resources for the research investigation. Common commercial science magazines in your school library could include *New Scientist*, *Cosmos*, *Scientific American* and *The Helix* (Figure 1.13.4). Table 1.13.3 outlines some advantages and disadvantages of non-fiction books as sources for your research.

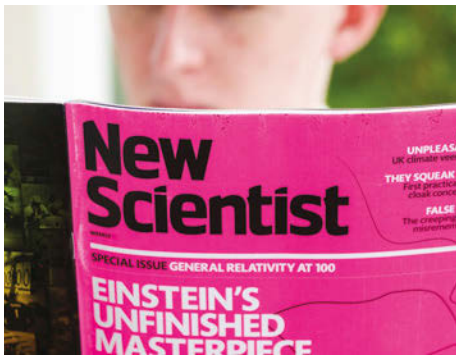


FIGURE 1.13.4 A science magazine you might find in your school library

TABLE 1.13.3 Advantages and disadvantages of using book resources for the research investigation

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 • can be accessed by only one person at a time • may have more bias than primary sources

Searching online

Online sources include online scientific organisations such as CSIRO, NCBI, AIMS, Bioscience (Oxford Academic) and other university publications and presses. Many government and privately funded science organisations publish material, as do not-for-profit scientific organisations. Websites may direct you to magazines and scientific journals, such as those described above, the news, podcasts, blogs and videos (institutional, company and personal).

Information on the internet must be very carefully scrutinised. The openness and ease of publishing on the internet means information may not be valid and reliable. Use the earlier guidelines (see page e92) to help you evaluate sources. Table 1.13.4 outlines advantages and disadvantages of locating and using information online.

When searching for relevant information, you will need to use a search engine and use appropriate search terms. Some tips when searching online include the following.

- Break your search statement into concepts and key words.
- Find synonyms, other related terms and concepts that apply to the topic.
- Create concepts of 1–3 words to enter into the search engine.
- Try different combinations of terms.
- Don't settle for the first sites on the list for 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, WEHI, NIH; .gov, .org), universities (.edu) and science journals and magazines.

TABLE 1.13.4 Advantages and disadvantages of using internet resources for the research report

Advantages	Disadvantages
• quick and easy to access • allows access to hard-to-find information • allows 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 become distracted by 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 • 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 make them more credible than other sources.

SKILLBUILDER

Evaluating sources for validity and reliability

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

These tables outline examples of evaluating a resource step by step, for a claim about the effect of temperature on enzyme activity

SOURCE EVALUATED: Observing single enzyme molecules interconvert between activity states upon heating—scientific research article

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	primary	• Research article published in PLOS • Research results published in article
Validity	Does it contain information that is specifically related to the claim?	yes	• Outlines information directly related to effect of temperature on enzyme structure and activity
	Is the evidence and information pertinent to the variables in the research question?	yes	• Information, experiment and results are specific to temperature (independent variable) and enzyme activity (dependent variable)
Reliability	Is it current/recent information?	yes	• Published January 2014
	Is it up to date in its understanding of relationships?	yes	• Information outlines fast dynamic changes to enzyme conformity (structure) due to temperature cited from recent resources (up to 2012).
	Is the evidence equivalent to other sources?	mostly	• Some results are new and previously untested, therefore provides new knowledge never before seen.
	Check credibility—consider who the author is, their qualifications and expertise		• Authors Marcin J. Rojek, David R. Walt are scientists from the Department of Chemistry, Tufts University, Medford, Massachusetts, USA • David R. Walt is the scientific founder of Quanterix, which funded the experiment
	Try to find the sample size	known	• 1000 individual samples for each temperature
	Try to establish what variables were controlled or measured	known	• Temperature (40°C, 45°C and 50°C) • Sample size • Solution concentrations (of all solutions) • Equipment (numerous pieces of equipment I do not understand) • Numerous others I do not understand

SOURCE EVALUATED: Bioninja enzyme activity

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	secondary	• General info with schematic diagrams
Validity	Does it contain information that is specifically related to the claim?	yes	• Effect of temperature on enzymes
	Is the evidence and information pertinent to the variables in the research question?	yes	• Temperature (independent variable) and enzyme activity (dependent variable)
Reliability	Is it current/recent information?	unknown	• No dates provided; however, corroborates with other sources
	Is it up to date in its understanding of relationships?	unknown	• Resources not listed; however, corroborates with other sources
	Is the evidence equivalent to other sources?	yes	• Equivalent to other sources
	Check credibility—consider who the author is, their qualifications and expertise	unknown	• No author published
	Try to find the sample size	unknown	• Not published
	Try to establish what variables were controlled or measured	unknown	• Not published

Test the skill

In researching the claim 'There is more than one way to photosynthesise', the article 'The photosynthetic process' at https://www.life.illinois.edu/govindjee/paper/gov.html was found. Evaluate this source in relation to its usefulness in investigating the claim. Use a table like those in the examples above, to make a judgement of the validity and reliability of the source.

SOURCE EVALUATED: The photosynthetic process https://www.life.illinois.edu/govindjee/paper/gov.html

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?		
Validity	Does it contain information that is specifically related to the claim?		
	Is the evidence and information pertinent to the variables in the research question?		
Reliability	Is it current/recent information?		
	Is it up to date in its understanding of relationships?		
	Is the evidence equivalent to other sources?		
	Check credibility—consider who the author is, their qualifications and expertise. Are they qualified?		
	Try to find the sample size		
	Try to establish what variables were controlled or measured		

1.13 Review

SUMMARY

- Scientific evidence for the research investigation can be sourced from numerous publications including scientific journals, scientific articles and commercial articles.
- A primary source is written by the observer/witness of an event, or the scientist who conducted the research.
- A secondary source is a document that refers to or analyses a primary source.

KEY QUESTIONS

Retrieval

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

a a newspaper article about global warming

b an experiment to investigate chemical changes when mixing combinations of chemicals

c an interview with a forensic scientist about using science in tracking criminals

d a website with information about genetic engineering

Comprehension

2 Use a graphic organiser to depict the characteristics of primary and secondary sources, and when to use each.

Analysis

3 You are learning about genetically inherited diseases and are searching for facts about cystic fibrosis. Determine which of the following resources should be the most valid, after applying the evaluation step-by-step guide in the Skillbuilder on pages e96 and e97. Explain your answer.

A the book *Cystic Fibrosis*, published in 1997

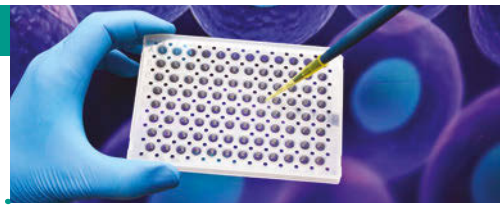
B the article 'Living with cystic fibrosis' published in the *Daily Mail* on 23 February 2008

C the website www.cysticfibrosis.org.au, accessed on 30 October 2015

1.14 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, you should keep a journal to 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 research investigation report. There is no need to produce new work because it is already completed in the journal.

Scientists organise their journal notes to record the:

- 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 beginning of the work you are doing. This is how professionals catalogue and file information. When trying to find previous work completed, most people try to remember 'when' they completed the work. They think 'I'm sure I did the research of Y after I found the information on X last week'. Always date your work and research; it will become a simple yet effective filing system.

Many professionals use a couple of cataloguing systems when they are recording information in their journals. They usually record the date of entries and provide 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 recording the source.

RECORDING JOURNAL ENTRIES

Each journal entry should follow a cataloging system; most typically this is the date and a title. A reference point or cataloging 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 which 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. Later they may:

- save you time by:
  - preventing you from 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
- provide links between concepts in the future that are currently unknown
- provide answers (or partial answers) to future issues, conceptual blocks and questions
- develop understanding of unrelated concepts that become pertinent later.

The content and recordings in your journal will not be in a logical conceptual order, as are your class notes or a textbook. This is because you are researching unfamiliar knowledge and you won't know how it all fits together until the research is complete. The journal will contain all you need to complete the report later. Before you add an entry to your journal, make sure you have recorded the date and provided your own title for the entry.

Researching 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 you are not tempted to plagiarise when you write up the research investigation.

It can be difficult sometimes to paraphrase (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 understand its meaning. 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. In your journal, your notes should be detailed with extended explanations that you will fully comprehend when you refer back to them at a future date. See Worked example 1.14.1 for a few examples of re-wording information.

Worked example 1.14.1

RE-WORDING INFORMATION FROM SOURCES

An information source states that:

'It can be expected that the days will be warm and the nights will be cool over the next 3 days due to the high-pressure system moving across the region.'

Re-word this information into your own words.

Thinking	Working
Can swap the order of information, the object (the warm days and cool nights) with the reason (high pressure system).	Due to the high-pressure system moving across the region, the days will be warm while the nights will be cool.
Can change numerous words such as adjectives, verbs, adverbs and nouns.	It has been predicted that during the daytime it will be warm while the evenings will be cool for about 3 days, as a high-pressure system travels over the region.
Can elaborate on the information to explicitly outline explanations.	The weather forecast expects (made a prediction based on computer simulations) that the temperature during the day will be warm (22–25°C) and the evenings will be cool (below 12°C) due to a high-pressure system (weak high-pressure system), which dissipates clouds and allows direct sunshine to warm the Earth's surface. However, in the evenings this system brings cool air from higher altitudes that is no longer warmed by the Sun.

➤ Try yourself 1.14.1

RE-WORDING INFORMATION FROM SOURCES

An information source states that:

'This will be followed by a low-pressure system which will bring cooler days and not so cool nights.'

Re-word this information into your own words.

Personal explanations and interpretation

Your journal is a valuable tool that is personal to you. As such, it should be written and displayed in formats that you understand and that make meaning of information to produce the research investigation report. It can include writing, drawings and schematics (e.g. flow charts).

Sometimes, one form of recording information provides more details than others. The details are not only 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 encapsulate more comprehensive details. Figure 1.14.1 presents the same information in a few different ways.

a

Protein is synthesised using coded information from DNA. The DNA code is replicated into an RNA strand which is transported to the ribosome (which is at the endoplasmic reticulum). Here the ribosome uses the coded information to build a protein.

b

DNA is copied into RNA (coded information)

↓

RNA transported to Endoplasmic recticulum and Ribosome

↓

Ribosome uses coded information to build protein

c

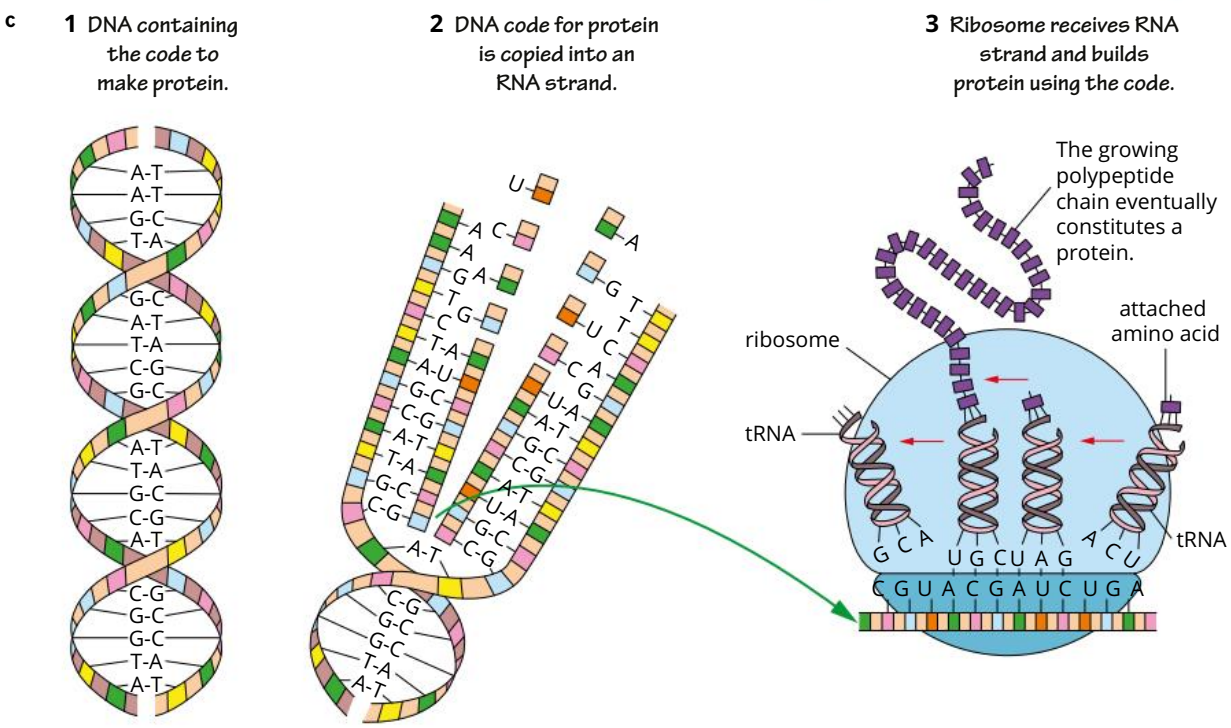


FIGURE 1.14.1 Three ways of recording the same information in a journal: (a) a written summary on protein synthesis; (b) a flow chart showing protein synthesis as a schematic; (c) a diagram explaining protein synthesis

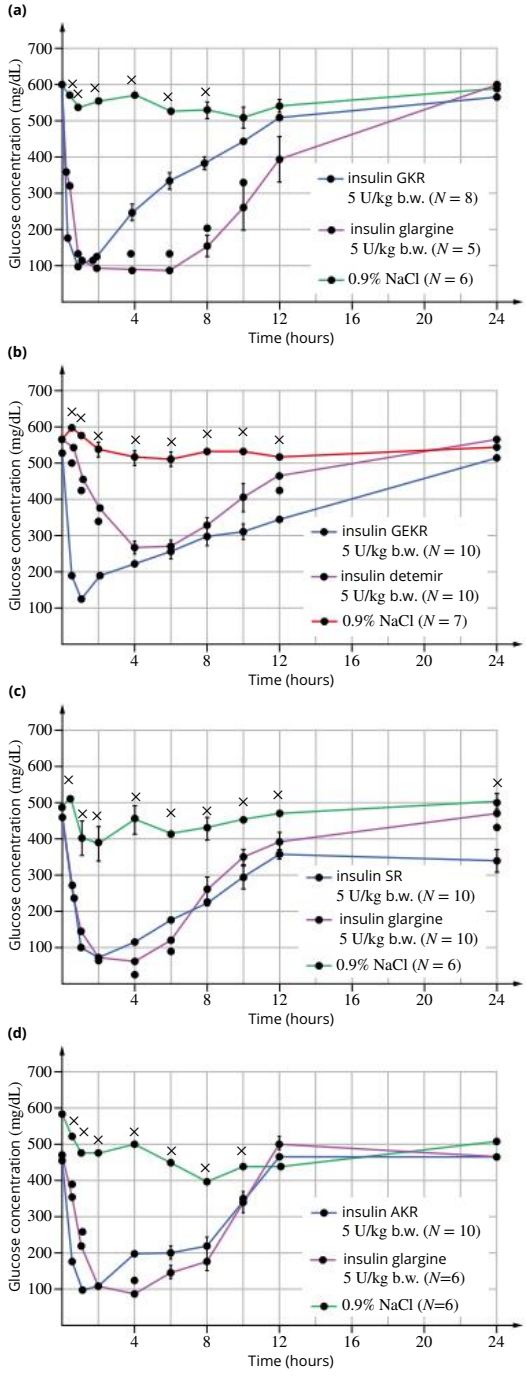
Results, data and evidence

When you find scientific results, data or evidence in a resource, it is important to record the values or reproduce them in the journal. Figure 1.14.2 shows examples of research evidence and how they can be reinterpreted for a journal entry. Along with the results, data or evidence includes:

- 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.

When making journal entries of data, statistics and methods (e.g. R^2 value, **confidence interval**, standard deviations or Pearson coefficients), it is important that you express the 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.

a



b

6/7/17

Data analysis

Fig 3 a-d Glycaemia profiles personal interpretation:

Each graph shows how much glucose is in the blood after being injected with a substance (over time). Each graph compares the amount of glucose removed from the blood by a control insulin molecule (already manufactured by companies for diabetics), a new insulin molecule (genetically engineered) and salt.

Graph a)

- Green line salt. Did not remove much glucose from the blood when injected.
- Blue line = insulin GKR 5 (genetically engineered). Removed a lot of glucose from the blood, then returned to normal reasonably quickly over 12min.
- Purple line = insulin glargine (typical manufactured molecule). Removed a lot of glucose from the blood, then returned slowly to normal by 20min.
- Crosses and black circles above data is significant according to $p < 0.5$

What does $p < 0.05$ mean:

Is a statistical calculation that estimates the probability of something occuring within natural variation (assuming a null hypothesis). Here, it is the probability that no difference will exist (except natural variation) between the salt and insulin results and also the GKR5 and glargine results. The crosses and black circles mean the probability of natural variation causing the results in less than 5%.

These results mean that there is more than a 95% chance that these results are due to the independent variable (the different type of insulin). (source: http://www.stasdirect.com/help/basics/p_values.htm)

FIGURE 1.14.2 The interpretation of original primary evidence from a research journal article: (a) primary evidence displayed in graphs with statistics; and (b) student's interpretation in their journal

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.

Table 1.14.1 shows what information to record about sources you use.

TABLE 1.14.1 Information that should be recorded about sources used in the research report

Books	Online
• author/s • title • date of publication • publisher • place of publication • page/s	• author/s or name of organisation • title • date website was written or updated • date website was accessed • website address (URL)

1.14 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 on the basis of previous experimentation and results.

KEY QUESTIONS

Retrieval

1 List the information that should be recorded about an online source in your journal.

Comprehension

2 Explain the benefit of keeping a scientific journal.

Analysis

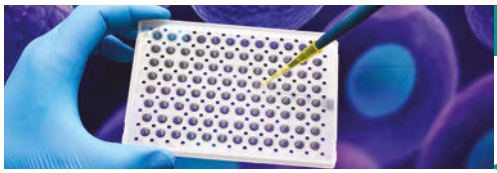
3 Rewrite the following text in your own words.

a A group of patients was administered adrenaline during a cardiac arrest to determine if adrenaline would improve patient outcomes. There was no statistically significant improvement in patient outcome between patients who received adrenaline and those who did not.

b A team of scientists from the Oregon Health and Science University and Korea's Institute for Basic Science successfully repaired a defective gene in human embryos. The gene that was targeted caused a heart defect, known as hypertrophic cardiomyopathy, which causes sudden death in young adults.

c This study found that water temperature had no significant effect on the amount of bacteria remaining on hands after washing. Rather, the length of time spent scrubbing hands, as well as the vigour of scrubbing, had the most effect on removing bacteria from hands.

1.15 Writing a report for the research investigation



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

- write a report for your research investigation
- write a literature review for your research investigation.

There are many ways to present your report of your research investigation. A written report should be 1500–2000 words long and can include a literature review, an empirical essay and an annotated bibliography. Alternatively, you can create a poster or a multimodal presentation of 9–11 minutes in length. This is not an exclusive list. Even though there are many ways to present your report, it must follow a scientific genre and meet the requirements of the Biology syllabus.

Writing a research investigation report requires scientific communication and you will need to follow scientific genre conventions. An explanation of these requirements has been provided in Module 1.11. A report should 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, while the focus of the research investigation is to explore a claim.

Table 1.15.1 summarises the characteristics of the genres for presenting the research investigation. This module focuses on the literature review.

TABLE 1.15.1 Summary of features of presentation genres for the research investigation

Science presentation genre	Brief description	Features
literature review	A report that evaluates information found in a publication, related to the selected topic. The report gives a theoretical base for the claim (question), and analyses and interprets information/data related to the claim. The objective is to point out strengths and weaknesses of the claim.	• Abstract • Introduction to topic, providing context • Discussion of information/data • Analysis of information/data • Evaluation of information/data • Conclusion related back to claim • Presented as paragraphs that flow on in a logical development of ideas • Uses subheadings
empirical essay	Very similar to a literature review.	
annotated bibliography	Notes, comments and explanations about article(s). An evaluation of a claim after investigating how other sources treat the claim.	
poster	An oral presentation accompanies the poster. Poster presents ideas concisely and clearly. These ideas are elaborated upon in the oral presentation.	• Includes all the above • Visual, oral and text presentation • Uses font size, colour, dot points, subheadings, logical flow of information to effectively deliver information

LITERATURE REVIEW

A literature review usually includes an introduction, a body and a conclusion. It critically analyses information and convinces the reader of the significance or importance of the topic being investigated. This is achieved by presenting information in a logical sequence that guides the reader through the material to understand its significance. The research question provides the foundational direction and guidance of the literature review.

Qualities found in a literature review

Not all qualities and elements of a full literature review will be appropriate for the research investigation. The literature review will be limited to the word count and ISMG characteristics in the syllabus. Depending on the research question and the topic being investigated, your literature review may:

- determine the current understanding of the topic
- provide an overview of key concepts (relevant to the research question)
- identify important relationships between variables (specific to variables that influence the independent or dependent variables stated in the research question)
- identify strengths and weaknesses of evidence in the information used for the above points
- identify any gaps in the research
- identify any conflicting evidence.

One of the key qualities of a literature review is that it is a critical analysis of the evidence to communicate a true understanding of the 'big picture' about a topic. It does not just summarise information. Very few phenomena are witnessed in science, especially biological science, so facts are not exactly known. Science is more about models, theories, laws and principles, and their continual development. The literature review should critically analyse evidence, both strengths and weaknesses, as well as the gaps and conflicts to convince the reader about the current state of a large jigsaw puzzle of conceptual relationships.

A literature review should:

- critically analyse the evidence—establish what it means and account for the statistical processing of data used (be sure to analyse the methodologies, samples, results and data processing and analysis)
- discriminate between relevant and irrelevant sources and content—only use the relevant in the literature review
- logically inform and convince the reader—plan the introduction, body and conclusion.

There is no strict rule about the number of articles you should consult for the research investigation. The term 'sufficient' is defined by the QCAA Biology syllabus as 'enough or adequate for the purpose'. The purpose of the research investigation is to evaluate the claim. Therefore, if the number of articles enables you to draw a justified conclusion about the research question and explore both sides of the argument, then the number of sources is sufficient. Relevant research is that which is connected to the rationale and unit under study.

A thorough analysis requires complete attention to every detail. Therefore, the research should include analysis and synthesis from different sources. It should identify patterns, trends and relationships that are related to the investigation. Also, it should be explicitly connected to the research question as well as clarify where the sources agree and disagree.

The analysis should identify all the limitations of the research because this may affect how valid the information (primary or secondary) is to the research question. Do not analyse data and its limitations in a way that only demonstrates what you want to show. Such bias will result in an inappropriate and erroneous conclusion that is invalid. Quality scientific analysis is open to any result.

Justified scientific arguments are those that are supported by sound reasons or evidence. Therefore, you must apply your scientific understanding and conceptual knowledge to the evidence that you have examined.

You should consider the following factors.

- State whether a pattern, trend or relationship was observed between the independent and dependent variables.
- Describe what kind of pattern it was and specify under what conditions it was observed.

- Note and explain any deviations in the data or information.
- Identify any limitations in the data or information researched. Why and how do these limitations affect the validity to the research question or conclusion?

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

Conclusion and evaluation

In the conclusion, the discussion should include an understanding of the features of the evidence that limit its usefulness. For example, did the sampled population reflect the population referred to in the research question? Is the data from measured samples or from estimated models? Did the studies occur under different conditions or categorise the independent variables differently so comparison was impossible?

The above questions require a justified discussion that evaluates 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 validity, accuracy, precision and reliability of evidence
- stating sources of systematic and random errors
- recommending improvements to the evidence to improve validity.

In the discussion, you should recommend improvements to the investigation that are linked to the evidence and would address the limitations and gaps in knowledge that have been identified during the research investigation. Your suggestions must be connected to the claim and allow further investigation.

Communication

This section will provide a guide to writing an appropriate scientific report and some of the general conventions that need to be followed for a literature review.

Once a plan for the literature review has been developed, word limit guides can be assigned to each section (Figure 1.15.1). The notes in your research journal will give you a good idea of which sections will require more words for explanations than others. The journal will also help you make decisions on which figures, data and evidence to include and 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 limit guide is not binding. As you complete your review you can alter the word guide and distribution of the word count if you feel it is necessary. However, make sure the limit outlined in the syllabus is never exceeded.

Planning the research investigation report will help address the syllabus ISMG. Figure 1.15.1 illustrates how planning can to be done to ensure the syllabus ISMG is addressed.

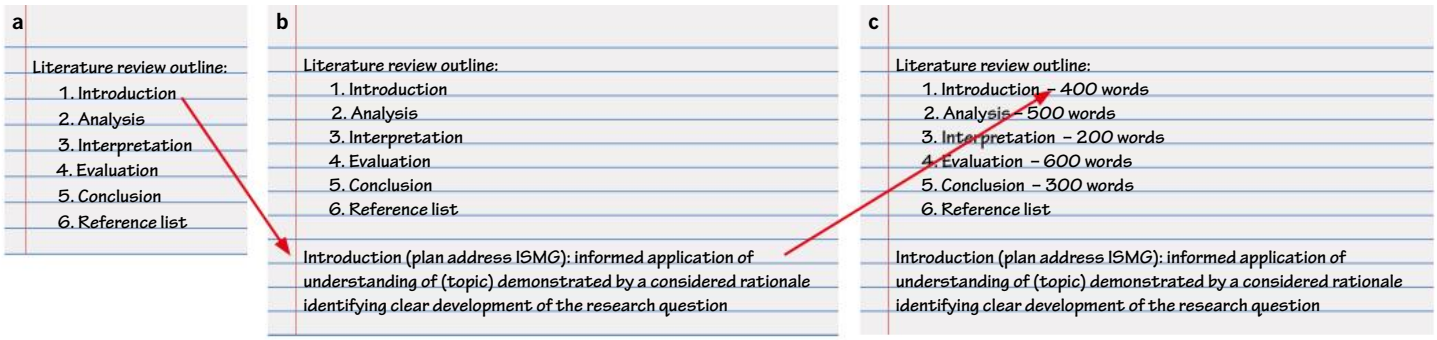


FIGURE 1.15.1 Planning the literature review. (a) A planned outline of the research investigation report to ensure the syllabus ISMG is addressed. (b) Assigning the ISMG characteristics to the sections in the planned outline. (c) The word count guide planned.

Structure of a written report

Although the use of headings in scientific reports is essential to guide and direct scientists to particular information, there is no single correct convention for a scientific report. A typical structure includes an introduction, body, conclusion and reference list.

Edit the report after you have completed it. Editing is an important part of the process. After editing your report, save new drafts with 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. When reading your own work, do not read it as what you intended to write it but what you have actually written. Reading the report out aloud to yourself will help you 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).

1.15 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 State the convention for the literature review genre.

Comprehension

2 Explain the purpose of a literature review.

3 Outline how you would achieve an analysis of the methodologies, samples and results in a literature review.

UNIT 1 Cells and multicellular organisms

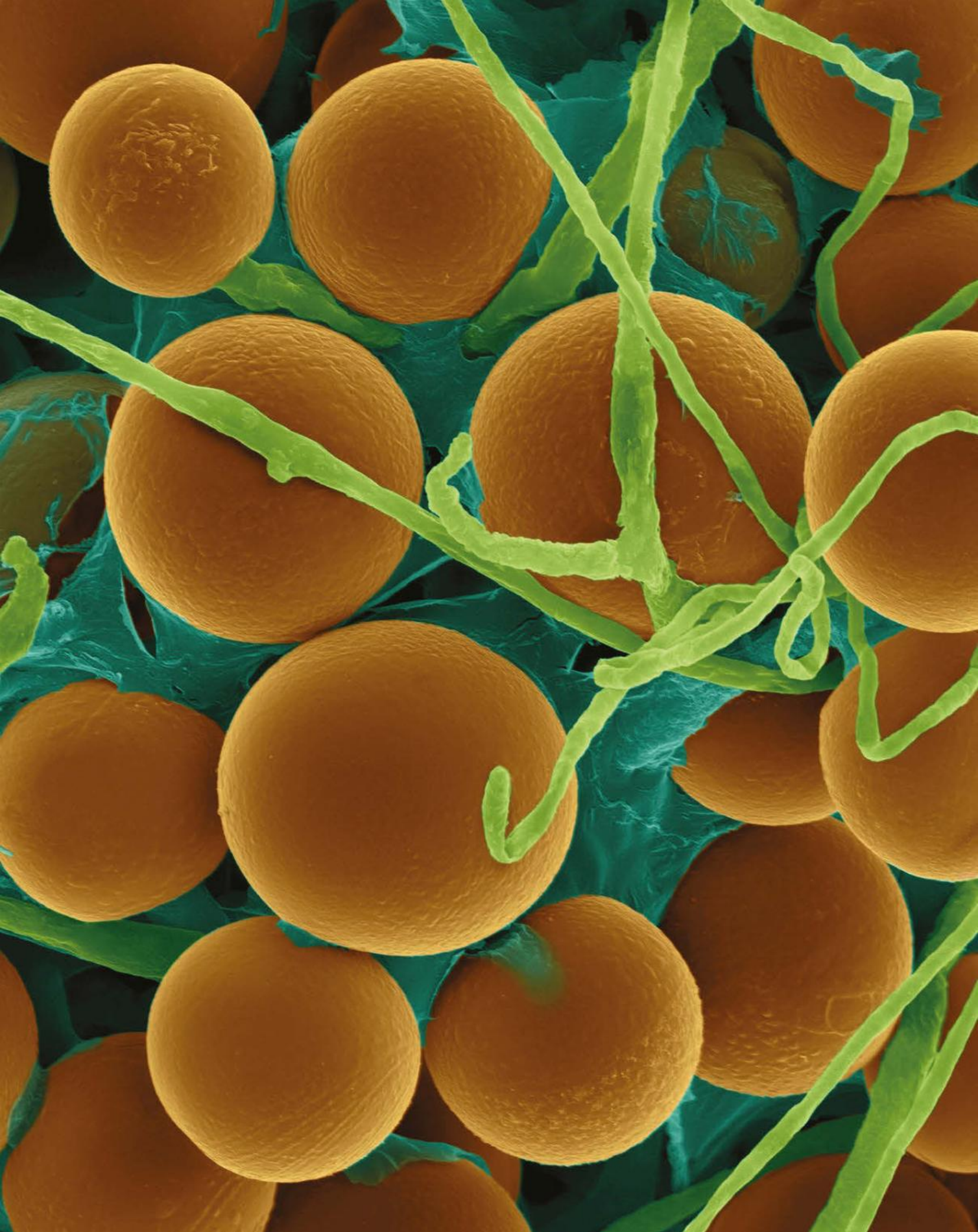
TOPIC 1 Cells as the basis of life

TOPIC 2 Multicellular organisms

Unit 1 objectives

Students will:

- describe and explain cells as the basis of life, and multicellular organisms
- apply understanding of cells as the basis of life, and multicellular organisms
- analyse evidence about cells as the basis of life, and multicellular organisms
- interpret evidence about cells as the basis of life, and multicellular organisms
- investigate phenomena associated with cells as the basis of life, and multicellular organisms
- evaluate processes, claims and conclusions about cells as the basis of life, and multicellular organisms
- communicate understandings, findings, arguments and conclusions about cells as the basis of life, and multicellular organisms.



CHAPTER

02 The fundamental cell

By the end of this chapter, you will understand the importance of cells as the basic structural and functional units of life on Earth and how the development of new technology continues to enhance our understanding of the structure of the cell and cellular processes. You will learn about the components of different types of cells, and how the structures and systems of cells function to sustain life. You will also have an understanding of the fluid mosaic model of the cell membrane and of the different processes by which a cell moves substances across this membrane.

Syllabus subject matter

WS 1.1.1

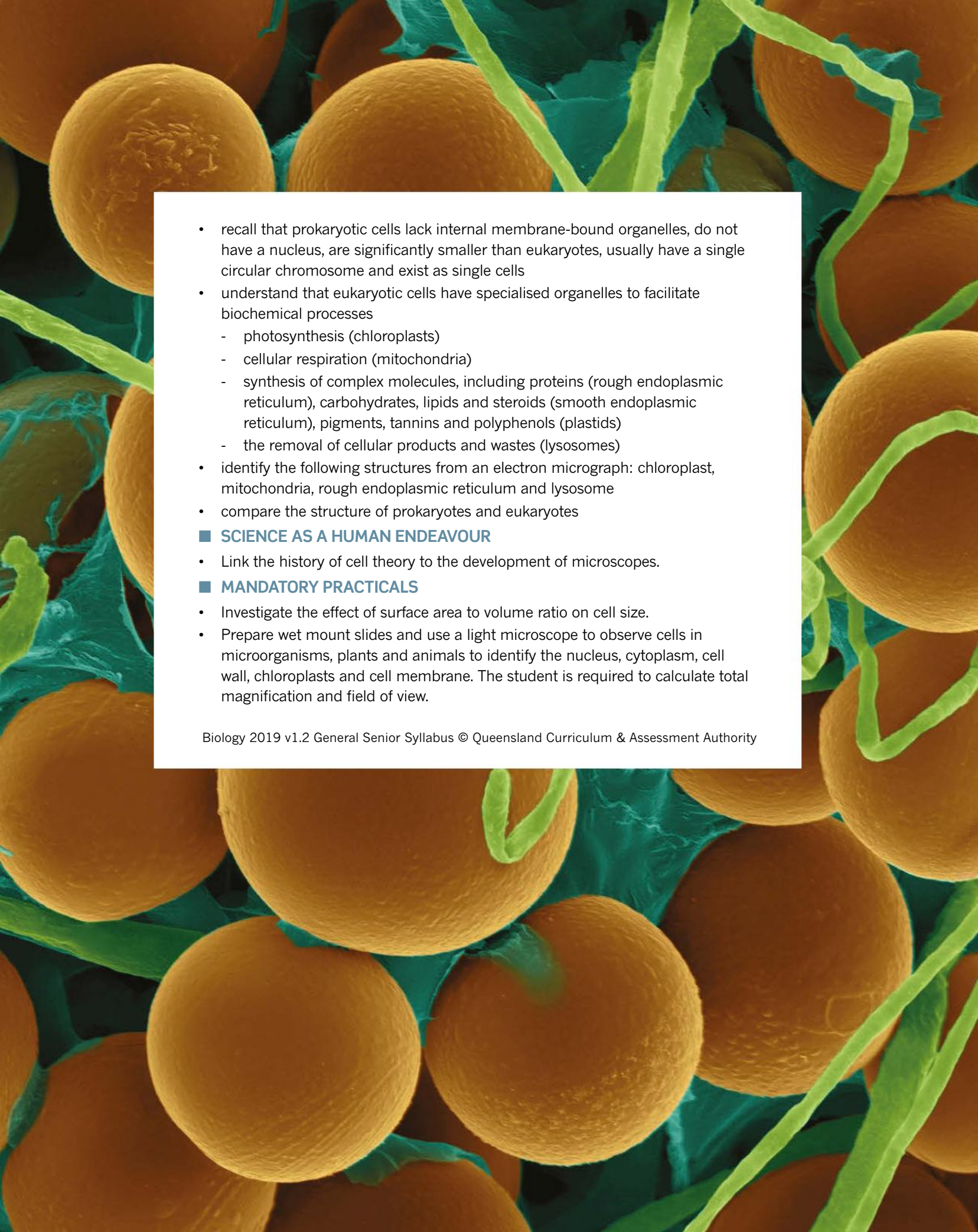
Topic 1 • Cells as the basis of life

CELL MEMBRANE

- describe the structure of the cell membrane (including protein channels, phospholipids, cholesterol and glycoproteins) based on the fluid mosaic phospholipid bilayer model
- describe how the cell membrane maintains relatively stable internal conditions via the passive movement (diffusion, osmosis) of some substances along a concentration gradient
- explain how the cell membrane maintains relatively stable internal conditions via the process of active transport of a named substance against a concentration gradient
- understand that endocytosis is a form of active transport that usually moves large polar molecules that cannot pass through the hydrophobic cell membrane into the cell
- recognise that phagocytosis is a form of endocytosis
- predict the direction of movement of materials across cell membranes based on factors such as concentration, physical and chemical nature of the materials
- explain how the size of a cell is limited by the relationship between surface area to volume ratio and the rate of diffusion

PROKARYOTIC AND EUKARYOTIC CELLS

- recognise the requirements of all cells for survival, including:
  - energy sources (light or chemical)
  - matter (gases such as carbon dioxide and oxygen)
  - simple nutrients in the form of monosaccharides, disaccharides, polysaccharides
  - amino acids, fatty acids, glycerol, nucleic acids, ions and water
  - removal of wastes (carbon dioxide, oxygen, urea, ammonia, uric acid, water, ions, metabolic heat)
- recognise that prokaryotic and eukaryotic cells have many features in common, which is a reflection of their common evolutionary past



- recall that prokaryotic cells lack internal membrane-bound organelles, do not have a nucleus, are significantly smaller than eukaryotes, usually have a single circular chromosome and exist as single cells
- understand that eukaryotic cells have specialised organelles to facilitate biochemical processes
  - photosynthesis (chloroplasts)
  - cellular respiration (mitochondria)
  - synthesis of complex molecules, including proteins (rough endoplasmic reticulum), carbohydrates, lipids and steroids (smooth endoplasmic reticulum), pigments, tannins and polyphenols (plastids)
  - the removal of cellular products and wastes (lysosomes)
- identify the following structures from an electron micrograph: chloroplast, mitochondria, rough endoplasmic reticulum and lysosome
- compare the structure of prokaryotes and eukaryotes

SCIENCE AS A HUMAN ENDEAVOUR

- Link the history of cell theory to the development of microscopes.

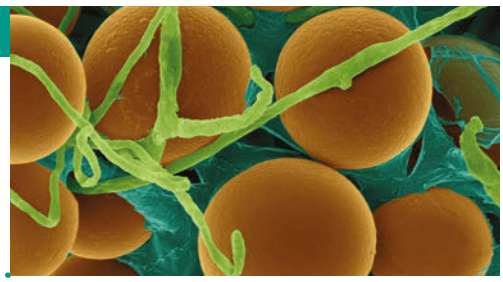
MANDATORY PRACTICALS

- Investigate the effect of surface area to volume ratio on cell size.
- Prepare wet mount slides and use a light microscope to observe cells in microorganisms, plants and animals to identify the nucleus, cytoplasm, cell wall, chloroplasts and cell membrane. The student is required to calculate total magnification and field of view.

2.1 Cell theory and microscopy

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

- understand the importance of cells as the basic structural and functional units of life on Earth
- understand the difference between light microscopy and electron microscopy
- calculate magnification of microscope images and field of view.



Cells are the basic structural units of all living things. The cell theory is one of the fundamental principles of biology. It is based on microscopic and experimental studies of tissues, from all types of organisms, carried out over the last 300 years.

In this module, you will learn about cell theory, the differences between plant and animal cells, and the microscopy techniques that are used to view cells and their components.

CELL THEORY

The cell theory was developed over hundreds of years by scientists of various nationalities and depended on the technology available at the time.

Cells are the basic structural units of living organisms. The cell theory states that:

- all organisms are composed of cells
- all cells come from pre-existing cells
- the cell is the smallest living organisational unit.

BIOGENESIS

The cell theory states that all cells arise from pre-existing cells. This is known as **biogenesis**.

Until the 1850s, the idea of spontaneous generation was accepted as the origin of small organisms, such as maggots. According to the theory of spontaneous generation, some organisms could suddenly form from certain types of matter, such as a grain of sand or dead flesh.

However, experiments by Francesco Redi on maggots in the 17th century and Lazzaro Spallanzani on microorganisms in the 18th century refuted spontaneous generation. These scientists showed that the presence of maggots and microorganisms was a result of contamination rather than spontaneous generation.

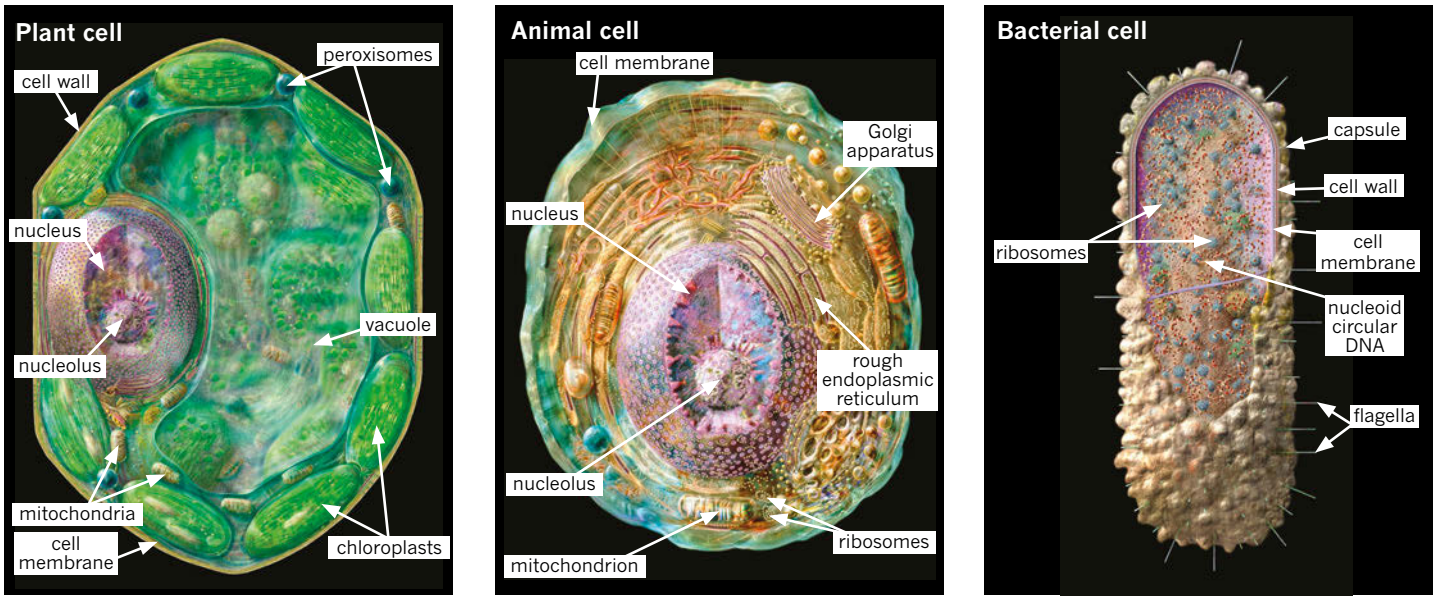


FIGURE 2.1.1 The cells in a plant, an animal and a bacterium have common features, including a cell membrane, cytoplasm, DNA and ribosomes. Not all features are visible here.

THE CELL

Cells are the basic structural unit of all living things. There are two fundamentally different cell types: prokaryotic cells and eukaryotic cells. The differences between the types of cells are explained in more detail in the next module.

Although there are different types of cells, the cells of plants, animals and bacteria have a number of common features. Some of these features are shown in Figure 2.1.1 and include:

- a **cell membrane**, which separates the interior of the cell from the outside environment
- **cytoplasm**, which consists of the **cytosol** and, in eukaryotes, the **organelles**; cytosol is a gel-like substance that is made up of more than 80% water and contains ions, salts and organic molecules
- **DNA** (**deoxyribonucleic acid**), which carries hereditary information, directs the cell's activities and is passed accurately from generation to generation
- **ribosomes**, which are organelles responsible for the synthesis of **proteins**.

Cells contain **organelles**, which have specialised functions. Organelles are subcellular structures involved in specific functions of the cell. This compartmentalisation of the cell ensures that the chemical processes of the cell can occur efficiently. Each organelle is functionally and structurally distinct. Organelles are surrounded by membranes to separate their processes from other parts of the cell and to provide an optimal cellular environment for the biochemical reactions occurring in the cell. Prokaryote cells do not contain any membrane-bound organelles.

Proteins are large molecules composed of one or more polypeptides. Polypeptides are long, chain-like molecules consisting of many amino acids linked together.

CELL SIZE

Cells vary greatly in size, as can be seen in Figure 2.1.2. Most cells are microscopic and, thus, you need a microscope to see them. Cell size is usually measured in micrometres. There are 1000 micrometres (μm) in 1 millimetre (mm). There are exceptions, such as the egg cell of some bird species, which can be many centimetres in diameter. Some typical cell sizes are as follows:

- bacterium: 0.1–5 μm long
- human: 10–200 μm long
- *Paramecium* (a single-celled eukaryote): about 150 μm long.

The thickness of cell membranes also differs and can be between 0.004 and 0.1 μm.

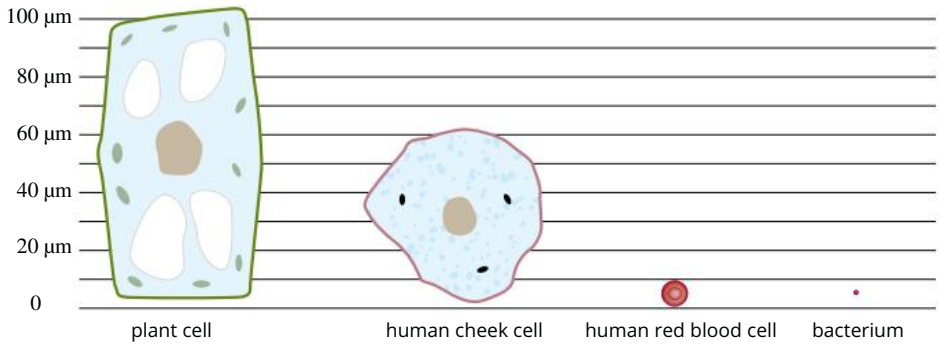


FIGURE 2.1.2 A typical plant cell, human cheek cell, human red blood cell and bacterium. Note the great difference in size between the eukaryotic cells and the prokaryotic cell (bacterium).

The size of the cell is determined by its ability to efficiently move substances into, out of and around the cell. Unicellular (single-celled) organisms, such as bacteria, must be able to absorb their requirements from their environment quickly and then move these materials around the cell to perform the necessary functions of life. These functions include basic metabolic processes such as cellular respiration, homeostasis and reproduction. However, as cells become larger, this movement becomes less efficient. Multicellular organisms have overcome this problem by developing complex transport systems to ensure that each cell is efficiently supplied with the nutrients and gases needed to sustain life.

Units of measurement

The development of sophisticated microscopy technology to observe cells and intracellular particles has allowed scientists to measure increasingly smaller objects (Figure 2.1.3). This has led to the development of appropriate units of measurement to describe microscopic lengths.

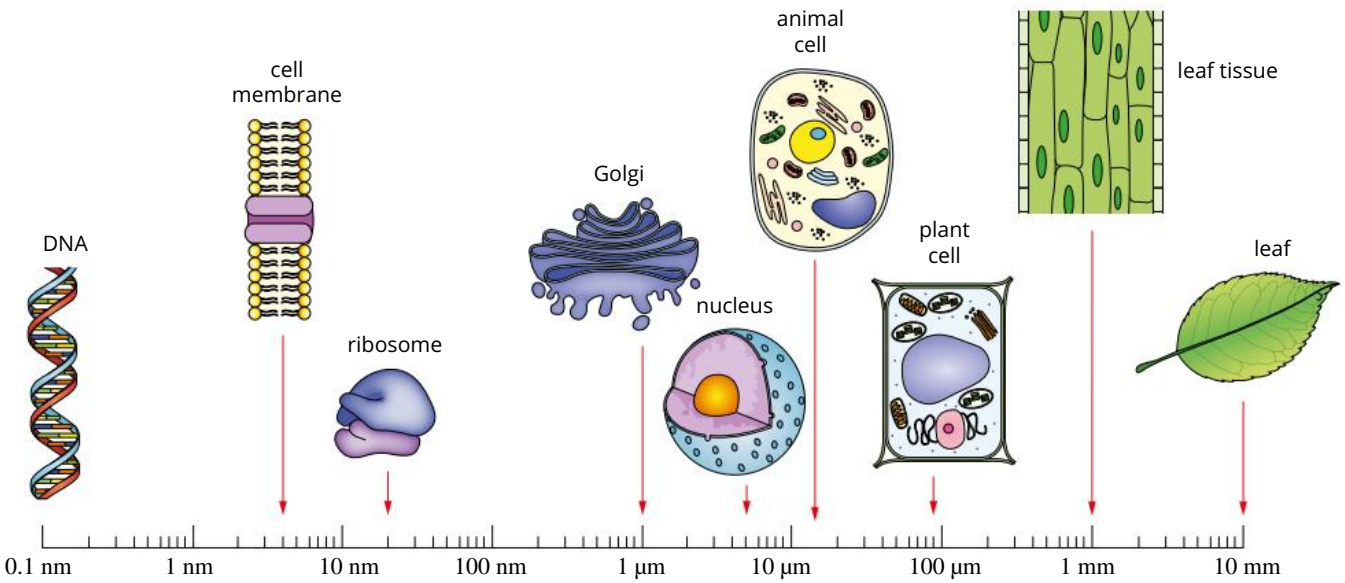
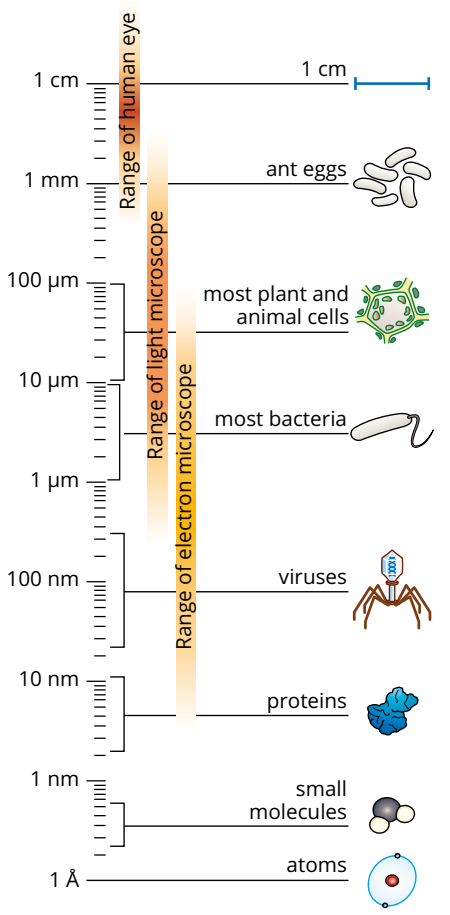


FIGURE 2.1.3 The scale shows the range of size of a variety of cells, organelles and molecules within a cell. The scale is logarithmic to accommodate the range of sizes shown.



$1\ cm = 10\ mm = 10^4\ \mu m = 10^7\ nm = 10^8\ Å$

FIGURE 2.1.4 A comparison of the ranges of the light and electron microscopes (the scale is logarithmic)

In the International System of Units (SI units), the unit for length is the metre (m). Table 2.1.1 illustrates the derivation of the smaller units of length in relation to the metre. Refer to Chapter 1 (Part A) for detailed assistance with units of measurements.

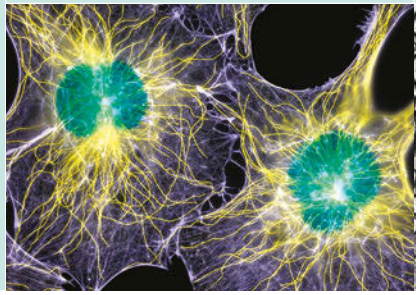
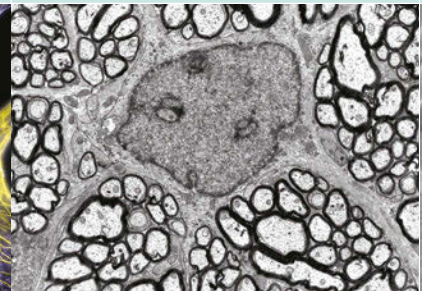
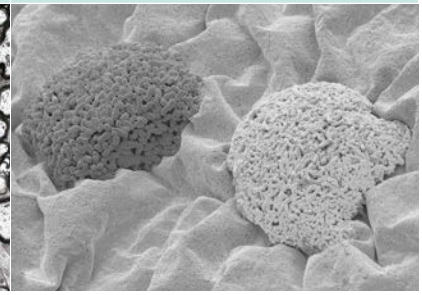
TABLE 2.1.1 SI units for smaller units of length relative to the metre

Fraction of a metre	Units	Symbol	
one hundredth = $\frac{1}{100}$ = 0.01 = 10^{-2} m	centimetre	cm	1 m = 10^2 cm
one thousandth = $\frac{1}{1000}$ = 0.001 = 10^{-3} m	millimetre	mm	1 m = 10^3 mm
one millionth = $\frac{1}{1\,000\,000}$ = 0.000 001 = 10^{-6} m	micrometre	µm	1 m = 10^6 µm
one thousand millionth = $\frac{1}{1\,000\,000\,000}$ = 0.000 000 001 = 10^{-9} m	nanometre	nm	1 m = 10^9 nm

INVESTIGATING CELLS

Cytology is the study of cells. Cytologists (scientists who study cell structure and function) and histologists (scientists who study tissue structure) use a variety of tools and techniques, including several microscopy techniques. Modern microscopy techniques, including light and electron microscopy (Table 2.1.2), have greatly advanced our understanding of the structure and function of cells. The type of microscope used depends on the characteristics and properties of the specimen to be observed, such as the size of cell or cell component and whether it is living or dead (Figure 2.1.4). Scientists also consider the access to and costs of using specialist facilities and preparing specimens when deciding which microscopy technique to use.

TABLE 2.1.2 A comparison of modern microscopy techniques

	Light microscope	Transmission electron microscope	Scanning electron microscope
Radiation source	light	electrons	electrons
Wavelength (nm)	400–700	0.005	0.005
Lenses	glass	electromagnetic	electromagnetic
Specimen	living or non-living supported on glass slide	non-living supported on a small copper grid in a vacuum	non-living supported on a metal disc within a vacuum
Maximum resolution (nm)	200	1	10
Maximum magnification	1500×	250 000×	100 000×
Stains	coloured dyes	impregnated with heavy metals	coated with carbon or gold
Type of image	may be coloured	monochrome unless stained	monochrome unless stained
			

LIGHT MICROSCOPY

Most cells are so small that they can only be seen with a microscope like the one shown in Figure 2.1.5. The light microscope uses light and a system of lenses to magnify the image. One lens is called the objective lens and the other is the eyepiece or ocular lens.

One of the main advantages of light microscopy is that it allows you to view living cells in colour.

Sample preparation is usually quick and simple. Stains can be used to highlight different components of cells in colour. A thin specimen is mounted on a glass slide and placed on the stage under the lenses. Light travels through the specimen and into the lens system, and the image is viewed by eye or with a digital camera (Figure 2.1.6).

The condenser lens beneath the movable stage concentrates light from the light source onto the specimen, and the image is focused by the coarse and fine adjusters. Different parts of the specimen can be viewed by moving the specimen on the stage.

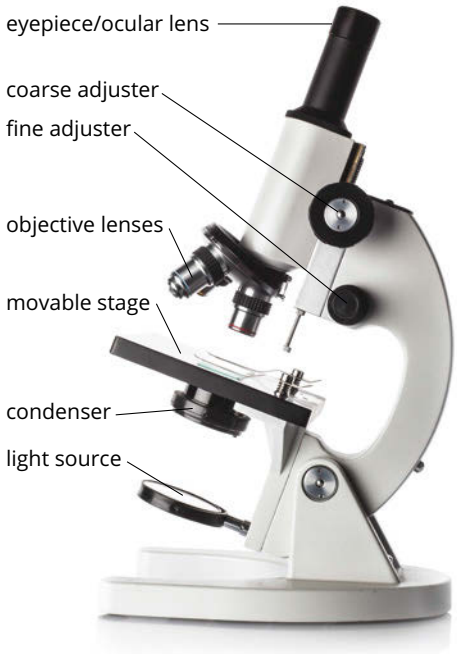


FIGURE 2.1.5 A light microscope and its parts

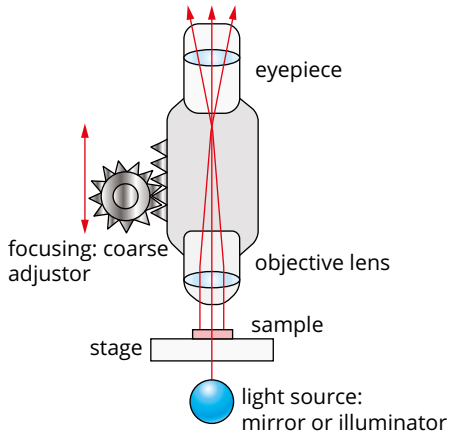


FIGURE 2.1.6 The lenses of a light microscope magnify the image.

Light microscopy techniques used in cytology include histology, autoradiography, fluorescence and confocal microscopy. Each of these uses visible light to examine cells and tissues.

Fluorescence microscopy

Figure 2.1.7 shows a fluorescent microscope, which is used to examine cells that are naturally or artificially fluorescent. Fluorescent cells contain molecules that absorb light of one wavelength (called the exciting wavelength, which is usually ultraviolet) and emit another wavelength (and therefore a different colour). By using filters to block out the exciting wavelength, the light emitted by the fluorescing molecules can then be seen against a black background, as shown in Figure 2.1.8. If the cells do not contain fluorescent molecules, fluorescent dyes (called markers) can be added that attach to the structures being investigated, such as DNA, particular proteins or cell wall components.

Immunofluorescence involves using a fluorescent tag that is linked to an antibody (see Chapter 7), which then attaches to its particular target antigen in the cell.

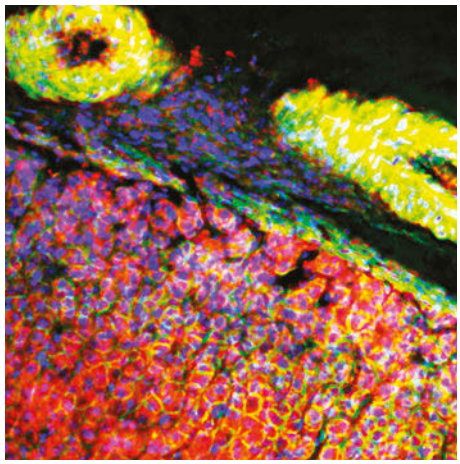


FIGURE 2.1.8 A fluorescence light micrograph of a stained section through an adrenal gland. This section through an adrenal gland has been stained with a fluorescent dye. The red parts are a particular enzyme, the blue parts are cell nuclei and the green–yellow parts are proteins in blood vessels.

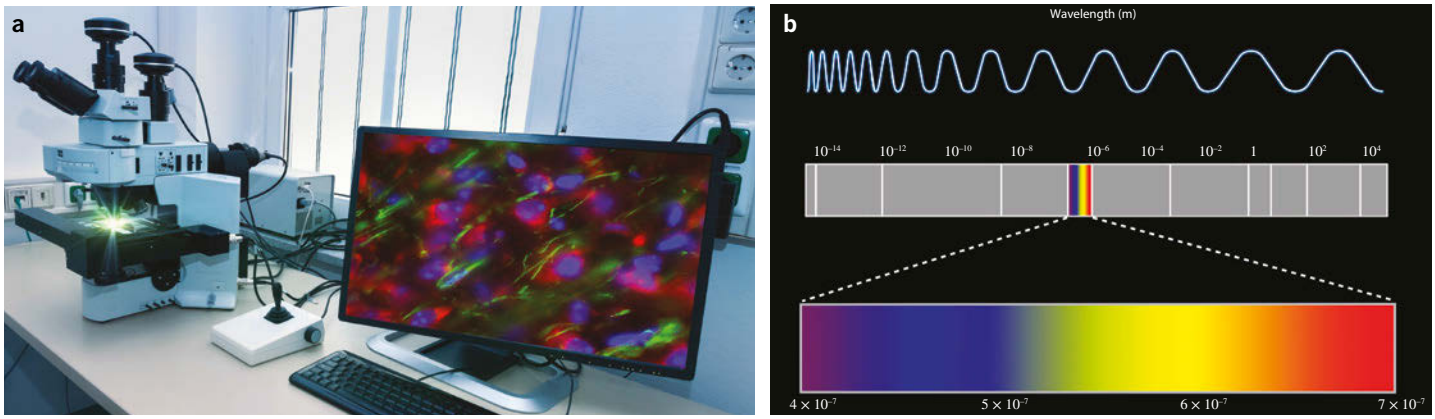


FIGURE 2.1.7 (a) A fluorescent microscope uses filters to alter the emitted wavelength of light to enable the cell components to be more easily seen in contrast with those surrounding it. (b) Visible light spectrum is part of the electromagnetic spectrum.

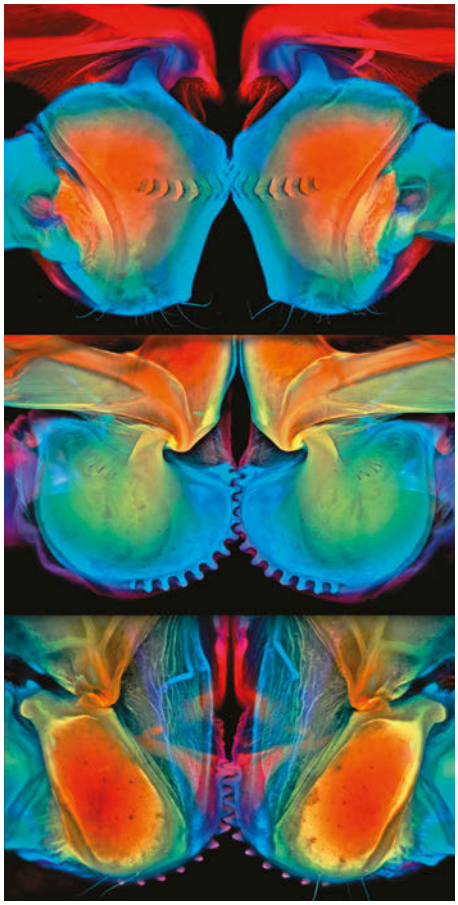


FIGURE 2.1.9 A confocal laser scanning micrograph of the green cone-headed planthopper (*Acanalonia conica*). The image (top to bottom: posterior, dorsal and ventral views) shows cog or gear-like structures of the structure at the top of each hind leg, which allows the hind legs to interlock and move together in perfect synchrony. Laser light from the microscope causes the stained specimen to fluoresce and reveal variations in the chitin (the main component in the exoskeleton) structures.

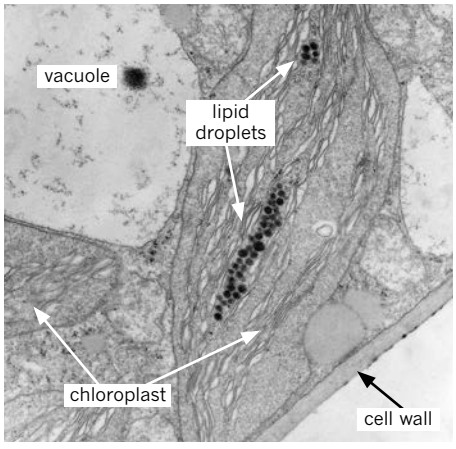


FIGURE 2.1.11 A transmission electron micrograph of a plant leaf, showing chloroplasts, with lipid droplets showing in one. The pale area to the upper left is a vacuole and the cell wall is also visible at the lower right.

Confocal microscopy

Confocal microscopy is a relatively new technique that allows scientists to obtain 'optical sections' of a cell or tissue, stained with fluorescent markers, without actually sectioning or slicing the cells. Confocal microscopy produces high-resolution images of very thin sections of a specimen. An example is shown in Figure 2.1.9. Laser light is passed through a pinhole and lens, which directs highly focused light onto only a tiny part of the specimen. This eliminates light reflecting from adjacent parts of the section, which normally blurs the image. When the object is slowly scanned in this way, an optical section of the sample is viewed on a computer screen. Thicker samples can be imaged in thin sections and then reconstructed in three dimensions by image analysis software. Confocal microscopes and the required computer software are very expensive, and the production of images is slow. However, they can produce startling three-dimensional views of living structures.

ELECTRON MICROSCOPY

In electron microscopy, an object is viewed by using an electron beam instead of light. This allows you to see structures in far more detail than is possible with light microscopy. An electron microscope produces a narrow beam of electrons that is maintained by electromagnetic lenses, which are coils that surround the tube and emit an electromagnetic field. Electrons striking the specimen are absorbed or scattered, or pass through it. The image is then recorded digitally and processed.

The image obtained with an electron microscope has a much higher resolution and greater depth of field than an image from a light microscope. Electron microscopy produces only black and white images, but these are often coloured later to highlight important features.

FIGURE 2.1.10 A transmission electron microscope. Specimens are specially prepared and the image is taken within a vacuum to ensure the electron beam remains focused. Therefore, only non-living materials can be observed under the transmission electron microscope.

Transmission electron microscopy

Figure 2.1.10 shows a transmission electron microscope. In transmission electron microscopy (TEM), the electron beam travels through an ultrathin section (less than 100 nm thick) of a specimen. This allows very fine details of cellular structures to be seen, like those shown in Figure 2.1.11.

Because the specimen must be in a vacuum in the transmission electron microscope, the specimen is first chemically fixed to stop the structures from collapsing and then dehydrated with alcohol. It is then embedded in a plastic resin, sectioned with a diamond cutter called an ultramicrotome, and stained.

Scanning electron microscopy

Figure 2.1.12 shows a scanning electron microscope. In scanning electron microscopy (SEM), the electrons bounce off a specimen that has been coated with an extremely thin layer of an electrically conducting material such as gold. This gives a high-resolution image of the surface features but cannot show internal details (Figure 2.1.13).

Autoradiography

Autoradiography is a method that allows scientists to identify specific organelles or the location of molecules within a cell or tissue. The tissue is first treated with a radioactively labelled substance that is taken up into the part of the cell that is being investigated, such as the nerve tissue shown in Figure 2.1.14. The tissue is sliced into very thin sections that are placed against a very thin high-resolution photographic film. The radioactive substance emits beta particles that produce an image on the film. The tissue sections are stained so that the photographic image can be located in relation to cellular structures. This technique can be used to indicate which organelles are active under particular circumstances.

Although autoradiography is still sometimes used with light microscopy, it is more commonly used with electron microscopy.

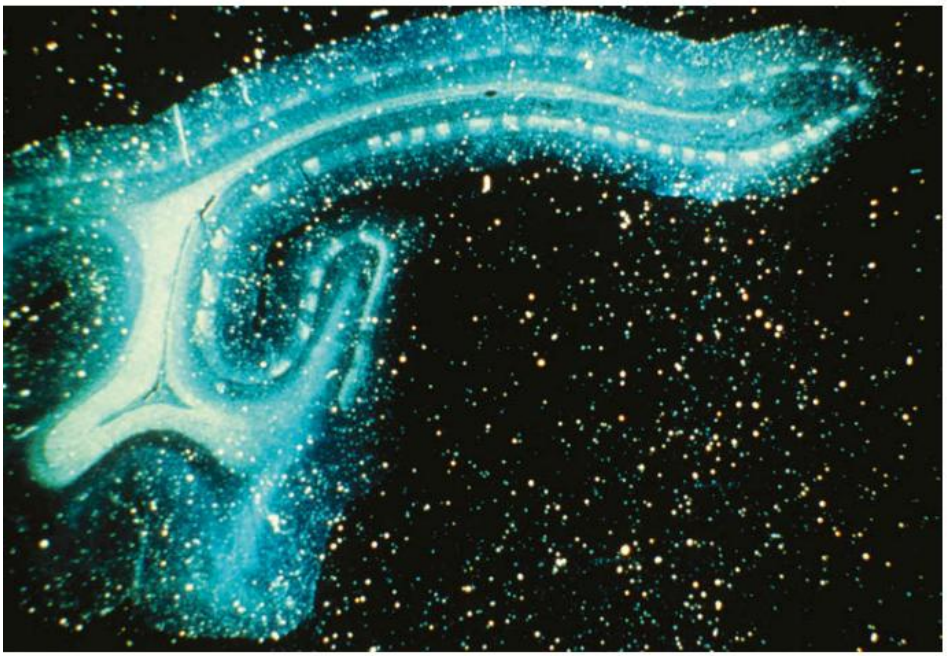


FIGURE 2.1.14 An autoradiograph of a slice through nerve tissue from the visual centre of the brain, showing how visual messages from one eye are received by the brain. Rows of neuron (nerve cell) cubes are laid out in columns on the outside of the brain tissue, and the active areas of the brain have absorbed a radioactive chemical. The glow is developed onto photographic paper and produces an autoradiograph.

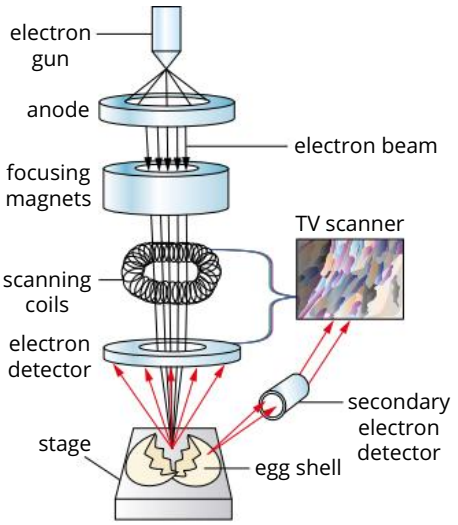


FIGURE 2.1.12 The scanning electron microscope detects secondary electrons emitted by atoms excited by the electron beam. The specimen is prepared by coating it with an electron-dense, electrically conductive material such as gold and therefore can only be used on non-living objects.

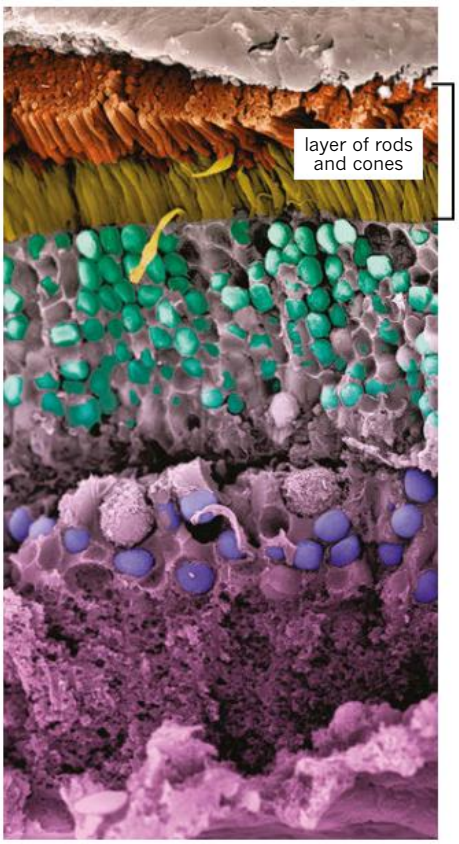


FIGURE 2.1.13 A coloured scanning electron micrograph of a section through the retina of an eye, showing cone and rod cells

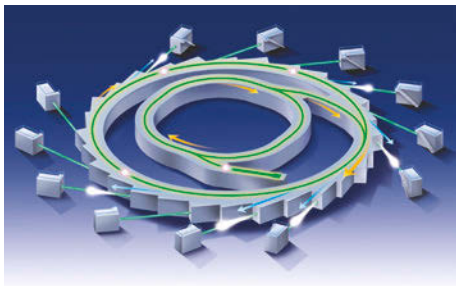


FIGURE 2.1.15 The Australian Synchrotron is about the size of the Brisbane Cricket Ground. The large diameter is needed to accelerate particles to almost the speed of light. Synchrotron light of different wavelengths can be obtained from several points around the circumference.

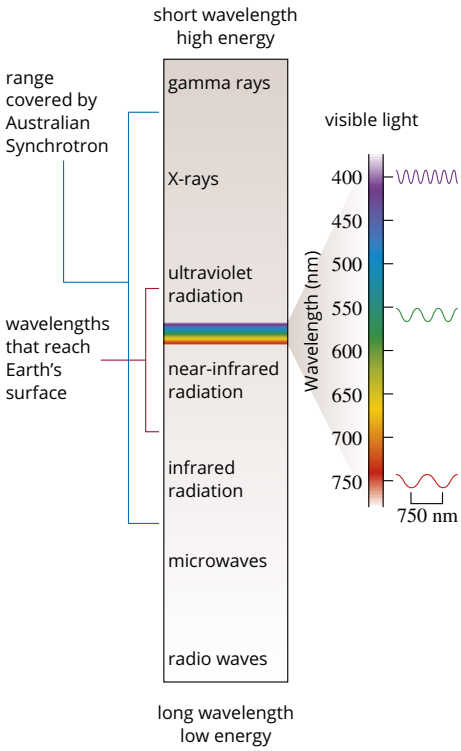


FIGURE 2.1.16 The electromagnetic spectrum, showing the range generated by the Australian Synchrotron and the range of visible light

The synchrotron and its use in biology

A synchrotron is a machine in which a beam of electrons is accelerated almost to the speed of light. Powerful magnets guide the beam into a particular path, usually a circle.

The first synchrotron was built in 1945 and was the size of a small room. The largest synchrotron is the Large Hadron Collider in Switzerland, which has a circumference of 27 km. Figure 2.1.15 shows a diagram of the Australian Synchrotron in Melbourne, which is one of the most advanced synchrotrons, and can produce an extremely intense beam of radiation in a wide range of wavelengths.

Most biological investigations using synchrotrons involve visible light. Visible light is a small part of the electromagnetic wavelengths that can be generated by a synchrotron. It lies between the longer wavelengths (radio waves, microwaves and infrared) and the shorter wavelengths of ultraviolet light, X-rays and gamma rays. This is shown in Figure 2.1.16.

Synchrotron light allows matter to be seen at the atomic scale, including the nanosecond-by-nanosecond behaviour of protein molecules such as antibodies. Scientists can collect, in hours, data on the structure of proteins that would once have taken weeks or months. While structural biology is their most important application, synchrotrons are useful in many other areas, such as nanotechnology and materials science.

Synchrotrons allow complex protein structures to be determined quickly and are central to drug design and development. They allow further development of medical imaging technologies and the analysis of biological samples to potentially help diagnose diseases.

MEASURING CELLS

A compound light microscope can be used to examine in detail thin sections of plant and animal tissues and determine the size of the cell and its visible components. To do this, you need to determine the magnification and field of view of the microscope.

Total magnification of a microscope

The total magnification of a microscope is calculated by multiplying the magnifying powers of the objective and the eyepiece. The eyepiece (or ocular lens) of a microscope is the lens closest to the eye, and usually magnifies objects by 10 times (×10) their actual size. The other lens is the objective lens and is located on the rotating part of the microscope barrel. There are usually three or four objective lenses, each allowing for a different degree of magnification.

For example, a ×10 objective used with a ×10 eyepiece gives a total magnification of ×100.

Worked example 2.1.1

CALCULATING TOTAL MAGNIFICATION OF A MICROSCOPE

Determine the total magnification of a compound light microscope if a ×10 ocular lens and a ×10 objective lens were used.	
Thinking	**Working**
Determine the magnification of the ocular lens by reading the markings on the outside of the eyepiece.	Ocular lens = ×10
Determine the magnification of the objective lens by reading the markings on the outside of the lens.	Objective lens = ×10
Multiply the ocular lens by the objective lens to calculate the total magnification	Total magnification = 10 × 10 = ×100

➤ Try yourself 2.1.1

CALCULATING TOTAL MAGNIFICATION OF A MICROSCOPE

Calculate the total magnification of a light microscope if a ×10 ocular lens and a ×40 objective lens were used.

Field of view and size of specimens

To estimate the size of specimens viewed, you need to calculate the field of view under the microscope. Also, all biological drawings require a scale. You can measure the initial field of view by using a stage micrometer slide, which is a minigrid on a microscope slide, as shown in Figures 2.1.17 and 2.1.18.

The minigrids or micrometers can be moved so that the edges of the grid lines are against the side of the field of view (circle of light visible when looking through the ocular lens). Then you can count the number of divisions across the field of view and measure the diameter of the circle of light visible.

If you change the field of view (what you see) by doubling it, then the magnification decreases by half; that is, you see more (field of view) but you see it in less detail.

If you change the field of view by halving it, then the magnification increases twofold; that is, you see less, but you see it in more detail (Figure 2.1.19).

i Increase field of view = decrease magnification
Decrease field of view = increase magnification

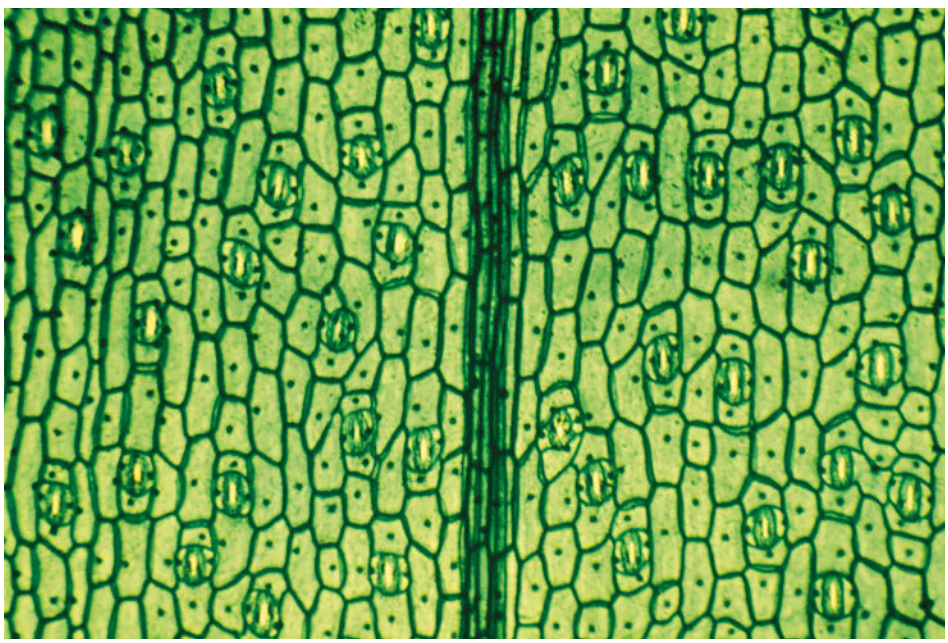
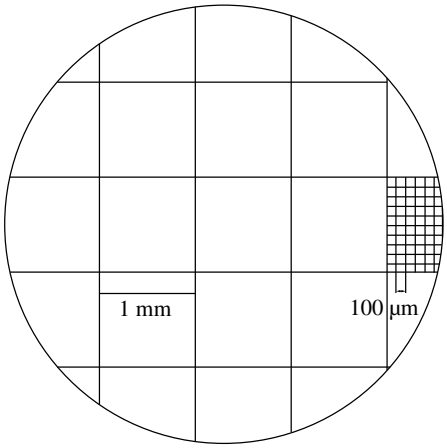


FIGURE 2.1.19 Leaf epidermis cells under a high power lens (×40). The field of view is 450 µm. There are about 30 cells across the field of view, so the average width of a leaf epidermis cell is 450/30 = 15 µm.



Field of view = 4000 µm + 600 µm
= 4600 µm
= 4.6 mm

FIGURE 2.1.17 The field of view of this microscope using the ×4 lens is 4.6 mm (or 4600 µm). You can work this out by using the minigrid.

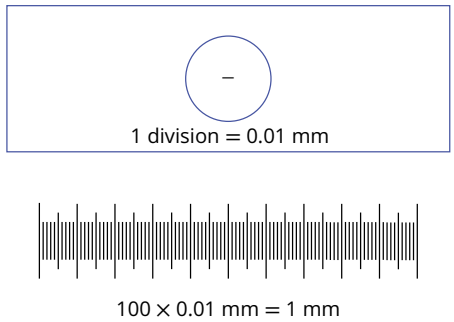


FIGURE 2.1.18 A stage micrometer slide for determining field of view

i School microscopes typically have the following magnifications and fields of view. Microscopes usually have ×10 eyepieces. The total magnification is the product of the eyepiece and objective lenses.

Objective lens	Total magnification	Field of view
×4	×40	4.5 mm
×10	×100	1.5 mm
×40	×400	450 µm
×100	×1000	150 µm

SKILLBUILDER

Measuring the field of view

To measure the field of view, follow these steps.

1. Place the micrometer grid on the microscope stage.
2. Focus using the ×4 objective lens so that you can see the grid clearly. Record this in Table 2.1.3.
3. Adjust the micrometer grid position so that it is in the field of view.
4. Adjust the slide position so that one line is on the edge of the field of view, as shown in Figure 2.1.17.
5. Count the grid lines across and estimate the diameter of the circle you see. On the lowest magnification, the field of view should be about 4.5 mm or 4500 µm.
6. Change to the ×10 objective lens and estimate the size again. The field of view should now be about 1.5 mm or 1500 µm. You should be able to use the microgrid to measure the exact distance across the field of view.
7. Move the microgrid to the centre of the field of view.
8. Focus on the microgrid using the ×40 objective lens, remembering that the microgrid lines are 100 µm apart. The field of view on high power should be about 450 µm.

TABLE 2.1.3 Measurement of field of view for three different magnifications

Microscope magnification	Field of view diameter

Worked example 2.1.2

DETERMINING FIELD OF VIEW

Thinking	Working
Calculate the total magnification at low power.	Magnification = ocular lens × objective lens = 10 × 4 = ×40
Calculate the total magnification at high power.	Magnification = ocular lens × objective lens = 10 × 40 = ×400
Measure the field of view using the stage micrometer at the lowest magnification.	Field of view = 4.5 mm = 4500 µm at low power
Increase the magnification of the image by changing the objective lens. Calculate the ratio between the initial magnification and the new magnification.	Ratio = $\frac{\text{high power}}{\text{low power}}$ = $\frac{400}{40}$ = 10
Reduce the field of view under high magnification by the same ratio.	If magnification has increased by 10 times, then field of view has reduced by 10 times. New field of view = $\frac{4500}{10}$ = 450 µm

It is important to measure the field of view every time you use a different microscope because there are differences between microscopes, which affect the estimates of the size of specimens. Once you have calculated the field of view for each lens, you can estimate the size of a whole specimen or the size of individual features, such as cells.

Knowing the field of view, you can estimate the size of the specimen. For example, if you are looking at a transverse section of a leaf and you can see exactly half of the leaf under extra low power, then you can estimate that the leaf is 2×4.5 mm = 9 mm long.

If you wish to calculate the size of the individual cells in the leaf, then you can count the number of cells across the high power field of view, as shown in Figure 2.1.19.

When measuring specimens, it may also be possible to use an eyepiece graticule. This apparatus is placed in the microscope eyepiece. The image appears as a transparent scale (usually with 100 divisions) at the same time as the specimen on the microscope slide. Before use, you must calibrate the graticule against a stage micrometer, as illustrated in Figure 2.1.20.

Determining the magnification of cells in images

We often see images of cells with an indication of the magnification scale beside them, as shown in Figure 2.1.21. Magnification refers to the number of times an image is larger than the original. This can be calculated using the formula:

$$\text{magnification} = \frac{\text{observed size of image (measured with a ruler)}}{\text{actual size (before magnification, usually in μm)}}$$

$$\text{or } M = \frac{I}{A}$$

SKILLBUILDER

Calibrating a graticule

To calibrate a graticule, follow these steps.

1. Superimpose the two images of the eyepiece graticule and the stage micrometer.
2. Determine the ratio between the graticule scale and the stage micrometer. 100 units of the graticule is equivalent to 0.25 mm on the stage micrometer. Therefore, each division of the eyepiece is $\frac{0.25}{100}$ = 0.0025 mm or 2.5 μm.
3. Place the specimen slide on the stage and use the eyepiece graticule to determine the size of the cells. Each cell in the diagram is about 20 eyepiece divisions in diameter. Therefore, the cell must be 20×2.5 μm or 50 μm in diameter.

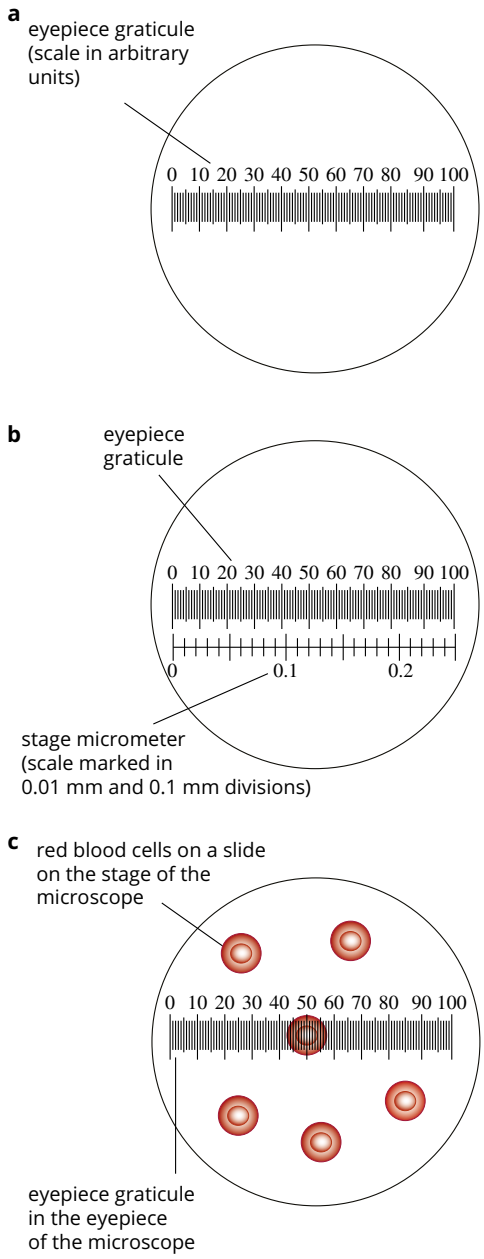


FIGURE 2.1.20 Using the eyepiece graticule and stage micrometer to determine size of specimen under a light microscope

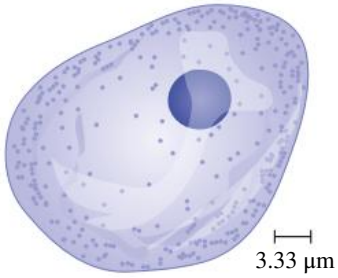


FIGURE 2.1.21 A human cheek cell, magnification unknown

Worked example 2.1.3

CALCULATING CELL SIZE USING A SCALE BAR

Calculate the length of the human cheek cell in Figure 2.1.21.

Thinking	Working
Measure the scale bar.	In Figure 2.1.21, it is 0.5 cm.
Convert to µm.	Every 0.5 cm = 3.33 µm
Measure the diameter of the cell image using a ruler.	The cell is approximately 4 cm in diameter.
Convert the diameter of the cell to µm.	Actual size $= \frac{4\text{ cm} \times 3.33\text{ µm}}{0.5\text{ cm}}$ $= 26.64\text{ µm}$

➤ Try yourself 2.1.3

CALCULATING CELL SIZE USING A SCALE BAR

Calculate the length of the cell and the diameter of the contractile vacuoles in the image of the *Paramecium* in Figure 2.1.22.

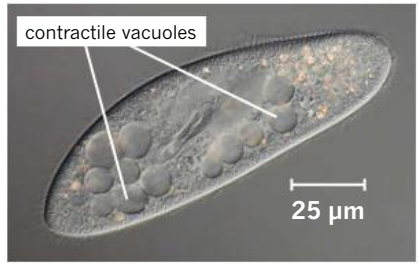


FIGURE 2.1.22 A *Paramecium* cell

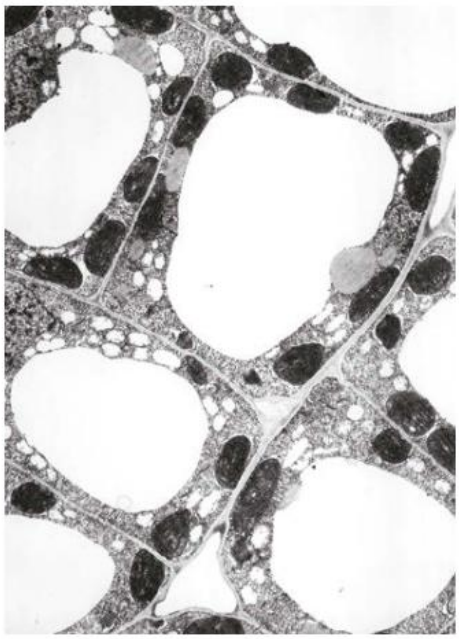


FIGURE 2.1.23 A transmission electron micrograph of mesophyll tissue (spongy tissue responsible for photosynthesis in leaves) taken from a young leaf of maize (*Zea mays*). It shows large central vacuoles (white), thin cell walls and air spaces. Each cell is about 80 µm in length.

Magnification is the number of times greater an image is than the actual object

$$\text{magnification} = \frac{\text{image size}}{\text{actual size of object}}$$

Resolution is the ability to distinguish between two objects that are very close together. The higher the resolution of an image, the greater the detail that can be seen (Figure 2.1.23).

Worked example 2.1.4

CALCULATING MAGNIFICATION OF A PHOTOGRAPH OR IMAGE

Calculate the magnification of the image in Figure 2.1.23.

Thinking	Working
Remember the formula for the determination of magnification.	$M = \frac{\text{image size}}{\text{actual size}}$
Use a ruler to measure the size of the cell in the image and convert to µm.	1 mm = 1000 µm So 60 mm = 60 000 µm
Use the equation to calculate the magnification.	$M = \frac{60\,000\text{ µm}}{80\text{ µm}}$ $= \times 750$

➤ Try yourself 2.1.4

CALCULATING MAGNIFICATION OF A PHOTOGRAPH OR IMAGE

Calculate the magnification of the image of the human cheek cell in Figure 2.1.21.

CELL REQUIREMENTS FOR LIFE

Like organisms, all cells have certain requirements. All life requires a source of energy. The amount of energy required depends on the type of cell, its stage of growth, and its level of activity. Cells also require nutrients and water for growth, maintenance and repair. The nutrients are organic compounds (including proteins, carbohydrates, lipids and vitamins) and minerals. These materials, or simpler substances from which they can be made, must be obtained from the surrounding environment. Cells also require constant environmental conditions to be maintained so that they survive and reproduce. Plants can use inorganic materials from their environment to manufacture their own organic materials in the process of photosynthesis. All cells use these organic materials to produce energy in the process of cellular respiration. This relationship is shown in Figure 2.1.24.

In using energy (e.g. from monosaccharides, disaccharides and polysaccharides, lipids and proteins, all explained in Module 3.1) and carrying out the processes of growth, maintenance and repair, cells produce substances that are of no use to them or may be harmful to the cell. These waste substances (e.g. carbon dioxide, oxygen, urea, ammonia, uric acid, water, ions and metabolic heat) are often removed by releasing them into the external cellular environment. The ways that cells exchange substances with their environment depend upon the type of material being exchanged. Cells must also be able to sense and respond to changes in their internal and external environments.

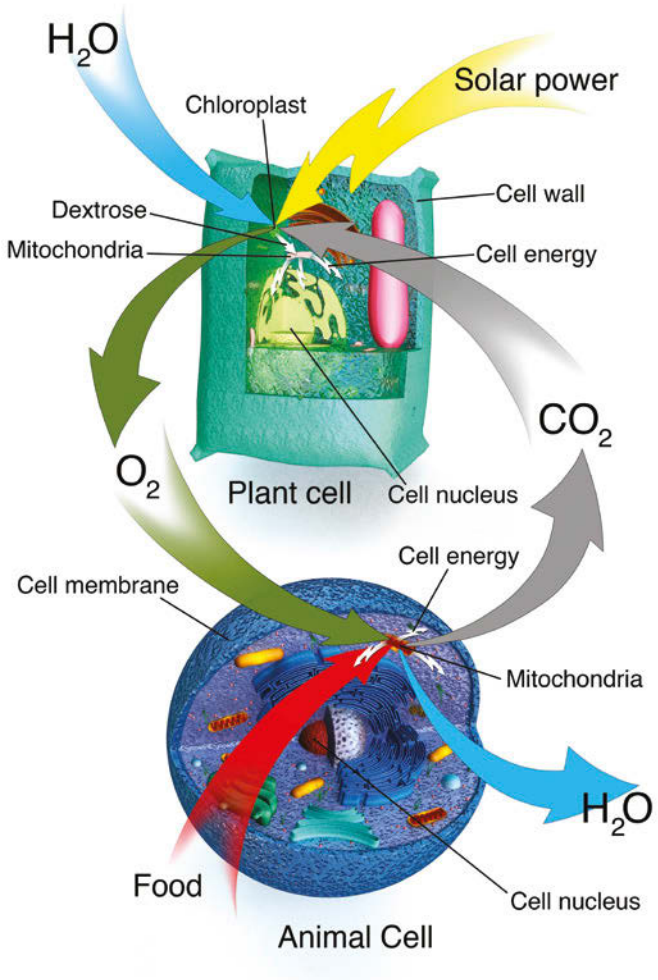


FIGURE 2.1.24 The relationship between photosynthesis and cellular respiration for the production of cellular energy in plant and animal cells

History of cell theory

Today, cells can be studied by many different types of microscopes. The two main types of microscopes are the light microscope and the electron microscope. The development of this technology over many centuries has led to our understanding of the fundamental principles of cell biology and the structure of the cell, and how the cellular processes are coordinated and controlled. Below is a brief outline of the history of cell theory, and demonstrates how our understanding of cells depends on advances in microscopy.

Hooke: the discovery of cells

The first description of cells was made by Robert Hooke in his book *Micrographia*, published in 1665. Hooke made a thin slice of cork from the bark of a tree and examined it under a very simple compound microscope he had made himself, as shown in Figure 2.1.25. He saw that the bark was made up of hundreds of little 'empty boxes', which gave it a honeycomb appearance. He called the boxes 'cells'. Hooke was looking at empty dead cells and could only see the plant cell walls with this microscope. When he later looked at fresh plant tissue, he noted the cells appeared to contain water. A few years later, Marcello Malpighi produced more detailed descriptions of plant cells.

FIGURE 2.1.25 Robert Hooke's drawing of his light microscope in *Micrographia*, published in 1665

Leeuwenhoek: first observations of living cells

In 1676, Anton van Leeuwenhoek observed many living cells under the microscope, including bacteria, blood cells and egg and sperm cells. He used compound light microscopes with improved lenses to view the cells magnified 270 times. Leeuwenhoek was the first scientist to describe the reproduction of unicellular organisms, which he called 'animalcules'. As a result of this discovery, he was able to infer that the sperm needed to enter the egg for fertilisation, questioning the theory of spontaneous generation for the formation of new organisms.

Pasteur: disproving the theory of spontaneous generation

In 1859, Louis Pasteur experimented with boiling beef broth in two flasks. Each flask had a glass 'swan-neck' (or 'goose-neck') to prevent contaminants in the air from reaching the broth (Figure 2.1.26). No microorganisms grew in either of the swan-neck flasks. When the swan neck was broken on one flask and the broth was exposed to the air, microorganisms began to grow in the broth. The unbroken flask remained free of microorganisms. Pasteur had finally disproved the theory of spontaneous generation.

Pasteur also showed that boiling and cooling wine and milk killed any microorganisms that may have been present in them. This process has been named after him and is called pasteurisation.

An important implication of Pasteur's experiment is that it provided the scientific basis for the germ theory of infection. This theory states that germs are widely present in the environment and are the cause of many diseases. Understanding germ theory eventually led to the development of antiseptic procedures in medicine.

Lamarck and Dutrochet: all living things are composed of cells

By the early 19th century, the compound light microscope had become a standard tool of biologists, and living animal and plant cells were easy to observe. In the early 19th century, Jean Lamarck stated that all living things consisted of a mass of cells, and that complex solutions move in and out of cells. René Dutrochet supported this idea, stating, 'plants are composed entirely of cells, or of organs that are obviously derived from cells ... the same is true for animals'.

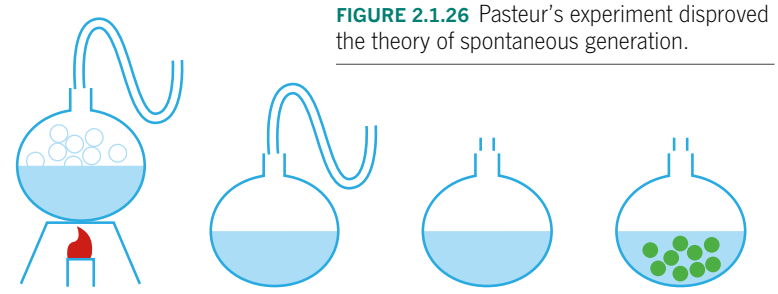


FIGURE 2.1.26 Pasteur's experiment disproved the theory of spontaneous generation.

Schleiden and Schwann: cells are organised into tissues

By the middle of the 19th century, the fundamental principle that entire organisms are composed of highly organised groups of cells was broadly accepted. This was largely due to the work of Matthias Schleiden (Figure 2.1.27) on plant tissues, and Theodor Schwann (Figure 2.1.28) on animal tissues. Working in collaboration in the 1830s, Schleiden and Schwann recognised that the organelle they had been independently studying played an important role in the development of both plant and animal cells and the formation of specialised tissue. The two scientists had been investigating the role of the nucleus and were able to identify that the cells develop or transform over time into the 'different and necessary elements of structure for the adult state'. Schwann defined the cell as containing a nucleus, fluid and a wall (even if not visible) and proposed a general cell theory that was to become the basis for our modern understanding of cell theory.

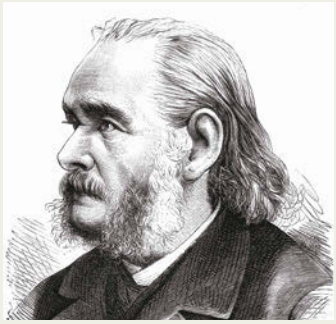


FIGURE 2.1.27 Matthias Jakob Schleiden (1804–1881)

FIGURE 2.1.28 Theodor Schwann (1810–1882)

Remak and Virchow: the theory of biogenesis

Until the 1840s, most biologists still believed that cells formed spontaneously from body fluids or from the nucleus, which they thought was the embryo of a new cell. Then Robert Remak discovered that new cells were formed by a single cell dividing in two, with the nucleus dividing at the same time, as shown in Figure 2.1.29. He did this by staining the cell membrane so the cell could be observed during cell division, proving that some cells originated from pre-existing cells. In the 1850s, Rudolph Virchow used

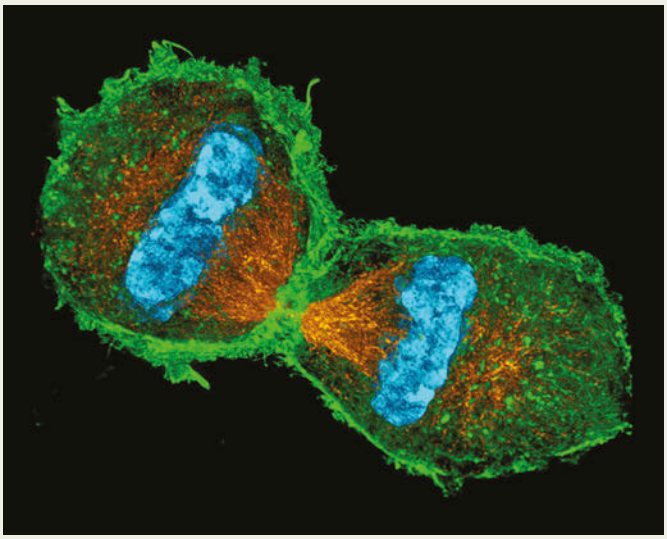


FIGURE 2.1.29 A cell dividing to form a new cell

Remak's discovery to popularise the theory of biogenesis: that all cells come from pre-existing cells. Because of Virchow's great popularity, this theory was quickly accepted in Europe, and then the rest of the world to become the third tenet in modern cell theory.

The development of cell theory over the centuries clearly illustrates how the use, development and improvement in microscope technology has influenced the evolution of scientific ideas. As microscopy techniques and lens quality improved, greater resolution and magnification of specimens was possible. This allowed new processes and structures to be observed and the development of cell theory. This process of scientific discovery continues with the development of new microscope technology such as electron microscopes and immunofluorescent microscopy to enable scientists to observe particles inside the cell at the nanoscale.

Review

1 Draw a timeline illustrating the historical development of the cell theory and the contributions of important scientists such as Hooke, Leeuwenhoek, Pasteur, Remak, Schleiden and Schwann.

2 Scientists have continued using light microscopy to observe cells despite the technological advances of electron microscopy. Discuss what advantages light microscopy has over electron microscopy and how this will continue to be of benefit for cytologists in the future.

2.1 Review

SUMMARY

- Living organisms have common characteristics and requirements—they are made of cells, are chemically complex and highly organised, exchange energy and materials with their environment, grow and reproduce, sense and respond to their environment, and show changes that are often adaptive.
- The cell theory is a fundamental principle of biology, and is based on evidence collected over the last 300 years.
- The cell theory states that:
  - all organisms are composed of cells
  - all cells come from pre-existing cells
  - the cell is the smallest living organisational unit.
- All cells have a cell membrane, cytoplasm, genetic material in the form of DNA and ribosomes.
- There are two fundamentally different types of cells: prokaryotic and eukaryotic.
- Cells vary greatly in size, and a microscope is needed to see most cells.
- Laboratory research techniques include microscopy.
  - The magnification of the microscope is determined by multiplying the magnification of the ocular lens by the magnification of the objective lens.
  - To calculate the field of view, you use a minigrid, and then you can estimate the size of your specimen.
- Light microscopes use visible light and a system of lenses to magnify images.
- Electron microscopes use an electron beam focused by electromagnets to view objects. They have a much higher magnification and resolution than a light microscope.

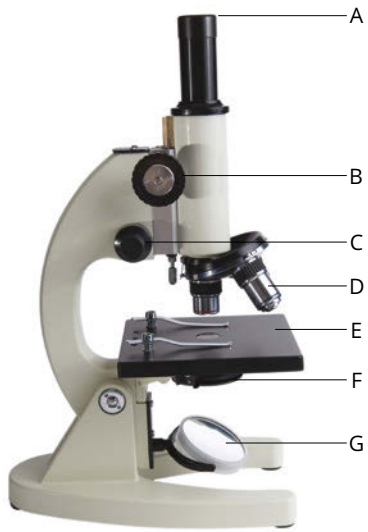
KEY QUESTIONS

Retrieval

1 State the cell theory.

2 Name three components that all cells possess.

3 Identify the parts of the light microscope labelled A–G in the following diagram.



Comprehension

4 Explain the main differences between light microscopy and electron microscopy.

5 Convert 2.5 mm (millimetres) into µm (micrometres).

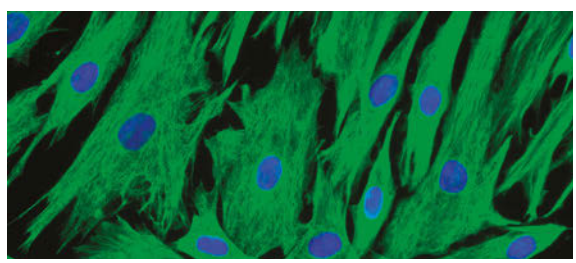
Analysis

6 Contrast prokaryotic and eukaryotic cells.

7 Compare transmission electron microscopy and scanning electron microscopy.

8 Assess how fluorescence microscopy might be used to visualise a bacterial capsule.

9 The following photo shows hair follicle cells. Deduce which type of microscope was used to take the image.



10 a Complete the following table.

Ocular lens	Objective lens	Total magnification	Field of view
×10	×4		
	×10		
	×40		
	×100		

b Determine which magnification and field of view would be best for viewing cells about:

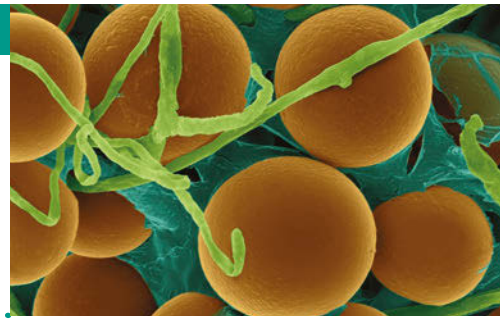
i 20 µm long

ii 0.7 mm in size.

2.2 Cell types

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

- understand the difference between prokaryotic and eukaryotic cells
- understand the classification of organisms into domains and kingdoms
- understand the importance of cell compartmentalisation and specialisation in multicellular eukaryotic organisms
- identify the differences between prokaryote and eukaryote cells
- sketch and label simple cell diagrams of plant and animal cells.



The two fundamentally different cell types are prokaryotic cells and eukaryotic cells. Organisms are classified according to which cell type they have. Protists, fungi, plants and animals are composed of eukaryotic cells and are classified as **eukaryotes**. Bacteria and archaea are composed of prokaryotic cells and are classified as **prokaryotes**. Prokaryotic cells are small and lack membrane-bound organelles, but they still have a number of features in common with eukaryotic cells. Figure 2.2.1 shows typical prokaryotic and eukaryotic cells.

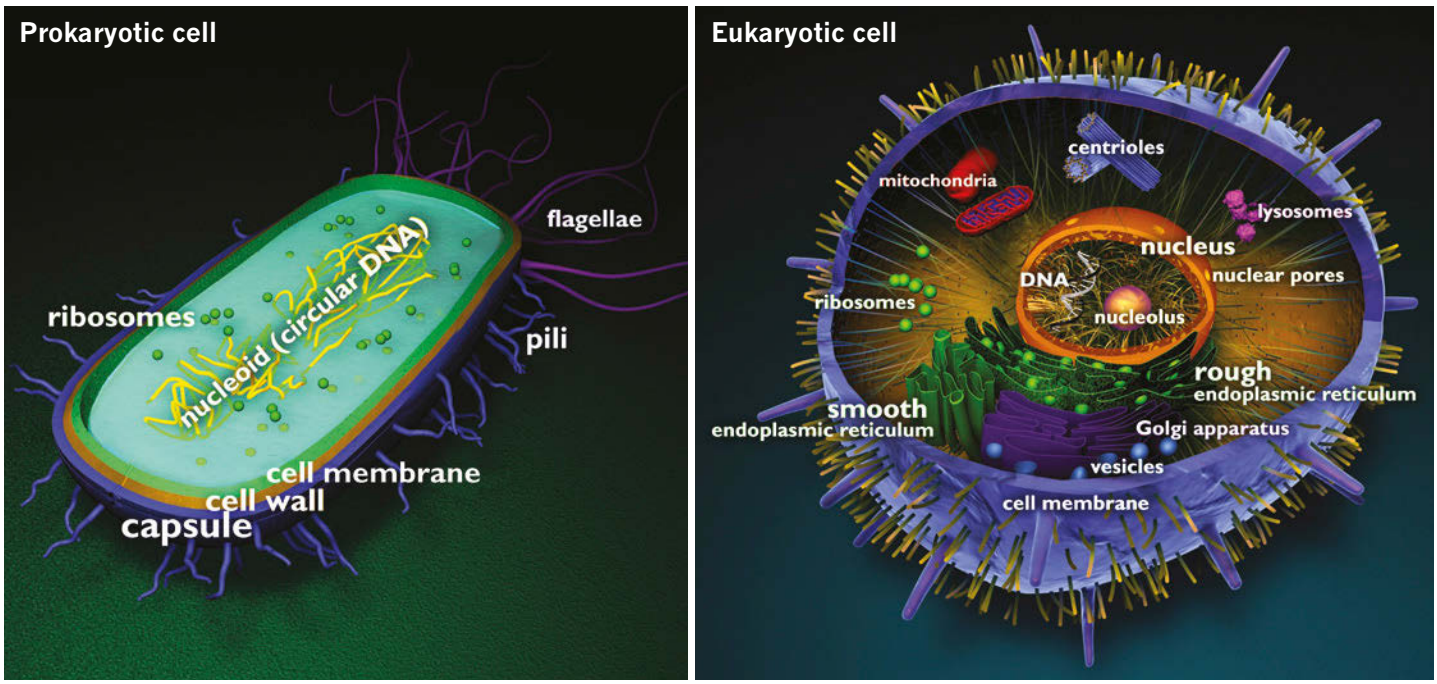


FIGURE 2.2.1 A typical prokaryotic cell and eukaryotic cell. Note the different membrane-bound organelles in the eukaryotic cell and the lack of such organelles in the prokaryotic cell.

CLASSIFICATION

In older classification systems, all organisms were divided into five ranks, called kingdoms. Prokaryotic organisms were placed in the kingdom Monera and eukaryotic organisms were placed in the kingdoms Protista, Plantae, Fungi and Animalia. These systems were based on the morphology (appearance and structure) of organisms.

However, in the late 1970s, the use of DNA techniques in the emerging field of evolutionary genetics led to the discovery of two different types of prokaryotic cells. This resulted in the development of a system with three domains and six kingdoms (Figure 2.2.2). Domains are now the highest rank in **taxonomy**, instead of kingdoms. Prokaryotes are divided into two domains: Bacteria and Archaea. All eukaryotic organisms are placed in a third domain called Eukarya. The four kingdoms within the Eukarya domain remain the same: Protista, Plantae, Fungi and Animalia. This is shown in Figure 2.2.2.

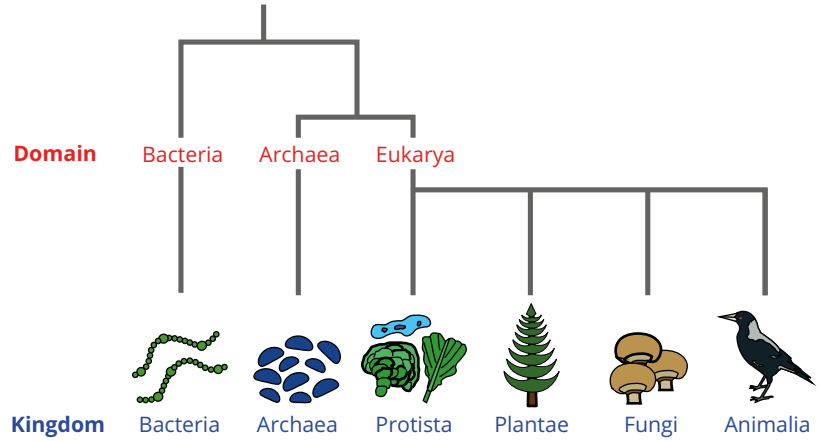


FIGURE 2.2.2 The classification of living things, showing the three domains based on cell types, and the six kingdoms. Bacteria and Archaea have prokaryotic cells. Protista, Plantae, Fungi and Animalia have eukaryotic cells.

PROKARYOTES

Prokaryotic organisms are unicellular and have a simple cell structure. Bacteria, cyanobacteria (photosynthetic bacteria) and archaea, such as methanogens, are examples of prokaryotes. Prokaryotic organisms can be found everywhere, even in extreme environments such as volcanoes.

Most prokaryotic cells are small and therefore have a large surface area relative to their volume (see Module 2.3 for a discussion of surface area to volume ratio). This allows the cells to take in and release materials efficiently and replicate quickly.

The structure of a typical prokaryotic cell is shown in Figure 2.2.3. Prokaryote cells lack membrane-bound organelles, and their cytoplasm contains scattered ribosomes that are involved in the synthesis of proteins. The genetic material of prokaryotic cells is usually a single, circular DNA **chromosome** called a **genophore**. The genophore is contained in an irregularly shaped region called the **nucleoid**. Unlike the nucleus of eukaryotes, the nucleoid does not have a nuclear membrane.

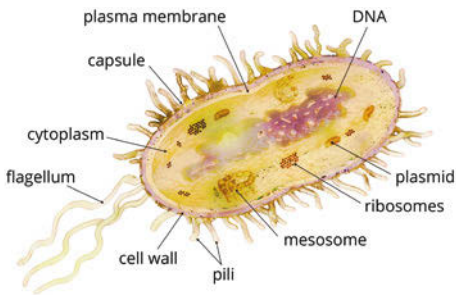


FIGURE 2.2.3 A typical prokaryotic bacterial cell

The chromosomal DNA of prokaryote cells is attached to the cell membranes by a region of the chromosome called the origin. In addition to this chromosomal DNA, many prokaryotic cells also contain small rings of double-stranded DNA called **plasmids**.

The cell membrane of prokaryotic cells is surrounded by an outer cell wall. Many bacteria also have a capsule outside the cell wall. The capsule protects the cell from damage and dehydration.

Many prokaryotes have flagella that enable them to move freely. Some also have small hair-like projections called pili, which are involved in the transfer of DNA between organisms and help movement. Specialised pili that can attach to surfaces are called fimbriae.

Bacteria

Most prokaryotes in the domain Bacteria are microscopic single-celled organisms. Fossil evidence dated at 3.5 billion years old confirms that bacteria were the first type of living organisms on Earth. Today, bacteria are still the most numerous type of organism in the biosphere.

Bacteria have very diverse metabolisms and can survive in a great range of habitats and conditions. For example, numerous species of bacteria are common in environments of moderate temperature that are moist and low in salt, where sunlight or **organic compounds** are plentiful, and in or on plants and animals.

Other species of bacteria need little oxygen to survive because they have evolved specialised chemical pathways to extract energy from their environment and manufacture complex energy-rich molecules such as carbohydrates (see Chapter 3). Bacteria can obtain energy from sunlight (photosynthesis) or by reducing **inorganic compounds** such as sulfates or ferric ions (chemosynthesis).

Bacteria play an important role in ecosystems because they break down many kinds of substances, including plant and animal remains and wastes. Bacteria are also widely used in industry to manufacture foods such as cheeses and yoghurt, and in medicine, to produce antibiotics, drugs and even human insulin. Some bacteria can break down oils and plastics, which makes them useful for pollution control.

Gram-positive and gram-negative bacteria

The cell walls of prokaryotes are distinctive for containing **murein** (also known as a peptidoglycan), which is a complex molecule consisting of sugars linked by **amino acids**. In most bacteria, the murein forms a cell wall in a mesh-like layer outside the cell membranes. Prokaryotic bacteria are commonly identified as either gram-negative or gram-positive depending upon the structure of their cell wall. A purple stain called crystal violet is used for this purpose.

Gram-positive bacteria have a thicker layer of murein that absorbs and holds the stain, so they give a purple or 'positive' result. Gram-negative bacteria have a much thinner layer of murein that does not retain the stain as well, so they give a pink or 'negative' result, as shown in Figure 2.2.4. The difference in colour on staining the bacterial cell wall is one way that cytologists identify the type of bacteria present in a sample. Other structural features of bacteria used for identification include their shape. Some bacterial shapes are shown in Figure 2.2.5.

i Carbohydrates are organic compounds of carbon, hydrogen and oxygen, with the number of hydrogen and oxygen atoms in the ratio 2:1. This ratio of 2:1 is the same ratio of hydrogen to oxygen for water. Sugars and starches are examples of carbohydrates. Proteins and carbohydrates molecules sometimes combine as complex structures (peptidoglycans) to become part of the cell wall of bacteria.

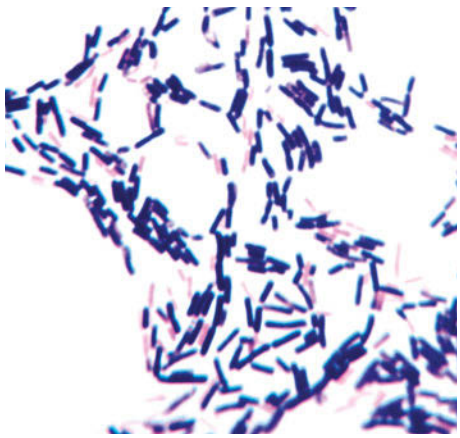


FIGURE 2.2.4 A light micrograph showing gram-positive (stained purple) and gram-negative (stained pink) bacteria

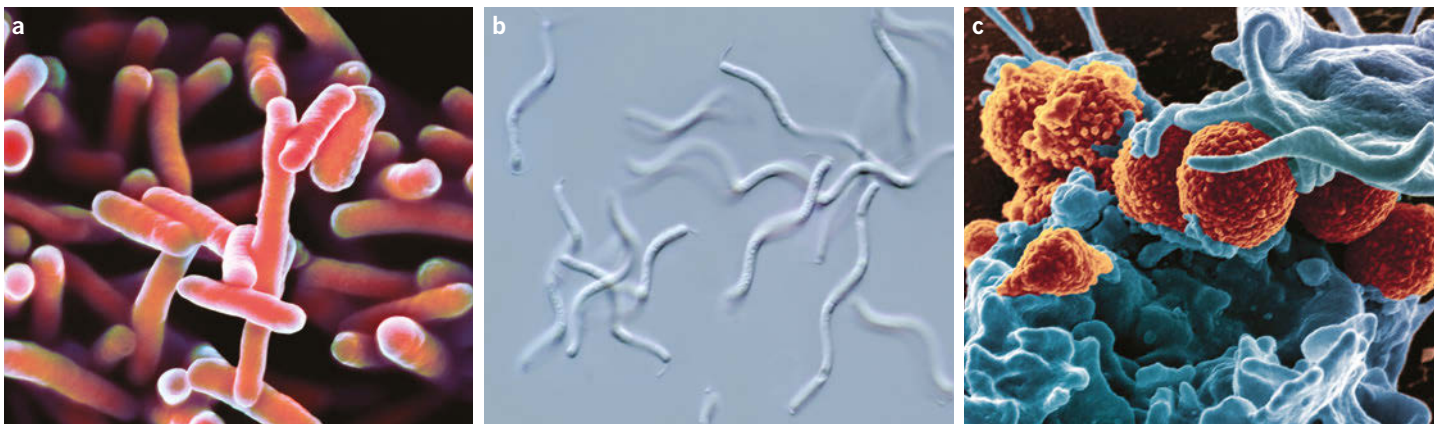


FIGURE 2.2.5 (a) A scanning electron micrograph of *Shigella dysenteria* bacteria—rod-shaped gram-negative bacteria that cause disease in humans. *Shigella dysenteria* is found in contaminated water supplies. (b) A light micrograph of a *Spirulli* species of bacteria—spiral-shaped bacteria found in marine environments. (c) A scanning electron micrograph of *Staphylococcus aureus* (commonly called 'golden staph')—spherical-shaped bacteria that cause disease in humans. Here the bacterial cells are being engulfed by a white blood cell. The bacteria are coloured orange in this image to represent their actual colour.

There are numerous types of gram-negative and gram-positive bacteria. For example, gram-positive cocci are spherical bacteria and include *Staphylococcus* (Figure 2.2.5c) and *Streptococcus*, which can cause serious diseases or death in humans. Antibiotic medicines such as penicillin have been used to treat diseases caused by bacterial infections. The different types of antibiotics are effective at preventing the formation of the murein cell wall or at disrupting other metabolic activities. You will learn more about the types of diseases and their treatments in Chapter 7.

An example of a gram-negative bacterium is a cyanobacterium, like those shown in Figure 2.2.6. Cyanobacteria were once called blue-green algae because they contain chlorophyll, but they are prokaryotes and are placed in the Bacteria domain. Cyanobacteria often form dense colonies in shallow estuaries or fresh water. Some species can form large colonies ('blooms') that produce toxins capable of killing fish and other aquatic life and cause illness in humans.

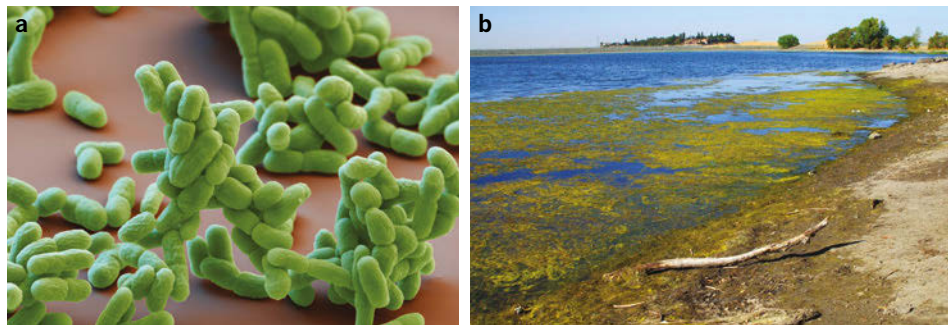


FIGURE 2.2.6 (a) A scanning electron micrograph of *Synechococcus* cyanobacteria. (b) A colony of *Synechococcus* cyanobacteria in a lake.

Archaea

The prokaryotes in the domain Archaea include **extremophiles**. These are organisms that can live in extreme conditions, such as:

- areas of high temperatures (thermophiles)
- areas of low temperatures
- the upper atmosphere
- very alkaline environments
- very acidic environments (acidophiles)
- very salty environments (halophiles)
- environments with little or no oxygen
- areas without light
- petroleum deposits deep underground.

Archaea hold records for living in the hottest places (121°C), the most acidic environments (pH 0), and the saltiest water (about 30% salt). However, some archaea live in less extreme environments, such as open seas.

The unique place of archaea among living organisms was not recognised for a long time. The main reason for this was because the extreme habitats where they live made it difficult for scientists to find archaea organisms and also to culture them in a laboratory. Another reason is that most archaea look very similar to bacteria, even though they are as different from bacteria as humans are.

The ability of archaea to live in extreme environments is partly due to their unique cell membranes. Like other living organisms, archaea possess a cell membrane composed mainly of lipids. Cell membranes need to be fluid to respond to external deformations and damage and allow proteins to move around.

The lipids in eukaryotic cell membranes have fluidity and selective permeability, but only in a narrow range of temperatures and pressure. The lipids in archaean membranes are different because they form a unique cell membrane structure.

Lipids are 'fatty' organic compounds, including fats and oils, composed mainly of carbon, hydrogen and oxygen. Lipids have proportionally less oxygen than carbohydrates, and may contain other elements. Lipids are an integral structural component of cell membranes.

The structure remains fluid and permeable over a wide range of temperatures, from freezing cold to boiling hot, and at extreme depths of the ocean floor.

There are many different types of extremophiles. Hyperthermophiles such as *Pyrococcus furiosus*, which is shown in Figure 2.2.7, can survive in very hot environments such as undersea vents, where temperatures are often above 100°C. *Pyrococcus* can also thrive under high pressure—they are barophilic. This means they can withstand the extremely high pressure at the ocean floor. *Sulfolobus* species, which live in volcanic springs, are thermophiles as well as acidophiles—they can survive both high temperatures and high acidity. You can see *Sulfolobus* in Figure 2.2.8. Extremophiles have evolved many unique adaptations to ensure their continued existence in environments where most organisms are not able to survive.

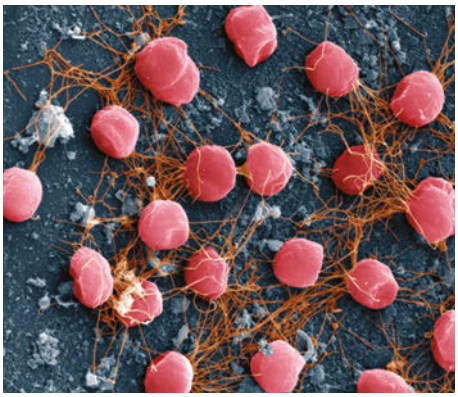


FIGURE 2.2.7 A scanning electron micrograph of hyperthermophile *Pyrococcus furiosus*. *Pyrococcus* can only exist in very hot environments such as hot undersea vents.

Differences between bacteria and archaea

Despite their name, archaea are not the most ancient group of organisms. DNA studies have shown that bacteria are the most ancient group. The evolutionary relationship between archaea, eukaryotes and bacteria remains unclear. While archaea and gram-positive bacteria share many structural features and metabolic pathways, suggesting a common ancestor, many other archaea genes are more similar to the genes found in eukaryotic cells.

The cells of bacteria and archaea are different in a number of ways.

- Archaea have a different type of lipid structure in the cell membranes.
- Bacterial cell walls contain murein; archaean cell walls do not contain murein (although there is a similar compound in some archaea).
- Both have diverse metabolic systems, but methanogenesis (in which methane is produced) is unique to archaea.

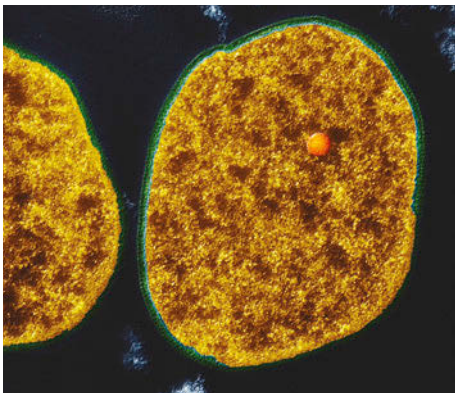


FIGURE 2.2.8 *Sulfolobus* are thermophiles as well as acidophiles. They thrive in hot, acidic environments.

EUKARYOTIC CELLS

Eukaryotic cells are relatively large and more complex than prokaryotic cells. They possess membrane-bound organelles such as a nucleus and mitochondria. Protists, fungi, plants and animals are called eukaryotes because they are composed of eukaryotic cells.

As well as a cell membrane surrounding the cytoplasm, eukaryotes have internal membranes that form specialised compartments within the cell. This is known as **cell compartmentalisation**. The membrane-bound compartments are organelles, which are specialised structures that have specific functions, as shown in Figure 2.2.9. However, not all organelles have membranes; for example, ribosomes and centrioles.

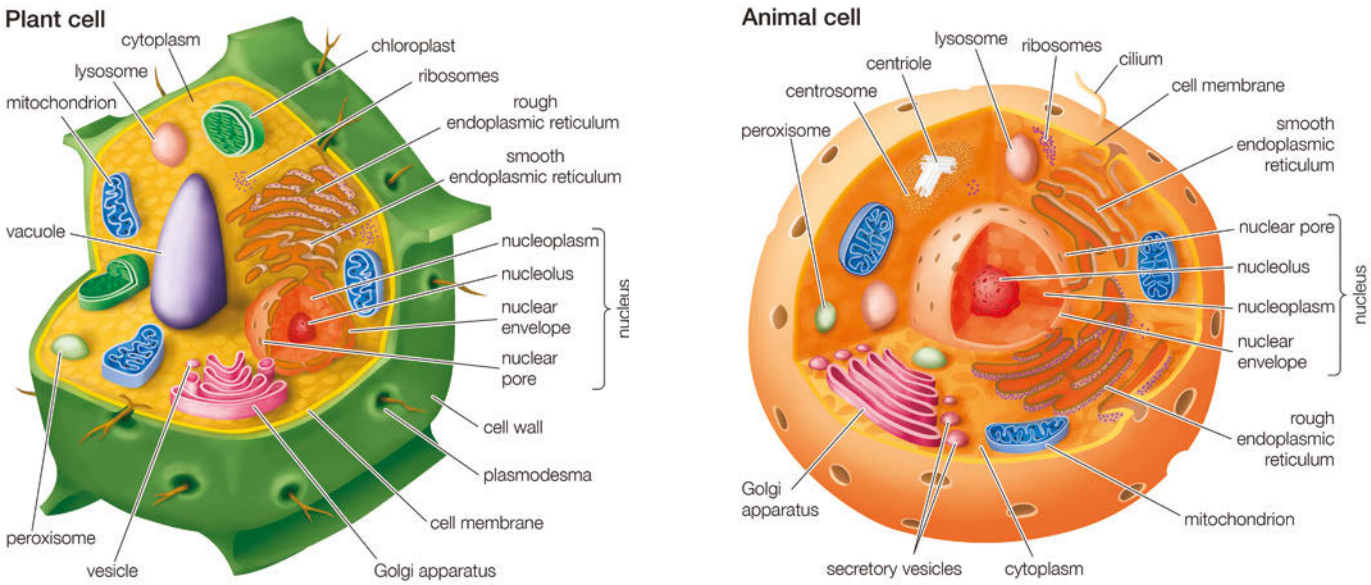


FIGURE 2.2.9 The many membrane-bound organelles of eukaryotic cells can be seen in these illustrations of a plant cell and an animal cell.

COMPARISON OF PROKARYOTIC AND EUKARYOTIC CELLS

There are a number of differences between prokaryotic and eukaryotic cells (Table 2.2.1). In eukaryotic cells, the DNA is contained in the nucleus, in the form of linear chromosomes. Their cytoplasm contains many different membrane-bound organelles. Some eukaryotic cells are surrounded by a cell wall composed of carbohydrates. You can identify the nucleus, cytoplasm and organelles in the diagram of typical eukaryotic cells illustrated in Figure 2.2.10.

TABLE 2.2.1 Comparison of prokaryotic and eukaryotic cells

Feature	Prokaryotic cells	Eukaryotic cells
Size	• Very small	• Larger, with large variation in size
Surface area to volume ratio (SA:V)	• Large • Allows materials to diffuse in and out of the cell rapidly	• Smaller • Results in slower diffusion
Membrane-bound organelles	• Absent	• Many organelles bound by membranes, forming an organised internal structure
Chromosomal DNA	• DNA chromosome in the form of a single-stranded loop • Located in a region of cytoplasm called the nucleoid, lacking a membrane	• DNA in the form of linear, thread-like chromosomes • Located in the nucleus, which is separated from the cytoplasm by a double-layered membrane
Ribosomes	• Many tiny ribosomes scattered in the cytoplasm	• Many ribosomes, either attached to the endoplasmic reticulum, or free in the cytoplasm
Cell membrane	• Bilayer of phospholipid molecules enclosing the cytoplasm in bacteria • Phospholipids are different and sometimes fuse into a monolayer in archaea	• Bilayer of phospholipid molecules enclosing the cytoplasm
Cell wall	• In bacteria, consists of a protein–carbohydrate compound called murein	• Present in fungi, plants and some protists • Consists mainly of carbohydrates: chitin in fungi and cellulose in plants
Flagella	• May have flagella to provide movement • Consist of three protein fibrils coiled in a helix and protruding through the cell membrane and wall	• May have flagella or cilia for motility (but not in fungi) • Consist of a highly organised array of microtubules (hollow protein tubes) enclosed by the extended cell membrane

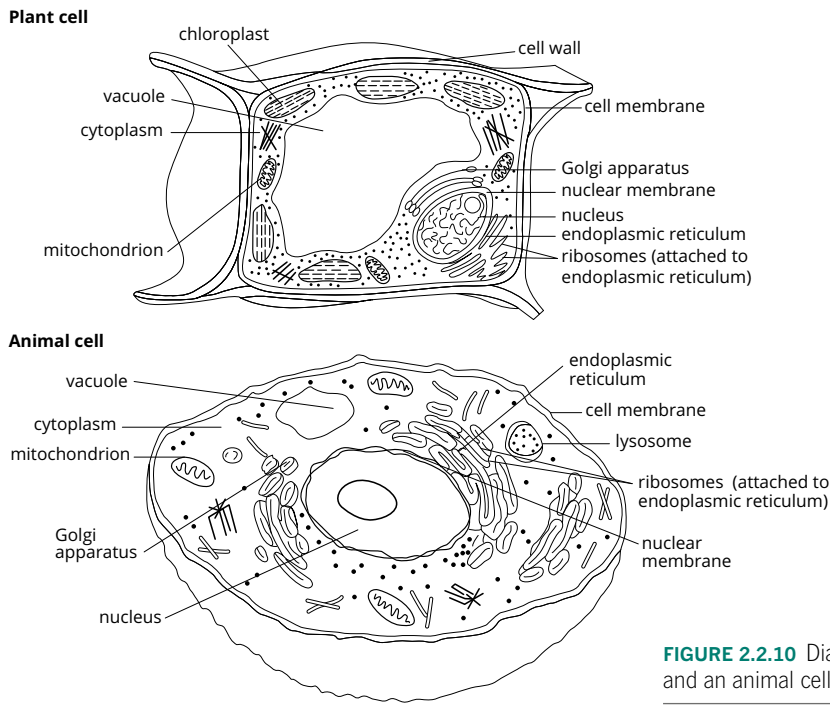


FIGURE 2.2.10 Diagram of a typical plant cell and an animal cell, showing major organelles

Each membrane-bound organelle has a different function, so each organelle requires a different internal composition, including a high concentration of enzymes and reactants.

Role of organelle membranes

The membranes surrounding organelles control the movement of substances between the organelle and the cell's cytosol. Just as cell membranes enable the cytosol to have a different composition from the cell's surrounding environment, membrane-bound organelles can have a different composition from the surrounding cytosol and other organelles. Because the environment on either side of the membrane is regulated, different types of biochemical reactions can occur in each region. Therefore, the metabolic reactions performed within the cells can occur efficiently within regions of optimal environmental conditions. The role of membranes to regulate cell function will be explored in Module 2.4.

Benefits of compartmentalisation

Cellular compartmentalisation benefits the cell in several ways. It:

- allows enzymes and reactants for a particular function to be close together in high concentrations and under the right conditions, such as optimum pH levels, so that the processes within the organelles are very efficient
- allows processes that require different environments to occur at the same time, in the same cell
- makes the cell less vulnerable to changes in its external environment, because changes affect the cytosol much more than the membrane-bound organelles such as mitochondria or chloroplasts.

Cell specialisation

In unicellular organisms, one cell must perform all functions. However, in multicellular organisms, such as animals and plants, there are many different types of cells, each with their specialised function. Muscle cells and red blood cells in mammals, and palisade cells in plants, are examples of specialised cells. These are shown in Figure 2.2.11.

Enzymes are proteins that act as biological catalysts. Enzymes speed up rates of biochemical reactions that would otherwise take place much more slowly. Their action is specific: they catalyse (cause or accelerate) only one type of reaction. You will learn more about enzymes and the factors affecting enzyme activity in Chapter 3.

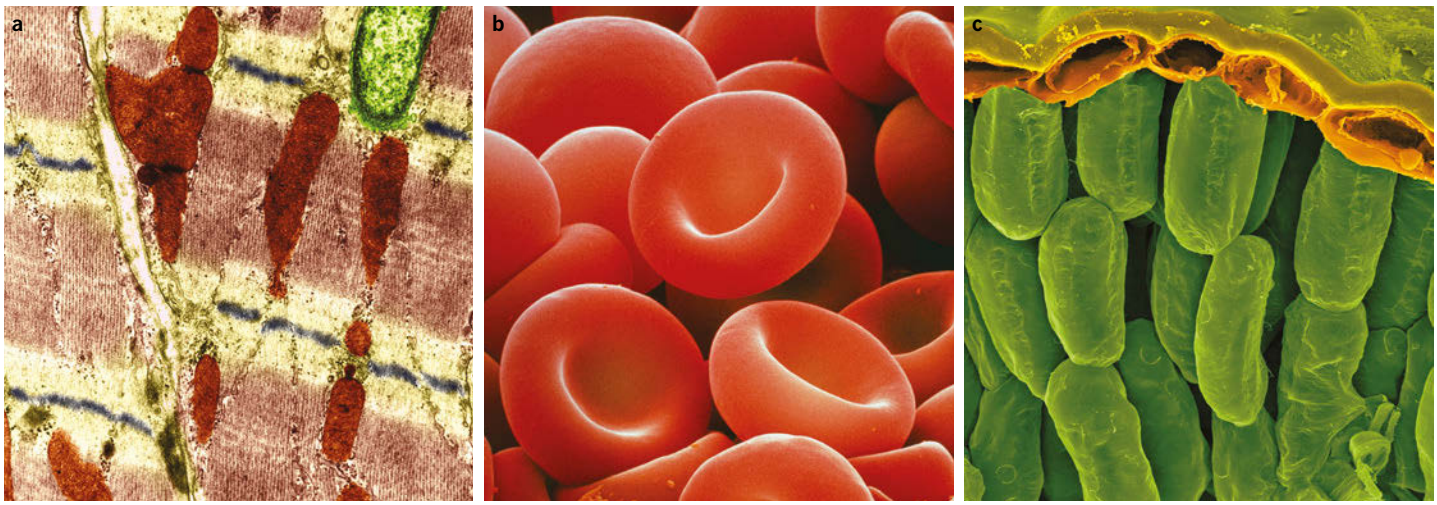


FIGURE 2.2.11 (a) A coloured transmission electron micrograph of a human heart muscle cell. (b) A coloured scanning electron micrograph of human red blood cells. (c) A coloured scanning electron micrograph of a cross-section of a rosemary leaf, showing palisade cells.

All the cells of an organism contain the same genetic instructions. During the early development of a multicellular organism, all of its cells look similar. As the organism develops, cells differentiate to become structurally and functionally distinct and produce different proteins and enzymes. The various proteins present in different cells arise from differences in the pattern of gene activity—certain genes are 'switched on' and others are 'switched off'. This is illustrated in Figure 2.2.12. Differentiated cells are said to be specialised. You will learn more about the process of cell specialisation in Chapter 4. Biologists have determined that certain proteins bind to some genes so that they are not 'switched on'.

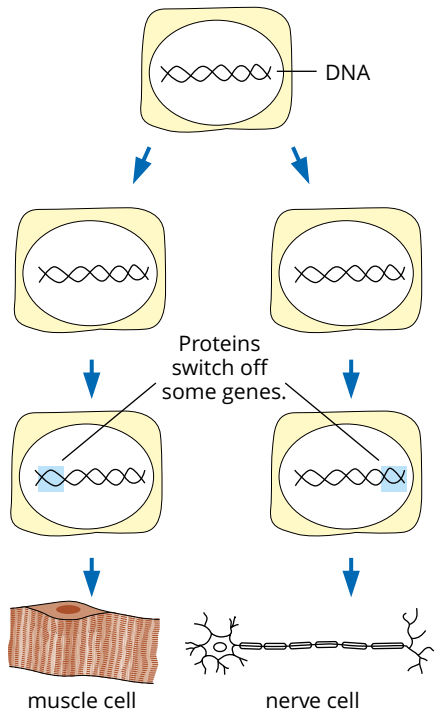


FIGURE 2.2.12 Cell differentiation occurs because different genes become active, and others become inactive, and produce the different types of cells, which are then specialised.

Cell specialisation is found in all multicellular organisms. Cells are more efficient if they carry out a single function rather than many functions. A nerve cell is specialised to carry signals rapidly across large distances. It could not do this if it also had to break down food to obtain nutrients or protect against disease.

Plants have cells specialised for photosynthesis, exchange, transport, strength and protection. Animal cells are specialised to conduct messages, to provide protection, movement and support, and for exchange and transport. The human body is composed of more than 200 different types of cells.

2.2 Review

SUMMARY

- There are two fundamentally different types of cells—prokaryotic and eukaryotic.
- Organisms with prokaryotic cells are called prokaryotes. They are classified into two domains: Bacteria and Archaea.
- Organisms with eukaryotic cells are called eukaryotes. They are classified into the domain Eukarya, which is divided into four kingdoms: Protista, Fungi, Plantae and Animalia.
- Prokaryotic cells have a simple structure, with a nucleoid lacking a membrane, scattered ribosomes, and DNA mainly in a single-stranded loop in the nucleoid.
- Eukaryotic cells have a complex structure, membrane-bound nucleus, many organelles in the cell cytoplasm, and DNA mainly in chromosomes in the nucleus.
- Archaea (the extremophiles) are often found in very harsh environments where their unique cell membrane structure protects them.
- Compartmentalisation in eukaryotic cells:
  - allows enzymes and reactants to be concentrated in particular organelles of the cell
  - maintains the right conditions for enzymes and reactants to function
  - allows incompatible chemical reactions to take place simultaneously within the cell
  - reduces the cell's vulnerability to environmental changes.

KEY QUESTIONS

Retrieval

1 Describe the differences between prokaryotes and eukaryotes.

2 Identify which kingdoms contain organisms that are composed of eukaryotic cells. Recall some examples from each kingdom.

Comprehension

3 Draw and label a typical plant and animal cell.

4 Explain what is meant by ‘cell specialisation’.

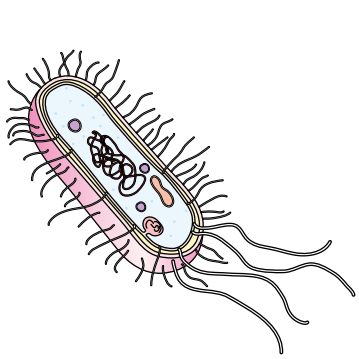
5 Explain what is meant by 'cell compartmentalisation'.

Analysis

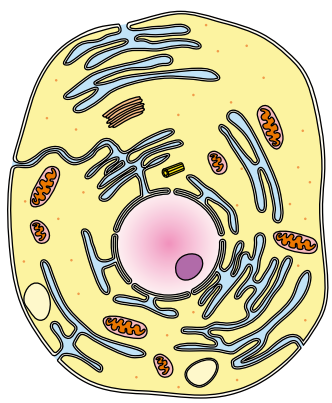
6 The following diagrams are of two cells observed with an electron microscope.

a Describe evidence that cell A is prokaryotic.

b Describe evidence that cell B is eukaryotic.

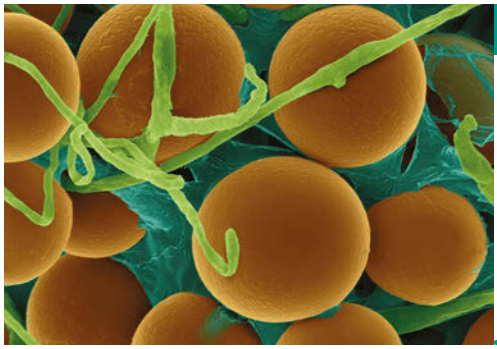


cell A (4500×)



cell B (3000×)

2.3 The cell membrane



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

- understand the role of the cell membrane in the regulation of movement of materials into and out of the cell
- describe the structure of the cell membrane (including protein channels, phospholipids, cholesterol and glycoproteins) based on the fluid mosaic phospholipid bilayer model
- sketch a diagram of the phospholipid bilayer and explain the functions of each of the molecules that make up the membrane.

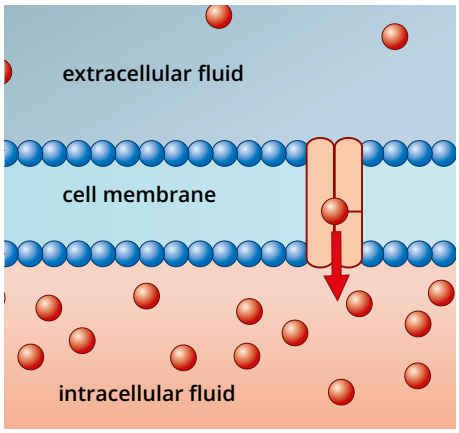


FIGURE 2.3.1 The cell membrane regulates the movement of substances between the extracellular fluid and intracellular fluid.

Extracellular fluid is body fluid outside the cell membranes; it includes blood plasma and interstitial fluid.

FIGURE 2.3.2 Crabs have an external skeleton that protects them from water loss when on land.

In this module, you will learn about the composition and characteristics of the cell membrane. You will also study the ways cells can increase the surface area of the cell membrane available for the exchange of substances.

THE CELL ENVIRONMENT

Cells exist in a watery environment of **extracellular fluid**, which can be a large amount of fluid or a thin surface layer of fluid. In plants, the cell wall is porous and has little effect on the movement of molecules. So all living cells exist in an environment that is a layer of fluid in contact with the outer cell membrane. The composition of this fluid is critical to the stability of cells because it is from this environment that cells obtain the nutrients they need. The cell membrane controls the movement of substances between the extracellular fluid outside and the **intracellular fluid** (or cytosol) inside the cell. A diagram of the cell membrane is shown in Figure 2.3.1.

Extracellular fluid in unicellular organisms

For unicellular organisms, the extracellular fluid is simply the watery external environment in which they live. Unicellular organisms can do little to control their environment and may die if it changes significantly.

However, some unicellular organisms such as yeasts can become dormant until their environment returns to optimal conditions. Other organisms can move slowly to a place where conditions are more suitable for their needs. For example, unicellular algae can move towards light, and some bacteria can detect and move towards nutrients or away from toxic substances.

Extracellular fluid in multicellular organisms

Conditions for cells in multicellular organisms are more stable than those of unicellular organisms. The more complex the organism, the more control it has over the environment in which its cells exist, and the more independent the organism is from its external environment. Whether they live in water or on land, multicellular organisms have an outer layer that acts as a protective barrier, such as a crab's exoskeleton as shown in Figure 2.3.2. This outer layer creates an internal environment for the organism that is different from their external environment, and organisms can better regulate their internal environment for optimal cell function. Therefore, in multicellular organisms, the environment of the cells is the extracellular fluid that surrounds them.

Most multicellular organisms can regulate their internal environment, often very precisely. This allows them to provide the specific conditions needed by specialised cells and tissues, and for their cells to function more efficiently. Commonly regulated aspects of the internal environment are:

- temperature
- oxygen concentration
- carbon dioxide concentration
- pH (acidity or alkalinity)
- osmotic pressure (concentrations of salts or ions)
- nitrogen waste concentration
- glucose concentration.

Importantly, the way cells interact with the extracellular fluid of the internal environment is regulated by the cell membrane.

CELL MEMBRANE COMPOSITION

Cell membranes have the same basic structure in all organisms, which serves to separate the interior of the cell (the cytoplasm) from its external environment. Most membranes are also asymmetrical, meaning one layer has different properties from the other. For example, the pattern of proteins and carbohydrate molecules in the external surface is different from the pattern in its internal surface.

The composition and characteristics of the cell membrane are related to the needs and function of the cell. The cell membrane performs important functions such as transporting molecules into and out of the cell, and recognising and communicating with other cells.

Phospholipids and the phospholipid bilayer

The cell membrane is a lipid–protein barrier that surrounds the cell and regulates the movement of materials between the inside and outside environment of a cell. It is typically about 7 nm wide. The **phospholipids** found in the cell membrane are composed of a phosphate group, a glycerol molecule and two **hydrophobic** fatty acid tails, as shown in Figure 2.3.3. The phosphate end of the molecule, which is polar and therefore hydrophilic ('water loving'), faces the aqueous regions of the cellular environment. The non-polar, fatty acid, part of the phospholipid is hydrophobic ('water hating') and faces inwards to the bilayer to form an oily region that becomes the barrier for most water-soluble materials.

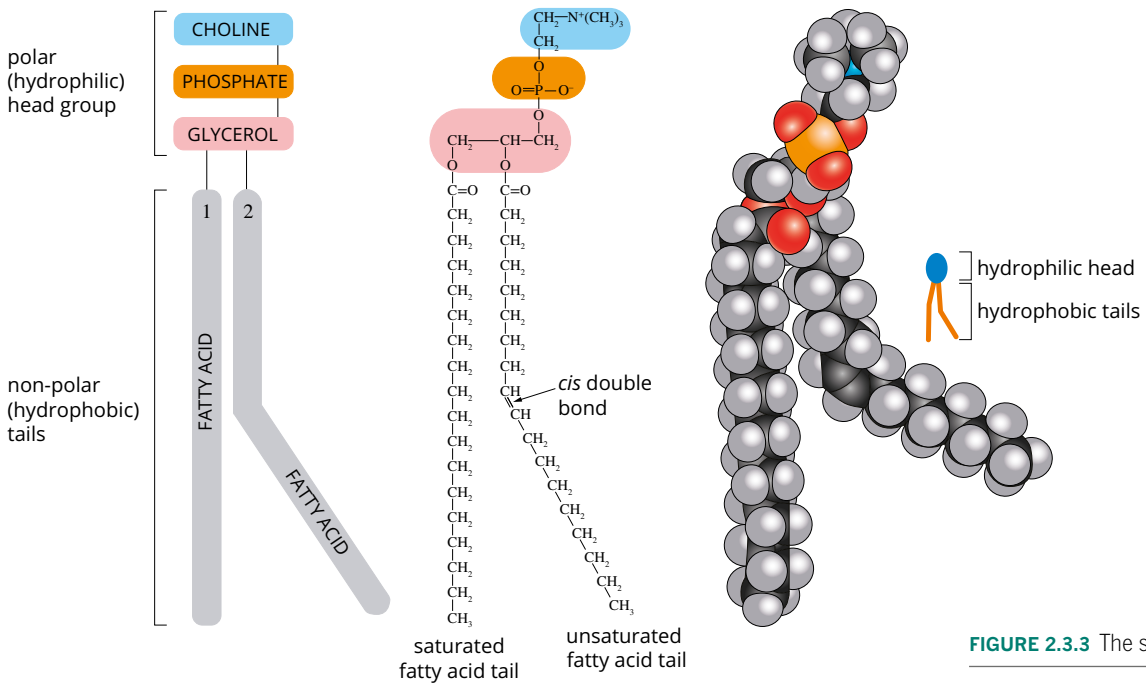


FIGURE 2.3.3 The structure of a phospholipid

The phospholipid bilayer of the cell membrane is called a bilayer because it has two layers of phospholipids. The hydrophilic heads form the outside and inside lining of the cell membrane, and the hydrophobic tails of the two layers of phospholipids meet in the middle. This is illustrated in Figure 2.3.4.

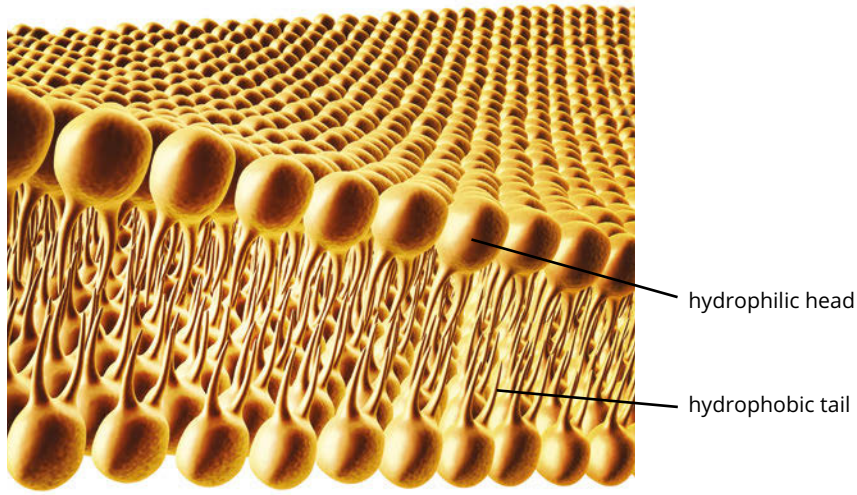


FIGURE 2.3.4 A phospholipid has a hydrophobic 'tail' and a hydrophilic 'head'.

Figure 2.3.5 shows how phospholipids arrange themselves in water and in oil. The phospholipids make cell membranes impermeable to water-soluble particles, ions and polar molecules. The movement of these molecules across the membrane is controlled by protein channels, which allow the cell to regulate the exchange of molecules with the environment. Controlling the movement of substances into and out of the cell is central to important processes that keep the cell alive, such as cell respiration, digestion and elimination of wastes. You will learn more about transport across cell membranes later in this module and in Module 2.4.

A phospholipid is a molecule consisting of long-chain fatty acids (which are hydrophobic), a phosphate group and glycerol (which is hydrophillic). It is the major component of cell membranes.

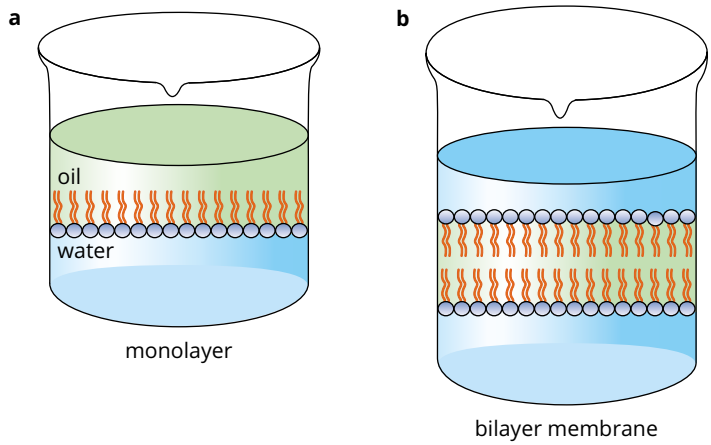


FIGURE 2.3.5 (a) The arrangement of phospholipids when water is on one side and oil is on the other side. (b) The arrangement of phospholipids when water is on both sides—a bilayer is formed.

Fluid mosaic model

Singer and Nicolson initially described the dynamic nature of the cell membrane as a 'fluid mosaic' in 1972. In their model, the phospholipids can move within the membrane by diffusion and a mosaic of discontinuous protein particles may be found floating in the phospholipid bilayer like icebergs. Figure 2.3.6 illustrates the fluid mosaic model.

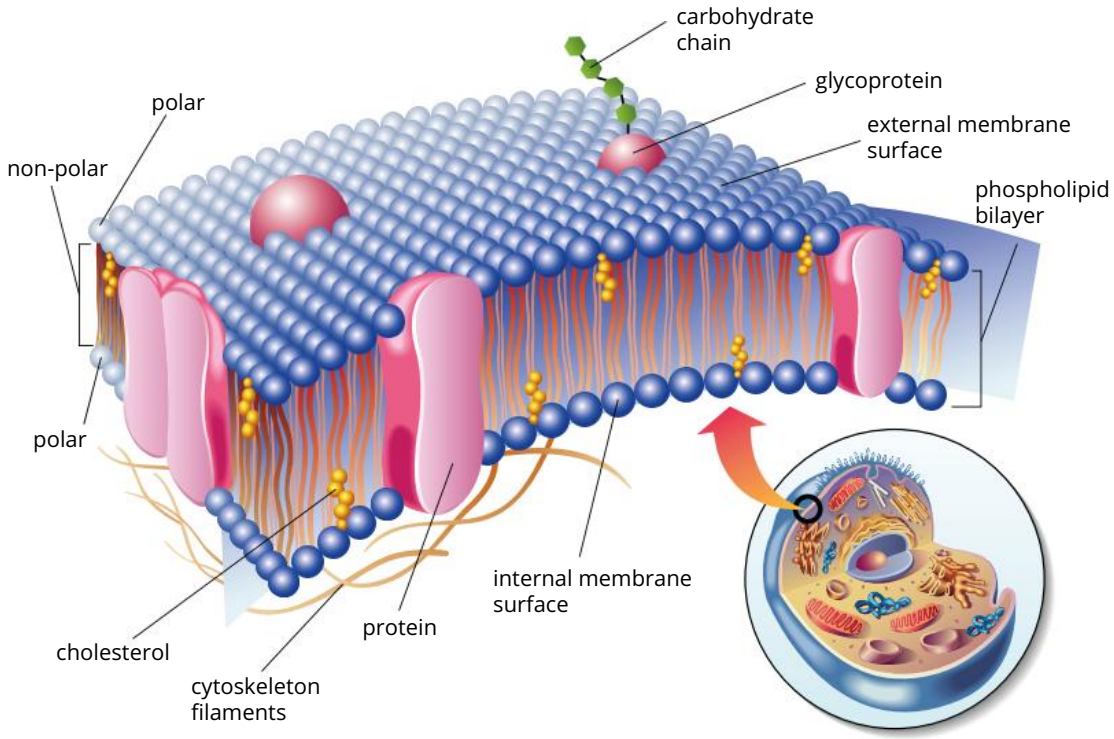


FIGURE 2.3.6 The fluid mosaic model of a cell membrane, showing the phospholipid bilayer in which large protein molecules are embedded

This fluid mosaic model is now widely accepted as the basic model of all biological membranes. According to this model, cell membranes consist of two layers of phospholipid molecules, with other molecules such as proteins, carbohydrates and cholesterol scattered throughout the membrane.

Molecules of the cell membrane are not fixed in place. Cell membranes are fluid structures, which means that individual phospholipid molecules (and some proteins) are free to move about within the layers. However, they rarely cross from one side of the membrane to the other. Most of the phospholipids and some of the proteins can move laterally, and sometimes some molecules are able to flip-flop transversely across the membrane. This movement is shown in Figure 2.3.7. The rate at which the molecules move within a layer of the cell membrane varies. Proteins in the membrane can move sideways throughout the membrane, but they move much slower than the phospholipids.

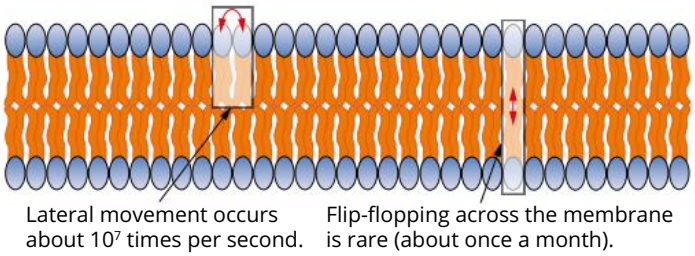


FIGURE 2.3.7 The movement of phospholipids in cell membranes

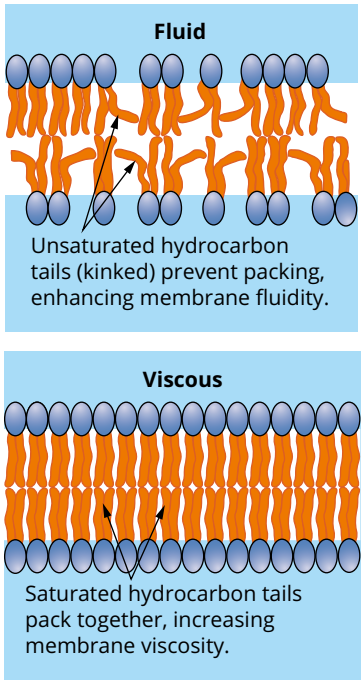


FIGURE 2.3.8 These two diagrams show the effects of unsaturated and saturated fatty acid tails on the fluidity of the cell membrane.

Cell membranes are phospholipid bilayers that enclose the cytoplasm and subdivide the cell into compartments (organelles).

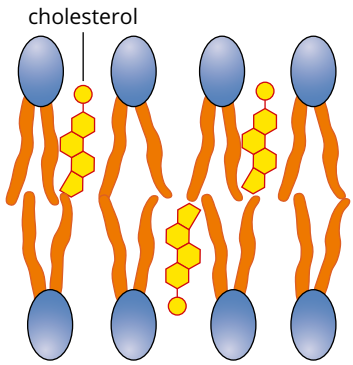


FIGURE 2.3.10 The cholesterol molecules are embedded within the hydrophobic fatty acid region of the cell membrane.

The ability of the phospholipids and proteins to move gives the cell membrane its fluid nature. Membrane fluidity is also influenced by how much unsaturated fatty acids are in the phospholipid molecules—more unsaturated fatty acids make the membrane more fluid, as shown in Figure 2.3.8. The fluidity of the cell membrane is very important because it affects how permeable the membrane is. It also makes it possible for proteins to move within the membrane to particular areas where they are required to carry out their function.

Figure 2.3.9 shows the components of the cell membrane. As well as the phospholipid bilayer, the cell membrane comprises cholesterol, proteins and carbohydrates.

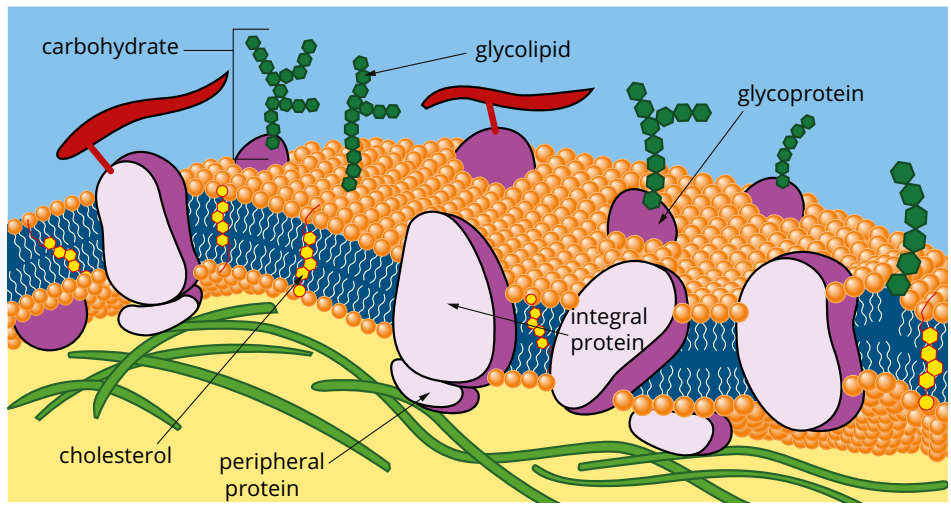


FIGURE 2.3.9 Components of the cell membrane

Cholesterol

Figure 2.3.10 shows how the cell membranes of eukaryotes contain **cholesterol**, a type of fatty molecule, between the phospholipid molecules. Cholesterol stabilises the membrane but does not affect its fluidity, and reduces the permeability of the membrane to small water-soluble molecules.

Cholesterol acts as a buffer against changing temperatures. At high temperatures, cholesterol stops the cell membrane from becoming too fluid by restricting the movement of phospholipids. At low temperatures, cholesterol prevents the cell membrane from solidifying by restricting the tight packing of phospholipids.

Proteins

Like phospholipid molecules, proteins in the cell membrane can move about to some extent, but this movement may be limited to particular regions of the cell membrane.

Proteins that are a permanent part of the cell membrane are called **integral proteins**. Proteins that are a temporary part of the cell membrane are called **peripheral proteins**. Peripheral proteins bind to integral proteins or penetrate into one surface of the cell membrane (Figure 2.3.9). When integral proteins span both phospholipid layers they are also called **transmembrane proteins**. Transmembrane proteins are involved in a number of important cellular and intercellular activities. These activities are illustrated in Figure 2.3.11.

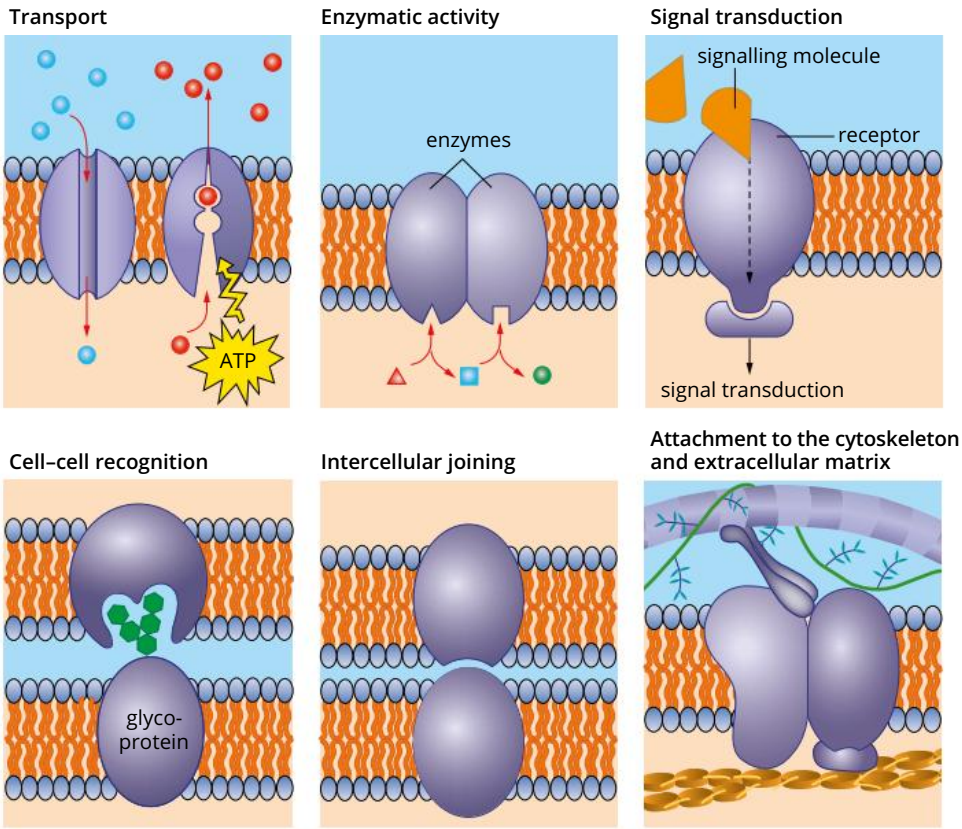


FIGURE 2.3.11 Different functions of cell membrane proteins

Integral proteins have many functions in the cell membrane (Figure 2.3.11). For example, these proteins:

- act as transport channels to transport molecules and ions through the membrane
- function as enzymes
- are involved in signal transduction
- function in cell–cell recognition
- connect cells to each other
- act as attachments to the cytoskeleton and the extracellular matrix.

Carbohydrates

Carbohydrates associated with cell membranes are usually linked to protruding proteins (forming **glycoproteins**) or to lipids (forming **glycolipids**) on the outer surface of the membrane (Figure 2.3.9). They play a role in recognition and adhesion between cells, and in the recognition of antibodies, hormones and viruses by cells.

WS 1.1.3

2.3 Review

SUMMARY

- The external environment of living cells is the layer of extracellular fluid that is in direct contact with the cell membrane.
- For unicellular organisms, the extracellular fluid is the watery environment in which they live and that they can do little to control.
- Multicellular organisms have an internal environment that is more or less independent from the external environment. The external environment of the cells is therefore the extracellular fluid that surrounds them.
- Cell membranes separate the interior of the cell, the cytoplasm, from the external environment and control the movement of substances between the two.
- Cell membranes consist of a double layer of phospholipid molecules. They contain protein molecules of various sizes as well as fatty molecules such as cholesterol. They are also associated with other molecules, including carbohydrates.
- The phospholipid nature of the cell membrane makes it impermeable to water-soluble particles, ions and polar molecules.
- Cell membrane proteins:
  - provide selective channels that enable water-soluble particles and ions to travel through the cell membrane
  - catalyse reactions associated with the cell membrane
  - communicate with the external environment and other cells
  - bind with other cells.

KEY QUESTIONS

Retrieval

1 List three functions of the cell membrane.

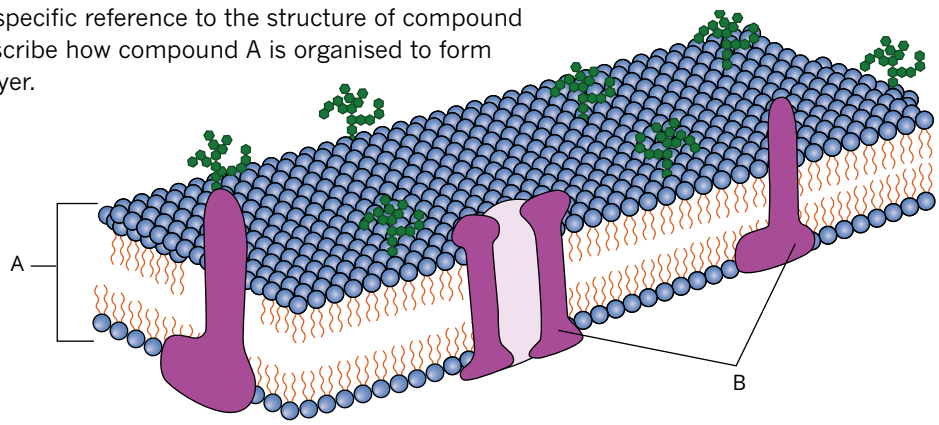
2 Identify the component of the phospholipid molecule that does not allow most water-soluble substances to pass through the phospholipid bilayer barrier of the cell membrane.

Comprehension

3 Membrane-bound proteins may have carbohydrates attached. Explain the role these proteins play in the cell membrane.

4 **a** The illustration shows the structure of a typical cell membrane. Identify the compounds labelled A and B.

b With specific reference to the structure of compound A, describe how compound A is organised to form a bilayer.



5 Explain the importance of the fluidity of the cell membrane for the function of eukaryotic cells.

6 Explain the role the cell membrane plays in regulating the internal environment of a cell.

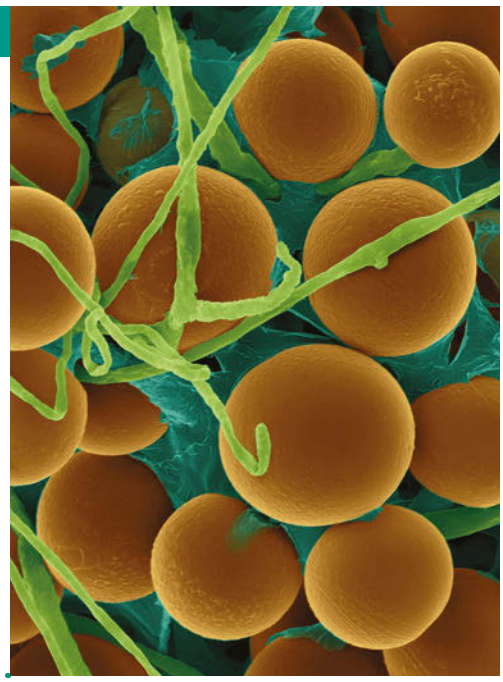
Analysis

7 You are asked to give a one-minute summary to the class on the fluid mosaic model of the cell membrane. Consider the key points necessary for your response and organise them appropriately to clearly explain the fluid mosaic model to your class.

2.4 Crossing the membrane

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

- understand the differences between diffusion, osmosis, facilitated diffusion and active transport and name some examples of the types of substances transferred by each method
- understand the importance of surface area to volume ratio for cell function
- understand that endocytosis is a form of active transport that usually moves large polar molecules that cannot pass through the hydrophobic cell membrane into the cell
- understand that phagocytosis is a form of endocytosis
- predict the direction of movement of materials across the cell membrane on the basis of factors such as concentration, physical and chemical nature of the materials
- explain how the size of a cell is limited by the relationship between surface area to volume ratio and the rate of diffusion
- calculate surface area to volume ratios
- conduct an investigation to compare the efficiency of movement of materials that have different surface area to volume ratios.



In the previous module, you learnt about the composition of the cell membrane, and that one of its main characteristics is exchanges of molecules between the cytoplasm and the external environment of the cell. Small molecules and water are constantly transported across the cell membrane in both directions. Depending on their size and polarity, molecules diffuse between the phospholipid molecules or pass through channels formed by proteins embedded within the membrane. For larger molecules such as proteins and polysaccharides, bulk transport across the cell membrane is used. In this section, you will learn about the selective permeability of the cell membrane. You will also explore the various methods employed to control the exchange of molecules, including diffusion, facilitated diffusion, osmosis, active transport and bulk transport by endocytosis or exocytosis.

CELL MEMBRANE PERMEABILITY

To maintain the composition of the intracellular fluid, cells can control which molecules move into and out of the cell across the cell membrane. The regulation of movement is because of two features of biological membranes. Cell membranes are **semipermeable**, and have transmembrane proteins. The phospholipid bilayer acts like a molecular sieve, controlling what moves between the intracellular and extracellular environments. As Figure 2.4.1 shows, many different types of molecules can move across cell membranes, and they do so in different ways, depending on their properties, such as size, charge, polarity and solubility (Table 2.4.1).

Semipermeable membranes allow solvent molecules to pass through, but prevents at least some of the solute molecules from doing so.

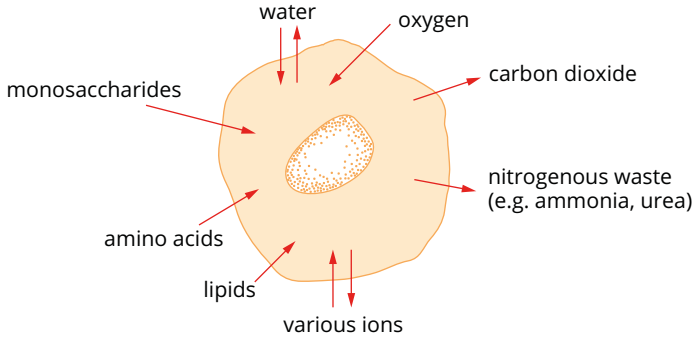


FIGURE 2.4.1 Cells exchange many substances with their environment across the cell membrane.

TABLE 2.4.1 The cell membrane's permeability to different molecules

Molecule or ion	Examples	Permeability of membrane to the molecule or ion
small uncharged molecule	oxygen, carbon dioxide	permeable
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	permeable
small polar molecule	water, urea	permeable or semipermeable
small ion	potassium ion (K^+) sodium ion (Na^+), chloride ion (Cl^-)	non-permeable (molecule passes through protein channels)
large, polar, water-soluble molecule	amino acid, glucose	non-permeable (molecule passes through protein channels)

A solute is a substance dissolved in another substance, known as the solvent.

Permeable membranes are not selective in what molecules pass through them. All solutes and the solvent can pass easily across permeable membranes. Membranes are said to be 'semipermeable' or 'selectively permeable' when they allow some particles or solutes and the solvent to pass through the phospholipid part of the cell membrane, but not other solutes. Figure 2.4.2 illustrates the movement of particles across permeable and semipermeable membranes.

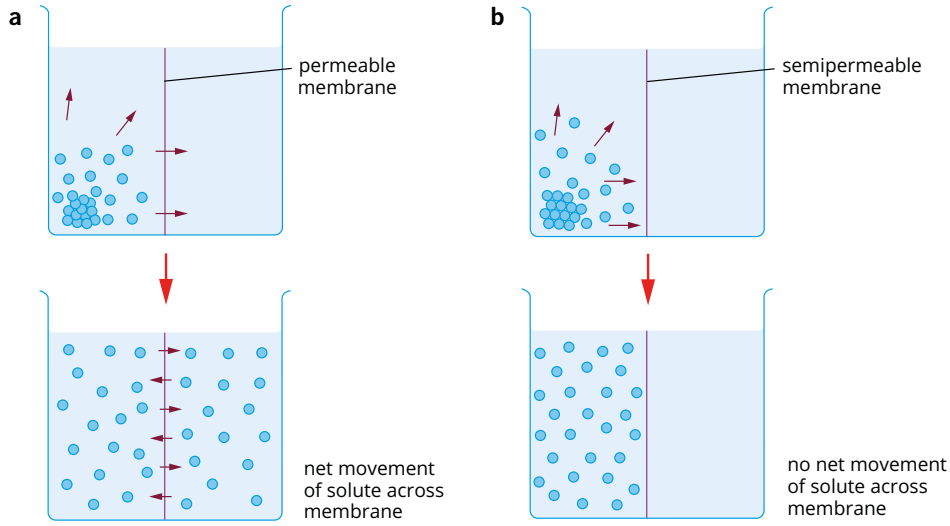


FIGURE 2.4.2 (a) When a membrane is permeable, to the solute and the solvent, the solute particles cross the membrane down the concentration gradient. (b) If the membrane is impermeable to the solute, then only the solvent can cross the membrane and the solute is prevented from diffusing through the membrane.

Because of their hydrophobic lipid nature, cell membranes are permeable to small, uncharged molecules and lipid-soluble molecules. In other words, small, uncharged molecules and lipid-soluble molecules can move freely through the phospholipid bilayer. However, the lipid nature of cell membranes makes them impermeable to:

- most water-soluble molecules
- ions (atoms or groups of atoms with an overall positive or negative charge)
- polar molecules (molecules with charged regions but no overall charge).

Membranes that do not allow substances to diffuse across them are referred to as **non-permeable**. Molecules that cannot diffuse across the phospholipid bilayer may enter and exit the cell through specific protein channels in the cell membrane, which are shown in Figure 2.4.3.

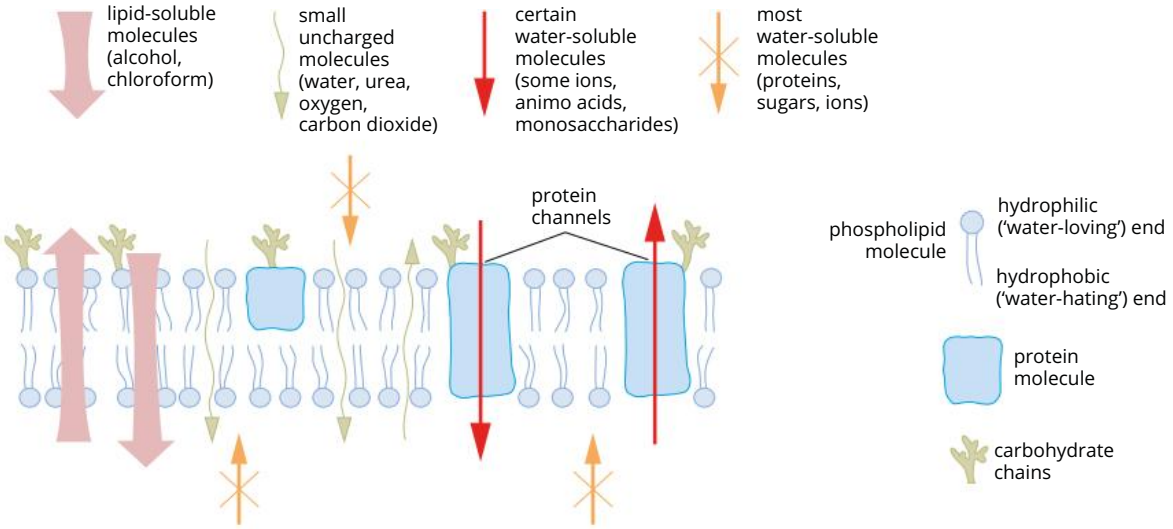


FIGURE 2.4.3 If the cell membrane is not permeable to molecules, protein channels must assist the molecules to cross the membrane.

PASSIVE TRANSPORT

Diffusion of molecules across the cell membrane without the expenditure of energy is known as **passive transport**. The three types of passive transport across membranes are diffusion, facilitated diffusion and osmosis. The movement of a molecule across a biological membrane is called passive transport when the cell does not have to expend energy to make it happen.

Diffusion

Particles in a solution move from an area of high concentration to an area of low concentration. This process is called diffusion and is shown in Figure 2.4.4.

Particles are always in constant random motion. The random motion is a result of the kinetic energy (energy of movement) of the molecules or ions and results in many collisions of the particles. Because there are many particles colliding with each other during this process, the overall movement of particles is very slow.

Solute molecules can diffuse across a membrane only if the membrane is permeable to them. There is a constant movement of solute molecules backwards and forwards across the membrane. If the solute concentration is higher on one side of the membrane than the other, more solute molecules cross from the area of higher concentration to the area of lower concentration (i.e. down its **concentration gradient**), as you can see on the left side of Figure 2.4.5. However, if the concentration of solute molecules is the same on both sides of the membrane, there is always about the same number moving across in either direction. That is, there is no net movement from one side to the other.

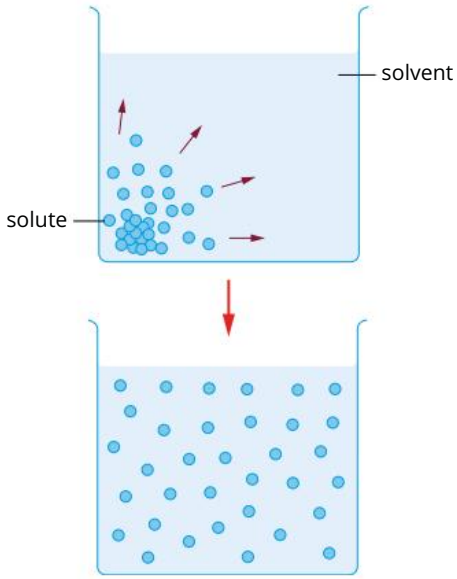


FIGURE 2.4.4 Diffusion results in the random dispersal of solute molecules throughout a solvent.

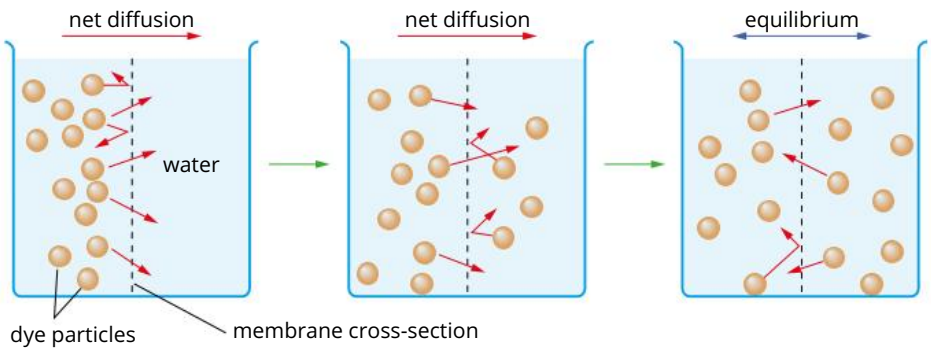


FIGURE 2.4.5 The solute particles are able to diffuse across the semipermeable membrane from high concentration (on the left) to low concentration. When equilibrium is reached, solute particles continue to randomly diffuse from both sides of the membrane but there is no change to the overall concentration. Dynamic equilibrium has been established.

If the membrane is semipermeable (i.e. it is impermeable to some molecules) there is no movement of those molecules from the area of higher concentration to the area of lower concentration, as you can see on the right side of Figure 2.4.2 on page 38.

Diffusion can be seen when a drop of ink (the **solute**) is placed in a jar of still water (the **solvent**). The dye particles in the ink move randomly through the water until the colour is homogenous (evenly spread). In other words, the solute particles move from an area of high solute concentration (the drop of ink) to the areas of low solute concentration (the rest of the jar). The solute particles are said to have moved down the concentration gradient.

Diffusion is called a passive process because it does not require additional energy from outside the system (in the form of ATP). It occurs only because there is a concentration gradient. The types of diffusion across membranes include simple diffusion, facilitated diffusion and osmosis (a special form of diffusion).

Diffusion is the passive net movement of molecules from a region where they are in high concentration to a region where they are in low concentration.

Factors affecting rate of diffusion

The three main factors that affect the rate of diffusion across a membrane are:

- concentration—the greater the difference in concentration, the higher the rate of diffusion. When the concentration is equal on both sides of the membrane, the net diffusion is zero, even at high temperatures
- temperature—the higher the temperature, the higher the rate of diffusion. Increasing the temperature increases the speed at which molecules move
- particle size—the smaller the particles, the higher the rate of diffusion through a membrane.

Facilitated diffusion

The phospholipid bilayer of the membrane is impermeable to certain particles, including ions and large polar molecules. However, certain proteins in the membrane allow for the diffusion of these particles into and out of the cell. Because the diffusion of these molecules is assisted by proteins, and does not require any additional energy to be added to the system, the process is called **facilitated diffusion**.

In facilitated diffusion:

- the membrane transport proteins are specific for particular particles, so transport is selective; some particles are transported and others are not
- transport is more rapid than by simple diffusion
- the transport proteins can become saturated (fully occupied) as the concentration of the transported substances increases
- the transport of one particle may be inhibited by the presence of another particle that uses the same transport protein
- no additional energy is required; the particles move down their own concentration gradient.

The two main types of membrane transport proteins in facilitated diffusion are **channel proteins** and **carrier proteins**. Membrane proteins provide channels for the passage of water-soluble (polar) molecules and ions across the phospholipid bilayer. Channel proteins are specific for a substance. They do not usually bind with the molecules being transported. Channel proteins function like pores that open and close to allow the passage of specific molecules. They are mainly involved in the passage of water-soluble polar particles, such as ions.

Carrier proteins bind the molecules being transported, causing the protein to change shape (conformation), which allows specific molecules to be transported across the membrane. You can see this in Figure 2.4.6. After the molecule has crossed the membrane, the carrier protein is restored to its original shape.

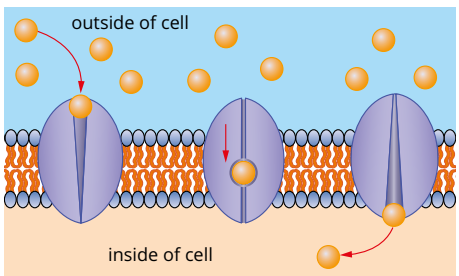


FIGURE 2.4.6 In facilitated diffusion, particles move from one side of the membrane down the concentration gradient mediated by specific membrane carrier proteins or channel.

Osmosis

Osmosis refers to the net diffusion of water molecules across a semipermeable membrane.

If a dilute and a concentrated solution are separated by a semipermeable membrane that allows the movement of free water molecules but not solute molecules, the free water molecules move across the membrane from the dilute to the concentrated solution.

In osmosis, net diffusion of water occurs through a semipermeable membrane from a dilute to a concentrated solution in an effort to achieve equilibrium. Diffusion occurs down water's concentration gradient, which is also known as the **osmotic gradient** and is shown in Figure 2.4.7. The pressure causing the water to move along this gradient is called **osmotic pressure**.

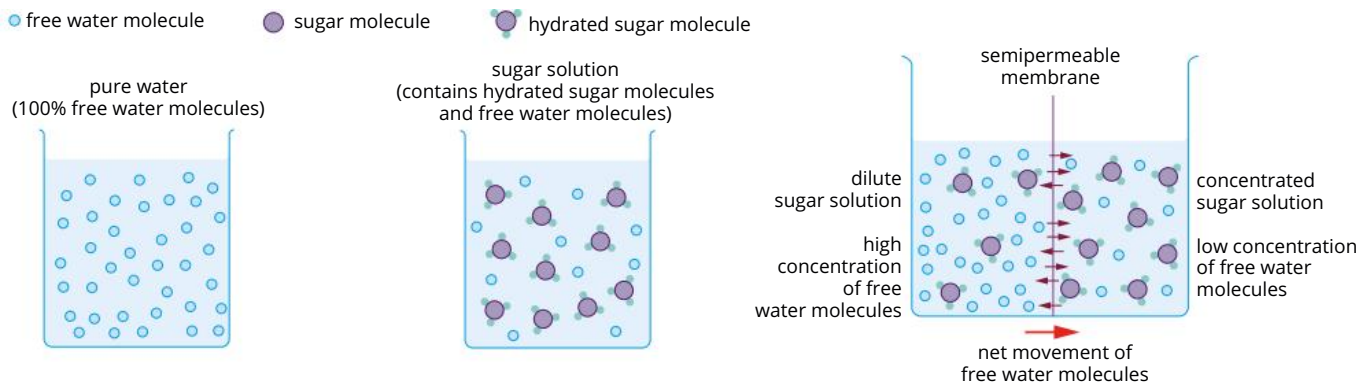


FIGURE 2.4.7 A net movement of water molecules from a dilute solution through a semipermeable membrane into a concentrated solution is osmosis.

Osmosis can be demonstrated by using Visking tubing (containing a strong sugar solution coloured with food dye) attached to a clear capillary tube and submerged in a beaker of water, as shown in Figure 2.4.8. Visking tubing is a synthetic semipermeable membrane made from cellulose. In the Visking tubing, water molecules bind to the sugar molecules. As a result, there are fewer free water molecules in the Visking tubing and a net movement of free water molecules into the tubing by osmosis occurs. This causes an increase in the volume of liquid in the tubing, increasing the pressure and forcing the coloured solution to rise up the capillary tube.

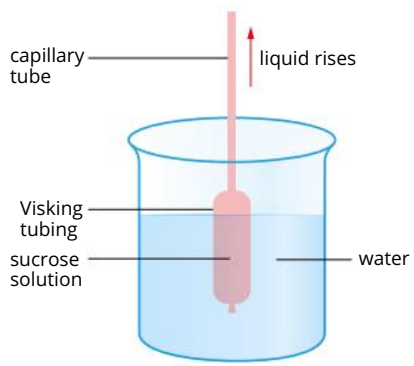


FIGURE 2.4.8 A Visking tubing apparatus for the demonstration of osmosis

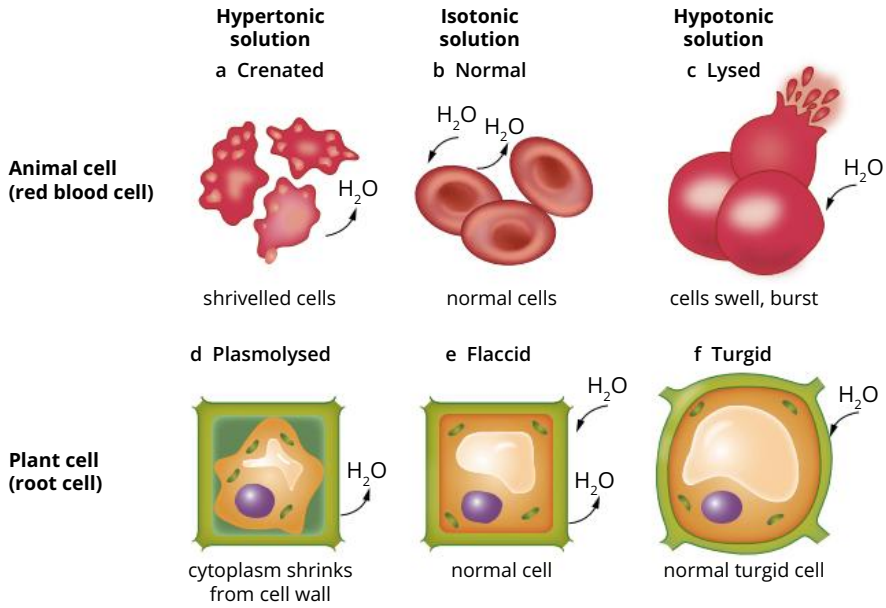
In osmosis, we are always comparing solute concentration between two solutions. The terms 'isotonic', 'hypertonic' and 'hypotonic' solutions are often used to describe the difference.

- Isotonic solutions: the solutions being compared have equal concentrations of solutes.
- Hypertonic solutions: the solutions with the higher concentration of solute (and hence lower concentration of free water molecules).
- Hypotonic solutions: the solutions with the lower concentration of solute (hence higher concentration of free water molecules).

Effect of osmosis on cells

The cell membrane is permeable to water, so when cells are placed in fresh water, an osmotic gradient draws water into the cells. This is because the cytosol is a concentrated solution containing many dissolved substances. In other words, the cytosol has a low concentration of water. For example, if red blood cells are placed in fresh water, the cells absorb so much water by osmosis that they swell and may eventually burst, releasing red pigment into the water, as shown in Figure 2.4.9c (page 42). Conversely, if red blood cells are placed in a solution that is more concentrated than their cytosol, water leaves the red blood cells by osmosis and causes them to shrink (crenation). This is shown in Figure 2.4.9a.

For cells with cell walls, such as plant cells and prokaryotes, the cell wall helps to maintain the cell's water balance. For example, if a plant cell loses water by osmosis, it starts to shrivel and the cell membrane starts to pull away from the cell wall—the cell is said to have become plasmolysed (Figure 2.4.9d). However, if the plant cell absorbs water by osmosis, it swells to some extent but the relatively inelastic cell wall prevents the cell from bursting. The cell wall expands until it exerts a pressure back on the cell, known as turgor pressure. Turgor pressure prevents further water uptake. At this point, the plant cell is turgid (Figure 2.4.9f).



PA 1.1.1

FIGURE 2.4.9 The effect of three different solution concentrations on an animal cell and a plant cell

ACTIVE TRANSPORT

Active transport requires the use of energy to move substances against a concentration gradient.

Figure 2.4.10 illustrates **active transport**. Active transport involves the use of energy by the cell to transport particles across membranes. Because active transport uses energy, it can move substances against a concentration gradient from low concentration to high concentrations. Active transport enables a cell to maintain internal concentrations of small solutes that differ from concentrations in its environment. The membrane transport proteins in active transport are all carrier proteins.

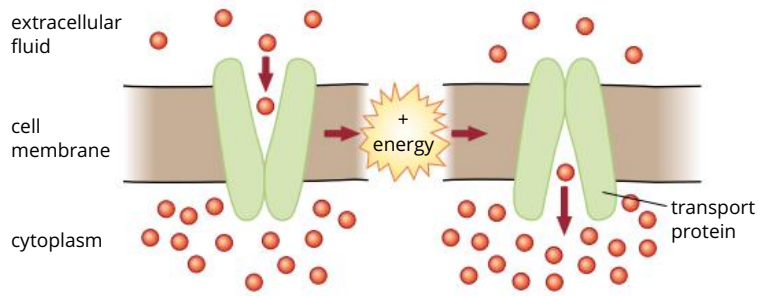


FIGURE 2.4.10 Active transport requires an energy source so that the molecules can be transported across the membrane.

Active transport and facilitated diffusion compared

Passive transport does not require an additional energy source. There are three types of passive transport: diffusion, facilitated diffusion and osmosis. Diffusion (Figure 2.4.11a) occurs when substances move from high to low concentrations. In facilitated diffusion (Figure 2.4.11b), substances move from high to low concentrations with help from a transport protein. Osmosis is the movement of water from high to low water concentrations. Active transport (Figure 2.4.11c) requires an energy source. As a result, it usually moves substances from low to high concentrations.

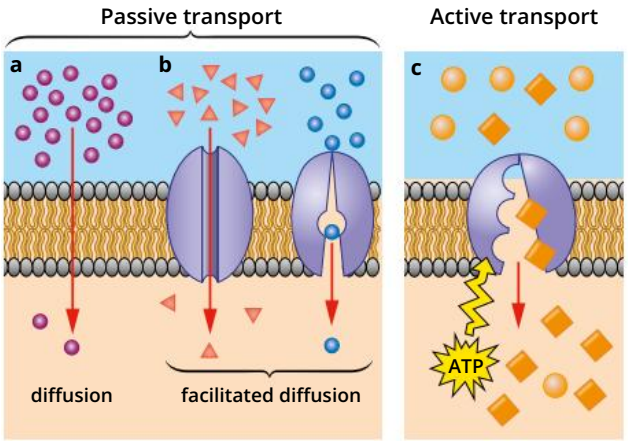


FIGURE 2.4.11 Passive transport of molecules across the membrane does not require energy. Active transport does require an energy source.

The comparison between passive transport and active transport can be seen in Table 2.4.2.

TABLE 2.4.2 A comparison of passive and active transport

	Passive transport			Active transport
	Simple diffusion	Osmosis	Facilitated diffusion	
Type of substance	hydrophobic molecules, small polar molecules; for example, water, oxygen, carbon dioxide	water	hydrophilic molecules; for example, calcium ions, glucose, amino acids, sodium ions	hydrophilic molecules; for example, glucose, amino acids, sodium ions, potassium ions
Type of membrane protein required	none	none	channel protein carrier protein	carrier protein
Direction of movement of molecules	down concentration gradient	down concentration gradient	down concentration gradient	against concentration gradient
Energy requirement	none	none	none	requires energy in the form of ATP

Active transport has the same properties of selectivity, saturation and competitive inhibition as facilitated diffusion because it also occurs through transport proteins (Figure 2.4.12 on page 44). Selectivity means that some substances are transported but others are not. Saturation means that there is no increase in the rate of transfer when all transport proteins are open. Competitive inhibition means that one substance can inhibit the transport of another substance by using the same transport protein.

But unlike facilitated diffusion, which can occur through either channel or carrier proteins, active transport only occurs through carrier proteins. Because active transport uses energy, it can move substances against a concentration gradient (from low concentrations to high concentrations). In comparison, facilitated diffusion uses no energy, so it can only move substances down a concentration gradient.

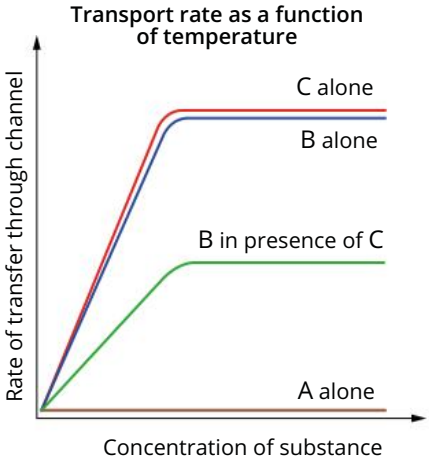


FIGURE 2.4.12 Theoretical transport rate versus concentration for the movement of three substances through a channel protein. Substances B and C are transported, but not substance A—this demonstrates selectivity. The rate of transfer of substances B and C flattens out when their concentrations reach a certain level, demonstrating saturation. The rate of transport of B is less when C is present, demonstrating competitive inhibition.

In different situations, either facilitated diffusion or active transport may be used to transport a particular molecule. Whether a cell uses facilitated diffusion or active transport depends on the specific needs of the cell.

For example, glucose is actively transported from the gut into epithelial cells lining the gut so it can enter the bloodstream. This process is regulated by hormones, principally insulin and glucagon. If gut glucose levels are high, blood glucose levels increase. If gut glucose levels are low, active transport makes sure that the little glucose that is in the gut gets pumped into the epithelium from where it can move to blood through facilitated diffusion.

In contrast, red blood cells move glucose by facilitated diffusion. This makes sense because glucose concentration in the blood is usually maintained within a narrow range. In addition, cells convert glucose into other chemicals as soon as it enters the cell, keeping the intracellular concentration of glucose lower than the blood concentration of glucose.

BULK TRANSPORT

Large polar molecules and other substances that cannot pass through the hydrophobic cell membrane can enter or exit the cell via bulk transport. Bulk transport includes exocytosis and endocytosis (Figure 2.4.13). Both exocytosis and endocytosis are forms of active transport because they require energy.

Exocytosis and endocytosis

Figure 2.4.13 illustrates how cells transport large molecules into and out of the cell. **Exocytosis** is the movement of substances out of the cell, from the cytoplasm to the extracellular fluid. A transport **vesicle**, which may contain wastes or substances needed for secretion (e.g. digestive enzymes), fuses with the cell membrane and the junction then breaks down, releasing the enclosed materials. Unicellular heterotrophs such as amoebas remove digestive wastes in this way.

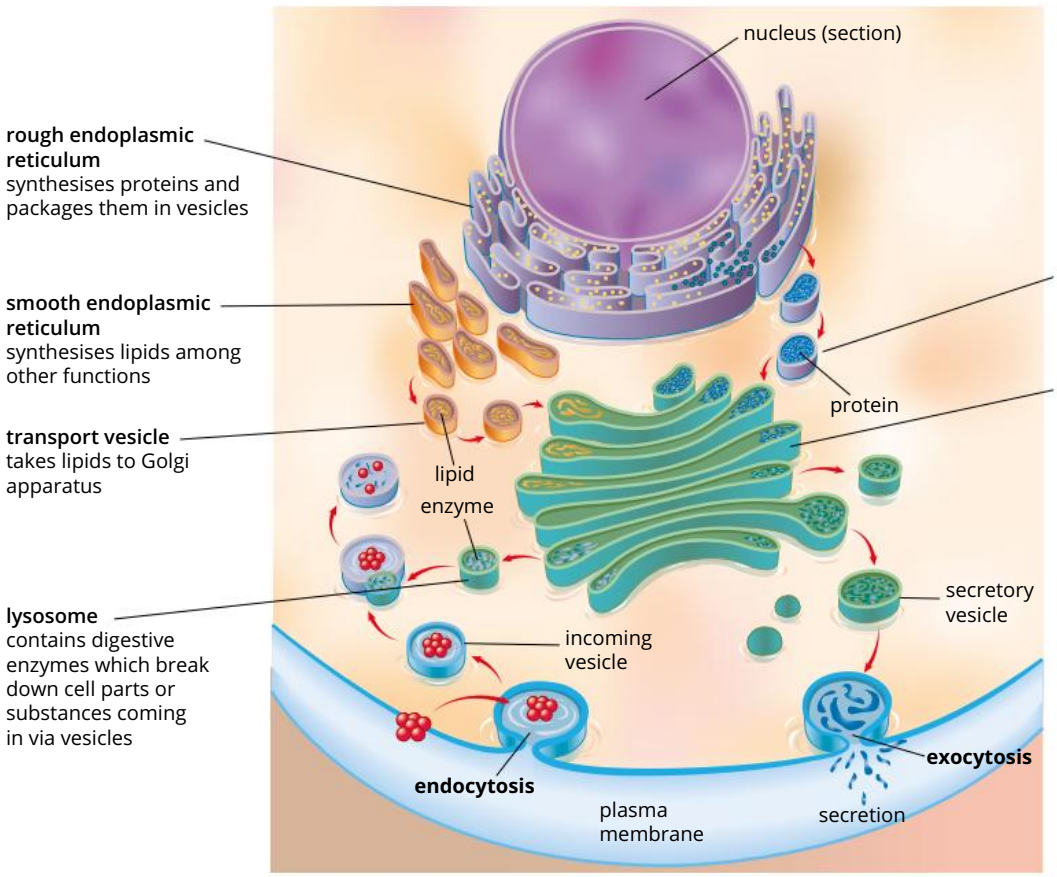


FIGURE 2.4.13 To transport large molecules that proteins cannot transport, cells use endocytosis and exocytosis, which require vesicles and energy.

Endocytosis is the movement of substances into the cell, from the extracellular fluid into the cytoplasm. Particles near the cell membrane are enclosed by the membrane, which then pinches off to form a vesicle enclosing the particle. In eukaryotes, this vesicle may then become fused with a lysosome so that its contents can be digested for use by the cell. The two forms of endocytosis are pinocytosis and phagocytosis. **Pinocytosis** is the entry of extracellular fluid and substances such as proteins and sugars that are carried in it. **Phagocytosis** is the entry of large particles such as bacteria and cell debris.

SURFACE AREA TO VOLUME RATIO AND CELL SIZE

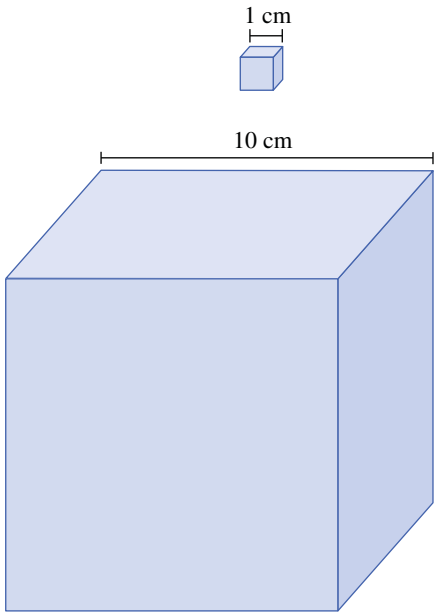
All cells must exchange nutrients and wastes with their environment via the cell membrane. In addition, enzymes that are bound to the cell membrane catalyse many important cellular processes.

The surface area of the cell membrane around a cell affects the rate of exchange that is possible between the cell and its environment, and can affect certain processes catalysed by membrane-bound enzymes.

Larger cells have greater metabolic needs, so they need to exchange more nutrients and waste with their environment. However, because of the surface area to volume relationship, they do not have a proportionally larger surface area of cell membrane for this exchange to take place. So being small helps cells to maximise their efficiency in exchanging matter with their environment.

Surface area versus volume

The relationship between surface area and volume can be explained using cubes, as shown in Figure 2.4.14. A cube with a side length of 1 cm has a surface area of 6 cm^2 and a volume of 1 cm^3. The surface area to volume ratio of a 1 cm cube is thus 6:1 (or 6). A cube with a side length of 10 cm has a surface area of 600 cm^2 and a volume of 1000 cm^3. A 10 cm cube thus has a surface area to volume ratio of 600:1000, or 0.6. Comparing these two cubes, it can be observed that, while the volume of the bigger cube is 1000 times larger than the volume of the smaller cube, its surface area is only 100 times larger.



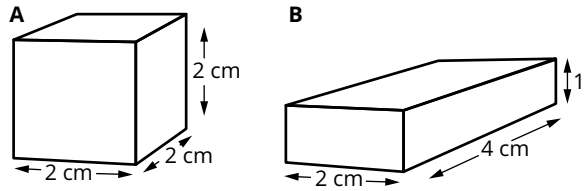
Side length	1 cm	10 cm
Surface area	6 cm^2	600 cm^2
Volume	1 cm^3	1000 cm^3
Surface area to volume ratio	6	0.6

FIGURE 2.4.14 Two cubes, showing the relationship between surface area and volume

Worked example 2.4.1

SURFACE AREA AND VOLUME

Consider the two objects shown below. Both objects have a volume of 8 cm^3. Which shape has the greater surface area to volume ratio?

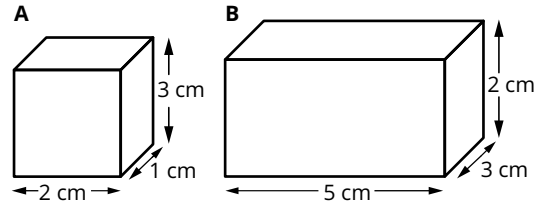


Thinking	Working
Look at shape A. Identify the dimensions of the cube.	Shape A: 6 sides, each with width of 2 cm and height of 2 cm
Calculate the surface area of shape A, given that there are six sides, each with the same area.	Surface area = $6 \times 2 \times 2$ = 24 cm^2
Calculate the surface area (SA) to volume (V) ratio of shape A.	$\frac{SA}{V} = \frac{24}{8}$ = 3
Look at shape B. Identify the dimensions of the cube.	Shape B: 2 sides, each with width of 2 cm and height of 1 cm 2 sides, each with width of 4 cm and height of 1 cm 2 sides, each with width of 2 cm and height of 4 cm
Calculate the surface area of shape B, given that there are six sides with three different areas.	Surface area = $(2 \times 2 \times 1) + (2 \times 4 \times 1) + (2 \times 2 \times 4)$ = 4 + 8 + 16 = 28 cm^2
Calculate the surface area to volume ratio of shape B.	$\frac{SA}{V} = \frac{28}{8}$ = 3.5
Compare the surface area to volume ratios.	Therefore, shape B has the greater surface area to volume ratio.

➤ Try yourself 2.4.1

SURFACE AREA AND VOLUME

Consider the two objects shown below. Which shape has the greater surface area to volume ratio?



2.4 Review

SUMMARY

- Membranes are impermeable to most water-soluble molecules, ions and polar molecules. These substances can only pass through protein channels.
- Lipid-soluble substances can diffuse through the phospholipid bilayer.
- Diffusion is the passive movement of solute molecules along a concentration gradient, from a region of high solute concentration to a region of low solute concentration.
- There are three types of diffusion across cell membranes: simple, facilitated and osmosis.
- Simple diffusion involves solutes to which the membrane is permeable, including lipid-soluble substances, small molecules and water molecules. The rate of diffusion is affected by concentration, temperature and particle size.
- Facilitated diffusion is through selective channels in membranes that permit or enhance the passive movement of particular ions and molecules down their own concentration gradient. Facilitated diffusion generally occurs at a more rapid rate than simple diffusion.
- Osmosis is the net diffusion of water across a semipermeable membrane down its own concentration gradient called the osmotic gradient (i.e. from a low solute concentration to a high solute concentration).
- In active transport, energy is expended to move substances across cell membranes through protein channels against their concentration gradient.
- Exocytosis (moving substances out of the cell) and endocytosis (moving substances into the cell) are forms of active transport involving vesicles that fuse with the cell membrane. These forms of active transport are generally used to transport larger molecules in bulk.
- A large object has a smaller surface area to volume ratio than a small object with the same shape.

KEY QUESTIONS

Retrieval

1 Complete the following table by recalling whether the phospholipid bilayer is permeable, semipermeable or not permeable to each substance described.

Substance	Examples	Permeability
small uncharged molecule	oxygen, carbon dioxide	
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	
small, polar molecule	water, urea	
small ion	potassium ion (K^+), sodium ion (Na^+), chloride ion (Cl^-)	
large, polar, water-soluble molecule	amino acid, glucose	

2 Define 'selective permeability'.

3 List the factors that increase the rate of diffusion.

Comprehension

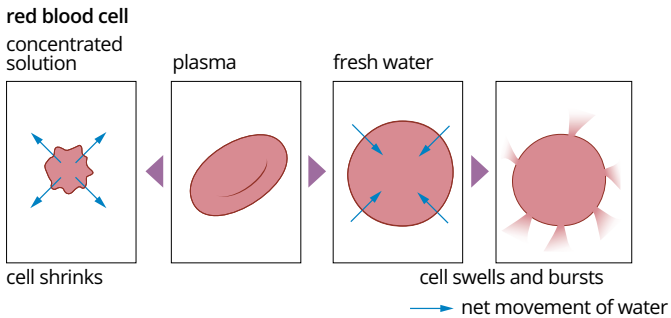
4 Osmosis is a special kind of diffusion. Define osmosis. Draw a diagram to illustrate your answer.

5 Explain how active transport is different from diffusion.

6 Consider the red blood cells in the illustrations below. The arrows indicate the net direction of water movement. Applying your understanding of osmosis, describe how red blood cells would:

a shrink

b swell and burst.



7 Explain why the cell membrane is permeable to chloroform (and equivalent chemicals).

8 Determine why a large surface area to volume ratio is important in exchanging materials between cells/organisms and the external environment.

continued over page

2.4 Review *continued*

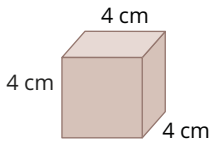
Analysis

9 Compare endocytosis, exocytosis, phagocytosis and pinocytosis. Describe where in your body you would expect each process to occur.

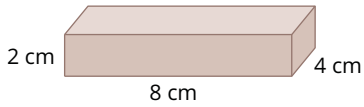
10 Compare simple and facilitated diffusion. Include an example of each.

11 Consider the two objects shown below, which have the same volume of 64 cm^3. Determine which shape has the greater surface area to volume ratio.

A



B

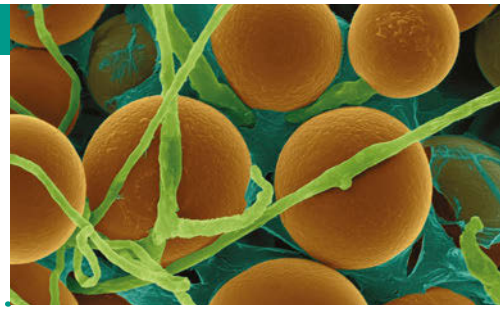


12 Determine whether a round cell of 6 mm diameter will absorb substances via diffusion at a greater rate than a round cell of 3 mm diameter.

2.5 Cell organelles

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

- know and understand that eukaryotic cells have specialised organelles to facilitate cellular processes such as the synthesis of complex molecules, energy transformation, the storage of materials and the removal of cellular wastes and products
- identify cell organelles including chloroplasts, mitochondria, rough endoplasmic reticulum and lysosomes in electron micrographs.



You will recall from Module 2.2 that the two fundamentally different types of cells are prokaryotic and eukaryotic cells, and that organisms are classified into one of three domains (Bacteria, Archaea or Eukarya), according to their cell type.

Bacteria and archaea are prokaryotes. Their cells do not contain membrane-bound organelles. Animals, plants, fungi and protists are eukaryotes. While eukaryote cells may differ in appearance and function, they all contain membrane-bound organelles, such as those seen in Figure 2.5.1.

In this module, you will learn more about the structure and function of organelles.

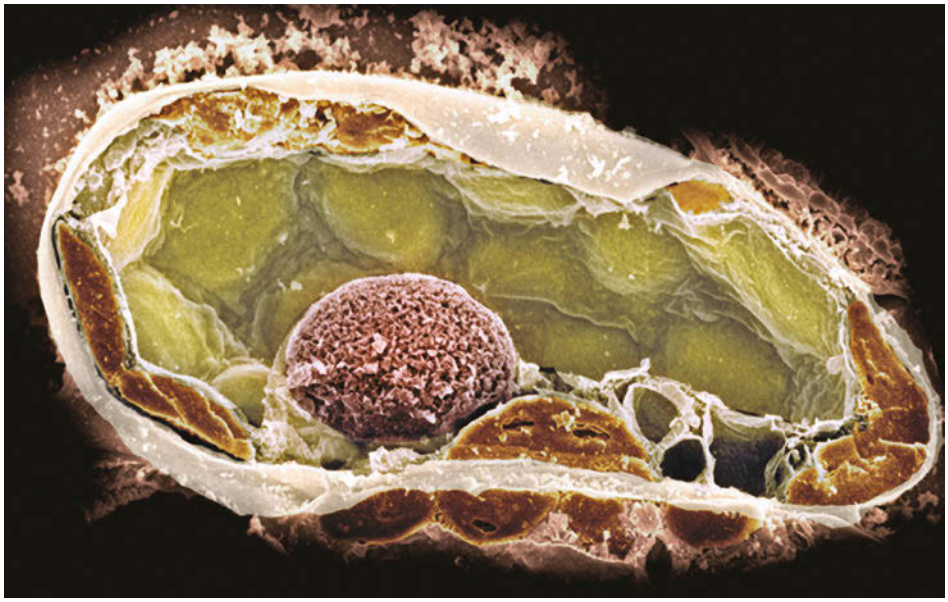


FIGURE 2.5.1 Plants are eukaryotes and so their cells have membrane-bound structures, some of which can be seen in this scanning electron micrograph. The cell wall is the external layer. Inside the cell wall are chloroplasts (brown), the nucleus (pink) and a large vacuole in the centre of the cell.

FUNCTION AND STRUCTURE OF ORGANELLES

Organelles are subcellular structures that have a specific function (Table 2.5.1). Some organelles, as mentioned earlier, are membrane-bound compartments within the cytoplasm. Membrane-bound organelles are only present in eukaryotic cells. Prokaryotic cells have some non-membrane-bound organelles, such as ribosomes, a cell wall and sometimes flagella, although the structure and composition of these are usually different from those of eukaryotic cells.

Enzymes are protein molecules that act as biological catalysts. Enzymes speed up the rate of reactions that would otherwise have taken place much more slowly. Their action is specific: they catalyse only one type of reaction. You will learn more about the role of enzymes in cellular processes in Chapter 3.

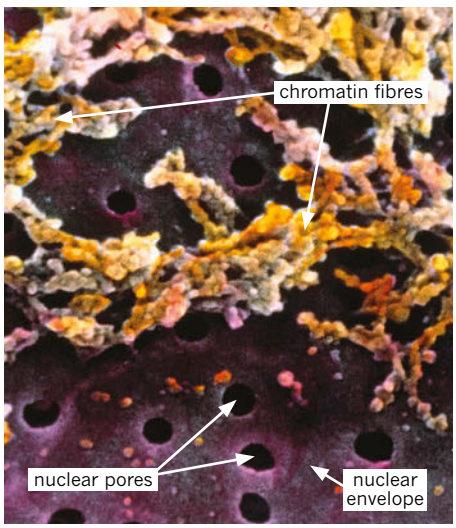


FIGURE 2.5.2 A scanning electron micrograph of the external surface of a nuclear envelope in an onion root tip cell. The envelope consists of a double membrane (purple), which encloses the nuclear DNA. The nuclear pores (black circles) are pathways for the transport of larger molecules between the nucleus and the cytoplasm. Contained within the nucleus are the chromatin fibres (yellow and orange), which contain the chromosomes.

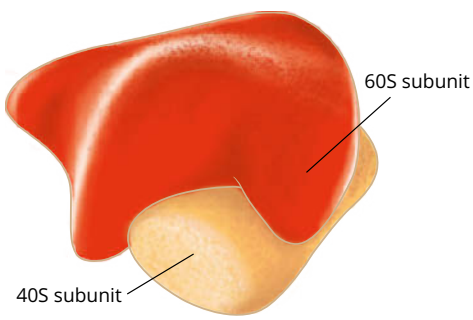


FIGURE 2.5.3 A single eukaryote ribosome consists of a larger 60S subunit and a smaller 40S subunit.

Role of organelle membranes

The membranes surrounding organelles control the movement of substances between the organelle and the cell's cytosol. Just as the cell membrane of a cell enables the cytosol to have a different composition from the cell's surrounding environment, the membranes of membrane-bound organelles enable each organelle to have a different composition from the surrounding cytosol and other organelles. Each membrane-bound organelle has a different function. For this reason, each organelle requires a different internal composition, including a high concentration of enzymes and reactants that are needed for the organelle's particular function.

Cellular organelles are involved in a number of different functions (Table 2.5.1). Their functions include the synthesis and processing of proteins and lipids, energy transformations, storage, and maintaining the structure of the cell.

TABLE 2.5.1 Organelles and their functions

Function	Organelle	Present in plants	Present in animals
Involved in synthesis and processing of proteins and lipids	nucleus	✔	✔
	ribosome	✔	✔
	rough endoplasmic reticulum	✔	✔
	Golgi apparatus	✔	✔
	lysosome	✘	✔
	smooth endoplasmic reticulum	✔	✔
Involved in energy transformations	mitochondrion	✔	✔
	chloroplast	✔	✘
Involved in storage and cell structure	centrioles	sometimes	✔
	flagellum or cilium	✔	✔
	vacuole	✔	small
	cell wall	✔	✘

Synthesis and processing of proteins and lipids

The following organelles are involved in the synthesis and processing of proteins and lipids in eukaryotic cells.

Nucleus

In eukaryotes, most of the DNA (genetic material and nucleic acids) is contained in the nucleus, which is a large organelle surrounded by a double-layered nuclear membrane. The genetic material in the nucleus takes the form of linear chromosomes composed of DNA and proteins. Chromosomes are usually not clearly visible, except during cell division. The nuclear membrane contains pores that link it with the cytoplasm. You can see these pores in Figure 2.5.2. The information for the synthesis of new proteins is present in the DNA.

The most visible structure inside the nucleus of a non-dividing cell is the **nucleolus**. The nucleolus is composed of proteins, DNA and **RNA**, and is where ribosomes are assembled.

Ribosomes

Cells contain many thousands of ribosomes, which are only about 30 nm in diameter and therefore only visible using an electron microscope. Ribosomes are composed of proteins and ribosomal RNA (**rRNA**), and are sites of protein synthesis. They consist of two subunits joined together, as shown in Figure 2.5.3.

The subunits in eukaryote ribosomes are different from those in prokaryote ribosomes. Ribosomes are either free in the cytoplasm or bound to rough endoplasmic reticulum.

Ribosomes translate **mRNA** into proteins. Proteins produced in free ribosomes will function in the cell's cytoplasm, while proteins synthesised in ribosomes bound to the rough endoplasmic reticulum are secreted out of the cell, packaged into organelles or inserted in cell membranes.

Endoplasmic reticulum

Endoplasmic reticulum is a network of intracellular membranous sacs (cisternae) and tubules that link with the cell membrane and other membranous organelles, including the nucleus. The endoplasmic reticulum can be rough or smooth.

Rough endoplasmic reticulum has ribosomes attached, which synthesise proteins. These ribosomes are bound to the membrane of the rough endoplasmic reticulum, as shown in Figure 2.5.4. After the proteins are made, they pass into the endoplasmic reticulum cavity containing enzymes. The enzymes add sugar molecules to the proteins to form glycoproteins.

Rough endoplasmic reticulum is abundant in cells that actively produce and export proteins, such as pancreatic cells, which secrete digestive enzymes. From the rough endoplasmic reticulum, proteins move into the Golgi apparatus for export from the cell.

Smooth endoplasmic reticulum contains the enzymes involved in the synthesis of molecules other than proteins, such as phospholipids and steroids. It is abundant in steroid-secreting cells in the testes, ovaries, kidneys and adrenal glands. Figure 2.5.5 shows smooth and rough endoplasmic reticulum in the cells of a human fetus.

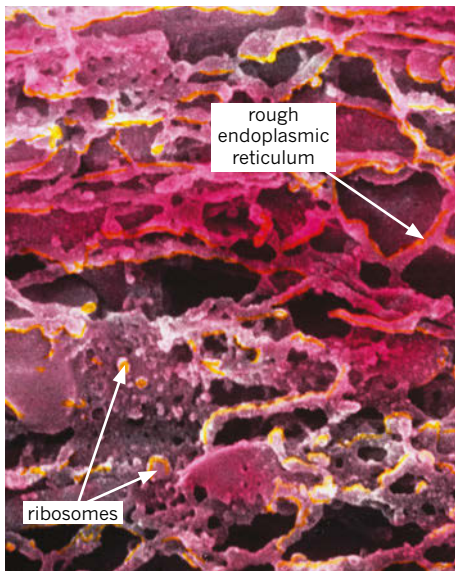


FIGURE 2.5.4 A scanning electron micrograph of endoplasmic reticulum in a cell found in the olfactory epithelium (inside the nasal cavity). Endoplasmic reticulum is a network of folded membranes forming sheets, tubes or flattened sacs in the cell cytoplasm. On the surface of some of the endoplasmic reticulum membranes are ribosomes (yellow spheres).

Golgi apparatus

Figure 2.5.6 shows the **Golgi apparatus** (also called the Golgi body or Golgi complex), which is a stack of flattened smooth membrane sacs called cisternae. Unlike the rough endoplasmic reticulum, the cisternae in the Golgi apparatus are not connected. When proteins formed in the rough endoplasmic reticulum reach the Golgi apparatus, vesicles are formed from each cisternae to transport the proteins from one cisternae to the next. The proteins are modified for use by the cell, or for transport out of the cell. The cisternae then form transport vesicles to move these materials into the cytosol or out of the cell, such as secreted hormones. Vesicles budding from the Golgi apparatus also carry membrane-bound proteins to the cell membrane and digestive enzymes into lysosomes.

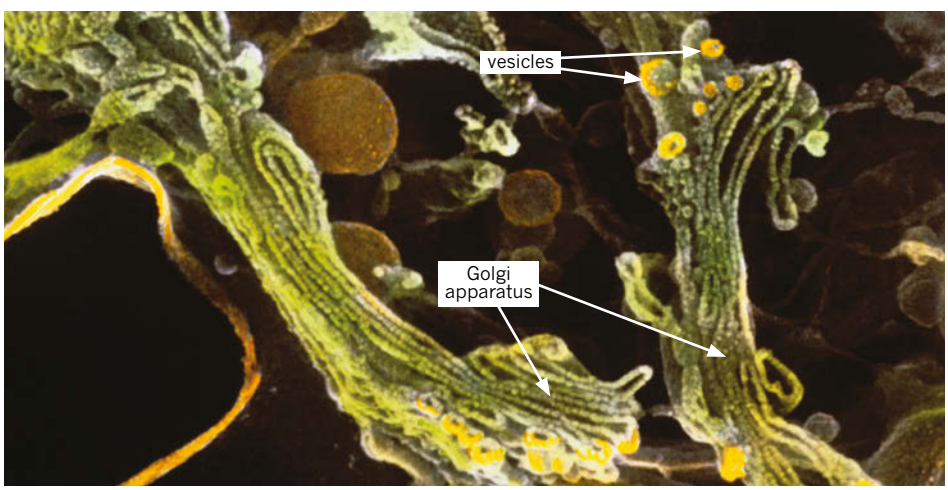


FIGURE 2.5.6 A scanning electron micrograph of the Golgi apparatus of an olfactory bulb cell (part of the brain involved with smell). The Golgi apparatus consists of a stack of flattened interconnecting membranous sacs. It is the site in the cell of synthesis of biochemicals that are packaged into swellings at the margins of the sacs and become pinched off as vesicles (small yellow spheres).

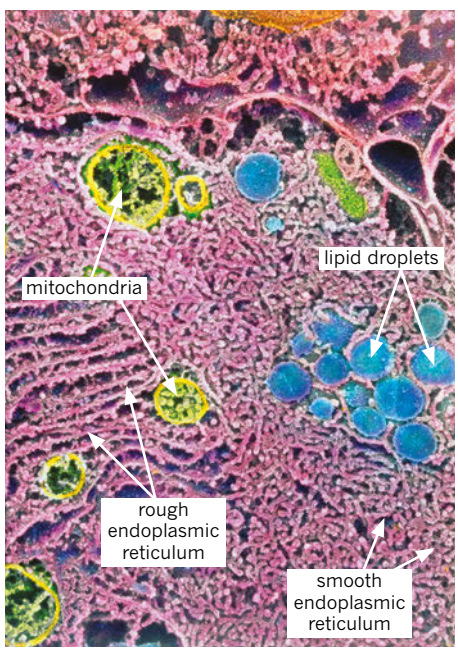


FIGURE 2.5.5 A scanning electron micrograph showing smooth (right) and rough (left) endoplasmic reticulum (light pink) inside a Leydig cell of a 14-week-old human fetus. Leydig cells synthesise steroid hormones in the male testis. Lipid droplets (round blue structures) supply the cholesterol needed for the biosynthesis of steroids. Mitochondria (yellow) produce chemical energy for the cell.

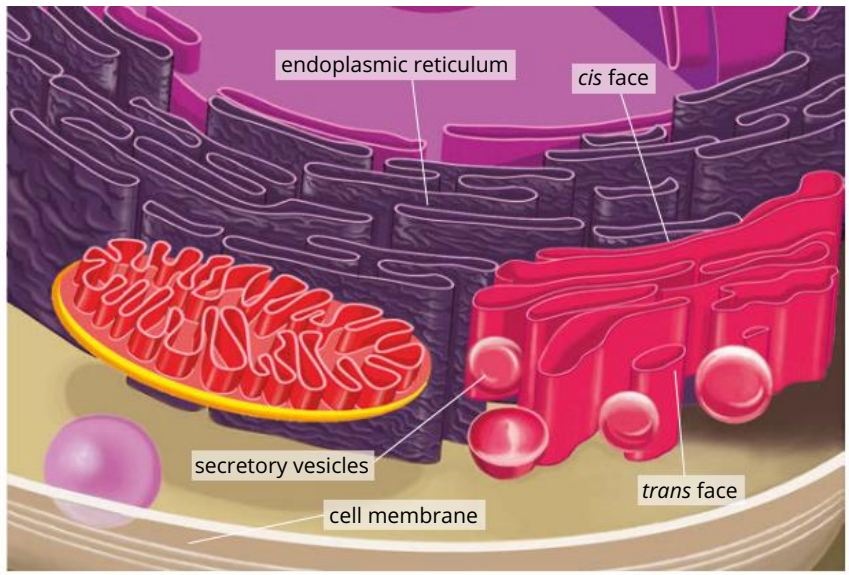


FIGURE 2.5.7 The Golgi apparatus has a *cis* face, which faces the endoplasmic reticulum, and a *trans* face, which faces the cell membrane.

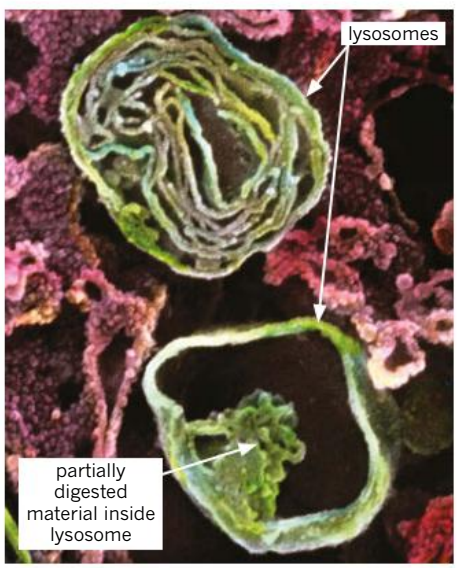


FIGURE 2.5.8 A scanning electron micrograph of two lysosomes in a pancreatic cell. Lysosomes (green) are small spherical vesicles bound by a single membrane (clearer on lower lysosome). Material that probably represents partially digested cell organelles can be seen in each lysosome.

Exocytosis is the fusion of a vesicle with the cell membrane, expelling its contents outside the cell.

The Golgi apparatus has two faces: the *cis* face and the *trans* face, as shown in Figure 2.5.7. The cisternae of the *cis* face are connected to the endoplasmic reticulum, either directly or by small transport vesicles. This allows the proteins made in the rough endoplasmic reticulum to enter the Golgi apparatus. The cisternae of the *trans* face are connected to the cell membrane by large secretory vesicles, which contain proteins to be secreted outside the cell. The membranes of the *cis* face more closely resemble the membranes of the endoplasmic reticulum, and the membranes of the *trans* face more closely resemble the cell membrane in their composition.

Secretory cells have a well-developed Golgi apparatus, but in other cells the Golgi apparatus is small. Some products packaged by the Golgi apparatus, such as the enzymes found in lysosomes, are not released from the cell.

Lysosomes

Figure 2.5.8 shows two **lysosomes**, which are specialised vesicles that digest (break down) unwanted matter. They are the recycling units of the cells. They are found only in animal cells. Lysosomes are formed when a transport vesicle containing enzymes is released from the Golgi apparatus and fuses with another vesicle called an endosome. The endosome contains molecules brought into the cell by endocytosis.

Lysosomes fuse with vesicles containing unwanted matter such as damaged organelles or foreign matter. The enzymes in the lysosome then digest the unwanted matter. Small molecules that the cell can re-use may diffuse back into the cytoplasm, but the rest are retained in the lysosome or released from the cell by exocytosis.

Summary: synthesis and processing proteins and lipids

Protein and lipid synthesis and processing is shown in Figure 2.5.9. DNA is transcribed inside the nucleus into RNA. RNA moves out of the nucleus and binds to ribosomes. Ribosomes synthesise proteins using the information on the RNA. Proteins that are secreted out of the cell are made in the ribosomes bound to the rough endoplasmic reticulum. These proteins are modified and packaged in the Golgi apparatus. Vesicles arising from the Golgi apparatus fuse with the cell membrane, releasing their contents from the cell. They also insert membrane-bound proteins into the cell membrane. Lipids are synthesised and processed in the smooth endoplasmic reticulum.

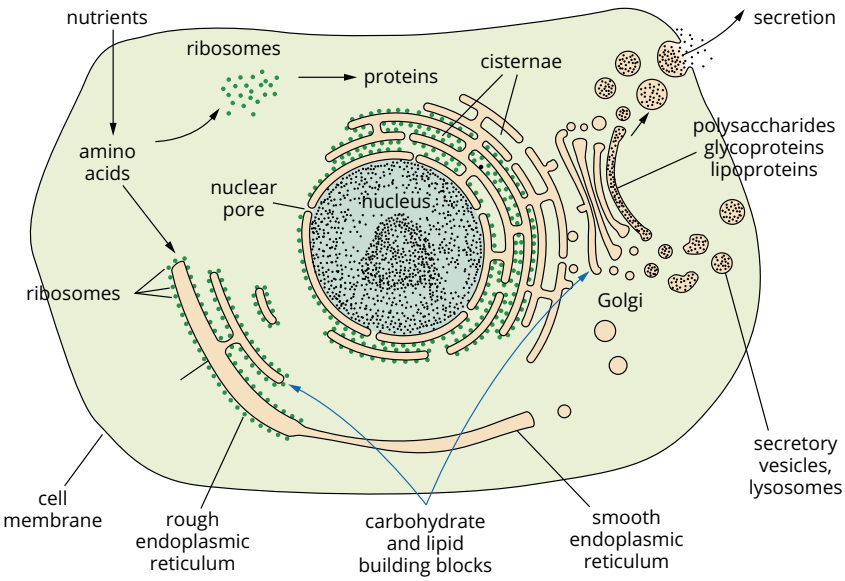


FIGURE 2.5.9 A typical animal cell, showing the organelles involved in synthesising and processing proteins and lipids

Energy transformations

Mitochondria and chloroplasts are the organelles involved in energy transformations within eukaryotic cells.

Mitochondria

Mitochondria (singular mitochondrion) are organelles composed of two membranes. The inner membrane of the mitochondria has folds called cristae, as shown in Figure 2.5.10. There are two different compartments inside mitochondria: an intermembrane space and the matrix. The matrix is the fluid-filled space enclosed by the inner membrane and contains a double-stranded DNA molecule. Different enzymes are found inside each compartment and on each membrane.

Mitochondria are involved in the energy transformations that release energy from organic molecules for use by the cell. The number of mitochondria in a cell is related to the cell's energy requirements. Very active cells, such as heart muscle cells, have many of thousands of mitochondria.

Chloroplasts

Figure 2.5.11 shows **chloroplasts**, which are organelles involved with photosynthesis. They have a double-stranded DNA molecule and are green because of the large amounts of chlorophyll (a green pigment) they contain. They are present in plants and many protists, but never in animals or fungi.

Chloroplasts are composed of a system of three membranes: the outer membrane, the inner membrane and the thylakoid system. Thylakoids are disc-shaped sacs. This system of membranes forms compartments within the chloroplast that contain different enzymes.

Chloroplasts trap light energy, which is used to split water molecules into hydrogen and oxygen. The hydrogen then combines with carbon dioxide to make glucose, and the oxygen is released into the atmosphere as a waste product.

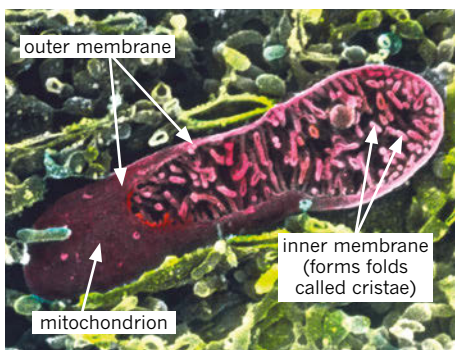


FIGURE 2.5.10 A scanning electron micrograph of a single mitochondrion in the cytoplasm of an intestinal epithelial cell. The cylindrical mitochondrion (pink, centre) has a highly folded internal membrane, which provides a large surface area for aerobic respiration.

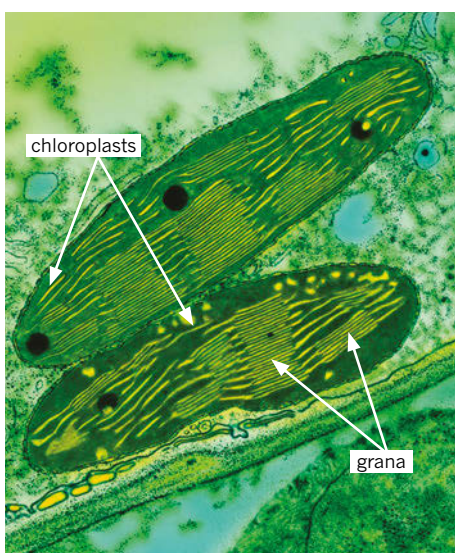


FIGURE 2.5.11 A transmission electron micrograph of two chloroplasts seen in the leaf of a pea plant, *Pisum sativum*. Each chloroplast is seen cut lengthways and contains stacks of flattened membranes (yellow) known as grana. The chloroplasts contain chlorophyll and are surrounded by an external double membrane.

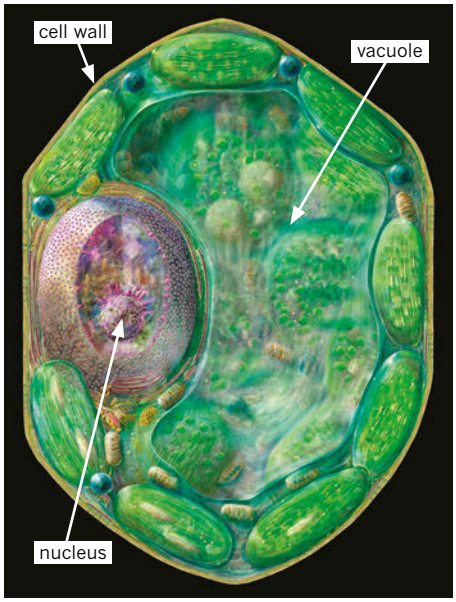


FIGURE 2.5.12 An illustration of a section through a plant cell, revealing its internal structure. At the centre of the cell is a large vacuole, which maintains the cell's shape, stores useful materials and digests the cell's waste products.

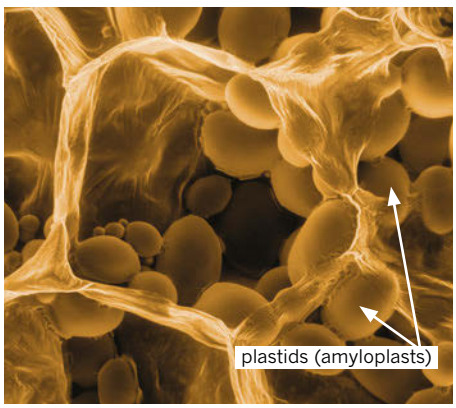


FIGURE 2.5.13 A scanning electron micrograph of amyloplasts (oval) in the sectioned cells of a potato (*Solanum tuberosum*). Amyloplasts are starch-storing plastids, or plant organelles.

Xylem is the tissue in vascular plants that transports water and nutrients upwards from the roots.

Storage and cell structure

The following organelles are involved in storage and also support the cell structure in eukaryotic cells.

Vacuoles

Vacuoles are membrane-bound, liquid-filled spaces that store enzymes and other organic and inorganic molecules. They occur in most cells, in different numbers. Figure 2.5.12 illustrates a plant cell vacuole. Vacuoles in animal cells and plant cells are different. Animal cells contain many small temporary vacuoles, but most plant cells contain a single large permanent vacuole surrounded by a membrane called the **tonoplast**. In plants the vacuole provides structural support by helping to maintain turgor and it seems that lysosome function also occurs here in the plant vacuole.

Plastids

Plastids are organelles involved in the synthesis and storage of different chemical compounds. They contain a double-stranded DNA molecule and possess a double membrane. Plastids develop from simple organelles called proplasts. Animal cells lack plastids. Plastids can be:

- chloroplasts, which are involved in photosynthesis and are found only in plants and some protists
- leucoplasts, which are involved in storage
- chromoplasts, which contain colour pigments and occur in petals and fruit.

Amyloplasts, as shown in Figure 2.5.13, are a type of leucoplast in plants. They are commonly responsible for synthesising and storing starch, but can also convert the starch back to sugar when the plant requires energy.

Cell wall

The cell wall is a rigid structure outside the cell membrane of plant cells, fungal cells and some prokaryote cells. You can see the cell wall in a *Hookeria* moss cell in Figure 2.5.14. In plants, the cell wall is composed mainly of cellulose. The fungal cell wall is made of chitin.

The cell wall provides support, prevents expansion of the cell, and allows water and dissolved substances to pass freely through it. Lignin in the cell walls of woody plants, especially in the xylem, gives them additional strength.

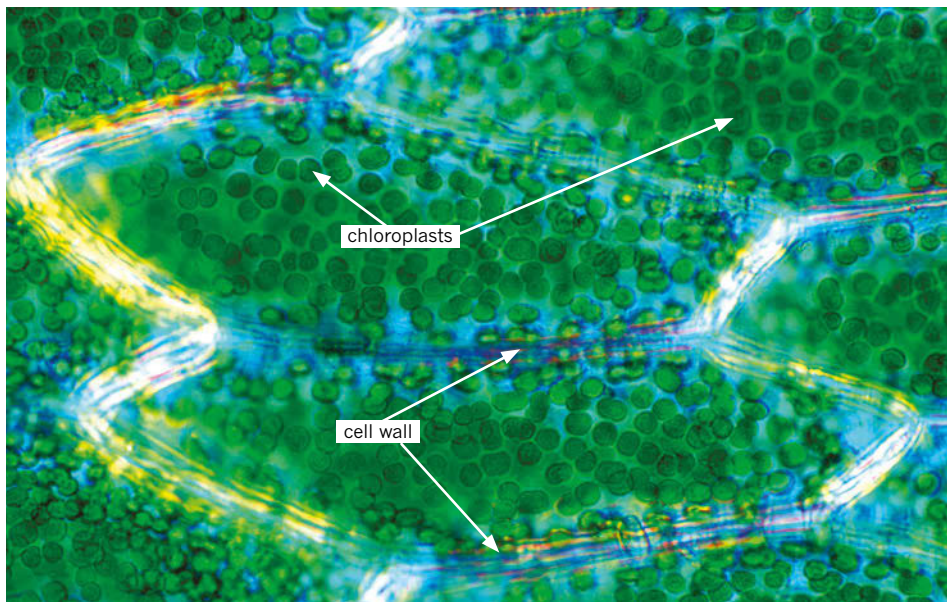


FIGURE 2.5.14 A light micrograph of cells in a leaf of shining *Hookeria* moss (*Hookeria lucens*). The leaf is made up of a single layer of cells. A cell wall (blue) encloses each cell, and numerous chloroplasts containing the pigment chlorophyll (green, round) are seen in each cell.

Cytoskeleton

Figure 2.5.15 shows fibroblast cells and their components. The cytoskeleton consists of microtubules of the protein tubulin and filaments of the protein actin. The cytoskeleton supports the cell's structure, allows the cell to move and assists in the transport of organelles and vesicles within the cell.

Centrioles

Centrioles are a pair of small cylindrical structures composed of microtubules, as shown in Figure 2.5.16. They are present in most eukaryotic cells, but many plant cells do not have centrioles. Centrioles are involved in cell division and in the formation of cell structures such as cilia and flagella.

Cilia and flagella

Cilia and flagella (singular cilium and flagellum) are hair-like structures on the surface of cells and are shown in Figures 2.5.17 and 2.5.18. They consist of an arrangement of microtubules enclosed by an extension of the cell membrane. Cilia move with an oar-like motion and are usually shorter and more numerous than flagella. Both structures are involved in the movement of the cell or things around the cell.

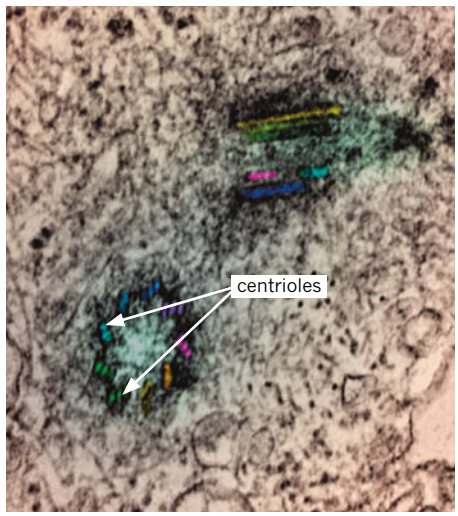


FIGURE 2.5.16 A transmission electron micrograph of centrioles (rainbow coloured objects in the centre of the image). Centrioles are are mainly composed of the protein tubulin and are involved in assembling the spindle that pulls cells apart during mitosis.

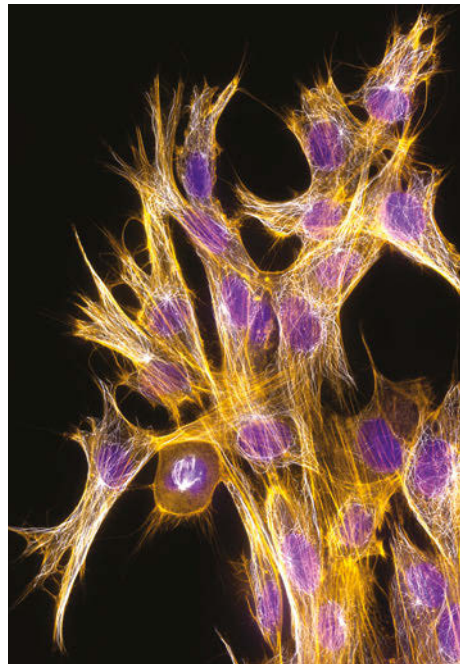


FIGURE 2.5.15 A fluorescent light micrograph of fibroblast cells. Fibroblasts are cells that give rise to connective tissue such as collagen, the main structural protein in the body. The cell nuclei are purple, actin filaments are yellow and microtubules of tubulin, protein filaments that make up part of the cytoskeleton, are white.

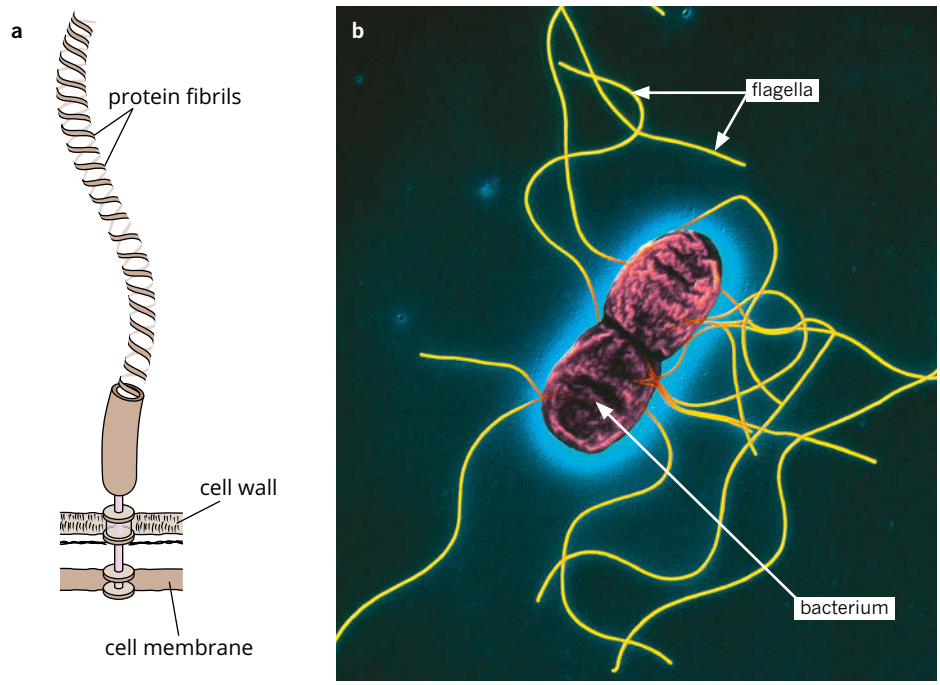


FIGURE 2.5.17 (a) Bacterial flagella consist of three protein fibrils coiled in a helical pattern. (b) A scanning electron micrograph of a *Salmonella typhimurium* bacterium. This rod-shaped, gram-negative bacterium moves by using its long, hair-like flagella (yellow).

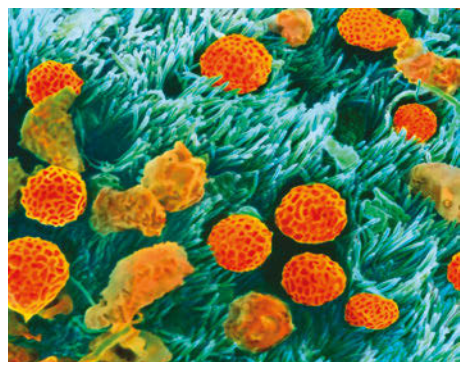


FIGURE 2.5.18 A scanning electron micrograph of the surface of the trachea (windpipe). Pollen (orange) and dust (brown) that have been breathed in can also be seen. The surface of the trachea is made up of cells with hair-like cilia (green), which, together with mucus, trap airborne particles and remove foreign matter from the air tubes and lungs.

WS 1.1.5

A summary of the structure and function of the major cell organelles is given in Table 2.5.2.

TABLE 2.5.2 Summary of organelle structure and function

Organelle	Structure	Function
nucleus	• membrane-bound: double membrane • contains DNA	contains hereditary information
rough endoplasmic reticulum	• membrane-bound: network of cisternae • ribosomes bind to its membranes	processes and modifies proteins
ribosome	• made of proteins and rRNA	synthesises proteins
Golgi apparatus	• membrane-bound: stack of cisternae that are not connected to each other	processes and packages proteins
lysosome	• membrane-bound: vesicle containing digestive enzymes	digests cellular waste material and foreign matter
smooth endoplasmic reticulum	• membrane-bound: network of cisternae	synthesises lipids
mitochondrion	• membrane-bound: double membrane, inner membrane is highly folded • contains DNA	obtains energy from organic compounds
chloroplast	• spherical or ellipsoidal, with double membrane • contains DNA and thylakoid sacs	uses light energy, carbon dioxide and water to produce glucose
centriole	• small structure in the cytoplasm, consisting of microtubules	involved in cell division and the formation of cell structures such as flagella and cilia
cilium or flagellum	• external structure consisting of microtubules	motility; movement of substances across cell surface
vacuole	• membrane-bound, fluid-filled vesicle	stores substances; also involved in cell structure in plant cells
plastid	• small, with double membrane • contains DNA	synthesises and stores various organic molecules
cell wall	• external structure surrounding cell membrane • composition depends on type of cell	cell structure and protection

2.5 Review

SUMMARY

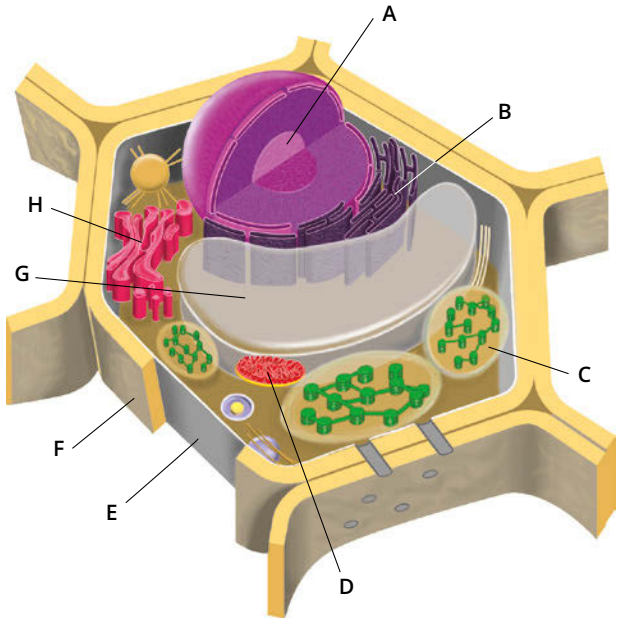
- Organelles are the functioning units of the eukaryotic cell.
- The main structures in a plant cell include the nucleus, tonoplast, vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum, ribosomes, plastids, mitochondria and cell wall.
- The main structures in an animal cell include the nucleus, ribosomes, Golgi apparatus, rough and smooth endoplasmic reticulum, vacuoles, mitochondria, lysosomes, vesicles and centrioles.

KEY QUESTIONS

Retrieval

1 Identify the common role of mitochondria and chloroplasts in a cell.

2 Label the parts of the following plant cell.

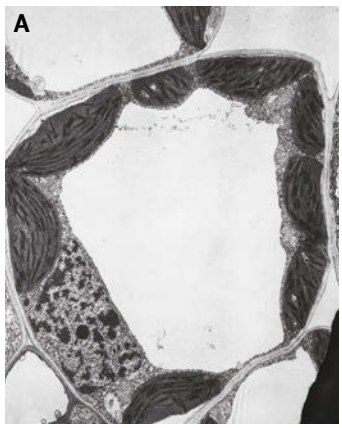


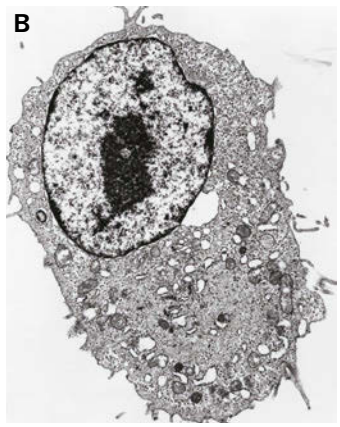
Comprehension

3 Identify which organelles would be most abundant in each of the following cell types.
- **a** enzyme-secreting cells
- **b** muscle cells
- **c** storage cells in a potato
- **d** cells that carry out photosynthesis in a leaf
- **e** cyanobacteria

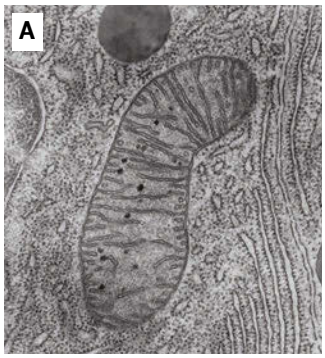
Explain your reasoning in each case.

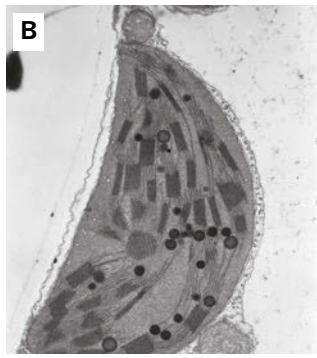
4 Consider the following images. Identify which cell is a plant cell and which is the animal cell.

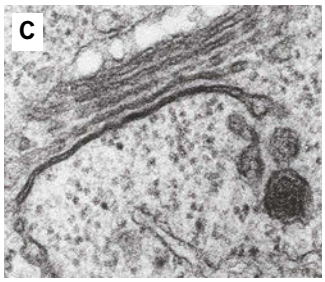


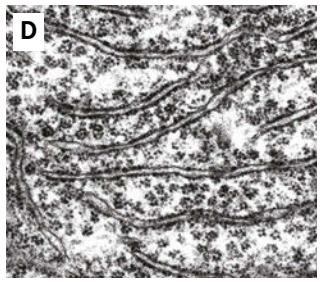


5 For each of the images A–D:
- **a** identify the name of the organelle
- **b** describe the organelle's function









Analysis

6 You have been assigned the task of determining whether a sample contains plant or animal cells. Identify what features of the sample would help you in this task.

7 An experiment was conducted to investigate the synthesis of a type of organic substance from β-cells in the pancreas.

A radioactive material was injected into the secretory tissue. The level of radioactivity in various organelles of this type of cell was then measured every 60 minutes. The results are summarised in the table below.

	Percentage of total radioactivity			
Time (min)	**Rough endoplasmic reticulum**	**Golgi apparatus**	**Immature secretory vesicles**	**Mature secretory vesicles**
0	77	10	0	13
60	17	57	15	11
120	20	15	45	10
180	21	13	16	50
240	21	11	13	55
300	20	11	12	57

- **a** Deduce the type of substance being synthesised.
- **b** Identify the trend or pattern in radioactivity in the:
  - **i** endoplasmic reticulum
  - **ii** Golgi apparatus.

Investigating surface area to volume ratio

Research and planning

Aim

To investigate the surface area to volume ratio of cells and link to the understanding that cells are limited by their ability to efficiently transport materials across the cell membrane.

Rationale (scientific background to the experiment)

All cells are surrounded by a cell membrane. The cell membrane is a semipermeable barrier that controls the movement of substances into and out of the cell. Movement across the cell membrane is two-directional, and occurs via diffusion, osmosis or active transport.

Generally, the larger the volume of a cell, the larger the surface area. Surface area to volume ratio (SA:V) is a measure of these two factors combined. Smaller cells usually have a larger surface area compared to their volume. This allows cells to move molecules across their cell membranes in an efficient manner. It also explains why single-celled organisms are limited in their size.

The 'pink agar' cubes are models of cell size. They have been prepared using sodium hydroxide and phenolphthalein. Phenolphthalein is an indicator that is pink in alkaline solutions and turns colourless in neutral and acidic solutions. The pink agar turns clear in the presence of sulfuric acid, which is evidence of diffusion.

Timing

60 minutes

Materials

- 3 'pink agar' cubes of the following dimensions: 1 cm^3, 2 cm^3, 3 cm^3
- 100 mL of 0.1 mol L^{-1} sulfuric acid
- cutting board and knife
- ruler with millimetre increments
- plastic spoon
- 250 mL glass beaker
- paper towelling
- timer

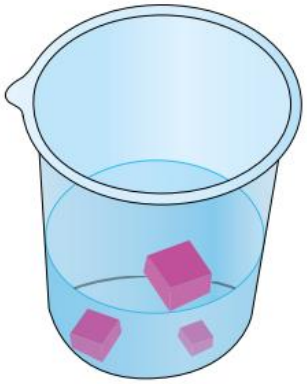
Method

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 Put on disposable gloves, a lab coat and safety glasses.

2 Gently place each of the three agar cubes in the beaker and cover them with sulfuric acid.

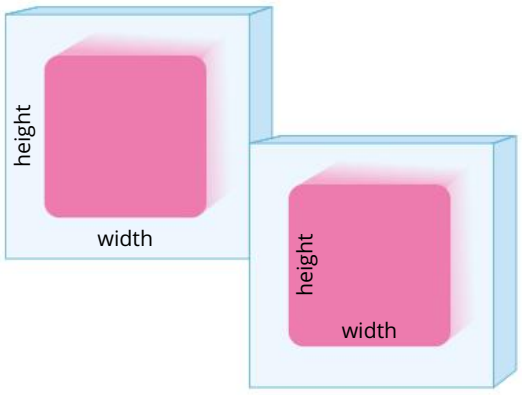


3 Set the timer for 10 minutes.

4 Every 2 minutes, gently turn the agar cubes to ensure even exposure to the acid.

5 At the end of the 10 minutes, gently remove the agar cubes with the spoon and blot onto paper towel to remove excess acid.

6 Cut each cube open and measure the height and width of the remaining pink prism. Assume that the length is the same as the height measurement. It is important to work efficiently at this point as diffusion will continue to occur.



7 Calculate the surface area to volume ratio of each cube.

8 Calculate the rate of diffusion in each cube.

Variables

i Independent: the volume of the cube

ii Dependent: the rate of diffusion

iii Controlled: concentration of sulfuric acid, temperature, time of exposure to acid, amount of stirring

Analysing

Raw data

1 Complete the following table. In the final column, calculate the SA:V so that the volume ratio is 1.

Length of each side of cube (cm)	Surface area (SA) (cm^2)	Volume (V) (cm^3)	SA:V	SA:V, where V is 1
10	$6 \times 10^2 = 600$	$10^3 = 1000$	600:1000	0.6:1
3				
2				
1				
0.1				

Note: 10 cm and 0.1 cm cubes are for comparison only.
Guide to calculations:
- surface area = length × width × number of sides
- volume = length × width × height

Processed data

2 Calculate the percentage of each block that has been reached by the diffusion of acid.

Cube	Dimensions of coloured prism remaining (length, width, height) (cm)	Volume of coloured prism remaining (X) (cm^3)	Volume of whole cube (Y) (cm^3)	Volume of uncoloured portion ($Y - X$) (cm^3)	% of cube uncoloured ($\frac{Y-X}{Y} \times 100$)
3 cm					
2 cm					
1 cm					

➤ 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

3 Create a new table that shows the relationship between SA:V and percentage of cube uncoloured for each cube.
Compare the percentages of cube uncoloured you obtained with those of three other groups.

a Explain why the results should be similar for each group.

b If a group did not obtain similar results, suggest a reason for this.

4 Identify two potential errors encountered in the procedure. Suggest how these could be minimised if the procedure were modified.

➤ 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 State the relationship between surface area to volume ratio and rate of diffusion.

2 Outline the data that you have collected that supports this conclusion.

3 Explain why cells are limited in their ability to grow larger over time.

Evaluation

4 Identify at least one assumption that this activity makes about the shape of cells.

5 Explain whether the potential errors you identified above had a significant effect on your conclusions. In other words, do you consider the level of uncertainty caused by the potential errors reasonable?

Improvements

6 If you were to repeat this experiment, identify the steps that you would do differently. Consider how you could:

- **a** change the methodology
- **b** improve your technique
- **c** reduce error and uncertainty.

Extension

7 If a single-celled organism, such as an amoeba, were to split in half, thus reducing the volume of each compared to the original, what would happen to the SA:V ratio of each new cell compared to the original?

8 In general, motile animal cells are significantly smaller than plant cells. Using the evidence collected in this activity, suggest why.

9 Investigate the cells that line the small intestine. Name the extensions that increase the SA:V ratio. Explain the purpose of these cells in relation to the role of the small intestine.

➤ 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

Observing cells

Research and planning

Aim

- To view different examples of cells under the light microscope and further understand cell structure and specialisation.
- To practise calculating total magnification, field of view and cell size.

Rationale (scientific background to the experiment)

Cells are the basic building blocks of life. Whether it is a unicellular organism or a complex multicellular organism, all cells have some common features. At the most basic level this includes a cell membrane, cytoplasm, DNA and ribosomes.

Cells are generally classified broadly into prokaryotes and eukaryotes. Eukaryotes are often grouped as either plant or animals cells. In this practical activity, you will view a range of plant and animal cells. Consider how the cells are both similar and specialised to allow each particular cell type to perform a specific role within the organism. You will also calculate the total magnification and field of view to determine cell size.

Timing

60 minutes

Materials

- light microscope
- microscope lamp
- micrometer grid
- teat pipette
- toothpick
- mounted needle
- small beaker of water
- white tile
- scalpel
- glass microscope slides and coverslips
- paper towel
- onion segment
- small piece of banana
- iodine stain in dropper bottle
- tweezers
- sample *Elodea* plant
- prepared slides of human cheek cells, human blood, mammalian nerve cell/s, and any other cell types available.

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.

Part A Preparing slides

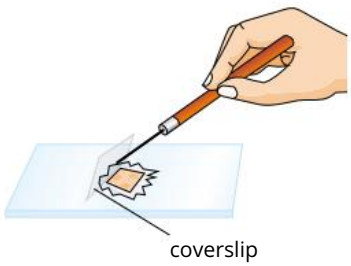
Onion cells

1 Cut off a thin piece of onion.

2 Use the tweezers to peel a very thin layer of epidermis (this looks like tissue paper).

3 Place the sample on a clean glass slide and flatten it as much as possible. Add a single drop of iodine.

4 Gently lower the coverslip onto the slide, using a mounted needle. Try to minimise any air bubbles. Blot any excess stain at the edge of the coverslip as required.

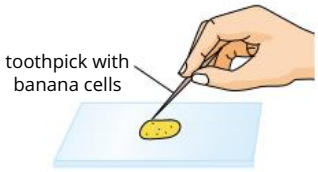


5 Set the sample aside until you are ready to view it under the microscope.

Banana cells

6 Smear some banana on the toothpick.

7 Put the banana cells on a clean glass slide.



8 Add a single drop of iodine solution and cover with a glass coverslip.

9 Blot any excess stain at the edge of the coverslip as required.

10 Set the sample aside until you are ready to view it under the microscope.

***Elodea* cells**

11 Select a small, thin leaf from the *Elodea* plant.

12 Place the leaf gently onto a glass slide and cover it gently with a coverslip.

13 Set the sample aside until you are ready to view it under the microscope.

Part B Viewing and drawing slides under the light microscope

14 Set up your microscope on the workbench.

15 Calculate the field of view diameter using the ×4, ×10 and ×40 objective lenses.

16 View each of the slides (those that you prepared and also the pre-prepared ones).

17 Sketch two or three cells accurately, showing the position of the cells in relation to each other. Try to select cells that are not overlapping one another.

18 Include the magnification and a scale of size for each sketch.

19 Note and label the visible organelles within each cell. For the slide of human blood, try to identify the different cell types.

Analysing

Raw data

1 Complete the table.

Microscope magnification	Field of view diameter

Processed data

2 Sketch two or three cells for each slide. For each diagram, include: slide title, magnification, scale, labelled organelles.

➤ 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

3 Explain why it is important that the specimens used to prepare a slide are as thin as possible.

4 List any organelles you did not see. Explain why you did not see these organelles.

5 Plant cells often contain chloroplasts. Suggest why chloroplasts were present in the *Elodea* cells but absent from the banana and onion.

6 Account for why chloroplasts tend to be found around the outer edge of the *Elodea* cells.

7 Suggest why bananas show a large number of leucoplasts in the cells of the fruit.

8 Suggest how the shape of a typical nerve cell (or neuron) enables it to communicate messages within the nervous system.

9 Mature human red blood cells lack a nucleus. Propose why. Summarise the role of red blood cells within the body.

➤ 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 Name the visible features that were common to all cells viewed.

2 Summarise the main ways that plant cells are different from animal cells.

Evaluation

3 Explain why it is necessary to look at multiple cell types before you make generalisations about cells and organelles.

4 Explain whether the potential errors you identified above had a significant effect on your conclusions. In other words, do you consider the level of uncertainty caused by the potential errors reasonable?

Improvements

5 If you were to repeat this experiment, identify the steps that you would do differently. Consider how you:

- **a** might change the methodology
- **b** might improve your technique
- **c** could reduce error and uncertainty.

Extension

6 There are a variety of white blood cells found in human blood. Research the name and role of two specific types of white blood cells.

7 Search the internet for electron micrographs of various cells. Print out the micrographs and label the organelles.

➤ 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

active transport
amino acid
biogenesis
carrier protein
cell
cell compartmentalisation
cell membrane
channel protein
chloroplast
cholesterol
chromosome
concentration gradient
cytology
cytoplasm
cytosol
diffusion
DNA (deoxyribonucleic acid)
endocytosis
eukaryote
exocytosis
extracellular fluid
extremophile
facilitated diffusion
genophore
glycolipid
glycoprotein
Golgi apparatus
hydrophobic
inorganic compound
integral protein
intracellular fluid
lysosome
mitochondria
mRNA
murein
non-permeable
nucleoid
nucleolus
organelle
organic compound
osmosis
osmotic gradient
osmotic pressure
passive transport
peripheral protein
phagocytosis
phospholipid
pinocytosis
plasmid
prokaryote
protein
ribosome
RNA (ribonucleic acid)
rough endoplasmic reticulum
rRNA
semipermeable
solute
solvent
taxonomy
tonoplast
transmembrane protein
vesicle

KEY QUESTIONS

Retrieval

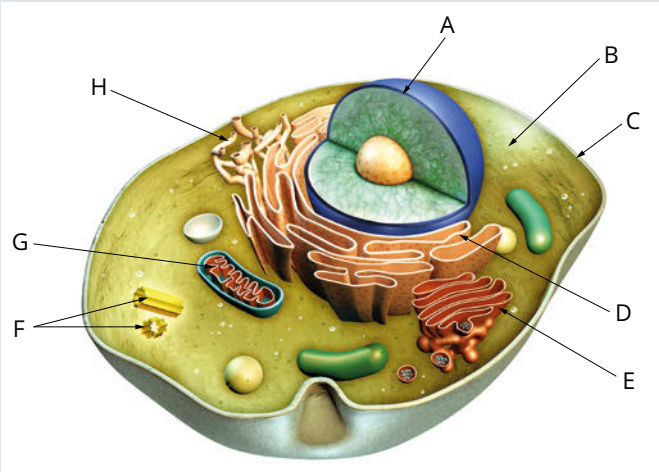
1 The cell theory states that:
- **A** all organisms are made up of cells.
- **B** all cells arise from pre-existing cells.
- **C** the cell is the smallest functional unit of living things.
- **D** all of the above.

2 Select the statement that accurately describes eukaryotic cells.
- **A** Eukaryotic cells have circular chromosomes and membrane-bound organelles, and some also have cell walls.
- **B** Eukaryotic cells have linear chromosomes but not membrane-bound organelles, and some have cell walls.
- **C** Eukaryotic cells have linear chromosomes and membrane-bound organelles, and some also have cell walls.
- **D** Eukaryotic cells have linear chromosomes and membrane-bound organelles, but not cell walls.

3 Identify which of the following is/are never found in prokaryotic cells.
- **A** DNA
- **B** mitochondria
- **C** cytosol
- **D** cell wall

4 List three features that distinguish prokaryotic from eukaryotic cells.

5 Label the parts of the animal cell in this diagram.



6 Draw and prepare a table to summarise the major functions of phospholipids, cholesterol, glycolipids, glycoproteins, and proteins in cell surface membranes.

7 Many single-celled organisms such as *Amoeba* feed by a process in which the cell membrane engulfs solid food particles to form a food vacuole. This process is called:

A phagocytosis.
B active transport.
C pinocytosis.
D osmosis.

8 The organelle on which proteins are assembled is called the:

A nucleus.
B endoplasmic reticulum.
C Golgi apparatus.
D ribosome.

Comprehension

9 Explain which type of microscope would be best for the study of:

a changes in a white blood cell
b details of surface texture of a hair.

10 Summarise the properties of archaean cell walls that allow them to be extremophiles.

11 Explain how the compartmental organisation of a eukaryotic cell contributes to its biochemical functioning.

12 According to the fluid mosaic model of membrane structure, proteins of the membrane are mostly:

A spread in a continuous layer over the inner and outer surfaces of the membrane.
B confined to the hydrophobic interior of the membrane.
C embedded in a lipid bilayer.
D randomly orientated in the membrane, with no fixed inside–outside polarity.
E free to depart from the fluid membrane and dissolve in the surrounding solution.

13 Identify which of the following factors would tend to increase membrane fluidity.

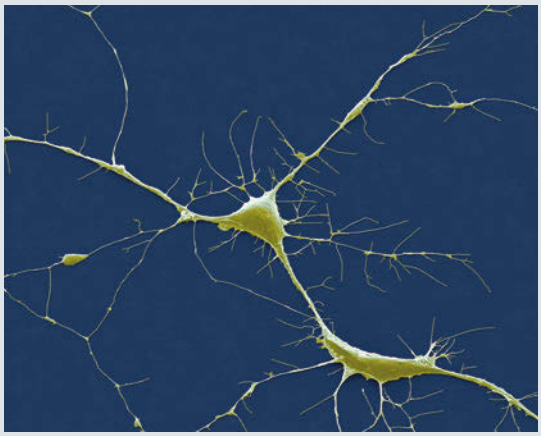
A a greater proportion of unsaturated phospholipids
B a greater proportion of saturated phospholipids
C a lower temperature
D a relatively high protein content in the membrane
E a greater proportion of relatively large glycolipids compared with lipids having smaller molecular masses

14 Explain why the phospholipid heads of the cell membrane are always pointed towards the cytosol and extracellular fluid, whereas the 'tails' are always orientated toward the middle of the membrane.

15 Describe the two types of proteins used in facilitated diffusion.

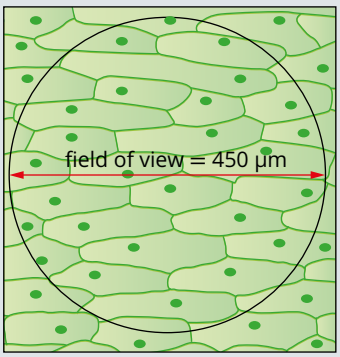
Analysis

16 The following image is a nerve cell. With specific reference to the visible structures of the cell, deduce whether this image was taken using an electron microscope or a light microscope.



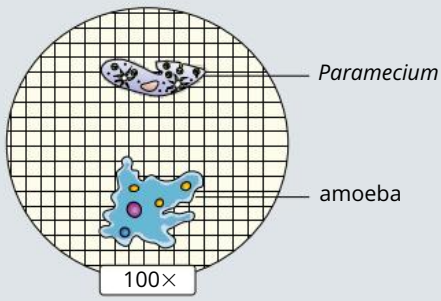
17 A microscope was set up to view some cells as illustrated in the following diagram.

a A microscope is set up with an ocular lens of ×10 magnification and an objective lens of ×4 magnification. Calculate the total magnification.
b Looking down a microscope, the field of view is determined to be 450 µm. Calculate the actual length of each cell measured in µm.

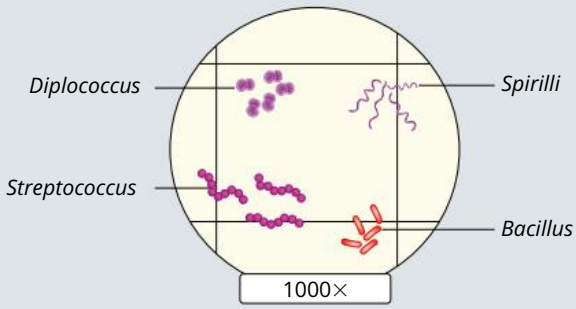


18 The following diagrams represent the field of view visible when a variety of cell types is viewed at different magnifications. The lines in the grids are 100 µm apart.

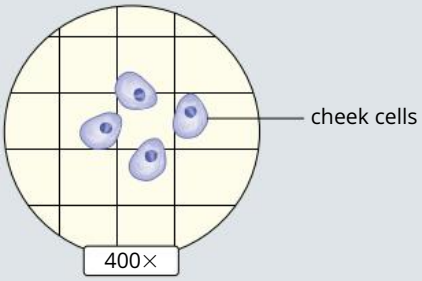
A Protozoans



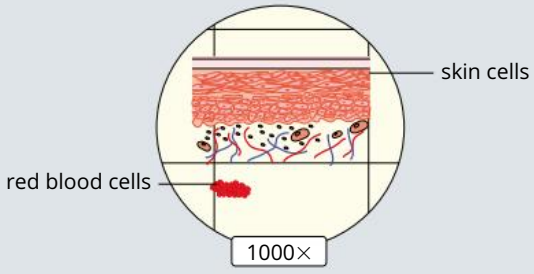
B Bacterial cells



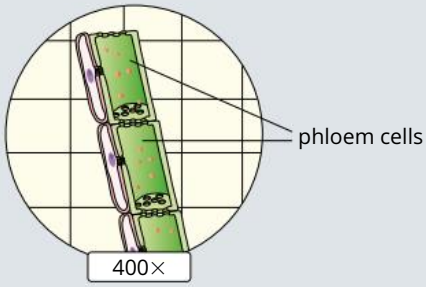
C Animal cells



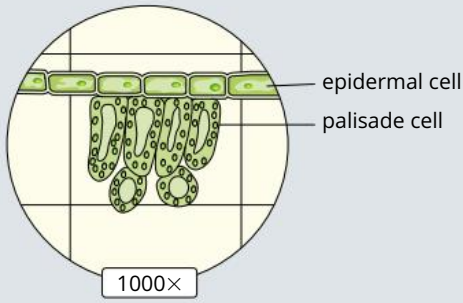
D Animal cells



E Cells from a plant stem



F Cells from the leaf of a plant

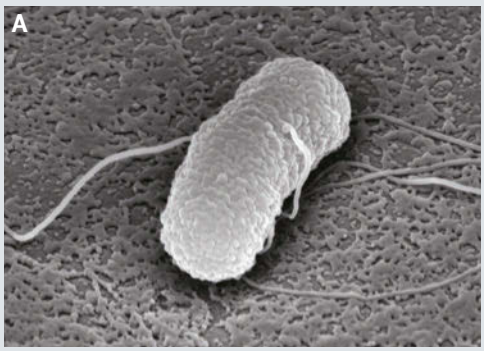


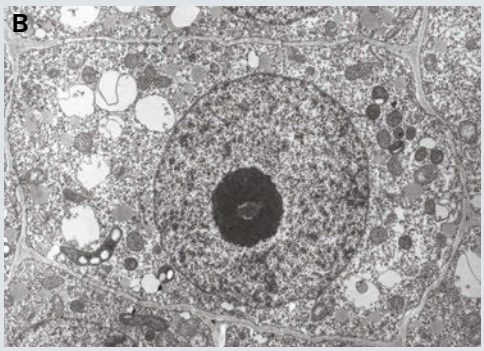
a Use the information in each image to estimate the length of each type of cell from the list below. In this instance, the length of the cell is the longest dimension of the cell, top to bottom or left to right.

b Organise the cells in the list below in order of size from smallest to largest.

phloem, palisade, *Diplococcus*, epidermal, *Spirilli*, cheek cells, human skin cells, *Streptococcus*, red blood cells, amoeba, *Paramecium*, *Bacillus*

19 Below are two cells observed under a scanning or a transmission electron microscope.





- **a** One of the two cells is from a prokaryote. Explain which one.
- **b** Determine if the eukaryotic cell is from an animal or a plant.

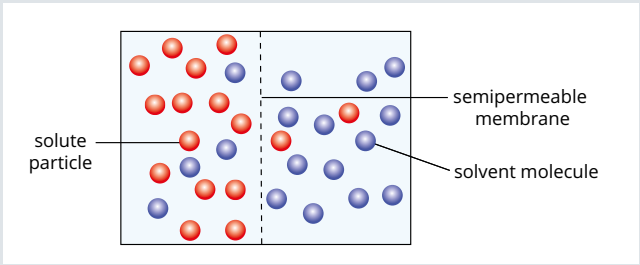
20 You are given a microscope slide with a sample of cells smeared on it and asked to identify the cell type. The cells are circular with a dark round mass at their centre. You estimate that the cells are approximately 20 µm in diameter.

- **a** Classify the cells as prokaryotic or eukaryotic cells.
- **b** Infer what organelle the dark round mass at the centre of the cells could be.

21 For each of the following responses to envrionmental factors, infer the most effective body shape and surface area to volume ratio of an organism for survival.

- **a** gaining heat from its environment
- **b** preventing heat loss
- **c** maximising heat loss.

22 Two solutions are separated by a semipermeable membrane as illustrated below.

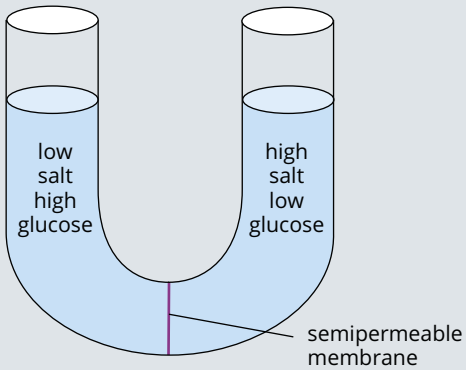


Deduce in which direction (if any) there would be a net movement of particles.

23 Two different solutions with the same volume are placed on either side of a semipermeable membrane in a U-shaped glass tube, as shown in the following diagram. The membrane is permeable to salt but not glucose.

The tube is then left to stand for several days. Predict what would happen to the:

- **a** salt concentration on each side of the membrane
- **b** glucose concentration on each side of the membrane
- **c** fluid levels on each side of the membrane.

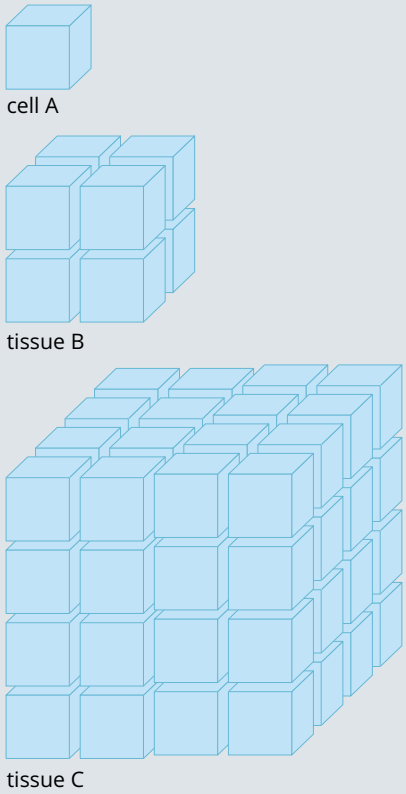


24 In mammals, cells lining the:

- **a** alveoli of the lung take up oxygen by diffusion
- **b** tubules of the kidney take up glucose by active transport
- **c** small intestine take up fat droplets by pinocytosis.

Explain why the different methods of uptake are appropriate for the substances taken up in each case.

25 The following diagram represents living cells. Cell A, tissue B and tissue C all have the same volume.



Determine which one of the follow statements is correct.

A In distilled water, tissue B would gain water at a greater rate than cell A.

B In distilled water, the cells in tissue C would shrink at a greater rate than cell A.

C In a concentrated salt solution, tissue C would gain water at a greater rate than cell A.

D In a concentrated salt solution, tissue C would lose water more slowly than tissue B.

26 Solutions of different sugar concentrations were prepared and a rod of peeled potato tissue of the same known mass was put into each solution. After 1 hour, the potato was removed and its mass was measured again. Results are summarised in the following table.

Concentration of sugar (g/100 mL)	Change in mass (g)	
20	0.68	Decrease
18	0.40	Decrease
14	0.01	Increase
12	0.18	Increase
10	0.32	Increase
6	0.59	Increase
2	0.84	Increase

a Use this data to plot a graph showing the change in mass of the potato tissue with changes of the concentration of sugar.

b Use the graph to predict the mass change if a rod of potato tissue was placed in a sugar solution of 8 g/100 mL.

c Identify any trends and patterns in the data and explain these results making specific reference to the data.

Knowledge utilisation

27 A new unicellular organism has been discovered by light microscopy. Its characteristics include:

- internal membrane-bound circular structures composed of DNA
- two whip-like structures located close to each other at one end of the cell
- a semirigid structure outside the cell membrane
- a length greater than its width
- a chloroplast.

In your studies on cell biology, you have identified six main groups of organisms based on their cell structures: plant cells, animal cells, fungal cells, protists, bacteria and archaea.

Hypothesise which group this new organism would most likely belong to and give two reasons to support your answer.

28 At the cellular level, materials move through the cell membrane by several processes. At the organ level, the exchange of materials is facilitated by the arrangement of cells, which provides a large surface area. Discuss this statement with specific reference to the processes by which materials move through the cell membrane. Outline three of the processes. For each process:

a give an example of a material taken up

b state where this uptake occurs

c explain why the process is appropriate.

CHAPTER

03 The functioning cell

It has long been acknowledged that because cells are the smallest discrete living unit, they are the building blocks of living organisms. The name 'cells' was coined by Robert Hooke as he examined empty, dead cork cells through his microscope. But it was only in the 20th century, with the advent of the fields of enzymatics and proteomics, that scientists have come to realise, and appreciate, the dynamic world that exists within a single cell. Every cellular function, every part of every metabolic pathway, depends on the actions of a unique group of molecules called enzymes.

In this chapter, you will learn about the intricate and definitive structures of these molecules, and the factors that influence their effectiveness as biological catalysts. You will journey down the metabolic pathways of photosynthesis and cellular respiration and understand their importance, not only in technological advances in food production and fitness, but in the life of every living organism on this planet.

Syllabus subject matter

Topic 1 • Cells as the basis of life

INTERNAL MEMBRANES AND ENZYMES

- explain, using an example, how the arrangement of internal membranes can control biochemical processes (e.g. folding of membrane in mitochondria increases the surface area for enzyme-controlled reactions)
- recognise that biochemical processes are controlled and regulated by a series of specific enzymes
- describe the structure and role of the active site of an enzyme
- explain how reaction rates of enzymes can be affected by factors, including temperature, pH, the presence of inhibitors, and the concentrations of reactants and products

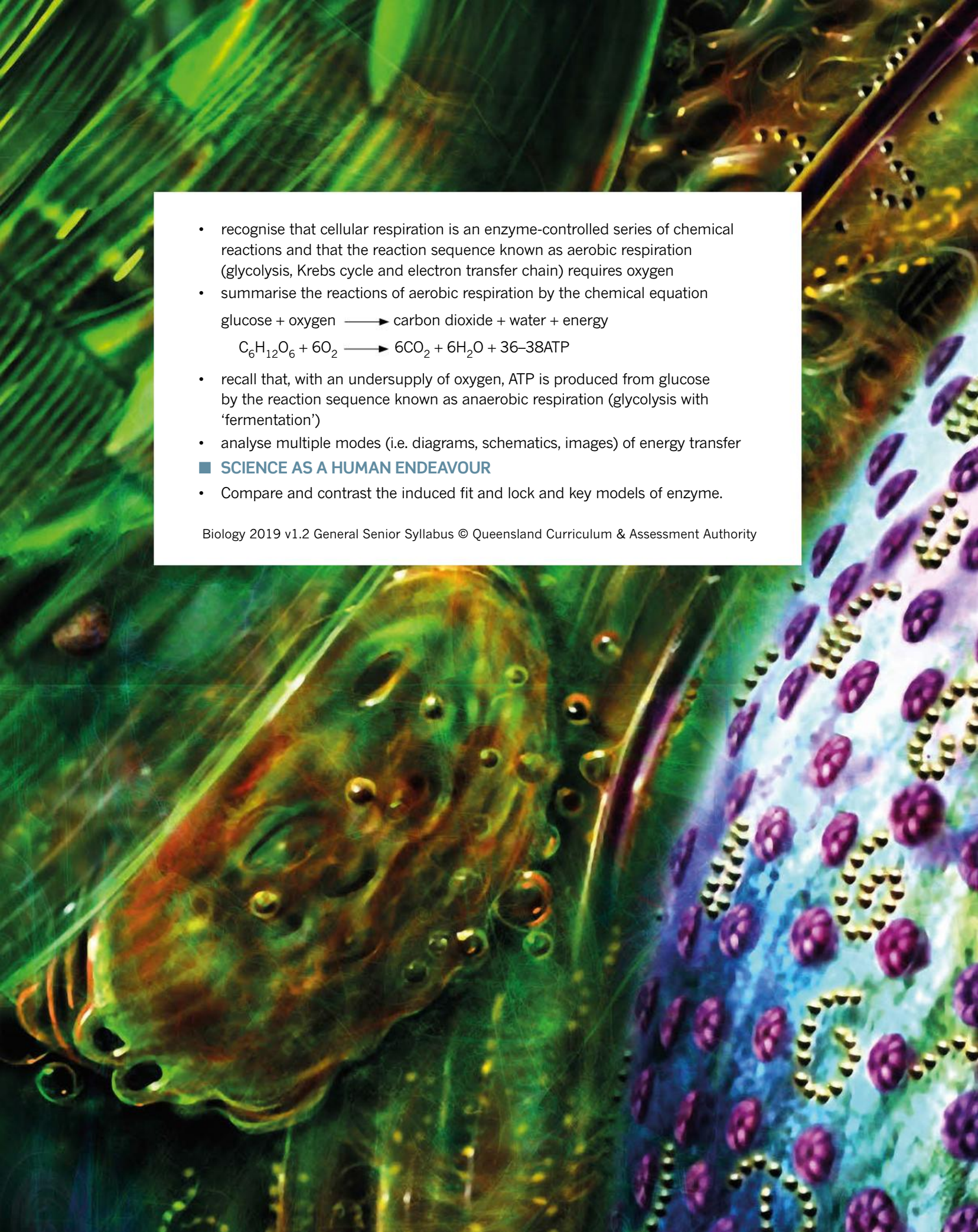
ENERGY AND METABOLISM

- recall that organisms obtain the energy needed to recycle adenosine triphosphate (ATP) from glucose molecules in the process of cellular respiration
- recall that the process of photosynthesis is an enzyme-controlled series of chemical reactions that occurs in the chloroplast in plant cells and uses light energy to synthesise organic compounds (glucose), and the overall process can be summarised in a balanced chemical equation

$$\text{carbon dioxide + water} \xrightarrow{\text{light energy}} \text{glucose + oxygen + water}$$

$$6CO_2 + 12H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

- summarise the process of photosynthesis in terms of the light-dependent reactions and light-independent reactions
- demonstrate the relationship between the light-dependent reactions and light-independent reactions



- recognise that cellular respiration is an enzyme-controlled series of chemical reactions and that the reaction sequence known as aerobic respiration (glycolysis, Krebs cycle and electron transfer chain) requires oxygen
- summarise the reactions of aerobic respiration by the chemical equation

  glucose + oxygen $\longrightarrow$ carbon dioxide + water + energy

  $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 36–38ATP$
- recall that, with an undersupply of oxygen, ATP is produced from glucose by the reaction sequence known as anaerobic respiration (glycolysis with 'fermentation')
- analyse multiple modes (i.e. diagrams, schematics, images) of energy transfer

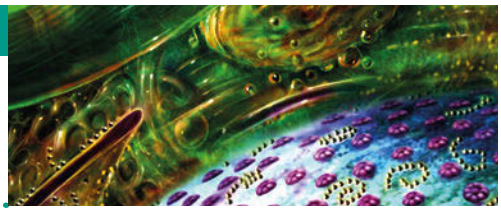
SCIENCE AS A HUMAN ENDEAVOUR

- Compare and contrast the induced fit and lock and key models of enzyme.

3.1 Molecular composition of organisms

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

- distinguish between organic and inorganic molecules
- identify the four main types of organic molecules
- understand the biological role of each type of organic molecule.



All life is composed of the same few elements. There are 92 naturally occurring elements. Only 11 of these are found in organisms in more than trace amounts, and four of these—carbon (C), hydrogen (H), oxygen (O) and nitrogen (N)—make up 99% of organisms by mass. The same elements are also found in rocks, soil and air. However, there is a difference in the way that these atoms are organised into larger compounds in living organisms. Organisms, such as the plants and animals in Figure 3.1.1, produce compounds that contain carbon and hydrogen known as organic compounds. All other compounds, whether in living or non-living things, are called inorganic compounds.

FIGURE 3.1.1 A river in the Daintree rainforest in North Queensland. The plants, animals, rocks and water found in the rainforest all contain molecules. Only the plants and animals produce organic compounds.

An element is a substance that contains one or more atoms that have the same number of protons.

A molecule contains two or more atoms chemically joined together.

A compound is a molecule that contains at least two different elements.

In this module, you will learn about the difference between organic and inorganic compounds. In addition, you will explore the four main types of organic molecules—nucleic acids, carbohydrates, lipids and proteins.

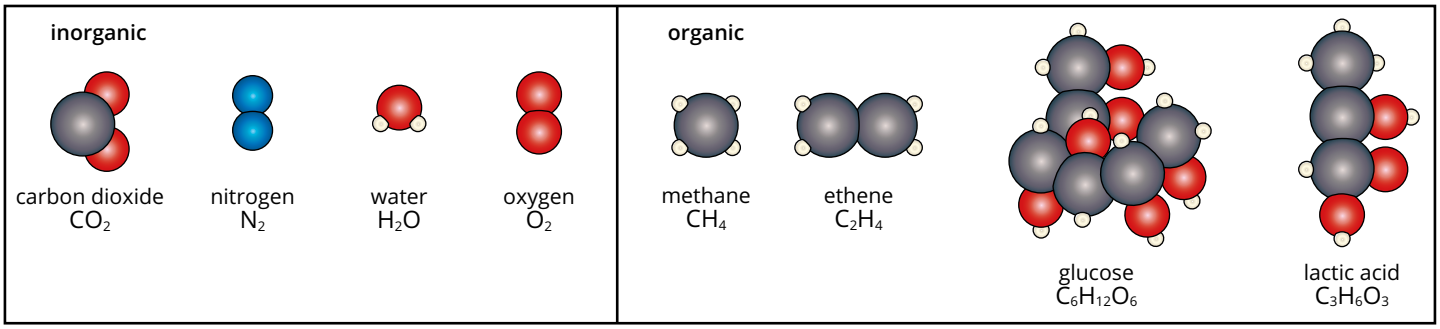


FIGURE 3.1.2 Some common molecules in organisms. Carbon atoms are coloured black, oxygen red, hydrogen white, and nitrogen blue.

ORGANIC MOLECULES

Any molecule that is found in a living organism is called a biomolecule. Examples of biomolecules are fatty acids, carbohydrates and hormones. Large biomolecules are called biomacromolecules. Biomacromolecules can be made up of thousands of atoms and include proteins and nucleic acids.

Organisms produce complex compounds that contain carbon and hydrogen, as shown in Figure 3.1.2 (on page 71). These are called organic compounds because the first compounds discovered were produced by or found in organisms. Most large organic molecules are composed of many smaller organic molecules linked together.

All other elements and compounds, whether in living or non-living things, are referred to as inorganic. Inorganic substances that are important for living organisms include water, oxygen, carbon dioxide, nitrogen and minerals (e.g. Mg^{2+} or Fe^{2+}).

The four main types of organic molecules are carbohydrates, proteins, nucleic acids and lipids. Carbohydrates, proteins and nucleic acids are huge and are also known as biomacromolecules. Biomacromolecules are chainlike molecules called polymers (*polys*, meaning 'many', and *meros*, meaning 'part'). Polymers are formed by joining together many smaller units (monomers) to form a chain.

In organisms, organic molecules can be converted from one form into another. Units may be linked together to form larger molecules. For example, glucose units may be linked together to form larger carbohydrates such as cellulose, shown in Figure 3.1.3. Other chemical groups may be attached to form molecules such as glycoproteins (proteins with sugars attached, Figure 3.1.4) and phospholipids (lipids with phosphate attached, Figure 3.1.5). When food is plentiful, carbohydrates are converted into fats for storage; when food is scarce, the reverse occurs and even proteins can be converted into small molecules to use for energy.

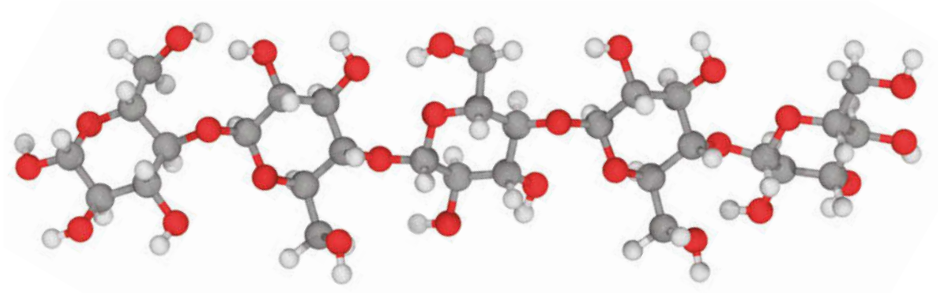


FIGURE 3.1.3 Cellulose is a polymer. A strand of cellulose is made of several glucose molecules joined together.

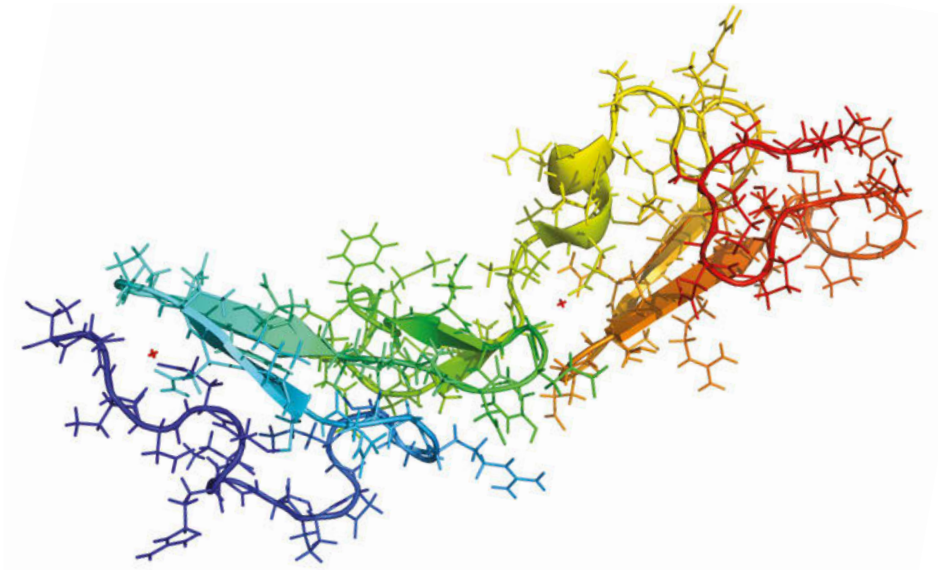


FIGURE 3.1.4 A computer model of a fibrillin glycoprotein. The protein component is represented by ribbons and the sugars are represented by the ring structures.

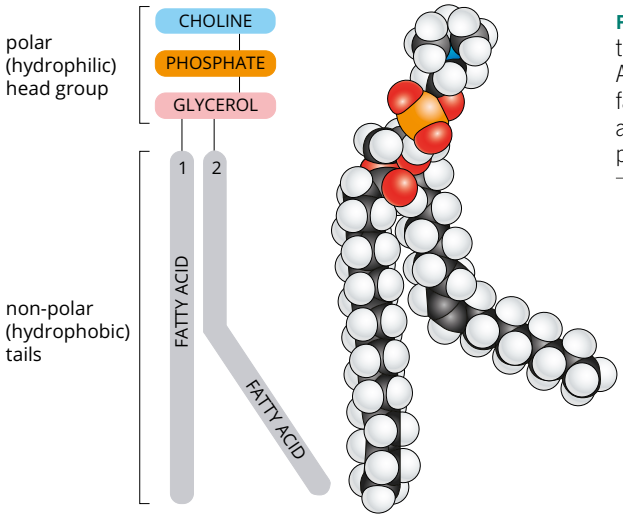


FIGURE 3.1.5 Two models showing the structure of a phospholipid. A phospholipid is made up of two fatty acid tails (lipid component), an alcohol (e.g. choline) and a phosphate group.

Carbohydrates

Carbohydrates are the most abundant organic molecules in nature. They are an important source of chemical energy for living organisms (e.g. glucose). Carbohydrates are also used for energy storage; in plants, energy is stored as starch, while in animals, energy is stored as glycogen. Carbohydrates, in the form of cellulose, are also used for structural support in plants.

Carbohydrates are compounds made of carbon, hydrogen and oxygen. There are three main groups of carbohydrates: monosaccharides, disaccharides and polysaccharides. You can see these in Figure 3.1.6. The basic subunits of carbohydrates are the simple sugars, called monosaccharides, meaning 'single sugar'. Examples of monosaccharides include glucose, fructose and galactose, shown in Figure 3.1.7. In monosaccharides, the hydrogen and oxygen are present in the same proportions as in water: two hydrogen atoms for each oxygen atom. The general formula is $C_nH_{2n}O_n$. For example, three monosaccharides have the same chemical formula, $C_6H_{12}O_6$: glucose, fructose and galactose. While these monosaccharides have the same number of carbon, hydrogen and oxygen atoms, each molecule has a different structure, and therefore has different properties.

Carbohydrates are organic compounds, such as sugars, starch and cellulose, that are made of carbon, hydrogen and oxygen. Carbohydrates as a class include monosaccharides, disaccharides and polysaccharides (complex carbohydrates). Only polysaccharides are polymers and hence also fall under the category of biomacromolecules.

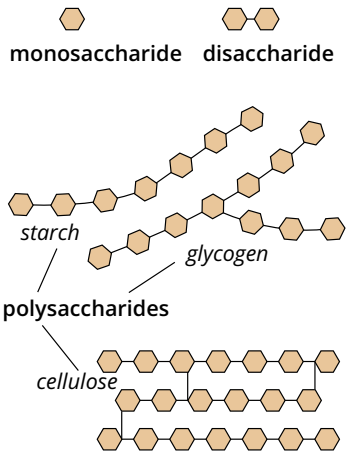


FIGURE 3.1.6 The structures of some carbohydrates

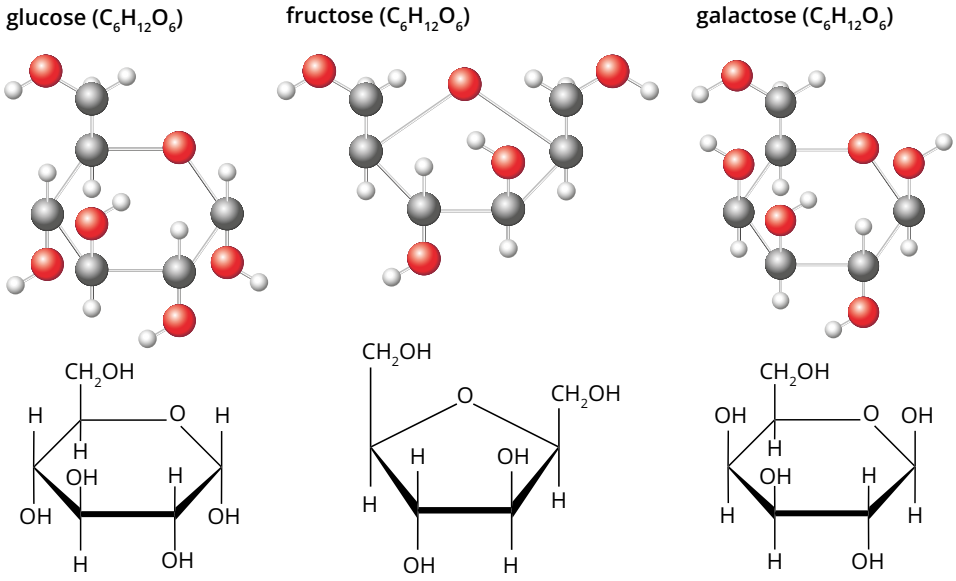


FIGURE 3.1.7 Structural chemical formulae and models of three monosaccharides: glucose, fructose and galactose. In the models, grey spheres represent carbon atoms, white spheres represent hydrogen atoms and red spheres represent oxygen atoms.

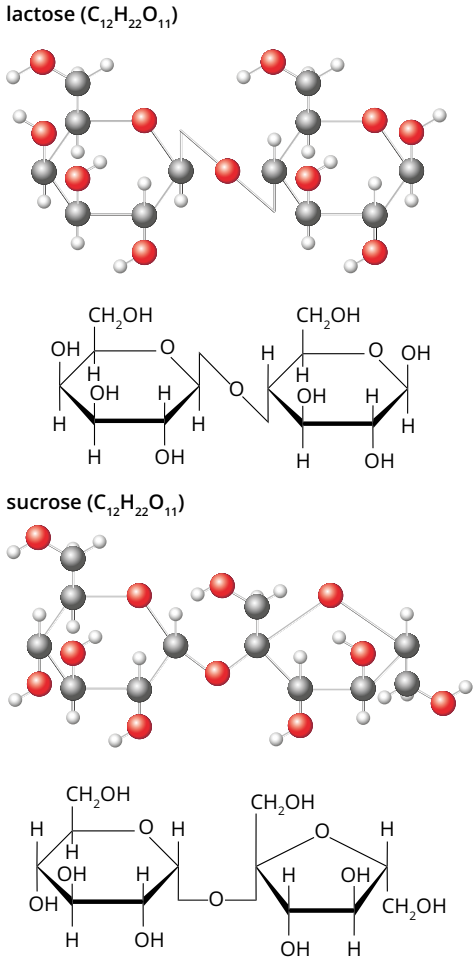


FIGURE 3.1.8 Structural chemical formulae and models of the disaccharides lactose and sucrose. In the models, grey spheres represent carbon atoms, white spheres represent hydrogen atoms and red spheres represent oxygen atoms.

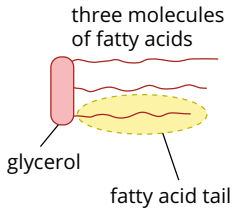


FIGURE 3.1.10 The structure of lipids

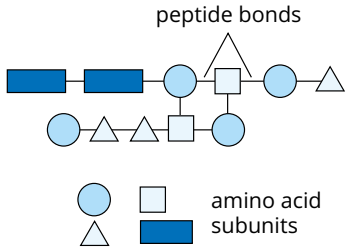


FIGURE 3.1.11 The structure of proteins

When two monosaccharides are joined together they form a disaccharide (meaning 'two sugars'), and a molecule of water is removed. Milk sugar (lactose) is made from glucose and galactose, whereas cane sugar (sucrose) is made from glucose and fructose. The two disaccharides have the same chemical formula ($C_{12}H_{22}O_{11}$), but the atoms are arranged differently, causing the molecules to have different properties. Figure 3.1.8 shows the structures of some disaccharides.

When many sugars are joined together, they form biomacromolecules called polysaccharides ('many sugars'). Some polysaccharides are composed of one type of monomer, such as starch and cellulose. Complex polysaccharides consist of different monosaccharide subunits in the same molecule, such as murein found in the cell walls of bacteria (Figure 3.1.9).

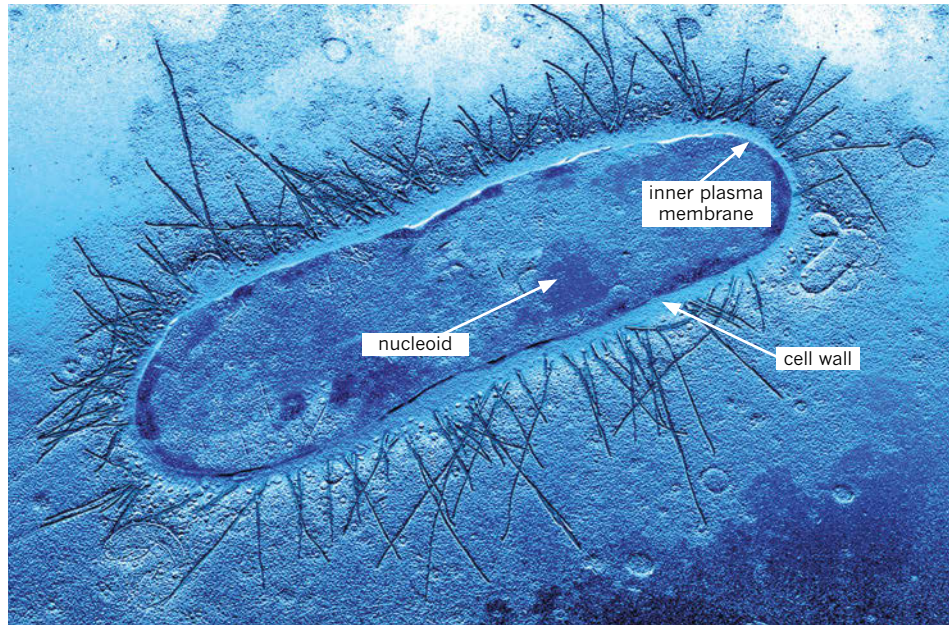


FIGURE 3.1.9 A coloured transmission electron micrograph of the bacterium *Bacillus megaterium*, showing the nucleoid, inner plasma membrane and cell wall, which contains murein

Lipids

Lipids are fatty substances that consist of non-polar hydrophobic molecules. They include fats and oils, which are important as energy-storing molecules. Figure 3.1.10 shows the structure of some lipids. Phospholipids are an important component of cell membranes, which contain the cell's contents and subdivide it into many sub-cellular compartments. Steroids are lipids that act as membrane components, hormones and vitamins.

Lipids are composed of carbon, hydrogen and oxygen, but in different proportions to carbohydrates. Lipids contain a much smaller proportion of oxygen and often contain hydrocarbon chains. Lipids can also contain other elements such as phosphorus and nitrogen.

Proteins

Proteins are more complex than carbohydrates or lipids. There are thousands of different kinds of proteins, and their functions vary widely. While carbohydrates and lipids are similar in all plants and animals, each kind of organism has its own unique proteins. Some proteins form structural components of cells; others are enzymes, hormones or carrier molecules. For example, haemoglobin is a protein that carries oxygen in the blood.

All proteins contain carbon, hydrogen, oxygen and nitrogen; many also contain sulfur and often phosphorus and other elements. Proteins are composed of chains of smaller subunits called **amino acids**, as shown in Figure 3.1.11. Amino acids in proteins are linked by a particular kind of chemical bond called a peptide bond, and proteins are called polypeptides or polypeptide chains (Figure 3.1.11). There are 20 different amino acids commonly found in proteins.

The study of all the proteins of an organism is known as proteomics. In medicine, 99% of all drugs are proteins, or act by binding to proteins. A better understanding of proteins and proteomes (all the proteins produced by organisms) will help develop new pharmaceuticals, clarify the relationships between genes and diseases (e.g. by identifying marker proteins for diseases) and lead to better treatments.

Nucleic acids

Nucleic acids are the genetic material of all organisms, and they determine many of the features of an organism. Nucleic acids are biomacromolecules composed of long chains of subunits called nucleotides. A nucleotide consists of a phosphate, a sugar and a nitrogen base, as shown in Figure 3.1.12.

There are two types of nucleic acids:

- deoxyribonucleic acid (DNA), which carries the 'instructions' for assembling proteins from amino acid subunits using a genetic code. DNA is passed accurately from cell to cell during cell division. The four bases in DNA are adenine (A), thymine (T), guanine (G) and cytosine (C)
- ribonucleic acid (RNA), which plays a major role in the manufacture of proteins within cells. The four bases in RNA are adenine (A), uracil (U), guanine (G) and cytosine (C).

Vitamins

Vitamins are organic molecules that animals require in small amounts for normal functioning. Animals can synthesise some vitamins, but must obtain others in their diet. For example, most mammals can synthesise vitamin C, but humans must obtain it in their diet. Vitamins may be water-soluble (such as vitamins B and C) or lipid-soluble (such as vitamins A, D, E and K). Water-soluble vitamins must be consumed regularly in the diet because they cannot be stored in body tissues. Lipid-soluble vitamins can be stored. Many vitamins are important because they are needed to make particular enzymes.

INORGANIC MOLECULES

Water

Life evolved in water. Most organisms are 70–90% water, and the chemical reactions that take place in cells take place in a watery medium. This is why the properties of water, such as pH, cohesiveness and heat capacity, are important in many biological processes. Water molecules are very cohesive, which means they have a strong tendency to stick together. This property allows thin columns of water to be pulled up tree trunks without breaking. (Figure 3.1.13). Bonds between surface molecules also cause surface tension, which allows small insects, such as the pond skater in Figure 3.1.14, to walk across the surface of water without breaking into the water molecules and sinking.

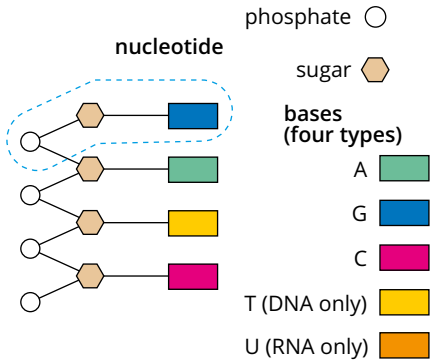


FIGURE 3.1.12 The structure of nucleic acids

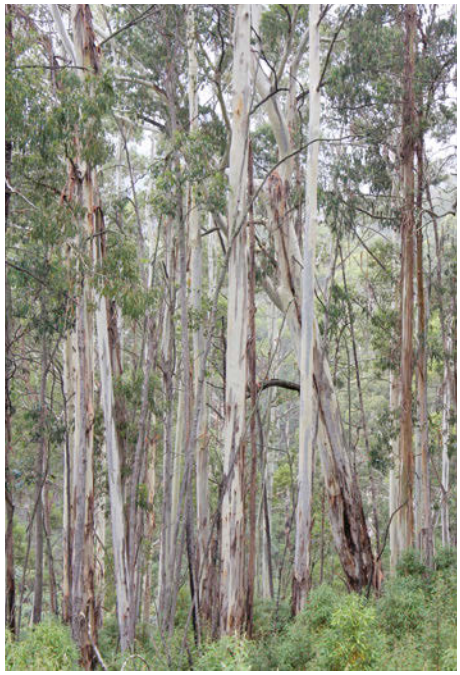


FIGURE 3.1.13 Mountain ash trees (*Eucalyptus regnans*) are the tallest of all flowering trees and can reach a height of up to 114 m. Cohesion between water molecules holds the water together and allows the water to be drawn up the trunks of the trees.

FIGURE 3.1.14 A common pond skater (*Gerris lacustris*) can walk on water. Notice that the legs of the pond skater seem to 'press' on the surface of the water.

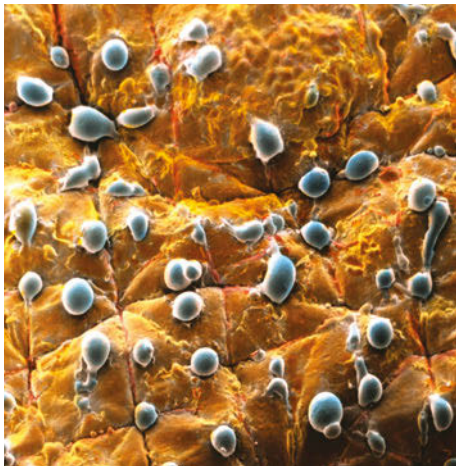


FIGURE 3.1.15 A coloured scanning electron micrograph of the skin surface of the back of a human hand, showing sweat droplets (blue). Evaporation of water on the skin surface is a method of controlling body temperature.

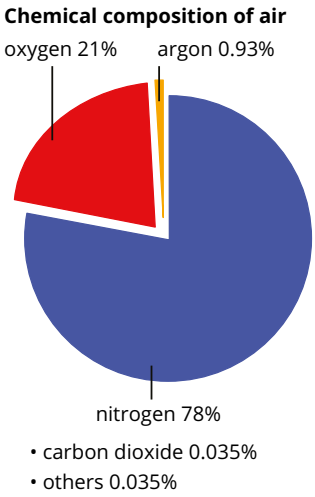


FIGURE 3.1.16 Air is a mixture of mainly nitrogen, oxygen and argon.

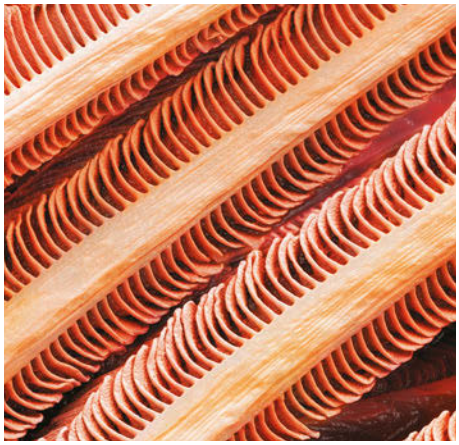


FIGURE 3.1.17 A coloured scanning electron micrograph of mackerel (*Scomber scombrus*) gills, showing the large surface area for gaseous exchange

Water has a high heat capacity—it can absorb a great deal of heat with very little increase in temperature. This is important for temperature regulation. When you exercise, the chemical reactions taking place in your cells produce heat. Much of this heat can be absorbed by the water in your body, without the cells heating up significantly. Because water has a high heat of vaporisation (a high amount of energy is required to transform 1 gram of liquid water into water vapour), evaporation of even small amounts of water is effective in cooling that part of the body surface (Figure 3.1.15).

Oxygen and carbon dioxide

Most cells need oxygen to release energy from food molecules in processes known collectively as **cellular respiration**. Therefore, a constant supply of oxygen is necessary to maintain the activity of these cells. It is usually easy for organisms that get their oxygen from air because the atmosphere is 21% oxygen (Figure 3.1.16). However, oxygen is not very soluble in water, so organisms that get their oxygen from water either are small, flat and relatively inactive, or have very efficient ventilation systems with a large surface area for gaseous exchange, such as the fish gills in Figure 3.1.17.

Carbon is the key atom in organic molecules, as many organic molecules are formed initially from chemical processes that use CO_2 in the atmosphere. Carbon dioxide (CO_2) is taken from the atmosphere (which contains approximately 0.035% by volume of carbon dioxide, Figure 3.1.16) by plants, some bacteria and some protists. It is used in the process of photosynthesis to make sugars, some of which are eaten by animals. Carbon dioxide is returned to the atmosphere mainly by the decay of organic material and as an end product of cellular respiration. This cycling of carbon through organisms and the atmosphere is critical to the survival of all organisms.

Nitrogen

Organisms require nitrogen in relatively large amounts because it is a key component of all proteins. There is an abundance of nitrogen available because the atmosphere comprises approximately 78% nitrogen gas (Figure 3.1.16); however, most organisms cannot use nitrogen in this form. Some bacteria and cyanobacteria convert atmospheric nitrogen into compounds that can be used by plants in a process known as nitrogen fixation. The most important nitrogen-fixing bacteria are the symbiotic bacteria found in the roots of plants, including legumes, casuarinas and acacias (Figure 3.1.18).

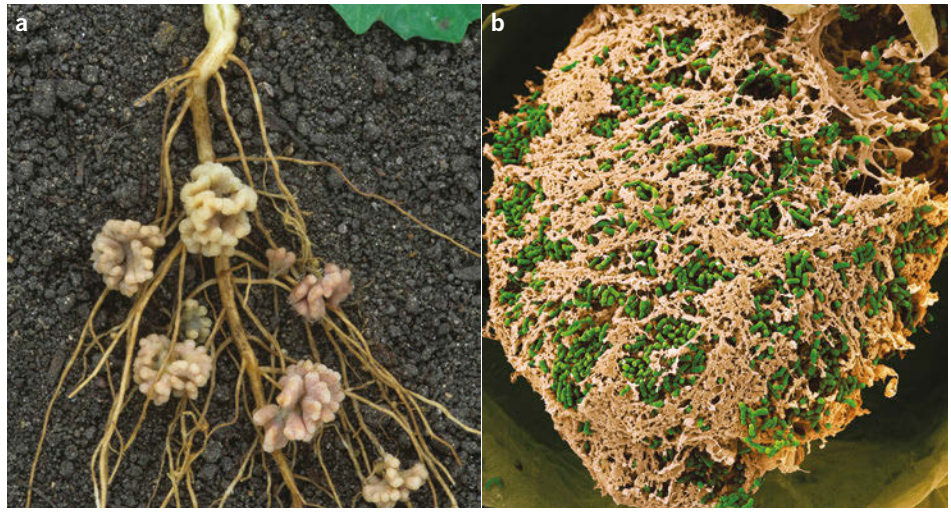


FIGURE 3.1.18 (a) Nodules containing nitrogen-fixing bacteria on the roots of a garden pea (*Pisum sativum*). (b) A coloured scanning electron micrograph of nitrogen-fixing soil bacteria (*Rhizobium* species) in a root nodule of a bean plant. These bacteria (green) have a symbiotic relationship with the plant.

Nitrogen compounds produced by the soil bacteria are absorbed by plants and used to make amino acids. Heterotrophs obtain their amino acids by consuming plants and other organisms. They also produce nitrogen-rich waste (manure), which has traditionally been used as a plant fertiliser.

Minerals

Mineral salts are naturally occurring inorganic compounds produced by the weathering of rocks. The water-soluble mineral salts produced by weathering are absorbed as ions into the roots of plants (Figure 3.1.19), making them available to be eaten by animals. Humans require more than 20 minerals. Biologically important minerals include phosphorus, potassium, calcium, magnesium, iron, sodium, iodine and sulfur. Many others are needed in small (trace) amounts.

Mineral ions are found in the cytosol of cells, in structural components (such as bone), and in the molecules of many enzymes and vitamins. They may also be incorporated into other important organic compounds in cells. Phosphorus is present in the phospholipids of cell membranes and in **ATP (adenosine triphosphate)**—an important energy carrier in cells (see Module 3.5). Magnesium is an important constituent of chlorophyll, and iron is the central atom in every haemoglobin molecule in red blood cells (Figure 3.1.20). Calcium, potassium and sodium ions are important for the normal performance of cardiac muscle cells, and calcium and phosphorus are found in bones and teeth (Figure 3.1.21).

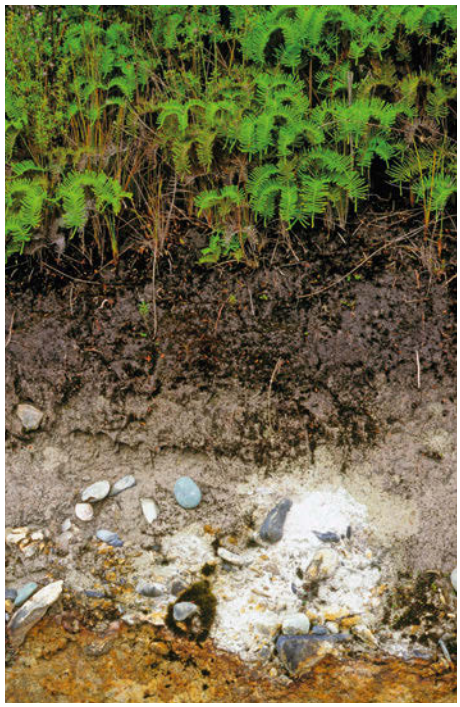


FIGURE 3.1.19 A soil profile showing the horizons (layers), which vary in colour depending on the mineral content in the soil. Plants absorb these minerals when they draw water out of the soil.

FIGURE 3.1.21 Bone matrix is made up of inorganic components including salts of calcium and phosphorus.

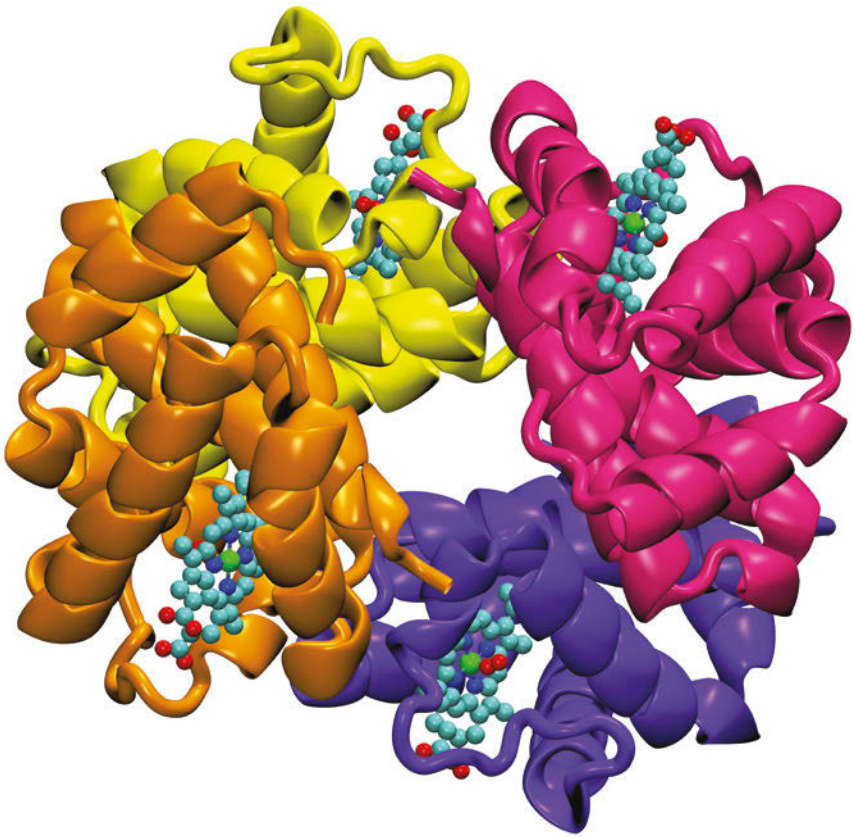


FIGURE 3.1.20 Haemoglobin is made up of four protein subunits (coloured ribbon structures). Each subunit has an oxygen-binding site, or haem group (turquoise). Within each haem group there is one atom of iron (green). Oxygen molecules are shown as paired red spheres.

3.1 Review

SUMMARY

- Organic components include carbohydrates, lipids, proteins and nucleic acids.
- Inorganic components of living organisms include water, oxygen, carbon dioxide, nitrogen and minerals.
- Carbohydrates are important as energy sources and for structural components of organisms.
- Lipids play an important role in cell membranes.
- Proteins are composed of amino acids and their functions vary. Organisms have their own unique proteins.
- Minerals are important for building many enzymes.
- Structural organic molecules and vitamins are small organic molecules that are vital for normal cell function.
- Nucleic acids carry the genetic information of cells.
- Important properties of water include cohesiveness, surface tension, heat capacity and pH.
- Oxygen is needed for efficient energy supply in organisms.
- Carbon dioxide is the ultimate source of carbon for organic molecules, and nitrogen is a key molecule of proteins.

KEY QUESTIONS

Retrieval

1 Define 'organic compound' and 'inorganic compound'.

2 Define 'polymer'.

3 List the two forms of nucleic acids and explain their roles.

4 Define 'mineral salts'.

Comprehension

5 Describe the four biomolecules. Indicate whether or not they are polymers, and describe the subunits involved.

6 Explain the difference between monosaccharides, disaccharides and polysaccharides.

7 Determine whether carbon dioxide is organic or inorganic. Explain why.

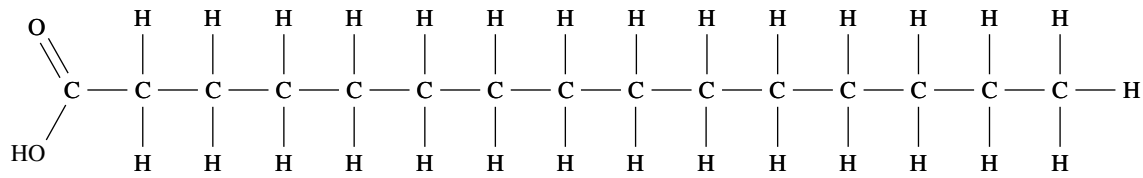
8 **a** Explain the importance of nitrogen for living organisms.

b Summarise what nitrogen-fixing bacteria are and why they are important.

Analysis

9 A biomolecule consists of carbon, hydrogen, oxygen, nitrogen and sulfur. Deduce what type of biomolecule it is.

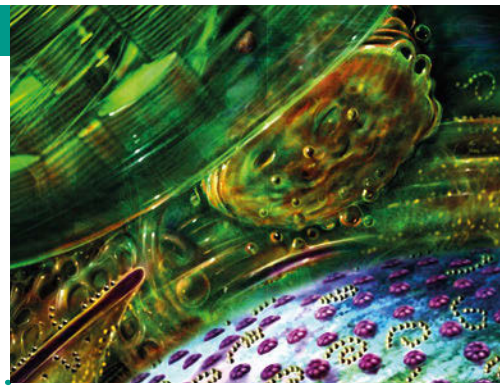
10 Determine the type of biomolecule represented by the image below.



3.2 Enzymes and biochemical pathways

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

- understand that enzymes act as catalysts to initiate chemical reactions by lowering the activation energy required for the reaction
- understand that enzymes have an active site, or groove, on their surface that is shaped to bind with specific molecules, called substrates
- recognise that 'induced fit' is the currently accepted model for enzyme function
- recognise that an enzyme's rate of reaction is influenced by temperature, pH, cofactors, inhibitors and concentration.



Nearly every function of a living organism depends on proteins. Proteins have a large range of functions in living organisms, including speeding up biochemical reactions, playing a role in cell-to-cell recognition and cellular communication, movement, storage and even structural support. A human has tens of thousands of different proteins, and each protein has a specific sequence of amino acids, giving it a unique shape that enables it to carry out its particular function.

In this module, you will learn about the features of a particular subset of proteins, **enzymes**. You will learn about enzymes' specificity for particular **substrates**, and how they interact with substrates to catalyse biochemical reactions. You will also learn about the importance of enzymes in biochemical pathways.

ENZYME STRUCTURE

As with every protein, enzymes are formed by linking together a DNA-programmed sequence of amino acids. The primary chain is then meticulously folded (secondary structure) and coiled (tertiary structure) into a precise and functional, three-dimensional, globular shape. Figure 3.2.1 shows the folding in the enzyme HIV-1 reverse transcriptase.

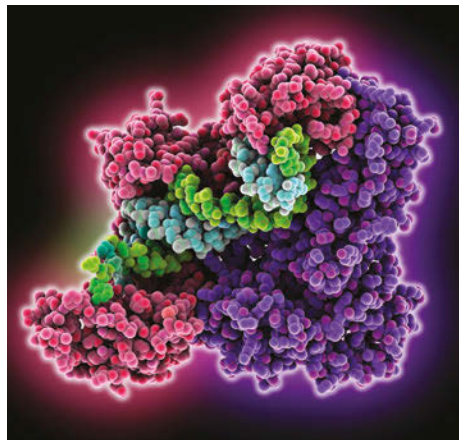


FIGURE 3.2.1 Enzymes are intricate and complex molecules that act as catalysts for biochemical reactions. This enzyme is HIV-1 reverse transcriptase that mediates the copying of genetic information, in this case by the human immunodeficiency virus (HIV) when infecting cells.

Most enzymes are complex globular proteins with one or more grooves around their surface. These grooves are called **active sites** and are fundamental to enzyme function. Active sites are unique in their size and shape, and only specific types of molecules will fit. The molecules that fit into an enzyme's active site are known as substrates. While most enzymes are highly specific, and act only on a single substrate, some enzymes can act on many substrates, and therefore regulate many biochemical reactions.

Enzymes are often named after the substrate that they act upon, and usually have an *-ase* ending. For example, the enzyme sucrase breaks down sucrose (a disaccharide) into its basic monosaccharides—glucose and fructose. Glucose and fructose can be absorbed into the bloodstream and then transported to your body cells (Figure 3.2.2).

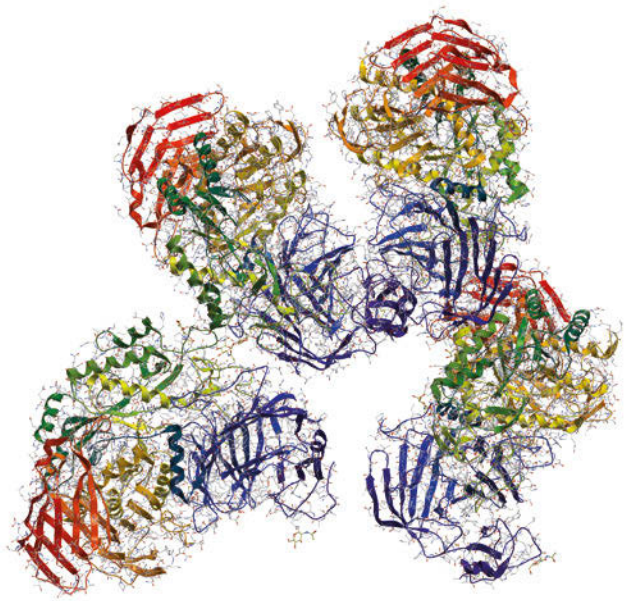


FIGURE 3.2.2 The enzyme sucrase is located in the walls of your villi lining in your small intestine. It breaks down sucrose into monosaccharides, which are then absorbed into your bloodstream for transportation.

ENZYME FUNCTION

Enzymes can join smaller molecules together to form a larger molecule, and others can break larger molecules into smaller ones. When the active site of an enzyme binds to a substrate, an **enzyme–substrate complex** is formed. The specific enzyme itself is not changed during the reaction, so it may be used over and over again as long as that reaction is required by the cell and there is a substrate present. Enzyme reactions are shown in Figure 3.2.3.

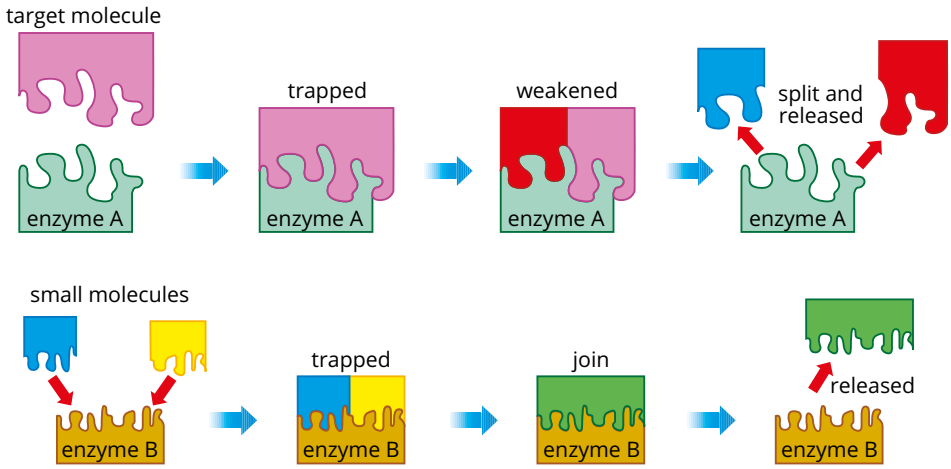


FIGURE 3.2.3 Enzyme reactions can be catabolic (breaking substrates apart) or anabolic (bringing molecules together).

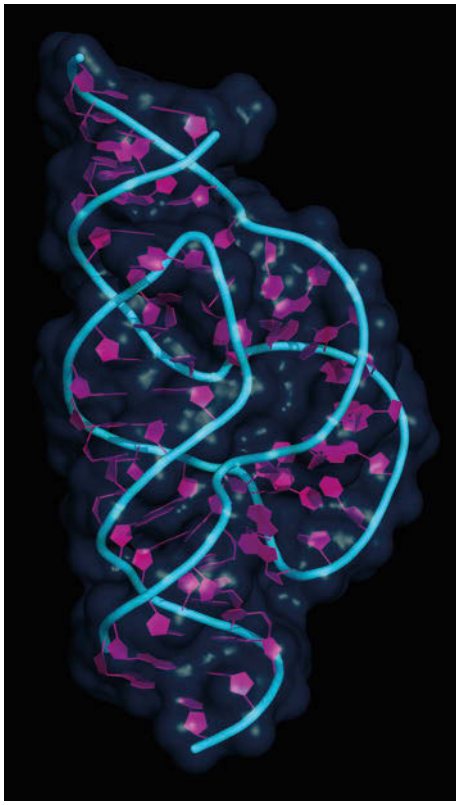


FIGURE 3.2.4 Hammerhead ribozyme is an RNA molecule that catalyses targeted RNA cleavage and has therapeutic potential.

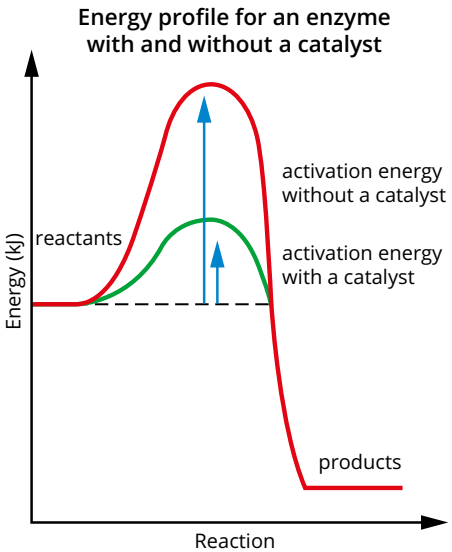


FIGURE 3.2.5 Enzymes act as catalysts to reduce the amount of energy required for substrate molecules to react with each other. This enables your cells to have millions of chemical reactions every minute at normal body temperature.

For this reason, enzymes are called substrate-specific **catalysts**. Enzymes are considered catalysts because they speed up the rate at which biochemical processes occur without being used up in the process. They are substrate-specific because they regulate a limited number of biochemical reactions. Enzymes may have a high specificity (able to act as a catalyst with one substrate only) or a low specificity and act as a catalyst for a range of similarly shaped substrates.

Enzymes are often embedded in membranes. The more enzymes present, the more chemical reactions can take place. Hence, many organelle membranes that are sites of metabolic activity are intricately folded. This increases the available surface area, and the number of enzymes, many times over. An example of this is the intricate folding of mitochondrial cristae. They are studded with ubiquinone and cytochrome c enzymes and are a vital part of ATP synthesis in the cell.

Ribozymes are a special class of enzymes and make up the large subunit of the ribosome. They catalyse peptide bonding between two amino acids in a peptide chain. They also cleave certain RNA bonds, such as those of transfer RNA attached to an amino acid (Figure 3.2.4).

ENZYME CATALYSIS

At any given moment, there are thousands of biochemical reactions taking place within living cells. Molecules are being joined together to form new compounds (anabolic reactions) or broken apart to form new smaller compounds (catabolic reactions).

Every chemical reaction requires a level of **activation energy** to initiate a reaction. This is shown in Figure 3.2.5. An enzyme's function is to control and regulate cellular biochemical processes within an organism. Often there is not enough energy present for these reactions to take place at the rate required by cells. This need to increase the rate of reactions necessitates the presence of an enzyme catalyst. Enzymes reduce activation energy of biochemical reactions.

An enzyme orientates and brings two molecules (substrates) together. When an enzyme–substrate complex forms, bonds in the substrate are placed next to charged amino acid side groups in the active site. The new bonds that form in the enzyme–substrate complex place stress on the substrate bonds. This reduces the amount of activation energy required for breaking the substrate bonds.

FACTORS AFFECTING ENZYME FUNCTION

The activity of enzymes can be affected by several factors, including cofactors, temperature, pH, inhibitors and the concentration of reactants and products.

Some enzymes will only be activated by the addition of a **cofactor**. Enzyme cofactors are either organic **coenzyme** molecules or inorganic ions, which are required for enzyme activity. Some cofactors are permanently attached to enzymes. Other cofactors only attach to an enzyme in response to a specific event in your body. The following modules provide more information on the factors that affect enzyme function.

SCIENCE AS A HUMAN ENDEAVOUR

Lock and key versus induced fit models

For many years, the lock and key model was considered to be the mechanism by which enzymes worked (Figure 3.2.6a). Then it was discovered that enzymes are not rigid; when the substrate enters the groove the enzyme induces a change in shape to fit itself tightly against the substrate. This brings the amino acid side groups into very close contact with the critical sites on the substrate. After the reaction occurs, the enzyme changes back to its original shape and releases the product. This more accurate model of understanding is known as the induced fit model and is shown in Figure 3.2.6b.

FIGURE 3.2.7 Biochemist Daniel Koshland proposed the induced fit model of enzyme action.

Sometimes it is very difficult for scientists to have their research findings accepted by everyone in the scientific community. If a theory, or model, has been in general use for a long time, some scientists are reluctant to admit they may have been using a limited concept to interpret their own research. The following quote is from Daniel Koshland, shown in Figure 3.2.7, who first proposed induced fit as model for enzyme interactions.

Although we did many experiments that in my opinion could only be explained by the induced-fit theory, gaining acceptance for the theory was still an uphill fight. One referee wrote, 'The Fischer Key–Lock theory has lasted 100 years and will not be overturned by speculation from an embryonic scientist'.

Daniel Koshland, Jr 1996 'How to get paid for having fun' *Annual Review of Biochemistry*, vol. 65, pp. 1–13.

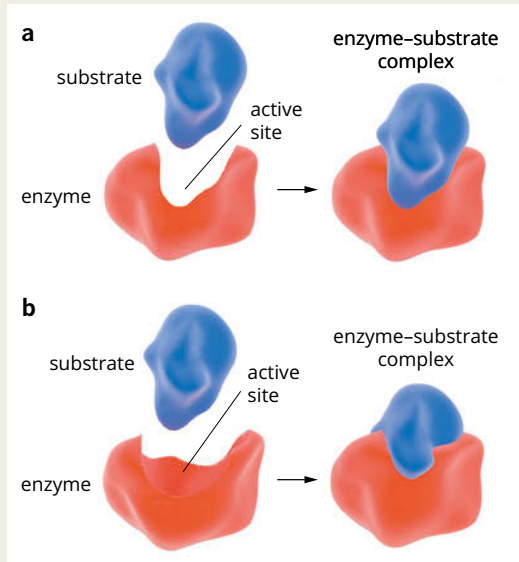


FIGURE 3.2.6 A comparison of the (a) lock and key mechanism with the (b) induced fit model of enzyme action. Notice in the induced fit model how the enzyme distorts and fits tightly around the substrate to form the enzyme–substrate complex.

Review

1. Compare the similarities of the two enzyme models, and contrast their differences.
2. Refer to the scientific method to determine what Koshland might have done to encourage a wider scientific acceptance of his induced fit model.

Temperature

High temperatures can directly affect the weak hydrogen bonds holding the enzyme into its specific shape. Heat energy causes bonds to weaken, permanently distorting the groove shape on the enzyme surface and preventing the substrate from binding. This permanently alters the three-dimensional structure of the enzyme, causing it to **denature**.

Lower temperatures increase the amount of activation energy required (even with the enzyme catalyst) and the rate of reaction is greatly impeded. While lower temperatures slow the rate of reaction, they do not cause enzyme denaturation (Figure 3.2.8).

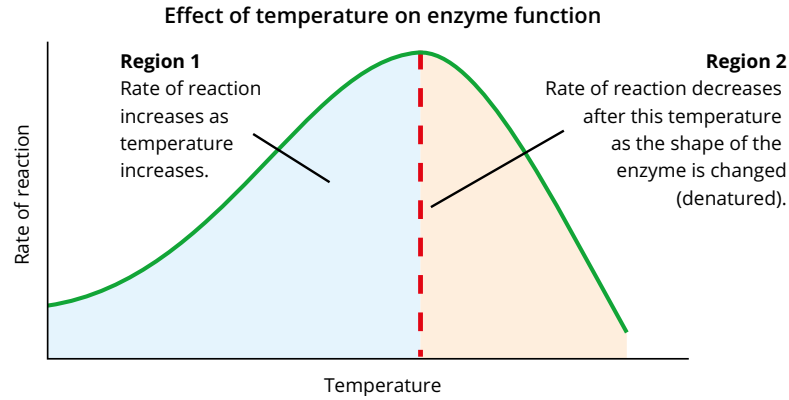


FIGURE 3.2.8 The rate of reaction increases as temperature increases (region 1). The rate of reaction decreases after this temperature because the shape of the enzyme is changed or denatured (region 2).

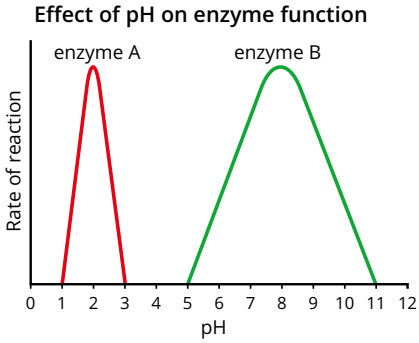


FIGURE 3.2.9 Different enzymes work best at different pH values. The pH at which an enzyme works best is called its optimum pH. The optimum pH of an enzyme depends on pH conditions under which the enzyme works. For example, intestinal enzymes work best under alkaline conditions so have an optimum pH of 8. Enzymes that work in the stomach have an optimum pH of 2 because the stomach is acidic.

pH

Some amino acid side chains can be negatively charged (e.g. glutamic acid) or positively charged (e.g. lysine). This means they are electrostatically attracted to one another, which strengthens the folding of the enzyme polypeptide chain. However, in extreme pH environments, both excess H^+ (hydrogen) and OH^- (hydroxide) ions can interfere with the positive-to-negative interactions and again, cause the enzyme to unfold and denature.

Enzymes have very narrow optimal pH environments, as can be seen in the graphs in Figure 3.2.9. For example, most enzymes in the human body have an optimal pH range of 6–8. However, pepsin functions in the stomach to break down other proteins as part of the digestion process. Pepsin has very strong hydrogen and ionic bonds between its amino side groups; consequently it has an optimal pH range of 3–4.

Inhibitors

Access to the active site on enzymes can also be impeded by molecules that have the same active site configuration. This is known as **competitive inhibition** and is shown in Figure 3.2.10. An example of competitive inhibition is the treatment of methanol poisoning with ethanol. Methanol is converted to toxic formaldehyde by the enzyme alcohol dehydrogenase (ADH). Ethanol competes for the same active site. So ethanol can be given to the patient, and it is oxidised to acetaldehyde, then to acetic acid, acetyl Co-A and finally carbon dioxide and water.

Non-competitive inhibition occurs when a molecule attaches to another site on the enzyme. The interaction of molecular forces causes the enzyme active site to change shape. This effectively blocks the docking of the enzyme's specific substrate. An example of this is potassium cyanide, which docks on the cytochrome molecules in the mitochondrial membrane. This effectively stops cellular respiration and the major production of ATP.

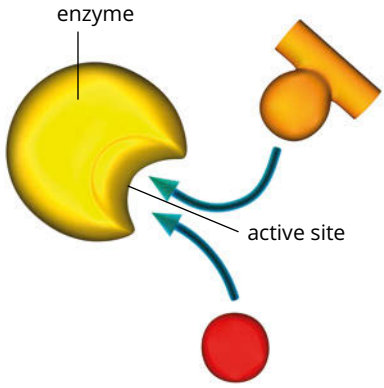


FIGURE 3.2.10 Competitive inhibition is when similarly shaped binding sites of molecules compete for access to an enzyme's active site.

Concentration

The concentration of enzymes, and substrate reactants, directly affects the rate of reaction until a saturation point is reached (Figure 3.2.11). More enzymes facilitate the reacting of a greater number of reactants in a shorter time and more reactants ensure a ready supply of substrate for reaction. Increasing the number of enzymes present will increase the rate at which the reaction increases to a certain point until all enzymes are working at the maximum rate. The reaction rate remains stable until either the substrate is used up or the product begins to block substrate access to the enzyme. At this point, all the available active sites are being used.

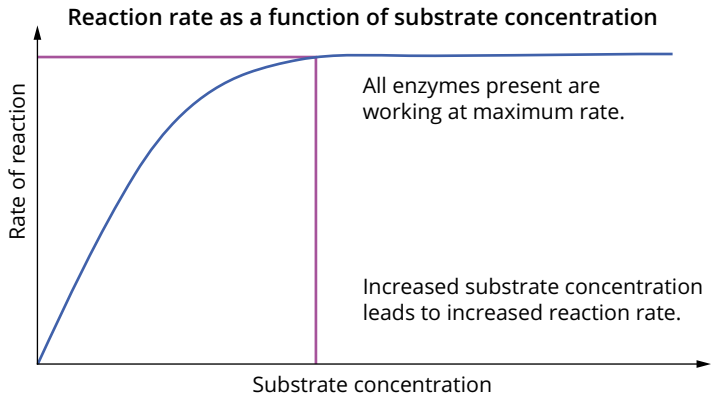


FIGURE 3.2.11 Increasing an enzyme substrate increases the rate of reaction until all the enzymes are working at their maximum capacity.

WS 1.1.6 WS 1.1.7

3.2 Review

SUMMARY

- Most enzymes are proteins that are substrate specific.
- Enzymes have a groove on their surface that contains active sites, which interact with the substrate.
- The accepted model for enzyme function is the induced fit model. According to this model, the enzyme shapes itself around the substrate thereby reducing the activation energy required for the biochemical process to occur.
- Enzymes act as catalysts to initiate a chemical reaction by lowering the activation energy required for the reaction.
- Enzymes that are deformed, or denatured, cannot act as catalysts.
- The rate of reaction is influenced by temperature, pH and the concentration of enzymes, substrate reactants and products.
- Some enzymes require cofactors to activate them.
- Most enzymes only effectively operate within a narrow temperature or pH range.
- Inhibitors may also affect the rate at which a substrate can bind to an enzyme.

KEY QUESTIONS

Retrieval

1 Define 'enzyme'.
2 Describe the generally accepted model of enzyme mechanism.
3 Identify the factors that directly affect enzyme function.
4 Describe a coenzyme.

Comprehension

5 Describe how enzymes reduce the activation energy of a reaction.
6 Explain enzyme substrate specificity and how it relates to enzyme structure.
7 Describe how a non-competing inhibitor can stop enzyme reactions.

continued over page

3.2 Review *continued*

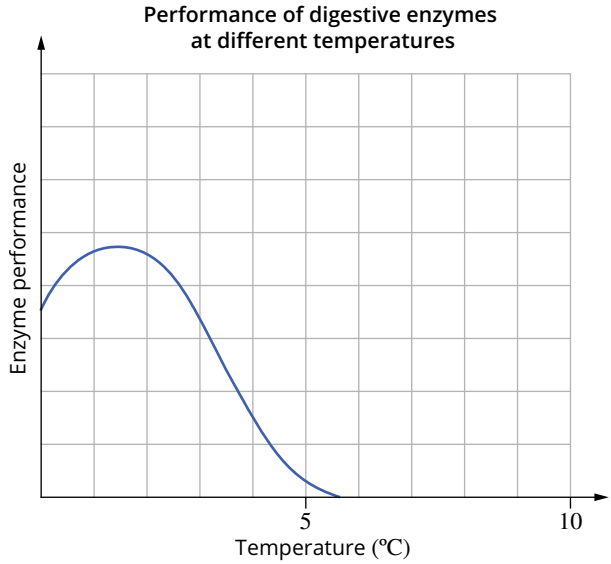
8 Describe how an enzyme–substrate complex forms.

9 Explain how a catalyst can facilitate a chemical reaction.

10 Summarise (in table form) how the four factors (temperature, pH, inhibitors and concentration) affect enzyme reaction rates.

Analysis

11 The following graph shows the effective temperature range of a particular animal's digestive enzyme. Infer what sort of environment this animal could be living in.

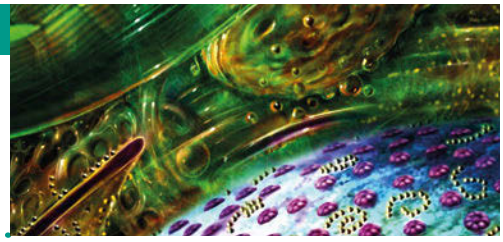


12 Robert O'Hara Burke and William Wills were famous Australian explorers. They were the first Europeans to cross Australia from south to north and nearly back again. It is thought that they perished from a lack of vitamin B_1 (thiamin), an important enzyme cofactor. Near the end of their lives, when they were stranded at Coopers Creek, they subsisted almost entirely on the ground sporocarps (spore cases) of the aquatic fern *Marsilea drummondii*, or nardoo (shown below). They mixed the flour from the sporocarps and nardoo with water to make a type of thin porridge. Nardoo contains the enzyme thiaminase. The local Yandruwandha women also used nardoo in their flour to bake damper. Determine why the thiaminase in the nardoo may have caused the death of Burke and Wills, but not the local Yandruwandha people.

3.3 Acquiring energy

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

- understand how organisms are divided into groups according to how they obtain organic compounds and how they obtain energy
- recognise that all life on Earth requires both an energy source and a carbon source.



Cells need energy to do work. The energy used by organisms and their cells is stored in organic compounds. Whether organisms are unicellular or multicellular, or whether they live at the bottom of the ocean or in a rainforest, they all need to take in nutrients and water, exchange gases, obtain energy and remove waste products. And ultimately, most biological systems primarily rely on one source of energy for their survival: sunlight (Figure 3.3.1).

FIGURE 3.3.1 Sunlight is the primary source of energy for biological systems and the organisms within them.

ENERGY VIA ATP

Energy can be defined as the ability to cause change. For example, you are using energy right now to move your eyes to read these words, just as the cells inside your body are currently using energy to transport substances across their membranes. You, like all organisms, are constantly expending energy.

Energy exists in many forms. The energy in sunlight is solar energy, the heat generated by your body is thermal energy, and when you turn a page this movement involves kinetic energy. Chemical energy is the potential energy that can be released by a chemical reaction. Chemical energy is stored in the bonds or connections that join atoms together; for example, between atoms of carbon and hydrogen in organic compounds such as glucose, fats and proteins. The cells of all organisms draw upon this chemical energy by breaking compounds down. The chemical energy released is then used to make a universal transport energy molecule. This molecule is adenosine triphosphate, or ATP.

ATP

ATP molecules are composed of three inorganic phosphate groups attached to a nitrogenous base, adenosine. The ATP molecule contains two high-energy bonds between the inorganic phosphate groups (Figure 3.3.2). These bonds can be easily broken to release a small 'packet' of energy. These packets of energy are used to carry out all the energy-dependent processes of cells. How many are used at once depends on how much energy is required.

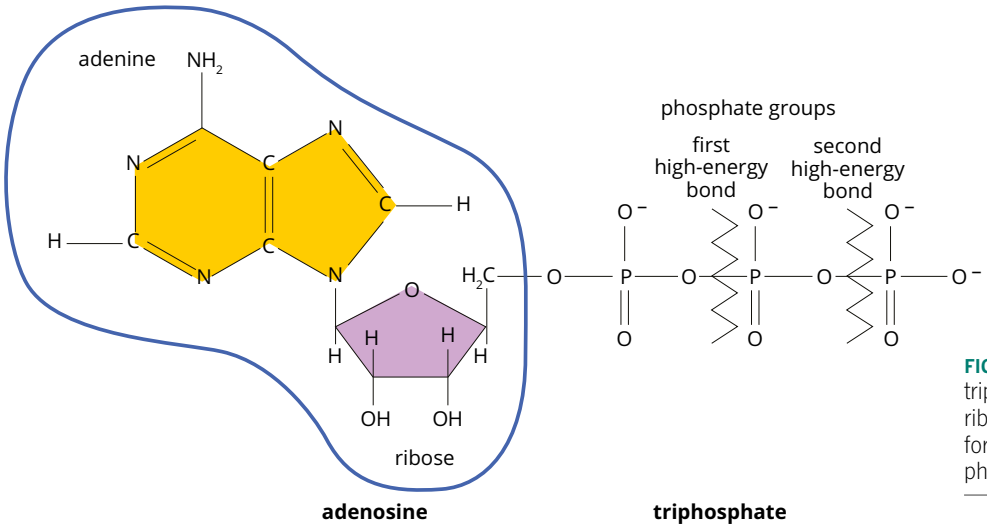


FIGURE 3.3.2 The structure of adenosine triphosphate (ATP). ATP contains the sugar ribose, the nitrogenous base adenine (together forming adenosine) and a chain of three phosphate groups (triphosphate) bonded to it.

When an ATP molecule gives up its energy, it splits into a molecule of ADP (adenosine diphosphate) and a molecule of phosphate. This process is reversible, because the ADP can combine with a phosphate molecule to form an ATP molecule again, using energy derived from the breakdown of glucose during cellular respiration (Figure 3.3.3). This recycling process requires much less energy than it would take to make an entirely new ATP molecule.

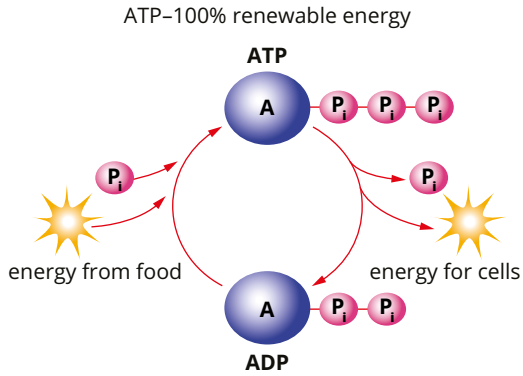


FIGURE 3.3.3 Breaking down ATP releases energy. Cells constantly replace their ATP by adding a spare phosphate onto ADP (adenosine diphosphate). Enzymes control the synthesis and breakdown of ATP.

Autotrophs and heterotrophs: producers and consumers

Organisms can be divided into two groups depending on the strategies they use to obtain organic compounds (Figure 3.3.4). **Autotrophs** obtain organic compounds by converting inorganic matter. Because they produce all the organic compounds in ecosystems, they are also called producers. Most autotrophs use **photosynthesis**. The typical photosynthetic organisms you might think of are green plants, but there are also photosynthetic protists such as algae, *Euglena* and cyanobacteria (Figure 3.3.5).

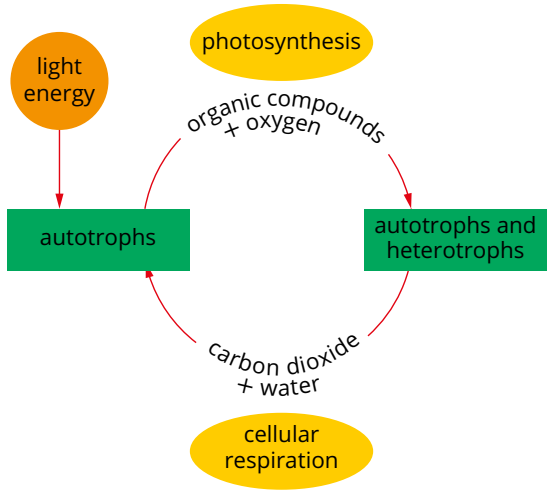


FIGURE 3.3.4 Autotrophic organisms make the organic compounds they require by combining inorganic compounds from their environment. Heterotrophic organisms obtain the organic compounds they require by eating other organisms or products of other organisms.

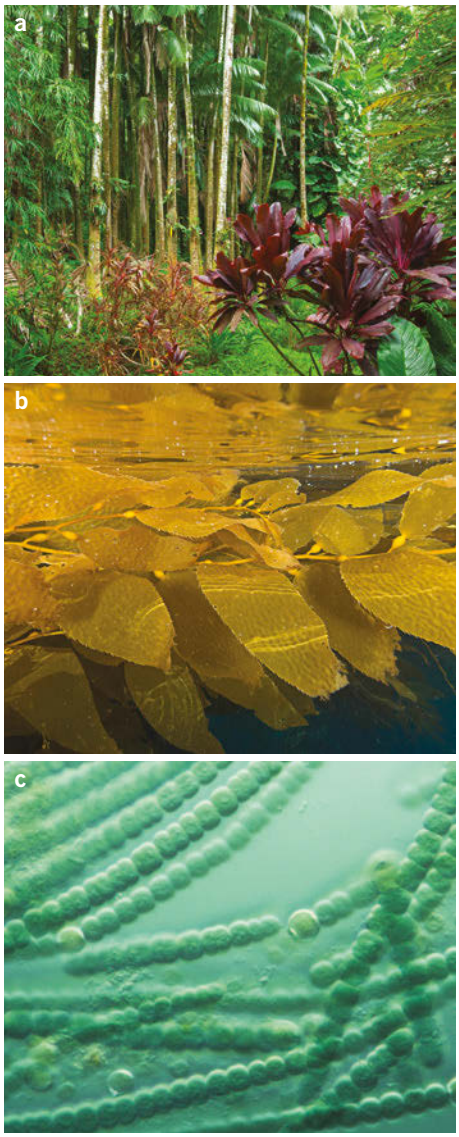


FIGURE 3.3.5 Photoautotrophs use light energy to synthesise organic molecules from carbon dioxide and water. (a) On land, plants are the main photoautotrophs. In aquatic environments, the main photoautotrophs are (b) algae such as this kelp and (c) prokaryotes called cyanobacteria.

Chemosynthetic autotrophs (**chemoautotrophs**) obtain the energy they need for carbon fixation from inorganic chemical reactions—a process known as chemosynthesis. All known chemosynthetic organisms are prokaryotes. Some chemosynthetic autotrophs obtain energy by the oxidation of inorganic molecules. Some of these conversions include:

- ammonium ions (NH_4^+) to nitrite ions (NO_2^-)
- nitrite ions (NO_2^-) to nitrate (NO_3^-)
- sulfide ions (S^{2-}) to sulfate ions (SO_4^{2-}).

Chemoautotrophs are able to live in the more extreme environments where these ions can be found. Methanogens are chemoautotrophs that live in environments where hydrogen is more readily available. They obtain energy from a carbon-fixing reaction in which carbon dioxide and hydrogen react to form a simple organic compound: methane (CH_4). Methanogens are poisoned by oxygen and live in places depleted of oxygen, such as wetlands and the digestive tract of animals.

Heterotrophs ('other feeders') are also called consumers because they are unable to make their own food. Unlike autotrophs, heterotrophs cannot use simple inorganic substances to make organic compounds. Instead, they must obtain the organic compounds they need by consuming other organisms or their products. All animals and fungi are heterotrophs. Some bacteria and many protozoans are also heterotrophs.

Heterotrophs and autotrophs can be further divided according to how they acquire energy and carbon, as shown in Table 3.3.1.

TABLE 3.3.1 Nutritional modes

Type of organism	Energy source	Carbon source
photoautotroph	solar energy (sunlight)	carbon dioxide
chemoautotroph	inorganic molecules	carbon dioxide
photoheterotroph	solar energy (sunlight)	organic matter
chemoheterotroph	organic compounds	organic matter

Some organisms are both autotrophic and heterotrophic. In sunlight, the protozoan *Euglena* species, shown in Figure 3.3.6, is photoautotrophic. But when there is no sunlight, they can absorb food from their environment, so they are also heterotrophic.

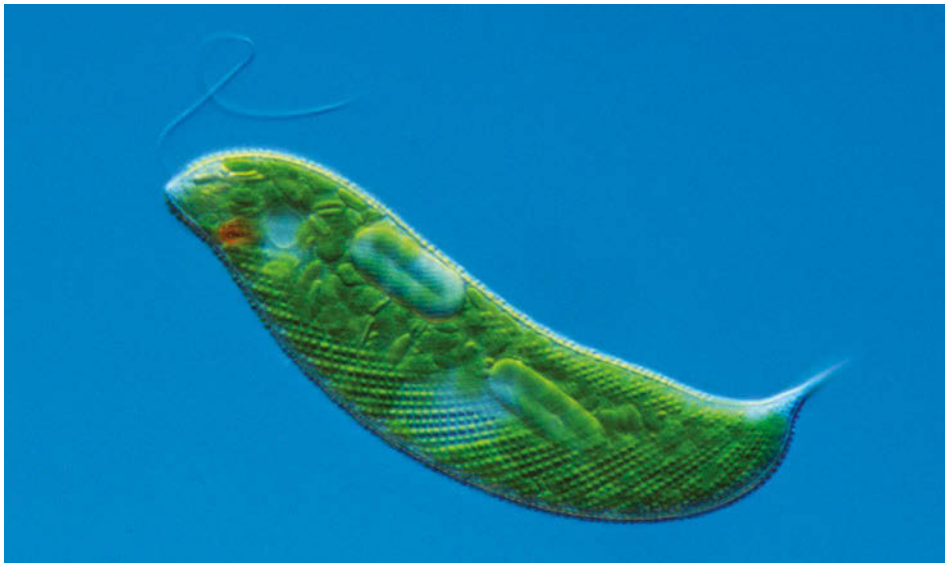


FIGURE 3.3.6 *Euglena* species are single-celled flagellate protozoans that can obtain energy from both sunlight and other organisms.

3.3 Review

SUMMARY

- ATP is a chemical energy transport molecule used by all living organisms.
- Autotrophs use energy and inorganic molecules from the physical environment to produce the organic compounds they need.
- Most autotrophs, including plants and algae, are photosynthetic. That is, they use solar energy for producing energy-rich organic compounds.
- Some autotrophs, including some bacteria and archaea, are chemosynthetic, meaning they obtain energy by carrying out energy-releasing reactions between inorganic molecules.
- Heterotrophs, including animals, fungi and some bacteria and protists, obtain organic compounds by eating other organisms or their products.

KEY QUESTIONS

Retrieval

1 Name a group of photoautotrophs and the compounds they use in photosynthesis to acquire carbon.

2 Explain what is meant by 'chemical energy'.

Comprehension

3 Determine the difference between photosynthetic autotrophs and chemosynthetic autotrophs.

Analysis

4 There are abundantly more photoautotrophs than chemoautotrophs on Earth. Argue why.

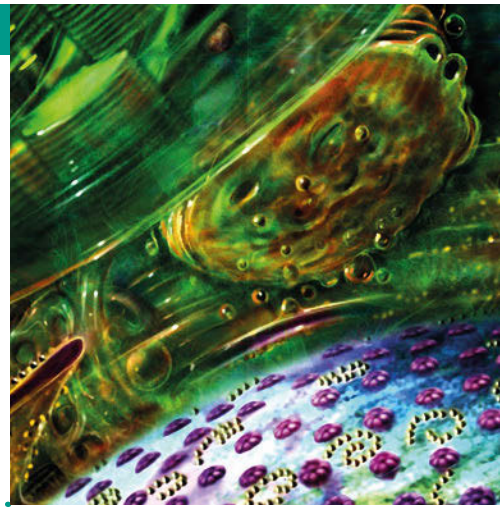
3.4 Photosynthesis

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

- understand that the process of photosynthesis is an enzyme-controlled series of chemical reactions that occurs in the chloroplast in plant cells and uses light energy to synthesise organic compounds (glucose)
- summarise the process of photosynthesis in terms of the light-dependent reactions and light-independent reactions
- demonstrate the relationship between the light-dependent reactions and light-independent reactions
- recognise that the overall process can be summarised in a balanced chemical equation:

$$\text{carbon dioxide + water} \xrightarrow{\text{light energy}} \text{glucose + oxygen + water}$$

$$6CO_2 + 12H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$



Simple experiments show that when plants have light, water and carbon dioxide, they make glucose in their green parts, such as leaves. They trap the energy of sunlight and convert it into chemical energy, which they store in the bonds of glucose molecules. This enzyme-controlled process is photosynthesis (*photo*, meaning 'light', and *synthesis*, meaning 'putting together'). All photosynthetic organisms, from single-celled algae to the largest trees, produce glucose in the same way (Figure 3.4.1).

FIGURE 3.4.1 Plants trap the energy of sunlight and convert it using photosynthesis into chemical energy.

PHOTOSYNTHESIS

Photosynthesis is sometimes called 'carbon fixation' because carbon atoms from the air are incorporated ('fixed') into organic molecules. Photosynthesis involves two stage: a light-dependent stage and a light-independent stage. Each stage involves a series of biochemical reactions, often referred to as a biochemical pathway (or metabolic pathway). Each reaction in the pathway is catalysed (accelerated) by a particular enzyme. Figure 3.4.2 illustrates the process of photosynthesis.

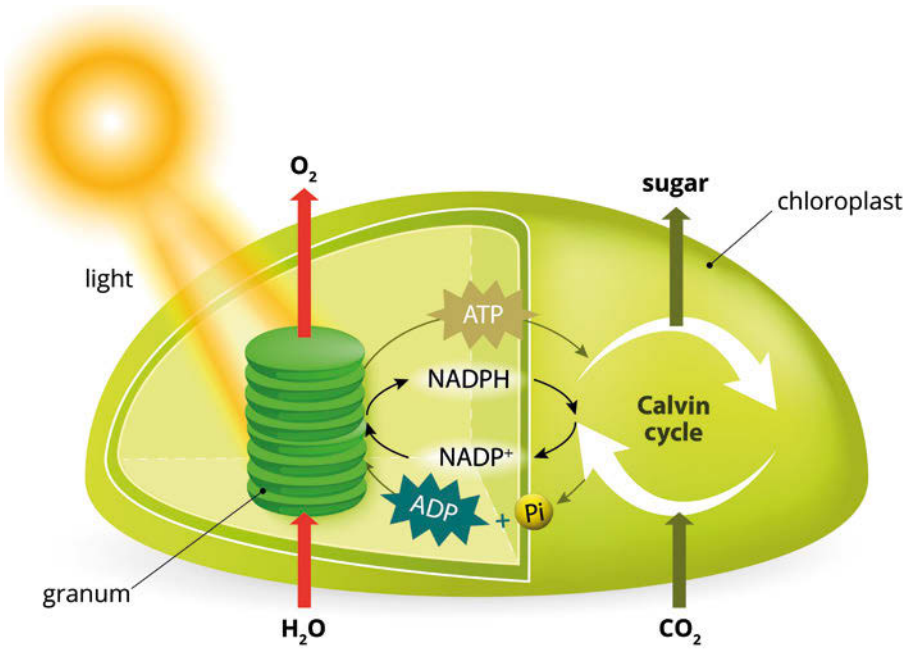


FIGURE 3.4.2 An overview of photosynthesis showing the processes and the products

The glucose formed in photosynthesis may be:

- used as an immediate source of energy by the plant
- stored by the plant as starch for later conversion back to glucose and then used as a source of energy
- used as a chemical starting point for the synthesis of complex compounds, such as cellulose and proteins.

The oxygen formed in photosynthesis may be used for aerobic cellular respiration by the plant or released into the atmosphere.

The reactions that occur during photosynthesis can be summarised by these overall equations:

Word equation: carbon dioxide + water → glucose + oxygen + water

Chemical equation: $6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$

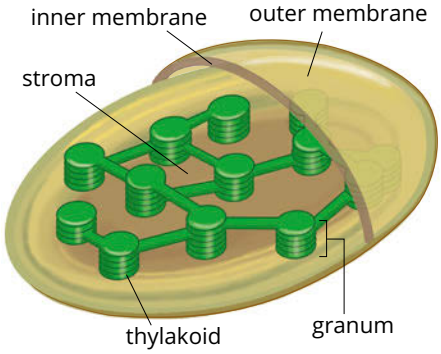


FIGURE 3.4.3 A three-dimensional model of the structure of a chloroplast

CHLOROPLAST STRUCTURE

As you will recall from Chapter 2, the cells of eukaryotic autotrophs, such as plant cells, have specialised organelles called chloroplasts. These lens-shaped organelles contain an outer and an inner membrane, which together regulate the movement of materials into and out of the organelle. Inside these membranes is a fluid matrix called stroma and a highly complex inner thylakoid membrane system increasing the surface area for enzyme-controlled reactions. The thylakoid membranes fold to form flat hollow discs, which form stacks called grana (Figure 3.4.3). Each granum looks like a stack of coins. Between the grana are flat membrane sheets called thylakoid lamellae.

Photosynthetic pigments

Photosynthetic pigments are coloured substances that collect the light energy that is used in photosynthesis. The green pigment in chloroplasts is chlorophyll. It is the most abundant and visible photosynthetic pigment found in plants.

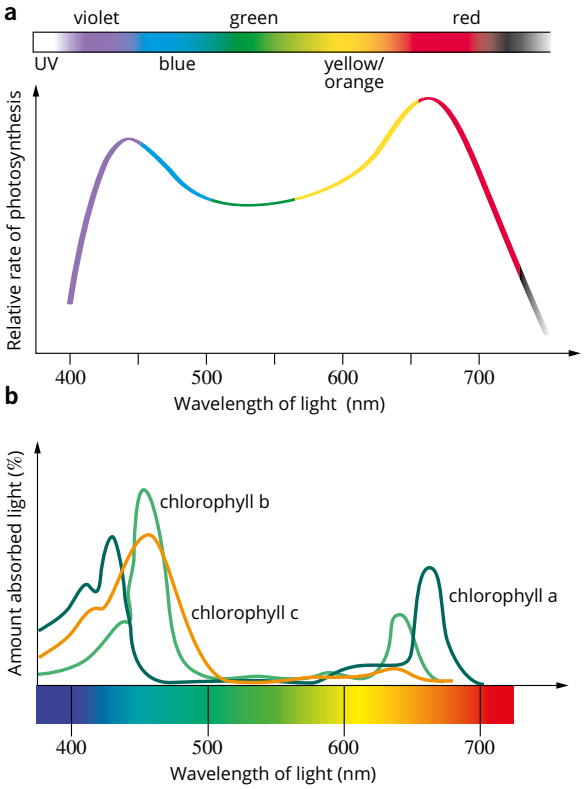


FIGURE 3.4.4 The rate of photosynthesis (a) occurs at different rates in light of different wavelengths. The pattern of photosynthetic activity is very similar to (b) the absorption spectrum of chlorophyll.

Figure 3.4.4a shows you that the rate of photosynthesis is highest under red light (650–700 nm). The rate of photosynthesis is also high under blue and violet light (400–450 nm). The lowest rate of photosynthesis occurs under green light (500–600 nm). We can explain this using Figure 3.4.4b, because different types of chlorophyll absorb different wavelengths of light. Chlorophyll absorbs many of the colours that make up the spectrum of white light, but it reflects green light. The spectrum (Figure 3.4.4b) shows clearly that red, blue and violet light are all strongly absorbed, while yellow is absorbed to a lesser extent and green is not absorbed at all.

There are several different types of chlorophyll found in various photosynthetic organisms.

- Chlorophyll a is found in all photosynthetic organisms.
- Chlorophyll b is found in some plants.
- Chlorophyll c is found in algae.
- Chlorophyll d and f are found in cyanobacteria.

These different types of chlorophyll have slightly different molecular shapes and so have different light-absorption spectra.

Photosynthetic organisms also contain pigments called carotenoids, which are red, orange and yellow and are also involved in capturing light. When chlorophyll is broken down in some plants in autumn, the colours of the carotenoids are no longer masked by the green chlorophyll and are exposed. This gives autumn leaves the colours shown in Figure 3.4.5. Carotenoids are known as accessory pigments because they cannot pass their absorbed energy directly to photosynthesis but can transfer it to chlorophyll to then be used in photosynthesis. Accessory pigments broaden the range of wavelengths of light absorbed and therefore increase the amount of light that a plant can absorb for use in photosynthesis.

LIGHT-DEPENDENT REACTIONS

The first stage of photosynthesis involves biochemical pathways known as the light-dependent reactions. These reactions occur on the thylakoid membranes of the chloroplast, where chlorophyll and the enzymes involved are located. The reactions can only take place in the presence of light.

First, light energy is absorbed by chlorophyll. The energy is then used to split water to produce oxygen, and to form the energy-carrying molecules ATP and NADPH from ADP, inorganic phosphate (P_i) and $NADP^+$ (nicotinamide adenine dinucleotide phosphate). The light-dependent reactions are summarised in Figure 3.4.6.

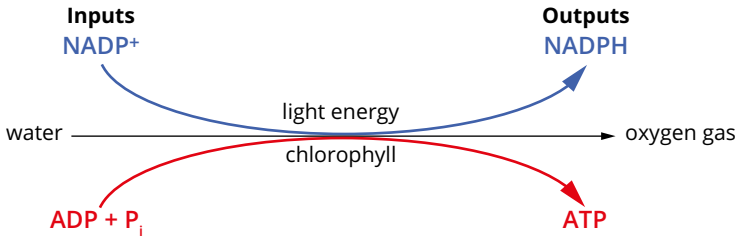


FIGURE 3.4.6 Water is split into oxygen and hydrogen. The oxygen is released as a gas. The NADPH and ATP are used in the second stage of photosynthesis.

FIGURE 3.4.5 Deciduous plants such as the red maple decrease chlorophyll production in autumn, before losing their leaves. The red, yellow, orange or brown colours of carotenoids are visible when there is no green-coloured chlorophyll in the leaves.

Photosystems I and II

Within the thylakoid membranes are a number of highly complex, linked chemical systems and a large number of enzymes. Two of the key chemical systems are photosystem I and photosystem II. Both systems contain chlorophyll and depend on light to function. Together with the enzyme ATP synthase, these systems carry out the processes called the light-dependent reactions.

The chlorophyll in photosystem II absorbs light energy that is used to split water into oxygen, hydrogen ions and electrons. This can be summarised as:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

water → oxygen + hydrogen ions + electrons

The chlorophyll in photosystem I absorbs light energy that is transferred together with hydrogen ions and electrons to form a coenzyme energy carrier NADPH from $NADP^+$. This reaction is summarised as:

$$NADP^+ + H^+ + 2e^- \rightarrow NADPH$$

low energy → high energy

ATP synthase is the enzyme that uses energy generated by both photosystems to form ATP from ADP and inorganic phosphate (P_i).

LIGHT-INDEPENDENT REACTIONS

The products of the light-dependent reactions, NADPH and ATP, are released into the stroma of the chloroplast. There, these coenzymes provide energy to drive a biochemical pathway known as the light-independent reactions. The light-independent reactions are summarised in Figure 3.4.7.

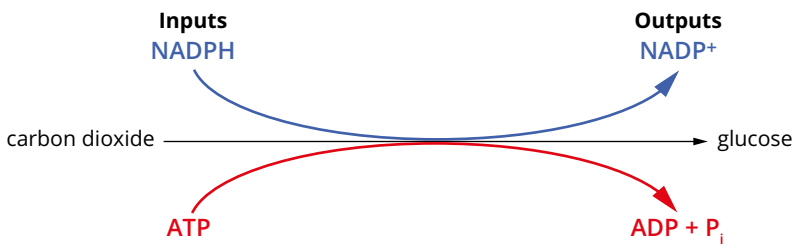


FIGURE 3.4.7 In the second stage of photosynthesis, carbon dioxide is reduced to form the sugar glucose.

The second stage of photosynthesis does not require light for the reaction to be able to proceed. However, it does require the NADPH and ATP of the light-dependent reactions. If NADPH and ATP are present, the reaction can continue in the absence of light (Figure 3.4.8).

The main stage of the light-independent reactions is called the Calvin cycle.

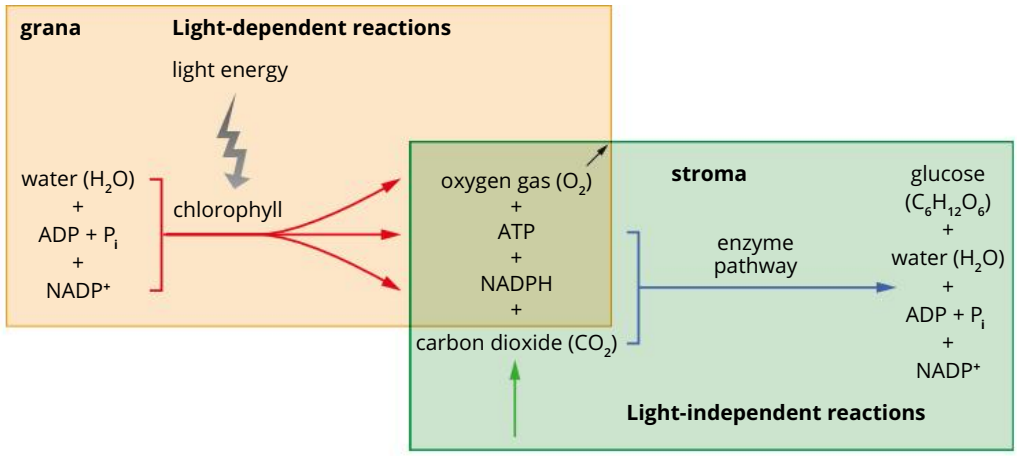


FIGURE 3.4.8 Photosynthesis occurs in two phases. The light-dependent reactions occur in the thylakoid membranes of the grana. The light-independent reactions occur in the stroma. The light-independent reactions require the carriers generated by the light-dependent reactions.

Calvin cycle

The Calvin cycle comprises all the light-independent reactions. This biochemical pathway of enzyme-catalysed reactions uses carbon dioxide and the energy in the NADPH and ATP produced in the light-dependent reactions to make carbohydrates (Figure 3.4.9). To understand how this process works, it is necessary to realise that each cycle does not exist as a separate entity. There are many instances of the same reactions occurring simultaneously in the stroma and therefore many concurrent Calvin cycles occurring. If it were possible to isolate a single cycle, then one carbon atom would be added to the system with each 'turn', but no one-carbon product is actually produced.

The identifiable product of the Calvin cycle is a three-carbon carbohydrate called glyceraldehyde-3-phosphate (GAP). In the cytoplasm, two GAP molecules combine to produce the glucose ($C_6H_{12}O_6$) molecule that is normally identified as the product of photosynthesis. The remaining GAP molecules are recycled into ribulose 1,5-bisphosphate (RuBP), which is the starting molecule of the light-independent reaction.

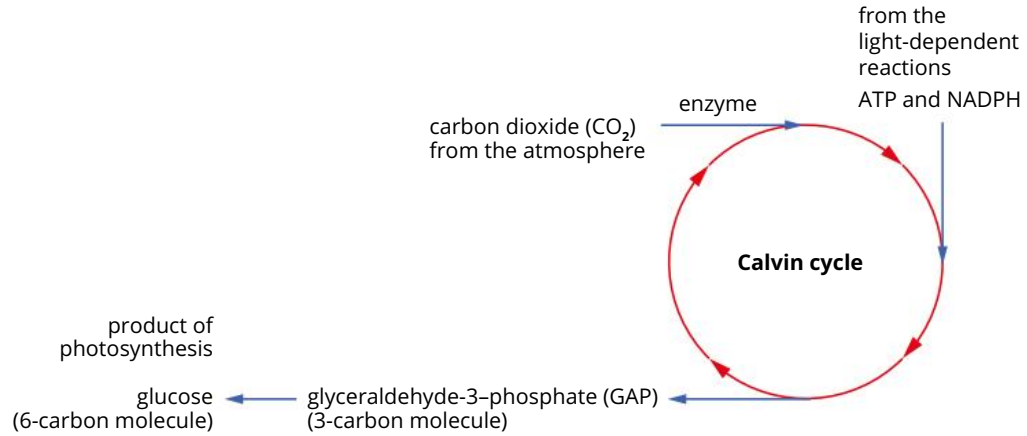


FIGURE 3.4.9 Carbon dioxide from the atmosphere feeds into the Calvin cycle, which uses energy carried by ATP and NADPH from the light-dependent reactions.

FACTORS AFFECTING THE RATE OF PHOTOSYNTHESIS

As for all biochemical processes, the rate of photosynthesis varies according to the internal conditions of the cell, which in turn is often affected by the external environmental conditions. Perhaps most obvious is that the rate of photosynthesis depends on the number of chloroplasts present in a leaf or plant.

Photosynthesis depends on other variables that are interconnected. For example, the opening of **stomata** controls both loss of water and entry of carbon dioxide, as shown in Figure 3.4.10. For this reason, the only way of studying the effect of each factor on the rate of photosynthesis is in the laboratory. Laboratory studies using suspensions of isolated chloroplasts or green algae enable scientists to test the effect of varying the amount of different factors on the rate of photosynthesis under controlled conditions.

The information below outlines the factors that affect the rate of photosynthesis in C_3 plants (3-carbon fixing plants, the most common type of plant). Two other plant types, C_4 and CAM, are discussed at the end of the module.

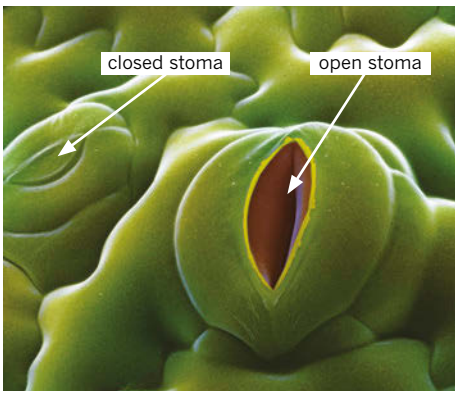


FIGURE 3.4.10 This coloured scanning electron micrograph image of a tobacco leaf shows one open stoma and one closed stoma. When the stoma is open, gas exchange can occur and water molecules can escape.

Inputs: carbon dioxide and light energy

If you look closely at the process of photosynthesis described in the overall equation, you can predict that the rate at which it occurs will be affected by a number of factors.

The main requirements of photosynthesis are carbon dioxide, water and light energy. If any one of these factors is in limited supply, it is reasonable to predict that the rate of photosynthesis will be limited also. Because the amount of water used in photosynthesis is small compared with the amount needed to keep the cells alive, a living plant cell normally has sufficient water for photosynthesis to occur. Therefore, water does not have a direct effect on the rate of photosynthesis in nature. However, water does have an indirect effect, because when the plant is suffering from water stress, such as the plant in Figure 3.4.11, the stomata in the leaf close and reduce the availability of carbon dioxide. So, under normal circumstances, photosynthesis is directly affected by the availability of carbon dioxide and light.

FIGURE 3.4.11 This plant has wilted due to water loss. When water is not available, the plant cells lose water, reducing the turgor (pressure) inside the cell. Therefore the cells cannot maintain a rigid shape, and the plant collapses.

Carbon dioxide

The carbon dioxide level in the air remains relatively constant. The factors that affect the amount available for photosynthesis in most terrestrial plants are the number of stomata in the leaves and whether these stomata are open or closed. If the stomata are closed, photosynthesis uses up the carbon dioxide inside the leaf, therefore lowering the carbon dioxide concentration in the leaf. With less carbon dioxide available, the rate of photosynthesis, even in the presence of light, is limited.

In the laboratory it is possible to control the concentration of carbon dioxide to which plants are exposed without changing other factors. Figure 3.4.12 shows a comparison of the rate of photosynthesis for a particular species of plant exposed to different concentrations of carbon dioxide at different light intensities.

Terrestrial plants receive their carbon dioxide from the air. Aquatic plants can use the carbon dioxide dissolved in the water.

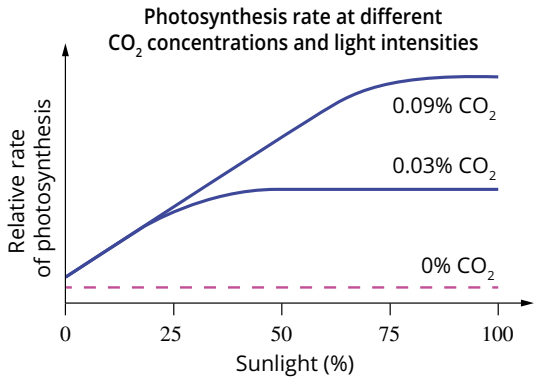


FIGURE 3.4.12 The rate of photosynthesis increases with increasing light intensity at two different concentrations of carbon dioxide. At 0.03% carbon dioxide, the rate of photosynthesis increases until approximately 30% sunlight at which point the rate of photosynthesis is limited by the availability of carbon dioxide. At 0.09% carbon dioxide, the rate of photosynthesis continues to increase up to about 80% sunlight. The concentration of carbon dioxide in the atmosphere is approximately 0.04%.

Light

In the laboratory, chloroplasts can be extracted from plant cells and tested in isolation. By varying the amount of light shining on these isolated chloroplasts, while keeping the carbon dioxide and water levels constant, it is possible to measure the rate at which photosynthesis occurs at different amounts of light. The results of this experiment are shown in Figure 3.4.13 and present what is referred to as a light saturation curve. The curve shows a steady increase in the photosynthesis rate with an increase in light intensity until a plateau begins to form. The plateau indicates that there is a maximum rate at which photosynthesis can occur. Assuming unlimited amounts of carbon dioxide (and water), the limit is the point at which all of the photosynthetic systems and enzymes in the chloroplasts are working at their maximum rate.

In the natural environment, the amount of light available to a plant for photosynthesis is determined by the amount of sunlight. Plants in different environments receive different amounts of sunlight, as shown in Figure 3.4.14. The amount of sunlight varies during the cycle of a day and changes with the seasons and the weather. Figure 3.4.13 shows how tomato plants grown under unshaded conditions have greater rates of photosynthesis than plants grown under shaded (50%) conditions.

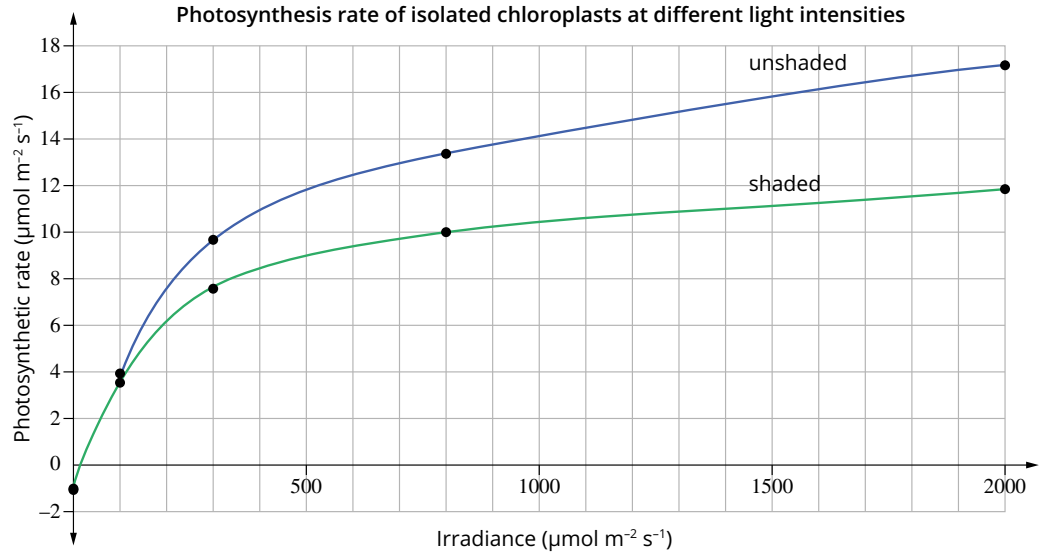


FIGURE 3.4.13 Light saturation curves of chloroplasts extracted from tomato plants grown under shaded (50%) and unshaded conditions.

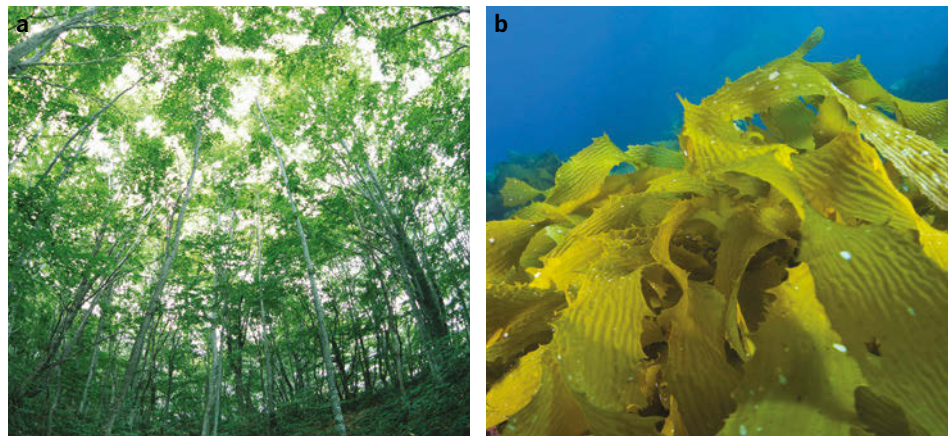


FIGURE 3.4.14 (a) Plants growing on the forest floor receive less light than taller trees. (b) Aquatic photosynthetic organisms, such as this sea kelp, can only grow near the water's surface. As you move deeper underwater, there is less light available.

Temperature

Many enzymes in chloroplasts catalyse the reactions of photosynthesis. Without these enzymes, photosynthesis would not occur. You will recall from Module 3.1 that the rate of an enzyme reaction is affected by temperature and so, accordingly, the reactions of photosynthesis are affected by temperature. The optimum condition for the functioning of the enzymes of photosynthesis is the temperature at which the maximum rate of photosynthesis occurs. Similarly, because enzymes are denatured and no longer functional at particularly high temperatures, photosynthesis ceases at these high temperatures. This is seen in Figure 3.4.15.

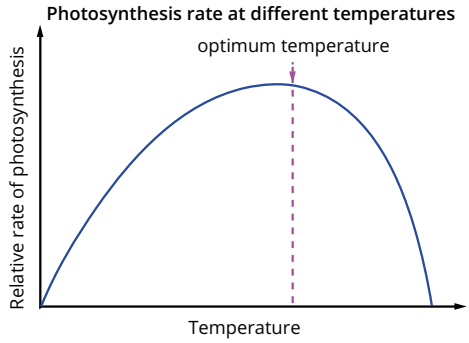


FIGURE 3.4.15 The rate of photosynthesis at different temperatures. The shape of the curve is typical for enzyme reactions. The rate rises with temperature to an optimum temperature and then falls to zero at high temperatures as the photosynthetic enzymes denature.

Photosynthesis in C_4 and CAM plants

Although photosynthesis seems to be an efficient method of fixing atmospheric CO_2 into a three-carbon molecule, there is a reverse system occurring at the same time. Photorespiration is where the RuBP carboxylase enzyme (which catalyses the key carbon-fixing reaction) also initiates the oxidation of ribulose 1,5-bisphosphate. The result is a loss of between one-quarter and one-half of the fixed carbon that can no longer be synthesised in the Calvin cycle. At higher temperatures, the loss is even greater, posing a distinct problem for the C_3 (three-carbon fixing) plant. This has led to the evolution of two different adaptations—those of the C_4 and the CAM plants.

C_4 plants (which include many grasses and crops, such as sugar cane (Figure 3.4.16a) and sorghum) operate differently in two ways—by fixing a four-carbon molecule rather than the three-carbon molecule made in the Calvin cycle, and by using ATP energy to concentrate CO_2 in mesophyll and bundle sheath cells. The CO_2 binds to the active site on the RuBP carboxylase enzyme, effectively commandeering it for photosynthesis.

CAM plants also fix four-carbon molecules but use crassulacean acid metabolism, or CAM. These plants are generally succulents living in hot climates, and include pineapples (Figure 3.4.16b), cacti and orchids. In CAM plants, the leaf stoma open at night, not during the day, and so prevent the excess loss of water, and concentrate CO_2 without the use of extra ATP.

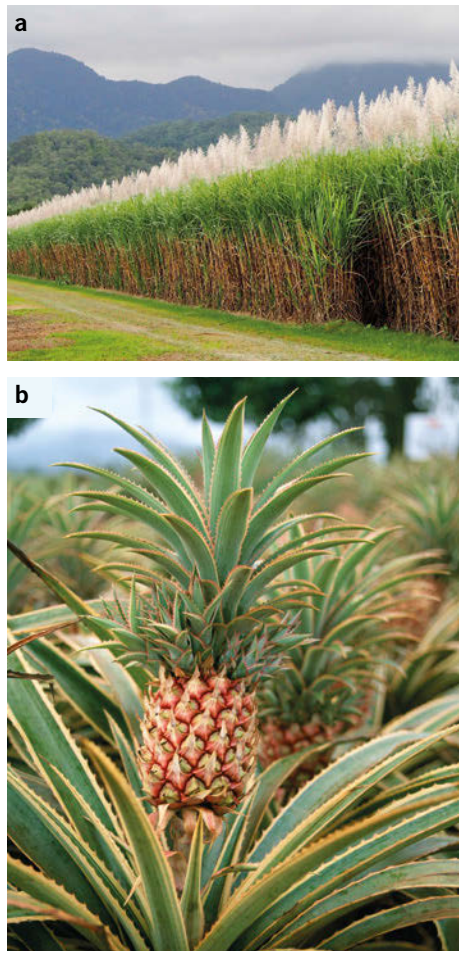


FIGURE 3.4.16 (a) C_4 (sugar cane) and (b) CAM (pineapple) plants are important commercial crops in tropical Queensland.

WS 1.1.2

3.4 Review

SUMMARY

- Photosynthesis is carried out in two stages: the light-dependent reactions and the light-independent reactions.
- Chloroplasts contain thylakoid membranes and fluid called stroma.
- The light-dependent reactions occur on the grana. Light energy is trapped by chlorophyll, water is split and oxygen is released as a product.
- The light-independent reactions occur in the stroma. Carbon dioxide is reduced to form glucose.
- The factors affecting the rate of photosynthesis are interconnected.
- An increase in carbon dioxide levels can increase the rate of photosynthesis.
- An increase in light intensity can increase the rate of photosynthesis.
- The availability of chloroplasts to carry out photosynthesis can limit the rate of reaction.
- Plants have an optimum temperature range for photosynthesis. If it is too cold, the rate of reaction is slow. If is is too hot, the enzymes in chloroplasts can denature.

continued over page

3.4 Review *continued*

KEY QUESTIONS

Retrieval

1 Recall and write the word equation and the chemical equation for photosynthesis.

2 List three things that might happen to the glucose that has been formed by photosynthesis in the plant.

3 Draw a chloroplast. Label the inner and outer membranes, stroma, granum and thylakoid.

4 Describe what chlorophyll is and identify the various types that occur in different photosynthetic organisms.

5 Describe the interactions that carotenoids have with chlorophyll pigments.

6 Name the light-dependent reactions in photosynthesis.

7 Identify the three main products that result from the two photosystems working together.

8 State what molecules need to be present for the light-independent phase of photosynthesis to occur.

9 Identify the carbohydrates produced by the Calvin cycle.

10 Make a table that lists three factors that directly affect the rate of photosynthesis. Briefly describe how each one does so.

Comprehension

11 Summarise the main features in the process of photosynthesis.

12 Using Figure 3.4.4b on page 90, determine the range of wavelengths in which chlorophyll a, b and c will absorb the greatest percentage of light.

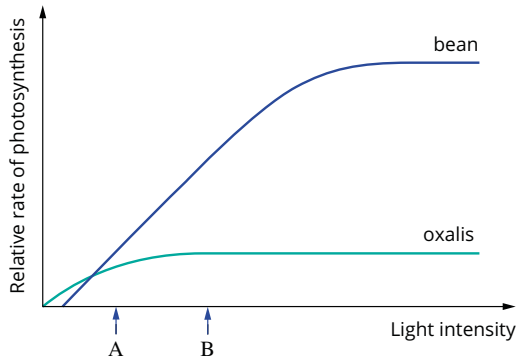
13 Using a diagram, represent the basic processes of photosystems I and II.

14 Describe how water has an indirect effect on photosynthesis and not a direct effect as does the abundance of CO_2, light and temperature.

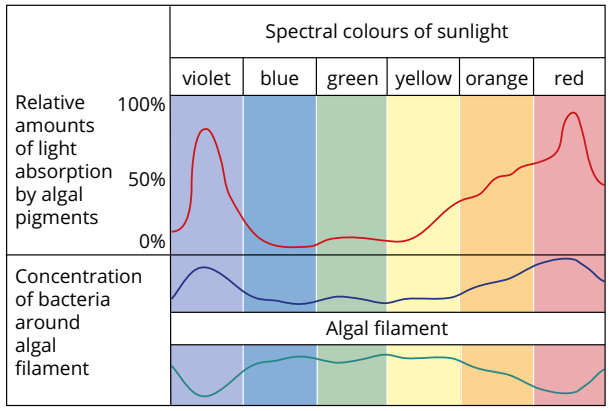
Analysis

15 Differentiate the photosynthetic pathways of C_3, C_4 and CAM plants.

16 The following graph shows the rate of photosynthesis in a bean plant and an oxalis plant.
Draw conclusions with respect to possible limiting factors at points A and B for each plant.



17 In an experiment, photosynthetic algae filaments were placed in a solution that was compartmentalised so that each compartment was exposed to different spectral light colours. Aerobic bacteria were added to the solution and were able to move through all compartments. The following diagram indicates the distribution of these bacteria after 1 hour. Explain why aerobic bacteria were used in this experiment. Draw conclusions as to what the distribution of bacteria implies about the relationship between the spectral light colour and the rate of photosynthesis.



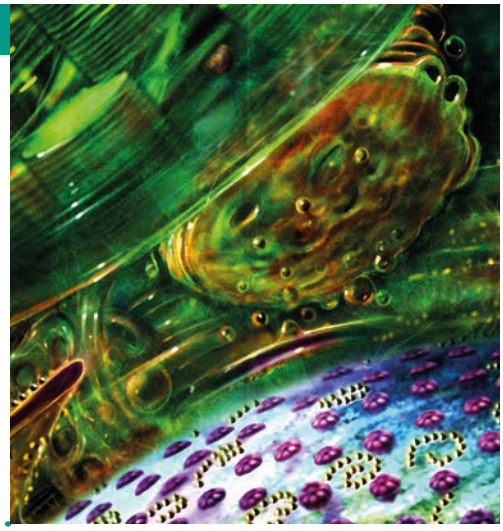
3.5 Cellular respiration

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

- understand that cellular respiration is an enzyme-controlled series of chemical reactions and that the reaction sequence known as aerobic respiration (glycolysis, Krebs cycle and electron transfer chain) requires oxygen
- understand that in conditions where there is a lack of oxygen, ATP is produced from glucose by the reaction sequence known as anaerobic respiration (glycolysis with fermentation in plants, yeasts and some bacteria, or lactic acid production in animals).
- recognise that the overall process can be summarised in a balanced chemical equation:

  glucose + oxygen → carbon dioxide + water + energy

  $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36–38ATP$



All cells need energy to function. They obtain this by releasing energy from organic compounds through a series of biochemical pathways; **glycolysis** is the first of these. Cellular respiration is the name given to the combination of biochemical pathways that together release energy from glucose, the structure of which is shown in Figure 3.5.1.

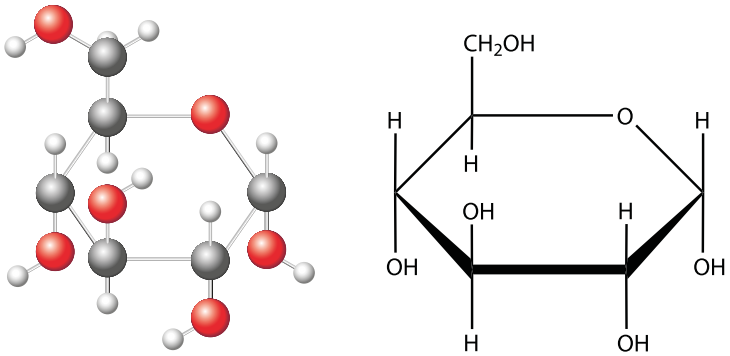


FIGURE 3.5.1 Glucose is the primary energy source for cellular respiration.

ENERGY FROM GLUCOSE

Cells can obtain energy from fats and other organic compounds, including proteins. However, most cells use glucose (which can be obtained by breaking down complex carbohydrates) as their immediate source of energy, as shown in Figure 3.5.2. To extract energy from other organic molecules, some must be converted into glucose first; others are broken down to small molecules that can also be used in the cellular respiration pathways.

Cellular respiration is the name given to the combination of biochemical pathways that occur within a cell to release energy from glucose. Each reaction in the pathway is catalysed (facilitated) by a particular enzyme.

The energy released from glucose through cellular respiration is used to generate the coenzyme adenosine triphosphate (ATP). The energy is transferred when ATP is formed from ADP and inorganic phosphate (P_i), and it is stored in the bond between ADP and phosphate. This can be represented as:

$$ADP + P \rightarrow ADP{\sim}P_i \text{ (ATP)}$$

The '~' represents the high-energy bond in which the energy is stored.

FIGURE 3.5.2 Complex carbohydrates are broken down by the digestive system into simple sugars, such as glucose.

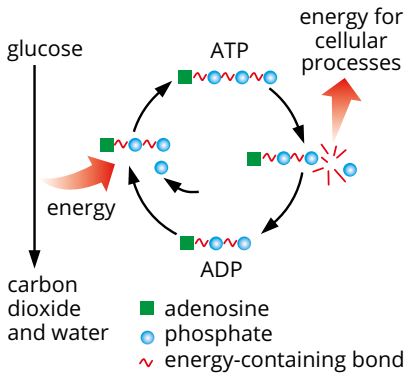


FIGURE 3.5.3 Energy from glucose is transferred in the synthesis of ATP from ADP and phosphate. The energy is stored in the phosphate bond. When the bond is broken, the energy is released to drive cellular processes. The ADP and phosphate are recycled.

When the high-energy bond in ATP is broken, energy is released for use in the many energy-demanding processes that occur in the cell. The transfer of energy is summarised in Figure 3.5.3.

Aerobic cellular respiration requires oxygen and consists of the three interconnected biochemical pathways known as:

- glycolysis
- the **Krebs cycle** (or the citric acid cycle)
- the **electron transfer chain** (or electron transport chain).

Anaerobic cellular respiration also involves glycolysis. In plant and yeast cells, the product of glycolysis undergoes a **fermentation** pathway in the absence of oxygen.

GLYCOLYSIS

Glycolysis is the first stage of cellular respiration and occurs in the cytosol of the cell. It results in the net production of two ATP molecules. During glycolysis, glucose (a six-carbon molecule) is broken down to two three-carbon molecules called **pyruvate** (or pyruvic acid).

During the process of glycolysis, a small amount of energy is released. This energy is transferred to the coenzymes ATP and **NADH**, which act as energy carriers. The overall reaction of glycolysis is:

reactants → products

$$\text{glucose} + 2\text{ADP} + 2\text{P}_i + 2\text{NAD}^+ \rightarrow 2\ \text{pyruvate} + 2\text{ATP} + 2\text{NADH}$$

NADH and $FADH_2$

Two very important coenzymes are NAD^+ and FAD (flavin adenine dinucleotide). NAD^+ acts as an energy carrier. There are various steps in cellular respiration in which energy is transferred in the making of NADH from NAD^+. During the final stage of aerobic cellular respiration (the electron transfer chain), NADH is converted back to NAD^+ and the energy released is used in the formation of ATP.

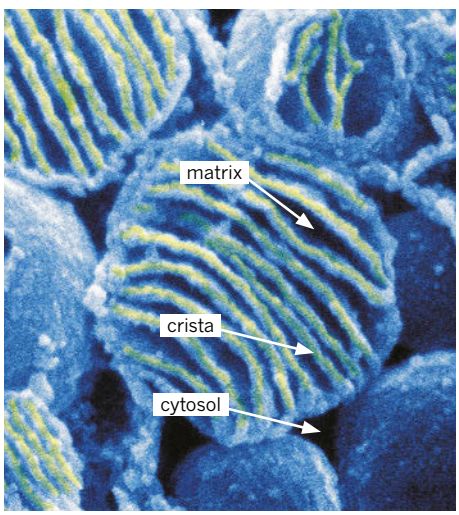


FIGURE 3.5.4 The first stage of aerobic cellular respiration (glycolysis) occurs in the cytosol. The second stage (the Krebs cycle) occurs in the matrix of the mitochondria. The last stage (the electron transfer chain) occurs on the cristae of the mitochondria.

FAD is also an energy carrier. During the second stage of aerobic cellular respiration (the Krebs cycle), energy is transferred, making **$FADH_2$** from FAD. During the electron transfer chain, $FADH_2$ is converted back to FAD and the energy released is used in the formation of ATP.

Aerobic and anaerobic respiration pathways

After glycolysis, cellular respiration can be diverted into one of two biochemical pathways depending on the availability of oxygen. These are **aerobic respiration** and **anaerobic respiration**, and here you will learn some of the details of the biochemical reactions involved, where these processes occur and the different amounts of energy released in each pathway.

AEROBIC RESPIRATION

If oxygen is available, most eukaryotic organisms use it to release energy from glucose in the process of aerobic respiration. Aerobic respiration comprises three stages: glycolysis, the Krebs cycle and the electron transfer chain, as shown in Figures 3.5.4 and 3.5.5. The latter two stages occur in the mitochondria and require oxygen. Glycolysis occurs in the cytoplasm and breaks down glucose molecules regardless if oxygen is present or not. The balanced chemical equation for aerobic cellular respiration is shown below:

$$\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} \qquad (36–38\text{ATP produced})$$

Mitochondria

Mitochondria are often referred to as the powerhouses of the cell. They are the sites of the Krebs cycle and the electron transfer chain—two of the three processes that comprise aerobic respiration. If the cell has a supply of oxygen, the pyruvate formed from glycolysis passes into the mitochondria, where it is further broken down through a series of biochemical steps into carbon dioxide and water.

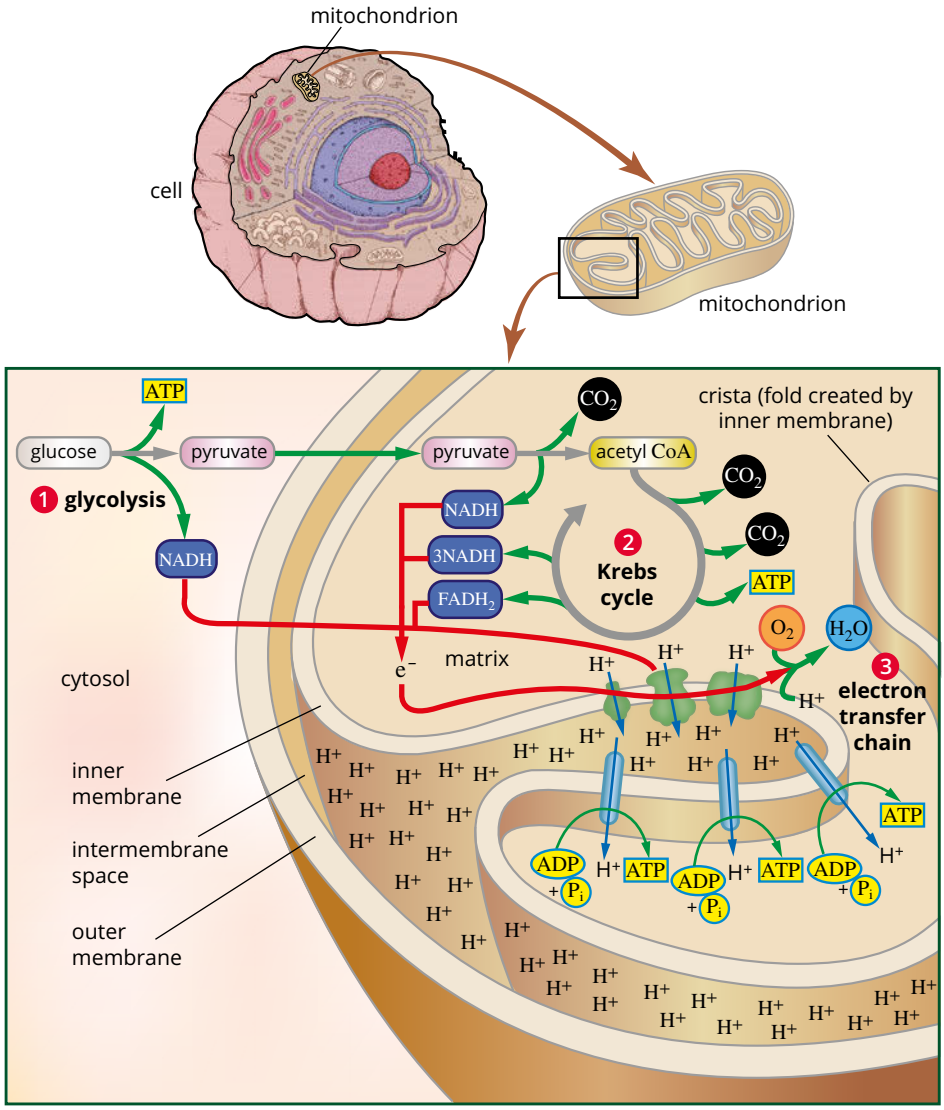


FIGURE 3.5.5 A summary of aerobic cellular respiration

Mitochondria are slightly smaller than chloroplasts. Inside the outer membrane, there is a folded inner membrane structure. The folded structures of the inner membrane are called cristae. Inside the cristae is the mitochondrial matrix, as shown in Figure 3.5.6.

The more intricately folded a membrane, the greater the surface area it has available for enzyme attachment. This is of great importance as you will see in the next two stages of aerobic respiration—the Krebs cycle and the electron transfer chain, both of which occur in the mitochondria.

KREBS CYCLE

The second important stage of aerobic respiration occurs after glycolysis and is called the Krebs cycle. It takes place in the mitochondrial matrix. The Krebs cycle is a series of eight reactions, each catalysed by a different enzyme. The pyruvate formed from glycolysis diffuses from the cytoplasm through the outer membrane of the mitochondria and is then moved by active transport through the inner membrane. Moving pyruvate into the mitochondria uses the ATP generated by glycolysis.

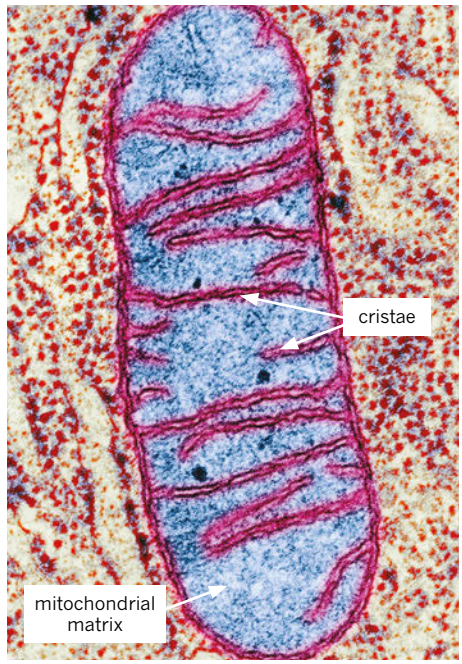


FIGURE 3.5.6 This coloured transmission electron micrograph of a mitochondrion shows the inner membrane (cristae) in pink and the matrix fluid in blue

When the pyruvate, a three-carbon molecule, is in the mitochondrial matrix, it is converted into acetyl coenzyme A (acetyl CoA), a two-carbon molecule, which is the substrate for the first of a series of reactions that make up the Krebs cycle. In the formation of acetyl CoA from pyruvate, one carbon dioxide molecule is formed. In addition, in one turn of the Krebs cycle two carbon dioxide molecules are formed. That is a total of three molecules of carbon dioxide formed for every pyruvate molecule and six molecules of carbon dioxide for every glucose molecule metabolised.

During the reactions of the Krebs cycle, energy is transferred to energy-carrying coenzymes such as NADH, $FADH_2$ and ATP. FAD can carry two hydrogen ions, becoming $FADH_2$. NAD^+ can carry one hydrogen ion, becoming NADH. From each turn of the Krebs cycle, one molecule of acetyl CoA is metabolised into two molecules of carbon dioxide, three molecules of NADH, one molecule of $FADH_2$ and one molecule of ATP. This is shown in Figure 3.5.7.

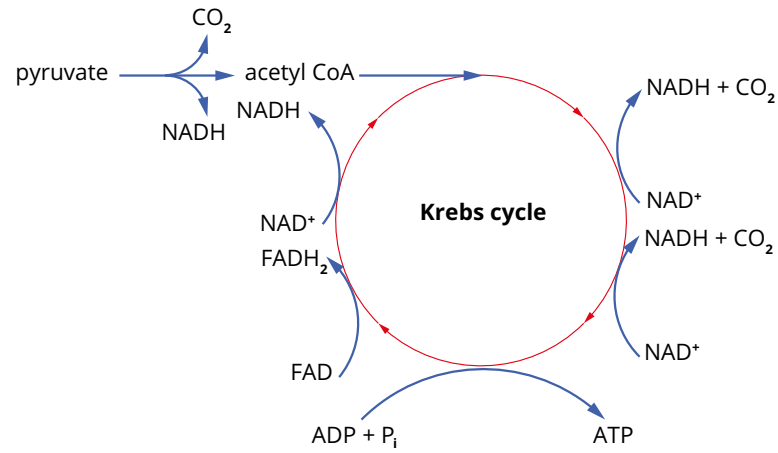


FIGURE 3.5.7 The three-carbon molecule pyruvate produced in glycolysis is converted to a two-carbon molecule acetyl CoA with the production of a carbon dioxide molecule. The acetyl CoA enters the Krebs cycle where it results in carbon dioxide, ATP, NADH and $FADH_2$ being formed.

ELECTRON TRANSFER CHAIN

The overall purpose of the electron transfer chain is to move protons and electrons across a membrane as a system for generating ATP. Oxygen is essential because it picks up electrons at the end of the chain. If oxygen is not available, the electron transfer chain stops.

Embedded in the inner membrane of the mitochondria are a number of protein complexes, including enzymes and cytochromes, as shown in Figure 3.5.8. These complexes form an interconnected series of reactions that together make up the electron transfer chain, which is the third stage of aerobic cellular respiration.

Energy-carrying molecules from the Krebs cycle feed into the electron transfer chain. NADH is converted back to NAD^+ by interacting with the first complex at the beginning of the electron transfer chain, and $FADH_2$ is converted back to FAD by interacting with the second complex.

The hydrogen ions (H^+) originating from the conversion of NADH and $FADH_2$ are moved into the intermembrane space of the mitochondria and the electrons are transferred along the chain. The energy obtained in this process is used to make ATP from ADP. At the end of the electron transfer chain, hydrogen ions and electrons combine with oxygen to form water:

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$$

The electron transfer chain forms 26–28 molecules of ATP, using the energy that was contained originally in each glucose molecule.

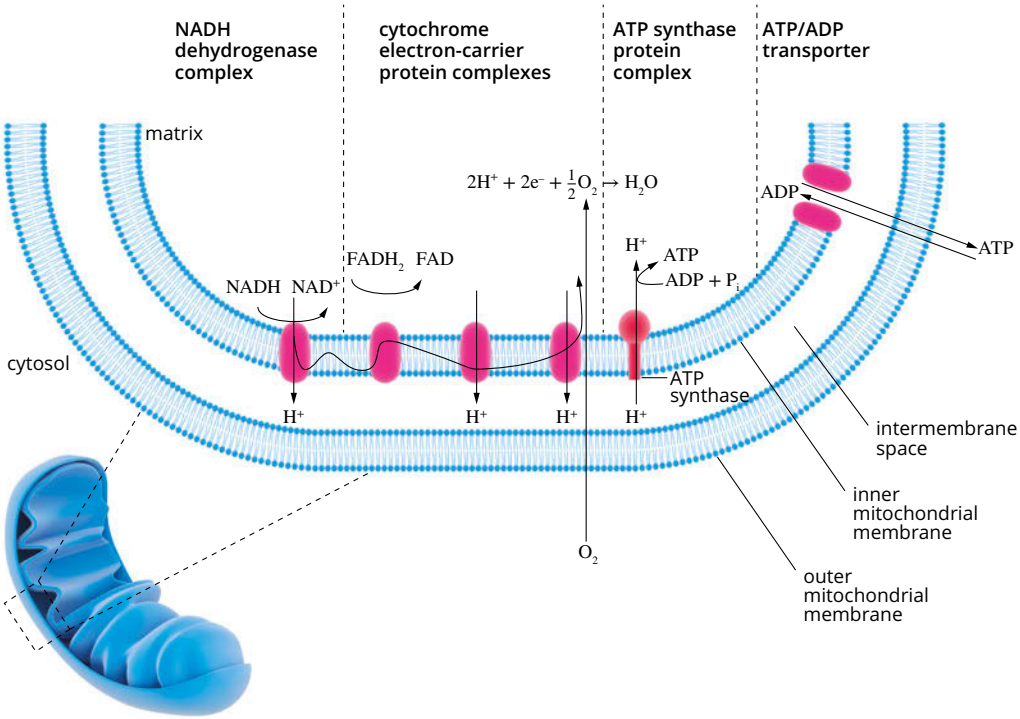


FIGURE 3.5.8 The inner mitochondrial membrane has several embedded proteins that pass along the energy and H^+ ions from carriers (NADH and $FADH_2$). The final enzyme in the pathway, ATP synthase, generates large amounts of ATP.

ATP yield in aerobic cellular respiration

If you add up the ATP molecules formed at each stage of aerobic cellular respiration, you find that for every molecule of glucose metabolised, 30–38 ATP molecules can be formed:

- 2 ATP from glycolysis
- 2 ATP from the Krebs cycle
- 26–28 ATP from the electron transfer chain.

Many sources state that 36–38 molecules of ATP are formed from the complete breakdown of one glucose molecule via aerobic cellular respiration, but it is now estimated that the overall production is closer to 30–32 ATP in the average cell. The revised estimate takes into account losses that may occur throughout the process, as well as the effect of moving substances into and around the mitochondrial matrix. This is another example of how our scientific knowledge is continually developing.

Aerobic cellular respiration is a very complex process and scientists are still making new discoveries. Recent research shows that $FADH_2$ is not as efficient as first thought and generates less ATP than previously stated. In conjunction with this, the energy used during the final stages of aerobic cellular respiration is also higher than originally estimated. Because of the internal structure of mitochondria, more energy is required to convert and move substances within the mitochondrial membranes and matrix, reducing the overall yield of ATP. In this research, the results suggest that the electron transfer chain produces 26–28 ATP per glucose molecule.

Some tissues and cells are more efficient than others, so scientists have varying results in their research. There is research to suggest that some cells can make 38 ATP from one glucose molecule. The number is usually quoted as a range (30–38 ATP), because the exact number depends on a range of conditions that can differ.

ANAEROBIC RESPIRATION

If there is little or no oxygen available, a eukaryotic organism can still release some energy from glucose through the anaerobic pathway known as fermentation. In animals, lactic acid fermentation is the name of the process that most often occurs in the cytoplasm of cells after glycolysis when oxygen is in short supply. In yeast and plants, a different type of fermentation occurs—ethanol fermentation. Figure 3.5.9 shows the products of these two types of anaerobic respiration.

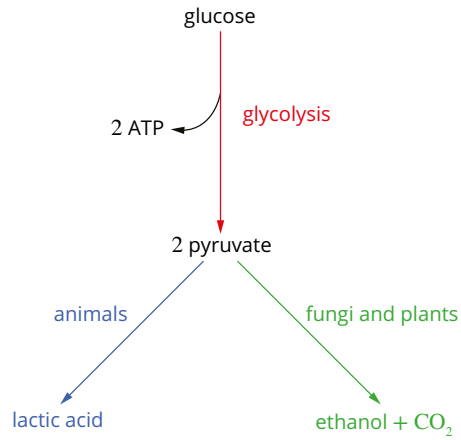


FIGURE 3.5.9 Anaerobic respiration occurs in the cytosol of cells when oxygen is not available.

Fermentation

When the product of a biochemical reaction increases in concentration, it usually slows down the reaction that produces it, causing the reactants to accumulate. For a biochemical pathway to continue, the products of each reaction must be processed by the next reaction in the chain. If the product is not removed, it slows down the reaction, which causes the reaction before it to be slowed down and so on, back through the pathway so that the whole pathway is slowed down or even stopped. Think of it like people moving in a queue. If the person at the head of the queue stops moving, the person behind must stop and so on back through the queue, until the whole queue stops moving.

The final reaction in the electron transfer chain requires oxygen. Lack of oxygen limits the rate of this final reaction, which in turn limits the reaction before it, and so on back through the pathways. NADH will not be converted back to NAD^+. The Krebs cycle will also be slowed down. When the Krebs cycle slows down, pyruvate begins to accumulate. An accumulation of pyruvate then causes glycolysis to slow down.

In addition, for glycolysis to occur, a constant supply of NAD^+ is required. If the NAD^+ is not being regenerated, glycolysis slows down or even stops.

To allow glycolysis to continue at low oxygen levels, some protists, fungi and some animal cells, such as muscle cells, contain an enzyme that can catalyse the conversion of pyruvate to lactic acid and NADH to NAD^+. This reaction solves both problems and enables glycolysis to continue. It first removes pyruvate so that the pathway is no longer blocked and then it provides a source of NAD^+, which is essential for glycolysis.

The lactic acid produced through fermentation can leave the cell by diffusion across the cell membrane and via a special membrane transport protein. This means the lactate level in the cell can remain low so that the pyruvate to lactate reaction can continue to occur, glycolysis can occur and ATP can continue to be produced to satisfy the cell's needs.

In humans, lactic acid produced by muscle cells, once diffused out, can be circulated in the blood to other tissues in the body including liver and heart muscle, where it is converted back to pyruvate and enters aerobic cellular respiration pathways to produce ATP. This process is shown in Figure 3.5.10.

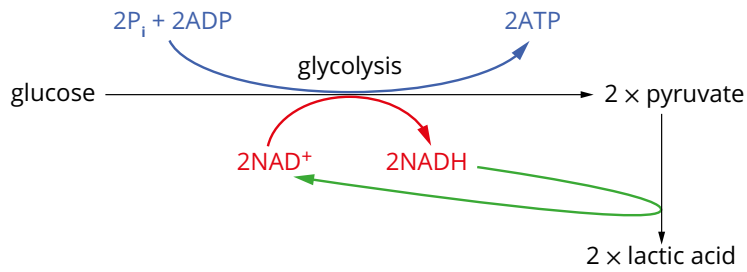


FIGURE 3.5.10 In animals, pyruvate is converted into lactic acid during anaerobic respiration to prevent a build-up of pyruvate. Later, the lactic acid can be converted back into pyruvate for aerobic cellular respiration.

Fermentation in yeast

Yeast cells, like those shown in Figure 3.5.11, carry out a different type of fermentation called ethanol fermentation (Figure 3.5.12). As in animal cells, one glucose molecule is broken down to two pyruvate molecules and NADH is formed from NAD^+. In yeast fermentation, the pyruvate is then broken down to ethanol (alcohol) and carbon dioxide, and NADH is converted back to NAD^+ through two reactions. In the first step, pyruvate is broken down to acetaldehyde and carbon dioxide. In the second step, the acetaldehyde is broken down to ethanol and NADH is converted to NAD^+.

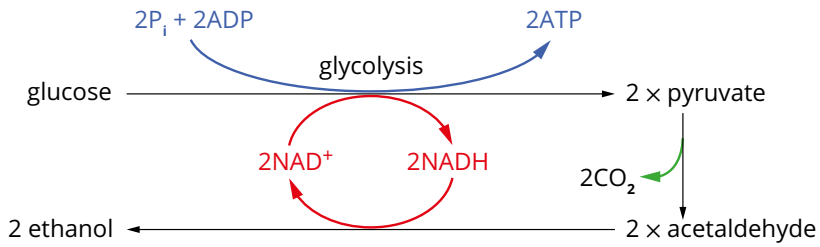


FIGURE 3.5.12 In yeast, pyruvate is converted into ethanol and carbon dioxide during anaerobic respiration.

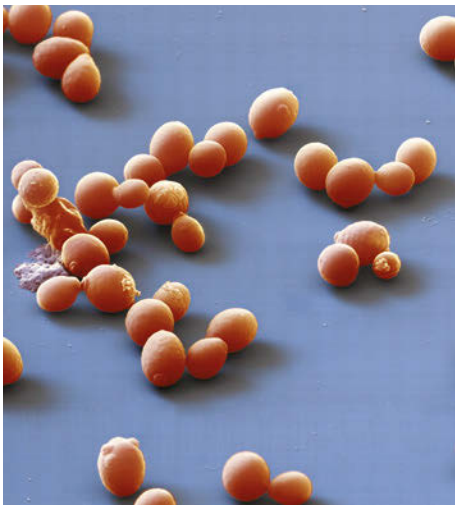


FIGURE 3.5.11 A coloured scanning electron micrograph of baker's yeast (*Saccharomyces cerevisiae*) cells

The ethanol readily diffuses out of the cell by passive diffusion into the surrounding environment. The loss of ethanol from the cytoplasm means that the reactions of fermentation can continue until the ethanol builds up to a level in the external environment where ethanol no longer diffuses from the cell; that is, there is no longer a concentration gradient. Ethanol then builds up in the cell to a point at which the fermentation reactions are blocked and they stop.

COMPARING AEROBIC AND ANAEROBIC RESPIRATION

Anaerobic respiration pathways in eukaryotes produce only two ATP molecules per molecule of glucose during glycolysis, whereas aerobic respiration produces 30–38 ATP molecules per molecule of glucose during glycolysis, the Krebs cycle and the electron transfer chain. Therefore, aerobic respiration is much more efficient in supplying the cell with energy. The organic products of anaerobic respiration (lactic acid from animals and alcohol from yeast) still contain much energy and both can be further metabolised to release more energy. Figure 3.5.13 and Table 3.5.1 compare the processes of aerobic and anaerobic cellular respiration.

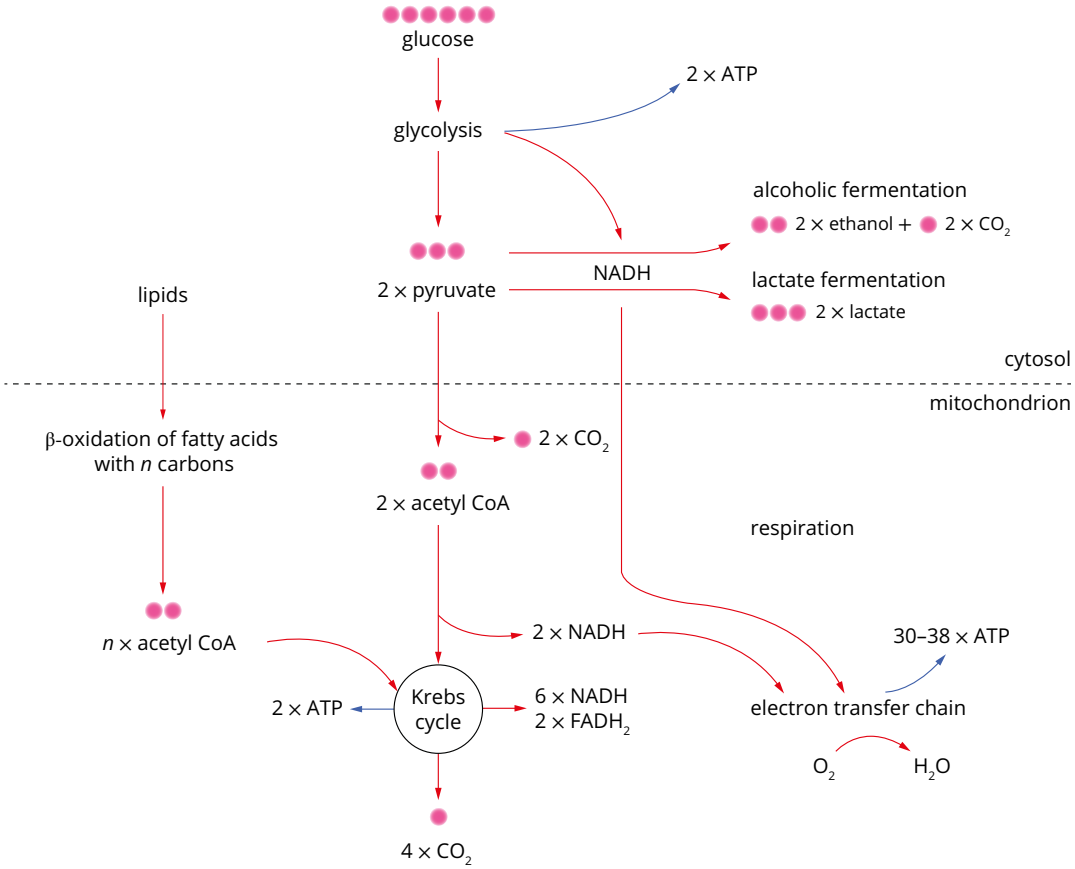


FIGURE 3.5.13 An overview of the stages of aerobic and anaerobic cellular respiration

FIGURE 3.5.14 Rebecca Clarke of New Zealand shows the exhaustion of completing a triathlon at the World Championship in Stockholm. During the race her glucose and oxygen levels would have been depleted. Her body would have worked hard to stop her body temperature from rising.

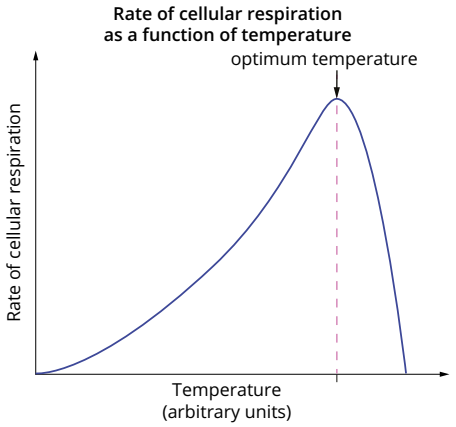


FIGURE 3.5.15 The relationship between temperature and the rate of cellular respiration. As the temperature increases towards the optimum range, the rate of cellular respiration speeds up. At the optimum temperature, cellular respiration occurs at the maximum rate. At temperatures above the optimum temperature, the rate of cellular respiration rapidly decreases.

TABLE 3.5.1 Summary of cellular respiration

	Aerobic	Anaerobic
location	cytosol and mitochondria	cytosol
reactants	glucose and oxygen	glucose
products	carbon dioxide and water	lactic acid (animals) ethanol and CO_2 (plants/fungi)
energy output (per glucose molecule)	30–38 ATP total	2 ATP total

FACTORS AFFECTING THE RATE OF CELLULAR RESPIRATION

Cellular respiration is affected by a number of factors including temperature, glucose availability and oxygen concentration (Figure 3.5.14).

Temperature

You have learnt that cellular respiration comprises a number of interconnected biochemical pathways and that each pathway is a series of chemical reactions catalysed by specific enzymes.You have also learnt that the rate of an enzyme reaction is affected by temperature and that each enzyme has an optimum temperature.

As the temperature either rises above or falls below the optimum temperature, the rate of the enzyme-controlled reactions occur, and therefore the rate at which cellular respiration occurs, slows down. The graph in Figure 3.5.15 shows the relationship between temperature and the rate of cellular respiration.

- When the temperature drops, the reactant molecules contain less kinetic energy and so do not react as quickly.
- When the temperature rises above the optimum level, the increased heat energy can disrupt the hydrogen bonds in the enzyme, causing the enzyme to denature. This means that the active site of the enzyme has lost its three-dimensional functional shape. This distortion in the shape means that the enzyme cannot bind to the substrate, effectively slowing down the rate of reaction.

Living organisms have particular temperature tolerance limits within which they will survive. More complex organisms such as birds and mammals control their body temperature at levels that are optimal for the functioning of their enzymes. Other organisms do not have the capacity to control the temperature of their cells, and the cellular respiration for these organisms is affected by the temperature of the external environment.

Glucose availability

All chemical reactions are limited by the concentration of the reactants. An enzyme's reaction is limited by the availability of its substrate(s). Glucose is the substrate for glycolysis, and therefore it is the substrate for the first reaction in cellular respiration. The availability of glucose affects the rate at which this first reaction occurs. The products of the first reaction become the substrates for the next and so on along the pathway. Hence, the availability of glucose affects the first and subsequent reactions in the cellular respiration biochemical pathways.

Oxygen concentration

For aerobic respiration, a constant supply of oxygen is necessary. Oxygen is supplied to cells by haemoglobin as shown in Figure 3.5.16. Oxygen is the final reactant of the electron transfer chain, so oxygen concentration affects the rate of aerobic cellular respiration.

When the concentration of oxygen is low, the rate at which the electron transfer chain can occur is reduced. As you learnt previously, when oxygen is in very short supply or absent, some cells use fermentation reactions so that pyruvate does not accumulate and the glycolysis reactions can continue. This means ATP continues to be produced, although at much lower rates, and the cell stays alive.

SUMMARY OF CELLULAR ENERGY TRANSFORMATIONS

Table 3.5.2 summarises cellular energy transformations.

TABLE 3.5.2 Summary of cellular energy transformations

	Photosynthesis	Cellular respiration	
		Aerobic	Anaerobic
location	chloroplasts	cytosol and mitochondria	cytosol
reactants	water and carbon dioxide	glucose and oxygen	glucose
products	glucose, oxygen and water	water and carbon dioxide	• lactic acid (animals) • ethanol and carbon dioxide (plants/fungi)
carriers	$NADP^+$	NAD^+ and FAD	NAD^+

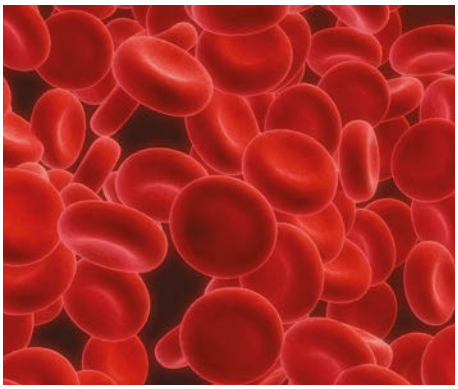


FIGURE 3.5.16 Red blood cells contain a red pigment (haemoglobin), which binds to oxygen. As blood moves through the capillaries in the lungs, the haemoglobin collects oxygen. As blood is pumped around the body, the red blood cells deliver oxygen to the cells in all of our tissues.

WS 1.1.8 PA 1.1.2

3.5 Review

SUMMARY

- Glucose is the primary energy source for cellular respiration.
- The energy released in the breakdown of glucose is carried by ATP.
- Two ATP molecules (per glucose molecule) are produced during glycolysis, which is the first stage of cellular respiration.
- Aerobic cellular respiration has three stages: glycolysis, the Krebs (citric acid) cycle and the electron transfer chain.
- The overall process of aerobic glycolysis produces 36–38 ATP per glucose molecule.
- Mitochondria contain folded membranes (cristae) and fluid (matrix).
- Glycolysis occurs in the cytosol and yields two ATP. Glucose is converted into two pyruvate molecules.
- The Krebs cycle occurs in the matrix of the mitochondria and yields two ATP. Pyruvate is broken down into carbon dioxide.
- The electron transfer chain occurs in the cristae of the mitochondria and yields 26–28 ATP. Oxygen accepts the hydrogen ions that are used to generate a large amount of energy.
- In animals, the product of anaerobic respiration is lactic acid. In yeast, the products of anaerobic respiration are ethanol and carbon dioxide.
- Aerobic respiration is more efficient than anaerobic respiration. Aerobic respiration produces 30–38 ATP per glucose molecule; anaerobic respiration only yields two ATP per glucose molecule.
- Aerobic cellular respiration is affected by temperature, glucose concentration and oxygen concentration.
- When the temperature is above or below the optimum range, the rate of cellular respiration is slower.
- Glucose is a substrate of glycolysis; therefore, an increase in glucose availability increases the rate of cellular respiration.
- Oxygen is a substrate of the electron transfer chain; therefore, an increase in oxygen concentration increases the rate of aerobic cellular respiration.

continued over page

3.5 Review *continued*

KEY QUESTIONS

Retrieval

1 List three types of organic compounds that can be used as a source of energy for cellular respiration.

2 Recall and write the word equation and the balanced chemical equation for the overall reaction of cellular aerobic respiration.

3 Identify what the molecule adenosine triphosphate is formed from.

4 Describe what happens when an inorganic phosphate group (P_i) is broken off from a molecule of ATP.

5 Recall whether or not the glycolysis stage of cellular respiration occurs regardless of the presence or absence of oxygen.

6 Identify the reactants and products of glycolysis.

7 Describe the roles of the two coenzymes NAD^+ and FAD.

8 Identify the main differences between aerobic and anaerobic respiration.

9 Describe the efficiency of aerobic and anaerobic respiration.

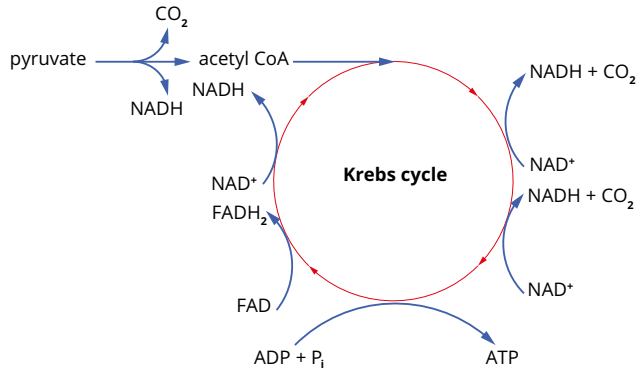
10 Complete the following table about the different energy releasing processes within cells.

Process	Location in cell	Products formed (per glucose molecule)	No. of ATP molecules produced (per glucose molecule)
glycolysis			
Krebs cycle			
electron transfer			
fermentation			

Comprehension

11 Explain the advantage to a cell of converting pyruvate to lactic acid or ethanol when this yields no extra ATP.

12 The following diagram shows the chemical changes that occur during the Krebs cycle for one molecule of pyruvate.



Use the information in the diagram and your understanding of cellular respiration to answer the following questions.

a Recall how many molecules of ATP are formed in the Krebs cycle from one molecule of glucose.

b Recall how many H^+ ions are loaded onto carriers during one turn of the Krebs cycle.

c i Recall how many molecules of CO_2 are produced during one turn of the Krebs cycle.

ii Describe the stage that produces the remainder of the CO_2.

d Explain why the electron transfer chain cannot occur without the Krebs cycle.

13 Mitochondria were extracted from some cells and isolated from the other cell contents. The mitochondria were suspended in a nutrient solution containing pyruvate in order to investigate respiration.

a Recall the stages of respiration that would be occurring in the mitochondria.

b Explain why the nutrient solution contained pyruvate rather than glucose.

c Describe how the concentrations of carbon dioxide and oxygen would change throughout the experiment, assuming that the mitochondria were in a sealed container.

Analysis

14 Compare lactic acid and ethanol fermentation.

15 The enzyme cytochrome c oxidase is found embedded in the cristae of mitochondria. It is the last enzyme involved in the electron transfer chain. It transfers electrons to oxygen and also binds protons (H^+) to oxygen to form water.

a State the significance of the electron transfer chain to living cells.

b Sodium azide is a pesticide that binds irreversibly to cytochrome c oxidase. Deduce why this results in the death of the pests.

c An experiment was performed on human skin cells that were grown in culture. The cells were separated into three test-tubes. The first test-tube contained whole cells, the second test-tube contained only the mitochondria that had been separated from the cells, and the third test-tube contained the residue from the cells in the second test-tube.

Samples from each of the test-tubes were grown in the following solutions:

A glucose + sodium azide
B pyruvate + sodium azide
C glucose alone
D pyruvate alone

The test-tubes were supplied with oxygen. All other variables were kept the same. After 30 minutes, the test-tubes were tested for the presence of CO_2 and lactic acid. The results are shown in the following table.

	A Glucose + sodium azide	**B Pyruvate + sodium azide**	**C Glucose only**	**D Pyruvate only**
whole cells	lactic acid	lactic acid	lactic acid, CO_2	lactic acid, CO_2
mitochondria	neither	neither	neither	CO_2
cell residue without mitochondria	lactic acid	neither	lactic acid	neither

i Determine the control(s) in this experiment.

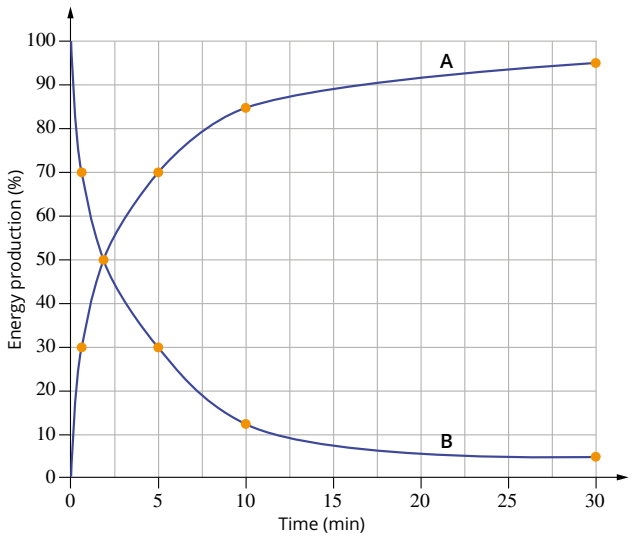
ii Conclude why CO_2 was produced in the 'pyruvate only' tube but not in the 'glucose only' tube, of the tubes that contained only mitochondria.

iii The experiment could not be extended beyond 30 minutes because after that time the whole cells in solution B died. The whole cells in solution A continued to live for some time. Determine why the cells with pyruvate + sodium azide died but those with glucose + sodium azide did not.

iv Assess whether the results of this experiment support the contention that sodium azide disrupts the electron transfer chain.

v Predict how the results would have differed if plant cells had been used for the experiment.

16 The graph shows the contributions of the two energy-producing pathways to physical activity.



a Athletes competing in sports requiring short-term power output, such as sprinting, obtain most of their ATP from the anaerobic pathway, but athletes requiring sustained energy use aerobic respiration to meet most of their energy needs.

i Interpret which graph (A or B) is most likely to represent ATP production by a sprinter.

ii Determine why anaerobic respiration cannot supply the energy needs of athletes in events requiring energy over a sustained period of time.

b Animals make lactic acid during anaerobic respiration but yeasts and plants produce ethanol and CO_2. Infer why the products are different in animals and plants.

Chapter review

WS 1.1.9 WS 1.1.10 SAT IA1

03

KEY TERMS

activation energy
active site
adenosine triphosphate (ATP)
aerobic respiration
amino acid
anaerobic respiration
autotroph
carbohydrate
catalyst
cellular respiration
chemoautotroph
coenzyme
cofactor
competitive inhibition
denature (or denaturation)
electron transfer chain
enzyme
enzyme–substrate complex
$FADH_2$
fermentation
glycolysis
heterotroph
Krebs cycle
lipid
NADH
photosynthesis
protein
pyruvate
ribozyme
stomata
substrate

KEY QUESTIONS

Retrieval

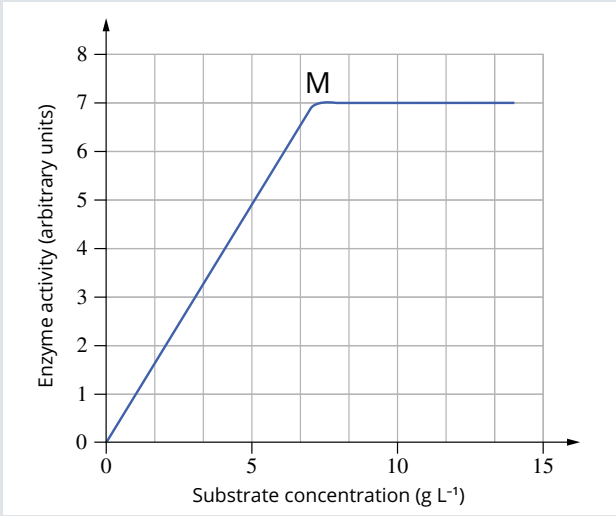
1 Identify which of the following lists represents key organic compounds in cells.
- **A** carbohydrates, water, proteins lipids
- **B** water, carbon dioxide, oxygen, enzymes
- **C** carbohydrates, proteins, lipids, nucleic acids
- **D** carbohydrates, proteins, lipids, minerals

2 Identify which of the following is not made of monomers and does not form a polymer.
- **A** carbohydrate
- **B** lipid
- **C** nucleic acid
- **D** protein

3 An organic molecule required by an enzyme, in order for it to function, is best described as:
- **A** a cofactor
- **B** a coenzyme
- **C** a chemical group
- **D** an enzyme activator

4 Recall that enzymes reduce the activation energy of a reaction by:
- **A** bringing the reactants close together so that a reaction is more likely to occur
- **B** orientating the reactants in the most favourable position for the reaction
- **C** providing a micro-environment favourable to the chemical reaction
- **D** all of the above

5 A student investigating the activity of the enzyme pepsin, which is found in the stomach of humans, observed the change in enzyme activity as the concentration of the substrate (protein) increased. The experiment was conducted at pH 3 and 37°C. The student's data was presented in the graph shown.



The student wanted to change the experiment so that the rate of reaction at point M was higher than that shown. In order to do this the student could:
- **A** increase the pH to 8
- **B** decrease the temperature
- **C** increase the amount of enzyme
- **D** increase the concentration of the substrate

6 Identify which of the statements about NAD^+ is not true.

A NAD^+ can accept a hydrogen ion.

B When NADH gives up a proton, NAD^+ results.

C Only a small amount of NAD^+ is needed in a cell.

D NAD^+ can only be used once before it must be resynthesised.

7 Recall the difference between autotrophs and heterotrophs.

8 Describe the difference between photosynthetic autotrophs and chemosynthetic autotrophs.

9 Chemoautotrophs acquire energy from inorganic chemical reactions.

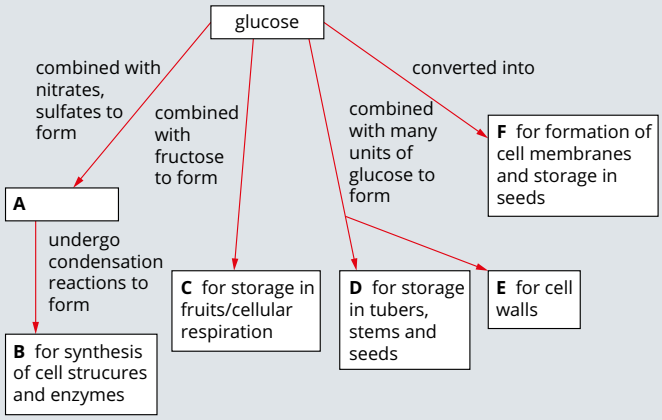
a Recall one chemical conversion used by a chemoautotroph.

b Recall one chemoautotroph and the organic compound it produces.

10 Recall what molecule is broken down by solar energy during photosynthesis.

11 The diagram is a summary of the major processes that occur during photosynthesis.

Identify the correct term for each of letters A–F.



12 Identify whether each of the following statements is true or false.

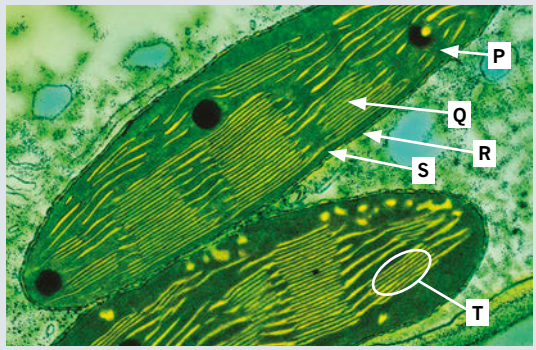
a Chlorophyll is a pigment that causes green colouring of leaves.

b Chloroplasts are pigments that absorb light.

c Chlorophyll is located in the thylakoid membranes.

d Chlorophyll absorbs light energy, which is then transformed into chemical energy.

13 The figure below shows a transmission electron micrograph of a chloroplast. Identify structures P–T.



14 Briefly describe what happens to pyruvate in the two processes that can occur after glycolysis when oxygen is:

a present

b absent

15 Determine the approximate efficiency of anaerobic respiration compared to aerobic respiration in the release of energy from one glucose molecule.

16 The following expressions can be used to write a word equation for photosynthesis and cellular respiration.

P carbon dioxide and water

Q carbon dioxide, water and energy

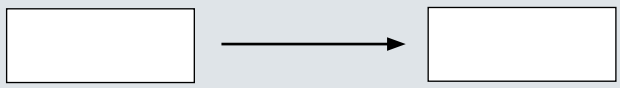
R solar energy and chlorophyll

S glucose and oxygen

Select from the expressions P–S to complete the word equations for photosynthesis and cellular aerobic respiration.

a Word equation for photosynthesis:

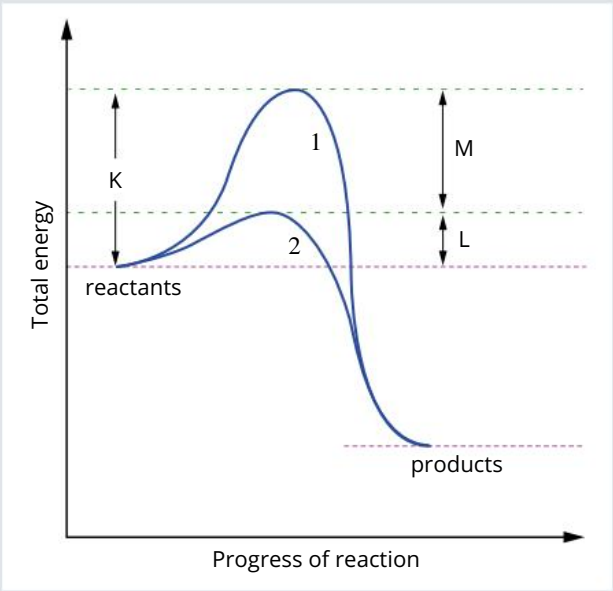
b Word equation for cellular respiration:



17 Explain why photosynthesis is not the opposite of aerobic respiration.

Comprehension

18 The breaking or formation of bonds between atoms during biochemical reactions results in changes in the energy content of the molecules. Formation of new chemical bonds requires energy and the breaking of chemical bonds releases energy. The graph shows the energy changes during one particular chemical reaction with and without an enzyme.

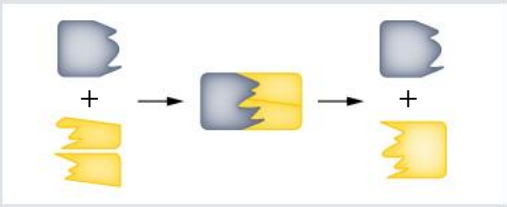


a Describe the energy change that is represented by:
- **i** K
- **ii** L
- **iii** M

b Determine if the overall reaction is exergonic (releases energy) or endergonic (requires energy).

c Explain which line shows the enzyme-catalysed reaction.

19 The following diagram illustrates one model of enzyme activity.



a Explain which model of enzyme activity is shown in this diagram.

b The structures of both substrates in the diagram have changed slightly. Explain why this would, or would not, be an indication that the enzyme could act on a range of substrates.

20 Many chemical reactions in living things occur as part of a metabolic pathway. Metabolic pathways involve a series of reactions with a different enzyme catalysing each step in the pathway. In these pathways, the product of one reaction is the substrate for the next reaction. The following diagram shows the enzymes involved in one such pathway.

The enzyme substrates are shown below.

a **i** Match each substrate with its enzyme.
ii Explain the basis of your decision.

b The following molecule is the final product of the reaction.

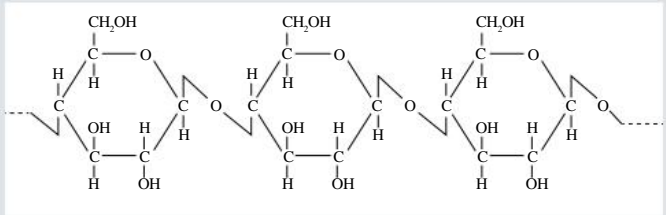
- **i** If the concentration of the final product builds up in the cell, the reaction stops. Explain how the increase in the concentration of the final product stops the reaction proceeding.
- **ii** Determine whether the product is acting as a competitive inhibitor. Explain your answer.

21 Draw up a table summarising and comparing:

a photosynthetic autotrophs, chemosynthetic autotrophs and heterotrophs.

b photosynthesis and cellular respiration.

22 Cellulose is a complex carbohydrate that is made up of many individual units of glucose. The molecule shown below, composed of carbon, hydrogen and oxygen, was found in the gut of an animal. Describe how an autotroph would have obtained this molecule.

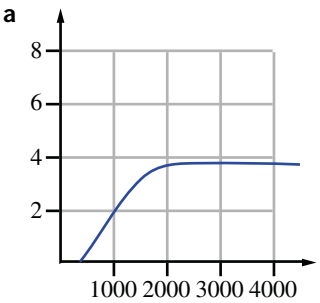


23 There are two stages of photosynthesis. Summarise what process occurs in each stage.

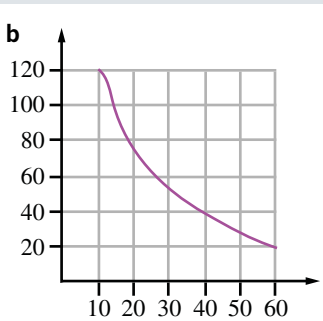
24 Pyridazinone herbicides are used in agriculture to reduce the number of pest plant species. Pyridazinone herbicides inhibit enzymes found in the light-dependent stage of photosynthesis. Explain how pyridazinone herbicides might act on a pest plant.

25 The following graphs represent the changes in rate of photosynthesis when temperature, light intensity or distance from a light source are increased. Label each graph with the factor that is best represented by the data presented.

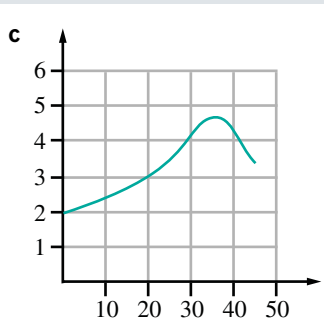
a



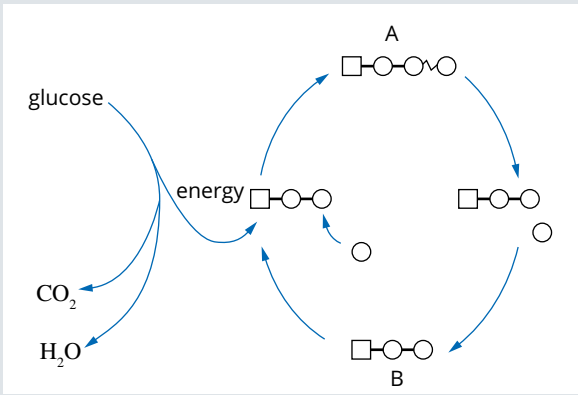
b



c



26 Study the diagram shown, which summarises the processes of energy release in cells.



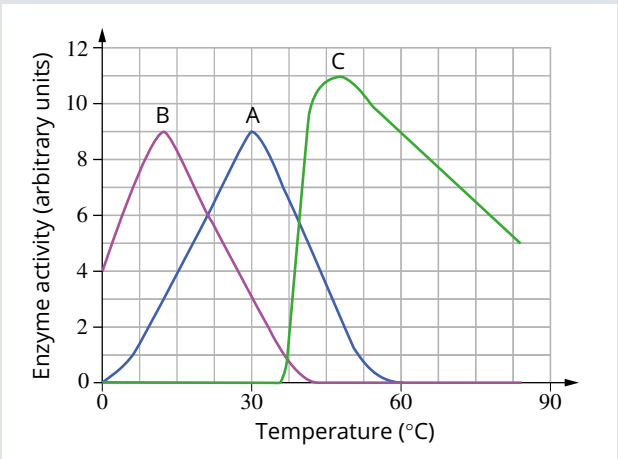
a In the diagram, name the molecule represented by the letter:
- **i** A
- **ii** B

b Describe how molecules A and B are related.

c Glucose is the energy-rich molecule that enters the glycolysis process. Describe the products of this process for each molecule of glucose.

Analysis

27 An experiment was performed to investigate enzyme activity in three different species: the two-toed sloth (a mammal), an Arctic trout, and a bacterium from a thermal spring. The activities of the enzymes from each organism are plotted on the graph below.



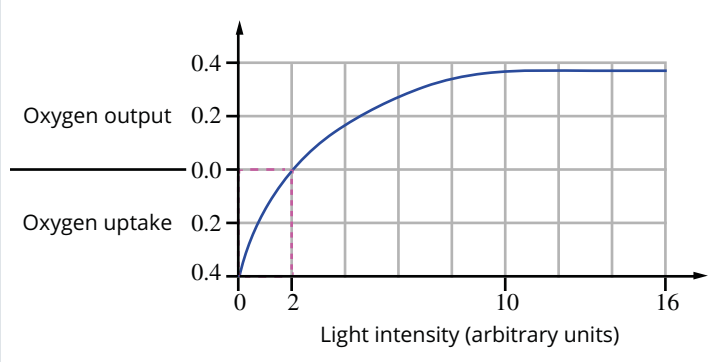
a Explain which graph belongs to each animal.

b Explain why no activity was observed at 60°C for enzyme A.

28 The following graph shows the relationship between net oxygen uptake or output and light intensity for a green plant. Explain what is happening when light intensity is at:

a 2 units.

b 16 units.



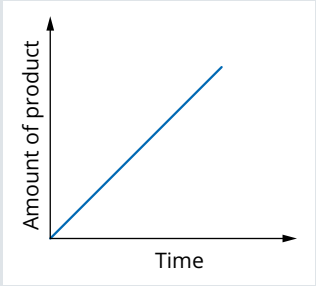
29 **a** Describe the energy-releasing processes that occur in the leg muscles of a sprinter in a 50 m race.

b Explain how the muscles recover their normal states after the race is over.

c Describe how these processes would be different in the leg muscles of someone who went for a gentle jog.

d Propose why the muscles of a sprinter might be sore 2 days after the race.

30 Consider the following incomplete graph for an enzyme-controlled reaction in which the enzyme is present at concentration x. Assume there is a fixed amount of substrate present.



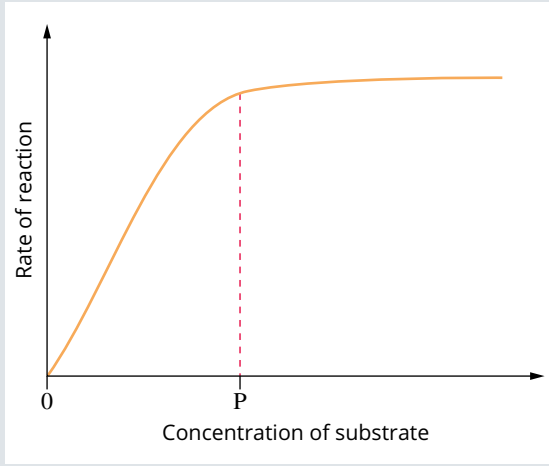
Eventually the shape of the graph will change. Continue the line graph according to your expectations and predict what happens. Redraw the graph for an enzyme concentration of $2x$.

31 Pepsin is an enzyme that is released into the stomach of humans (pH 1.5–3.5, 37°C), where it breaks down proteins into polypeptides. Predict how the activity of pepsin would change as the:

a temperature is increased from 37°C to 45°C.

b pH is increased above 5.

32 The following graph illustrates the relationship between the concentration of an enzyme substrate and rate of reaction.

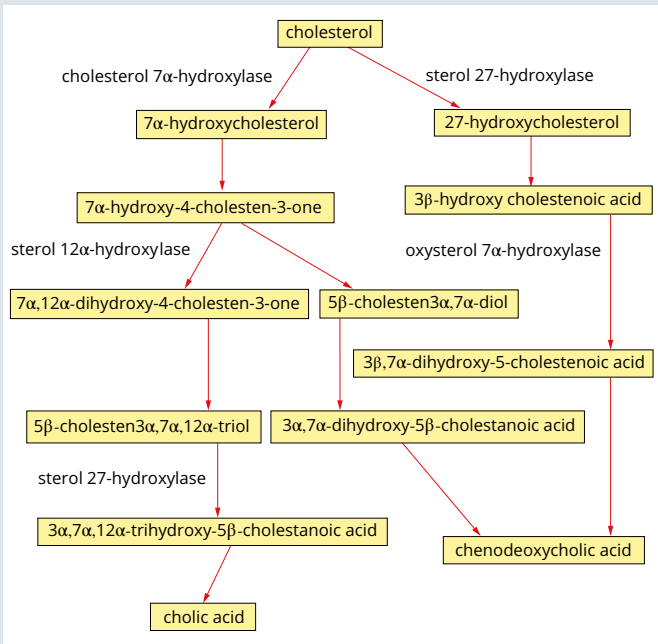


a Determine the relationship between the substrate concentration and the rate of reaction from 0 to P units of substrate concentration.

b Infer what will happen at and after point P.

c Explain what it means when the concentration of the enzyme is described as being a limiting factor.

33 Bile acids are processed in the liver to form bile salts. Bile salts are used in the small intestine to mechanically break down fats in the diet. The metabolic pathway for the formation of two bile acids is shown in the flow chart. The chart is simplified; some steps in the pathway between 3β,7α-dihydroxy-5-cholestenoic acid and chenodeoxycholic acid are not known, nor are some of the enzymes in the pathway.



a One enzyme used in the pathway is sterol 27-hydroxylase. If an individual was unable to make functional sterol 27-hydroxylase, conclude whether they would be able to make either of the bile acids shown in the flow chart.

b Determine whether it is likely that chenodeoxycholic acid acts as an inhibitor of sterol 27-hydroxylase.

c Infer how sterol 27-hydoxylase can catalyse two different steps in the pathway.

34 During chemical reactions, changes in free energy occur. The change of energy is given as ΔG (delta G). A positive energy change means that there had to be an input of energy for the reaction to occur (endergonic) and a negative energy change means the reaction released energy (exergonic). Energy released by one step can be used in subsequent steps.

A particular metabolic pathway involves four enzymes (K, L, M and N) in a four-step pathway. Molecule A is the initial substrate of the pathway and molecule E is the final product.

$$A \xrightarrow{K} B \xrightarrow{L} C \xrightarrow{M} D \xrightarrow{N} E$$

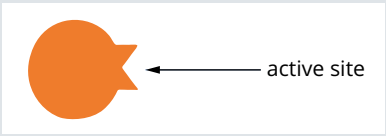
The energy requirements of each step are shown in the table below.

Step	ΔG (joules)	Enzyme
A → B	+5	K
B → C	+2	L
C → D	–6	M
D → E	–4	N

a Determine the exergonic steps.

b Assess whether the pathway is anabolic or catabolic.

c The shape of enzyme K is shown below. High concentrations of molecule E inhibit enzyme K.



i Deduce the shape of the substrate for enzyme K.

ii Draw a possible shape for molecule E.

iii Determine, using annotated diagrams, how molecule E inhibits enzyme K catalysing the formation of molecule B, thereby regulating the pathway.

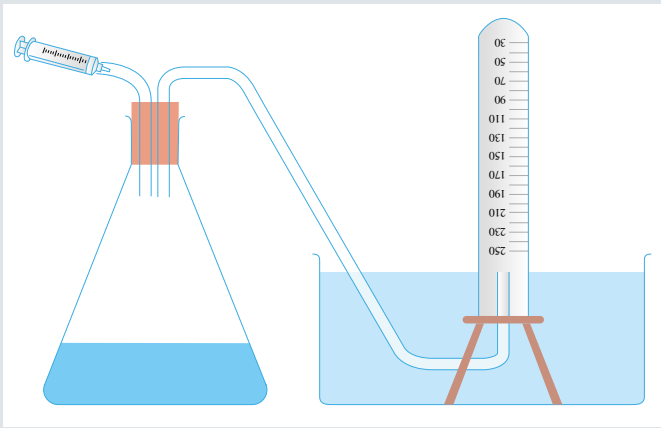
35 One toxic product of respiration is hydrogen peroxide (H_2O_2). Hydrogen peroxide is so toxic that even though it spontaneously breaks down to form water and oxygen all living things contain an enzyme, called catalase, which speeds up this reaction.

The chemical breakdown occurs according to the following equation:

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

A group of students performed an experiment to investigate the effects of varying substrate concentration on the activity of catalase. Potatoes were used as a source of catalase. The potatoes were pureed and then the puree was strained to collect the potato juice, which contains the enzyme catalase.

The equipment was set up to collect the oxygen gas as it was produced, as shown in the experimental setup below. The measuring cylinder was filled with water before being inverted into the tank, which was also filled with water. 20 mL of potato juice was placed in the flask and the flask was sealed as shown.



In the first test 2 mL of a 5% solution of H_2O_2 was used. Subsequent tests used 2 mL of 10%, 15%, 20% and 25% solutions of H_2O_2. The volume of oxygen produced in 5 minutes was measured. The results obtained by the students are shown in the table below.

Concentration of H_2O_2 (%)	Volume of oxygen collected (cm^3)
5	9.5
10	20
15	31
20	40.5
25	52

a Determine why the volume of oxygen produced can be used as a measure of the activity of catalase.

b **i** Plot a graph of the students' results.

ii Describe the relationship between the concentration of H_2O_2 and the volume of oxygen produced.

c i Deduce possible sources of error in the experimental design and equipment.

ii For each source of error identified, determine a way of reducing the error or its impact on the results.

d Determine how the reliability and accuracy of the results could be increased.

e Explain why the H_2O_2 and the potato mixture must be kept apart until timing starts.

f The breakdown of hydrogen peroxide is an exothermic reaction.

i Describe an exothermic reaction.

ii Determine how this might impact on the results of the experiment.

iii Explain how you might investigate the level of effect that the exothermic nature of the reaction is having on the outcome.

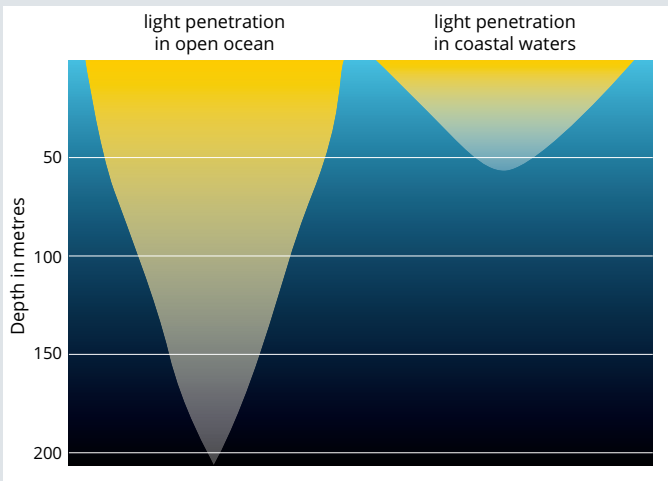
g Enzymes from plants often have a much greater range of temperatures over which they maintain their activity than mammalian enzymes. Conclude why this might be the case.

36 a Light availability is a significant limiting factor influencing the rate at which photosynthesis can occur.

i Define 'limiting factor'.

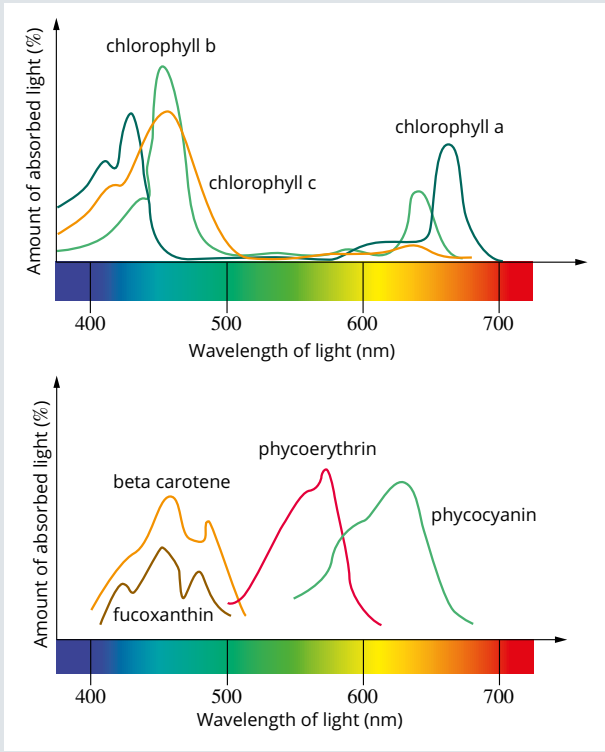
ii Explain why light is significant.

b Photosynthetic organisms living in deep water have especially difficult challenges to survival. The graph below shows light penetration levels in open and coastal waters. The greater the material (e.g. mud) in the water the less light can penetrate. Determine the depth beyond which photosynthetic organisms are unable to survive in the deep ocean.



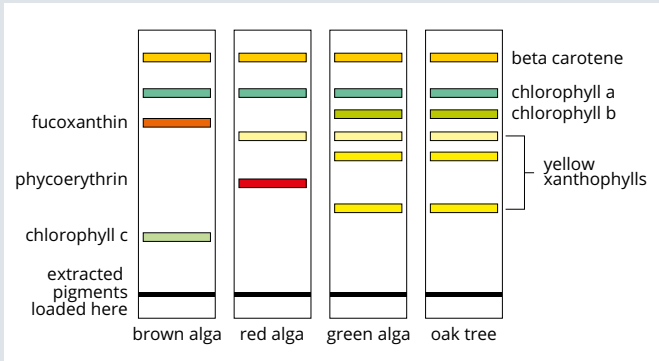
c Assess the validity of the statement, 'All photosynthetic organisms must contain chlorophyll'.

As well as chlorophyll, many photosynthetic organisms contain a range of other pigments called accessory pigments. Together, accessory pigments are able to absorb most wavelengths of light. The absorption spectra for various photosynthetic pigments are shown in the following graphs.



d Using the data presented in the graphs above and your knowledge of the pigments used in photosynthesis, deduce how having a range of accessory pigments could assist the survival of a photosynthetic organism.

e Plants are one of the major groups of photosynthetic organisms, another is algae. Algae are eukaryotic organisms belonging to the kingdom Protista. Seaweeds are a type of alga. The diagram below shows the results of a chromatography experiment in which the pigments of various types of seaweed and an oak tree are compared.



Chromatography is a method used to separate chemicals according to their solubility. The material to be separated is placed at one end of a special type of paper and that end is dipped into a solvent that is allowed to diffuse up the paper. The chemicals to be separated dissolve in the solvent and are carried up the paper. The chemicals separate according to their solubility. More soluble chemicals move further than less soluble chemicals.

i From the graphs, interpret which type of seaweed is most likely to be found in the deepest waters in coastal regions.

ii The brown algae tested lack chlorophyll b and yet they are very successful, with some growing to 60 m in length. Determine how, despite the lack of chlorophyll b, the brown algae can grow so large.

37 An experiment was set up to investigate photosynthesis. A plant was placed in a sealed container at 20°C. The air in the container was 0.09% CO_2 at the beginning of the experiment. (CO_2 concentration in room air is between 0.03 and 0.04%.) The experiment was undertaken at three different light intensities—dim, moderate and bright. The CO_2 concentration in the container was monitored over a 4-hour period. The results for each light intensity were collected and are shown in the table below.

Time (min)	Light intensity		
	Dim	Moderate	Bright
0	0.090	0.090	0.090
30	0.084	0.080	0.080
60	0.076	0.070	0.070
90	0.069	0.060	0.054
120	0.060	0.053	0.045
150	0.054	0.045	0.038
180	0.048	0.038	0.030
210	0.041	0.030	0.027
240	0.039	0.027	0.021

a Draw graphs of the information in the table. Use the same set of axes for the three light intensities. Ensure that the graphs comply with all of the graphing conventions.

b Describe the trends evident in the data.

c **i** Why can CO_2 uptake be used as a measure of the rate of photosynthesis?

ii Interpret why the CO_2 decreased fastest in bright light.

d Deduce why the reduction in CO_2 was the same for bright and moderate light until after 60 minutes had passed.

e Determine why all of the experiments were carried out at 20°C.

f Infer what hypothesis this experiment could have been testing.

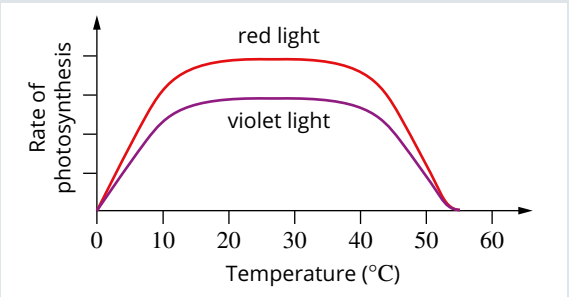
38 Atrazine is a chemical commonly used as a weed killer. It is absorbed by roots from the soil. In the leaves, it attaches to a protein, called D1, which is a part of the electron transfer chain used to generate ATP during photosynthesis. It blocks the movement of electrons along this chain.

a Deduce which phase of photosynthesis is disrupted by atrazine.

b ATP is not a final product of photosynthesis. Determine what happens to the ATP normally produced in the electron transfer chain.

c The advertising blurb on one particular brand of weed killer which has atrazine as its active ingredient says, '... this product works by starving the plant ...'. Evaluate this description of the action of atrazine.

39 The rate of photosynthesis for a particular species of plant was monitored under different wavelengths of light and varying temperature conditions.



a Interpret the information from the graph to name two factors that affect the rate of photosynthesis.

b Identify two other environmental factors that can affect the rate of photosynthesis.

c Determine under which wavelength of light—red or violet—the greater amount of oxygen gas is produced.

d Plants grown under both red and violet light showed a sharp decline in the rate of photosynthesis after approximately 40°C, until it ceased completely at approximately 55°C.

i Explain this observation.

ii From this observation, draw a conclusion about the process of photosynthesis.

e Evaluate whether or not photosynthesis is an endergonic or an exergonic reaction.

40 a An experiment was performed in which muscle cells were incubated in an oxygen-free environment at 20°C. The cumulative uptake of glucose was measured in grams. The results for the first 10 minutes are shown in the following table.

Glucose use in the absence of oxygen	
Time (min)	**Glucose uptake (g)**
2	5
4	10
6	15
8	20
10	25

After 10 minutes, oxygen was infused into the culture and measurement of the uptake of glucose continued. The results for the next 10 minutes are tabulated below. Temperature was maintained at 20°C.

Glucose use in the presence of oxygen	
Time (min)	**Glucose uptake (g)**
12	26
14	27
16	28
18	29
20	30

i Graph the uptake of glucose versus time for the 20 minutes of the experiment. Clearly mark the point at which oxygen was introduced into the culture.

ii Infer why the rate of glucose uptake declined so significantly after oxygen was added to the culture.

iii Identify the independent variable in the experiment.

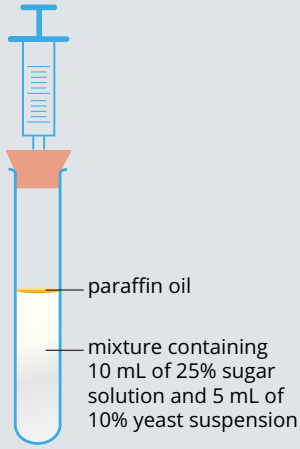
iv Determine why it was necessary to ensure that the temperature remained at 20°C throughout the experiment.

b Some mitochondrial diseases are caused by mutations in the genes needed for respiration. One mitochondrial disease is caused by a mutation in the gene that encodes the protein cytochrome c oxidase. Cytochrome c oxidase is the last of the cytochrome proteins forming the electron transfer chain. An experimenter investigating mitochondrial mutations performed the experiment from part **a** using cells with mitochondria possessing mutations. The scientist noted that when oxygen was added after 10 minutes to these cells no change in glucose use was observed. Evaluate this observation.

41 A student investigated the effect of varying types of sugar solutions (glucose, lactose, fructose, maltose and sucrose) on the rate of anaerobic respiration in yeast. The student hypothesised that the rate of respiration in yeast will be the highest for glucose. The steps in the experiment are described below.

Step 1: 10 mL of fructose solution (25% concentration), 5 mL of yeast suspension (10% concentration) and three drops of paraffin oil were added to a test-tube and mixed thoroughly.

Step 2: The test-tube was sealed with a rubber stopper with a syringe attached, as shown in the diagram.



Step 3: After 15 minutes, the volume of gas collected in the syringe was recorded.

Step 4: Steps 1 to 3 were repeated four more times. The experiment was then repeated using four other sugars: glucose, lactose, maltose and sucrose. The results are shown in the table below.

Volume of gas collected (mL)						
Sugar	**Set 1**	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Mean**
fructose	1.4	1.4	2.0	2.6	5.4	
glucose	9.0	8.2	7.0	8.6	8.8	
lactose	0.0	0.0	0.0	0.0	0.0	
maltose	2.8	3.2	3.0	3.0	6.2	
sucrose	7.4	7.0	7.0	6.6	6.8	

a Define 'anaerobic respiration'.

b Write the word equation that represents the anaerobic respiration of yeast.

c Determine the purpose of the paraffin oil in this experiment.

d Calculate the mean for the experimental results to complete the table. Use the calculated means to plot a graph of the data. Ensure the graph is labelled appropriately.

e Assess which type of sugar resulted in the:

i highest rate of respiration

ii lowest rate of respiration

f Judge whether or not the student's hypothesis was supported by the experimental results.

g Propose a suitable control for this experiment.

Knowledge utilisation

42 Many junior science books state that 'All enzymes are proteins. Each enzyme is specific to one reaction'. Appraise the truth, or otherwise, of this statement.

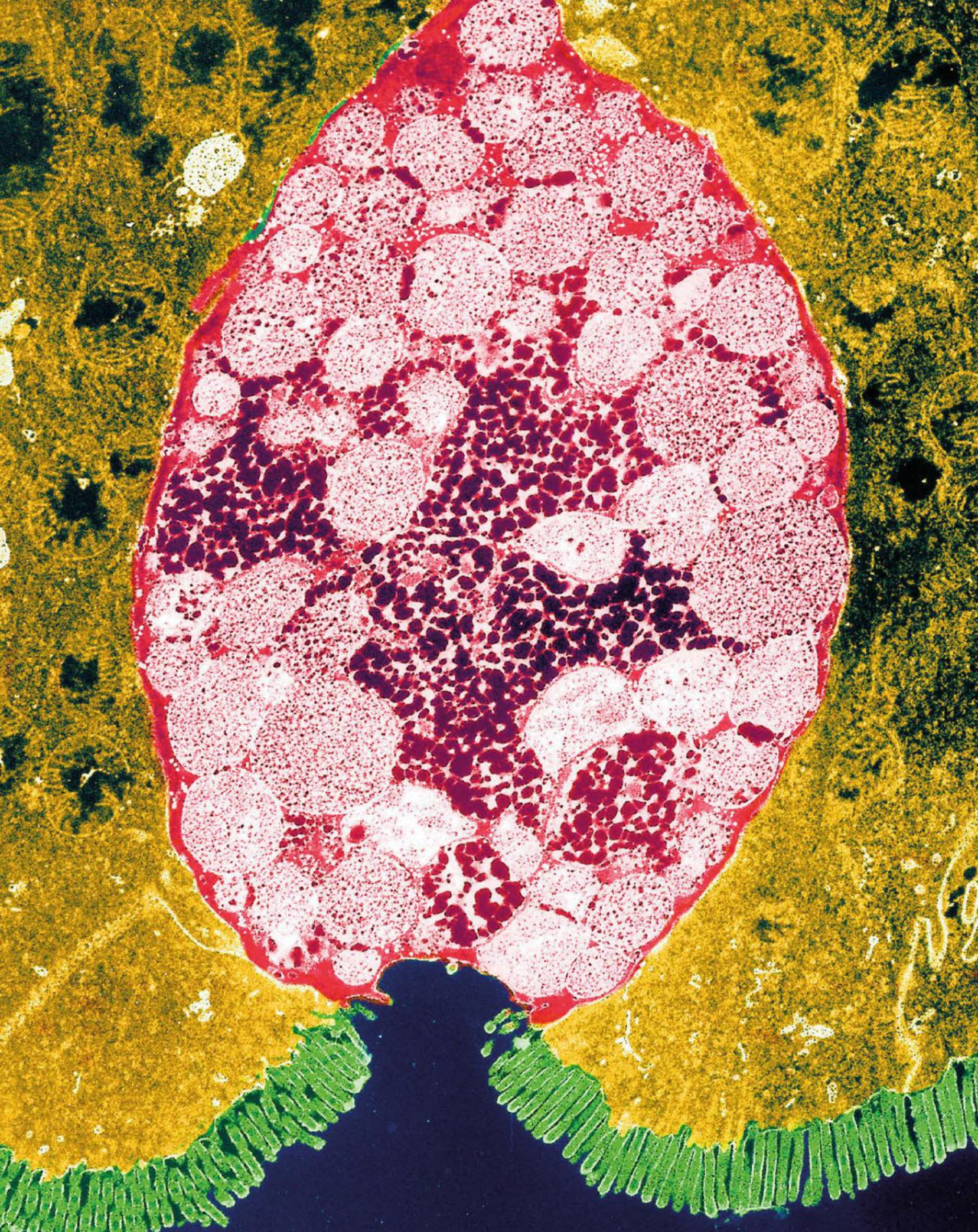
43 Many people believe that plants convert carbon dioxide into oxygen. Judge this belief.

44 An experiment was performed in which a plant was kept in a sealed container. The plant was supplied with air and water. The oxygen in the water was a radioactive isotope (^{18}O). This isotope can be used to monitor the location of the oxygen.

The plant was kept in bright light for 2 hours and then the plant and it surroundings were tested to find out where the radioactive oxygen could be found.

a Explain where you would expect the radioactive oxygen to be located, giving reasons for your opinion.

b Later the experiment was repeated using normal water but the surrounding air contained carbon dioxide incorporating the radioactive oxygen. Propose how you would expect the results of this second experiment to differ from those of the first experiment. Justify your opinion.



CHAPTER

04 Cell organisation

In this chapter, you will learn that the single cell that makes up a unicellular organism must carry out all of the functions necessary for the cell's survival. You will also learn about how the cells of multicellular organisms are organised to fulfil the needs of each cell and enable the whole organism to survive, grow, reproduce and take full advantage of multicellularity.

As multicellular organisms increase in complexity, their cells become more highly organised. The levels of organisation in multicellular organisms are specialised cells, tissues, organs and systems. You will look at each of these levels of organisation and the specialised structures and functions that have evolved to meet the needs of complex organisms. Although there are many advantages to multicellularity, there are also many challenges. You will explore some of these challenges and the functional adaptations that complex multicellular organisms have developed to overcome them.

Finally, you will learn about the significance of stem cells in the development and maintenance of an individual organism and the role of stem cells in cell specialisation. You will discover how stem cells are being used to develop medical therapies.

Syllabus subject matter

WS 1.2.1

Topic 2 • Multicellular organisms

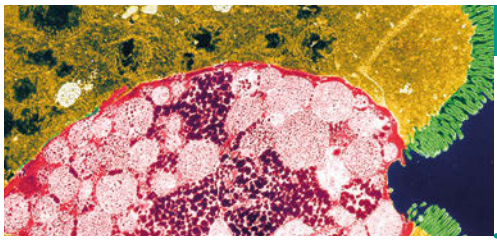
CELL DIFFERENTIATION AND SPECIALISATION

- recognise that multicellular organisms have a hierarchical structural organisation of cells, tissues, organs and systems
- understand that stem cells differ from other cells by being unspecialised, and have properties of self-renewal and potency
- recognise that stem cells differentiate into specialised cells to form tissues and organs in multicellular organisms

SCIENCE AS A HUMAN ENDEAVOUR

- Discuss the use of adult and embryonic stem cells in medical technology. Analyse data and evaluate a range of alternative perspectives on the use of stem cell research by considering a range of scientific media and texts.

4.1 Unicellularity and multicellularity



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

- understand the differences between unicellular and multicellular organisms
- appreciate the advantages and disadvantages of multicellularity and unicelluarity.

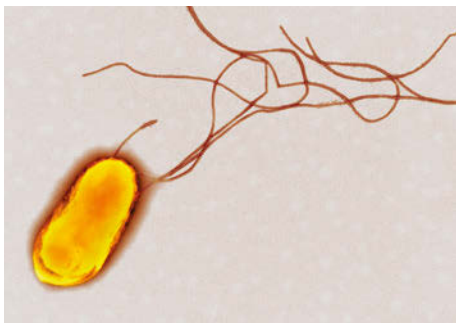


FIGURE 4.1.1 *Escherichia coli* is a unicellular bacterium. Although it is part of the native flora of the human gut, certain strains produce toxins that cause bloody diarrhoea and kidney failure.

FIGURE 4.1.2 *Euglena* is a eukaryotic unicellular protist. The single cell must carry out all of the functions and activities necessary for life.

Unicellular organisms are limited in size because they depend on diffusion for the exchange and transport of substances.

Cells carry out all of the functions necessary to sustain life, including obtaining nutrients and water, exchanging gases, sourcing energy, removing waste products and reproducing. **Unicellular** (single-celled) organisms consist of a single cell and, therefore, a single cell must carry out all of the necessary cellular functions.

All prokaryotes, such as *Escherichia coli* shown in Figure 4.1.1, are unicellular. However, there are many eukaryotic unicellular organisms; most protists (Figure 4.1.2) are unicellular, as are some fungi (Figure 4.1.3).

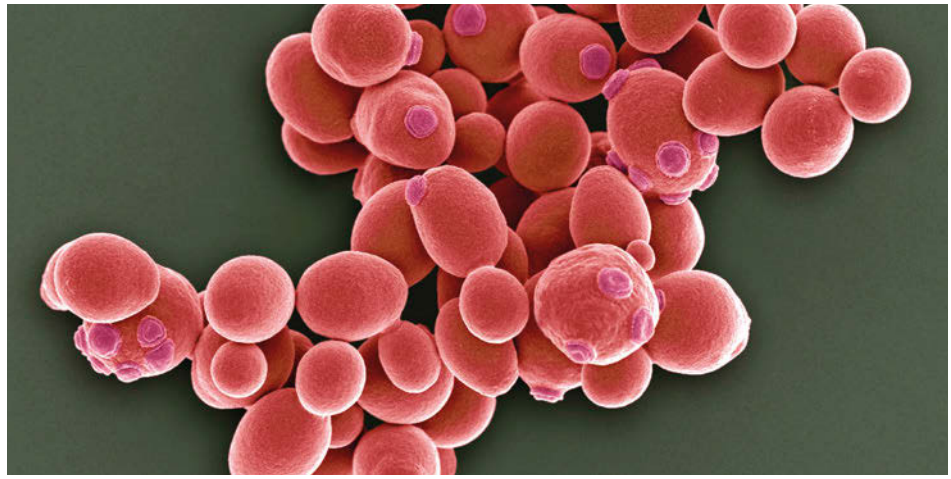


FIGURE 4.1.3 *Saccharomyces cerevisiae*, also known as Baker's yeast, is a unicellular fungus. Humans use this unicellular organism in baking and brewing.

As you will recall from Chapter 2, unicellular organisms are small in size and have a large surface area to volume ratio, which allows unicellular organisms to exchange substances efficiently with their environment. The small size of unicellular organisms also means that substances diffuse more quickly throughout the cell, enabling the cell to carry out necessary functions.

However, while unicellular organisms can be considered autonomous (living independently of other cells), many unicellular organisms live together.

Some bacteria, such as the cyanobacteria shown in Figure 4.1.4, grow in chains of cells, and others form aggregates or **colonies** of cells that behave in a coordinated fashion, such as species that form biofilms. Although unicellular organisms can benefit from living together (for example, colonial organisms may secrete substances that can be used by all of the colonial organisms), a unicellular organism is not dependent on other cells for its survival. In other words, if a unicellular organism separates from the colony, it can survive on its own.

A multicellular organism is like a community of cells that work cooperatively for the survival and reproduction of the organism. All multicellular organisms consist of eukaryotic cells. There is an enormous diversity of multicellular organisms, from simple mosses, sponges and corals, such as those shown in Figure 4.1.5, to complex flowering plants, birds and mammals.

FIGURE 4.1.5 Corals may look like single multicellular organisms, but they are groups of multicellular organisms (known as polyps) living in colonies.

FIGURE 4.1.4 Cyanobacteria are unicellular prokaryotes. Large colonies of this unicellular organism result in water blooms, a green scum on the surface of water.

A colony is a group of organisms of the same species that live together.

For an organism to be considered truly multicellular:

- its cells (except the reproductive cells) must have the same DNA
- its cells must be connected and must communicate and cooperate to function as a single organism
- it must have different cells that are specialised and responsible for specific functions (including reproduction)
- its cells must be dependent on each other for survival.

The features of unicellular and multicellular organisms are listed in Table 4.1.1.

TABLE 4.1.1 Features of multicellular and unicellular organisms

	Unicellular	Multicellular
Number of cells	Single cell	Many cells
Prokaryotes or eukaryotes	Prokaryotes and some eukaryotes	Eukaryotes only
Functions	• One cell carries out all the functions to sustain life • Functions are carried out by different organelles within the cell	• Cells are specialised to perform specific functions required by the organism • Functions are carried out at cellular, tissue, organ and organ system levels
Size	Microscopic size—surface area to volume ratio limits size	Macroscopic size—increasing the number of cells allows increased body size
Lifespan	Short lifespan due to energetically expensive workload	Long lifespan as work is efficiently divided between specialised cells
Reproduction	• Mostly asexual, clonal reproduction • Whole organism is involved in reproduction	• Mostly sexual reproduction • Only cells specialised for reproduction reproduce (gametes)

ADVANTAGES AND DISADVANTAGES OF MULTICELLULARITY

Almost all of the life forms you can see around you are multicellular, eukaryotic organisms. The microscopic prokaryotes that surround you are invisible to the naked eye, yet they are incredibly abundant and diverse, survive in a remarkable range of environments and have been around for billions of years. Despite the success of prokaryotes, multicellular organisms continue to evolve and thrive, suggesting that being multicellular with specialised cells must have its advantages. Table 4.1.2 lists some advantages and disadvantages of multicellularity and cell specialisation.

The suggested advantages of multicellularity are proposed to outweigh the disadvantages. It is not surprising then that evolution by natural selection has favoured complex multicellular organisms that are organised into tissues, organs and organ systems.

TABLE 4.1.2 Suggested advantages and disadvantages of multicellularity and cell specialisation

Advantages	Disadvantages
• Multicellular organisms have longer lifespans than unicellular organisms. • Sexual reproduction and genetic recombination promote increasing diversity and specialisation over generations, compared to asexual, clonal reproduction in unicellular organisms. • Multicellular organisms are less vulnerable to short-term changes in their environment. There are more systems to cope with change, and cell death does not necessarily affect the survival of the organism. • Multicellular organisms can grow significantly larger than unicellular organisms. • Increased size and specialisation of limbs means multicellular organisms are more mobile and therefore more efficient at locating resources and avoiding predators and other negative stimuli. • Specialised cells in multicellular organisms carry out limited and specialised functions. This increases the efficiency of cells.	• More cells means more energy is required for survival. • The cells cannot function independently; they are dependent on the whole organism for survival. • More energy is required for reproduction; most animals need to find a mate to reproduce, and most plants need another plant in order to reproduce. • Populations of multicellular organisms take much longer to evolve and adapt to long-term changes in their environment because they have much longer generation times than unicellular organisms.

EARLIEST MULTICELLULAR ANIMALS

The earliest known multicellular organisms are the Ediacaran biota. They are named after the Ediacara Hills in the Flinders Ranges of South Australia, where Reg Sprigg discovered some fossils in 1946. While many Ediacaran fossils had been discovered elsewhere in the world before then, the Australian fossils became internationally famous, hence they became known as Ediacaran fossils.

Ediacaran fossils imply evolution of the earliest known multicellular organisms more than 600 million years ago. They are a diverse group of organisms that lived in the Earth's oceans. They are represented in Figure 4.1.6. Some resemble modern sea jellies or segmented worms; others are unlike any other known organisms, such as the sea pen in Figure 4.1.7.

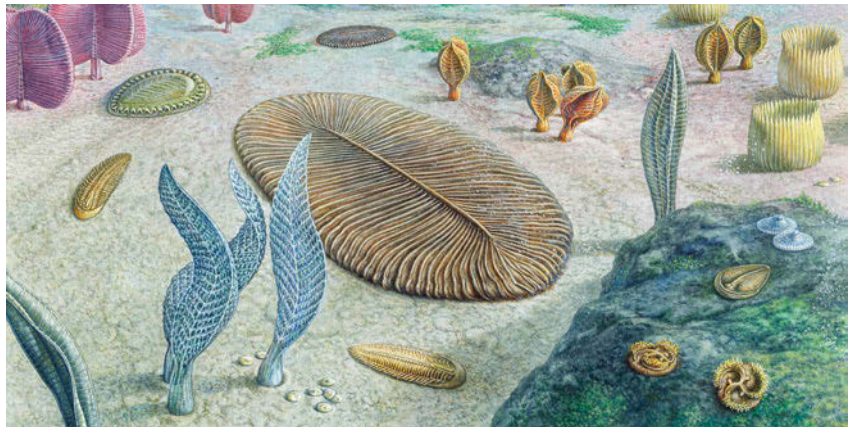


FIGURE 4.1.6 A representation of Ediacaran organisms, the earliest known multicellular organisms

FIGURE 4.1.7 A fossil of a sea pen, an Ediacaran organism. It is so named because of its resemblance to an antique quill pen.

4.1 Review

SUMMARY

- The single cell of a unicellular organism must carry out all of the necessary functions to sustain life.
- All prokaryote organisms are unicellular.
- Most protists and some fungi are the only eukaryotic unicellular organisms.
- Some unicellular organisms live close together, such as in colonies or as biofilms.
- For an organism to be considered truly multicellular:
  - its non-reproductive cells must have identical DNA
  - its cells must be connected and must communicate and cooperate to function as a single organism
  - it must have different cells that are specialised to carry out specific functions, one of which must be reproduction
  - its cells must be dependent on each other for survival.
- Multicellular organisms are all eukaryotic.
- Despite the success of prokaryotes, multicellular organisms continue to evolve and thrive, suggesting that being multicellular with specialised cells must have its advantages.
- Suggested advantages of multicellularity include:
  - increased size and mobility helps organisms find ideal conditions and avoid predators and negative stimuli
  - organisms are less vulnerable to short-term environmental changes
  - organisms can perform more complex functions
  - longer lifespans
  - increased diversity over generations through sexual reproduction and genetic recombination.
- Suggested disadvantages of multicellularity include:
  - more energy is required for survival and reproduction
  - cells cannot function independently
  - it takes longer for populations to evolve and adapt.

KEY QUESTIONS

Retrieval

1 List five differences between unicellular and multicellular organisms.

2 Recall the four characteristics that an organism must have to be considered truly multicellular.

3 List three suggested advantages of multicellularity.

Comprehension

4 Explain why unicellular organisms are limited in size.

5 Describe two suggested advantages of unicellularity.

Analysis

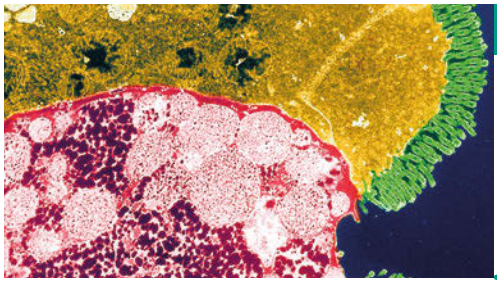
6 The green alga *Volvox* is a colonial organism. A *Volvox* colony is shaped like a hollow ball and can consist of thousands of cells.

Within the colony, there are two cell types: flagellate cells and germ cells. The flagellate cells have two flagella and an eyespot. These cells move in a coordinated fashion, enabling the colony to swim. Moreover, the cells towards the front of the sphere have more developed eyespots than the cells at the rear of the colony.

The *Volvox* can reproduce both sexually and asexually. Flagellate cells are able to reproduce asexually. The other cell type, germ cells, are involved in sexual reproduction.

Explain whether you consider *Volvox* to be unicellular or multicellular.

4.2 Levels of organisation in multicellular organisms



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

- understand the levels of cellular organisation in multicellular organisms
- be able to identify specialised cells, tissues, organs and systems
- be able to relate a speciliased cell's structure to its function
- understand the levels of cellular organisation in complex plants and animals.

FIGURE 4.2.1 A complex multicellular organism, such as a koala, is more than just a mass of cells. The cells are organised so that they can work together to carry out the functions required for life.

A multicellular organism can consist of many trillions of cells. In a mammal, such as the koala in Figure 4.2.1 or a human, these cells consist of hundreds of different types of specialised cells. For example, these include muscle cells, red blood cells, bone cells and nerve cells. Each of these cell types has a specific function that contributes to the survival and reproduction of the whole organism.

Although multicellularity has many advantages, it also has a number of challenges. An individual muscle cell is capable of shortening, yet on its own could not possibly bring about movement in a large organism. This requires the aid of numerous cells that have differentiated and specialised equivalently. The same muscle cell requires nutrients and oxygen, and produces waste. To ensure the cells can carry out their functions correctly and maintain healthy systems, the organism must expend energy finding the resources to fuel all of its cells.

In this module, you will look more closely at multicellular organisms and how they are organised to overcome these challenges and take full advantage of multicellularity.

LEVELS OF CELLULAR ORGANISATION

A cell must be able to obtain nutrients and remove waste, and physical conditions such as temperature, solute concentration and pH must remain within the tolerable limits of the cell. If any of these conditions are not met, the cell dies. This is also true for the individual cells that comprise a multicellular organism.

One advantage of being a large multicellular organism is that most body cells are isolated from the external environment by a protective outer layer called the **epidermis**. This outer layer provides a buffer against changes in the external environment, allowing conditions on the inside of the organism to be maintained at suitable levels for the efficient functioning of cells. This is shown in Figure 4.2.2.

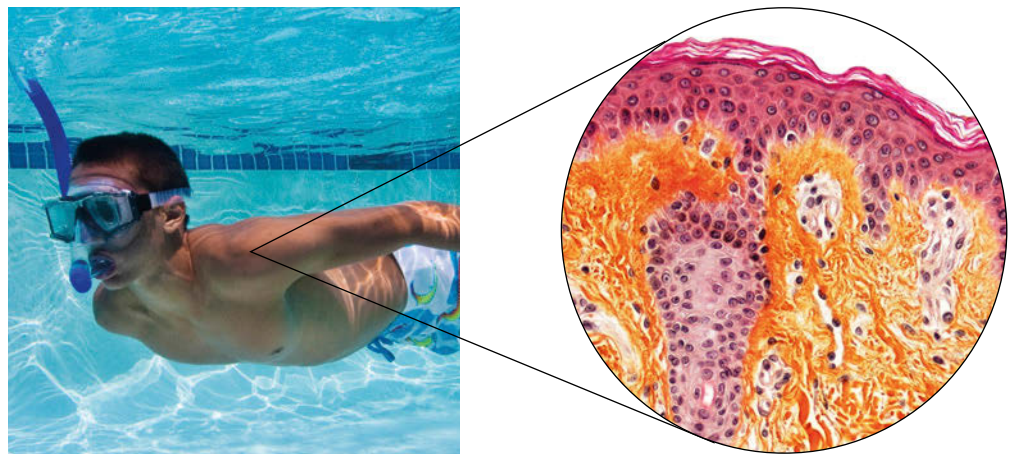


FIGURE 4.2.2 The epidermis provides a barrier between the internal and external environment of multicellular organisms, which helps to maintain the stable internal environment of multicellular organisms. The epidermis comprises several layers of specialised cells. Only the uppermost layer (pink) is in contact with the external environment.

However, the isolation of the internal environment from the external environment means that most cells do not have direct access to their essential requirements, such as oxygen. It also means that wastes expelled from the cells need to be removed from the internal environment so that they do not accumulate around the cell. As an organism increases in size and complexity, greater cooperation and coordination is required between its cells—the cells must be organised.

Multicellular organisms, depending on their complexity, can be organised into the following levels to provide the needs of the entire organism:

- specialised cells
- tissues
- organs
- systems.

The term 'organism' is derived from the French word *organisme*, which means 'organise'.

Specialised cells

Specialised cells are cells that have a specific function. All cells perform particular jobs in a multicellular organism and have unique structural adaptations that enable them to carry out these functions. Some specialised cells move independently around the body, such as red blood cells. However, most specialised cells form the building blocks of complex tissues and organs in multicellular organisms. Examples of specialised cells in plants are root hairs, palisade cells and guard cells. In animals, specialised cells include myocytes (muscle cells), erythrocytes (red blood cells), epithelial cells and neurons. Figure 4.2.3 shows some neurons.

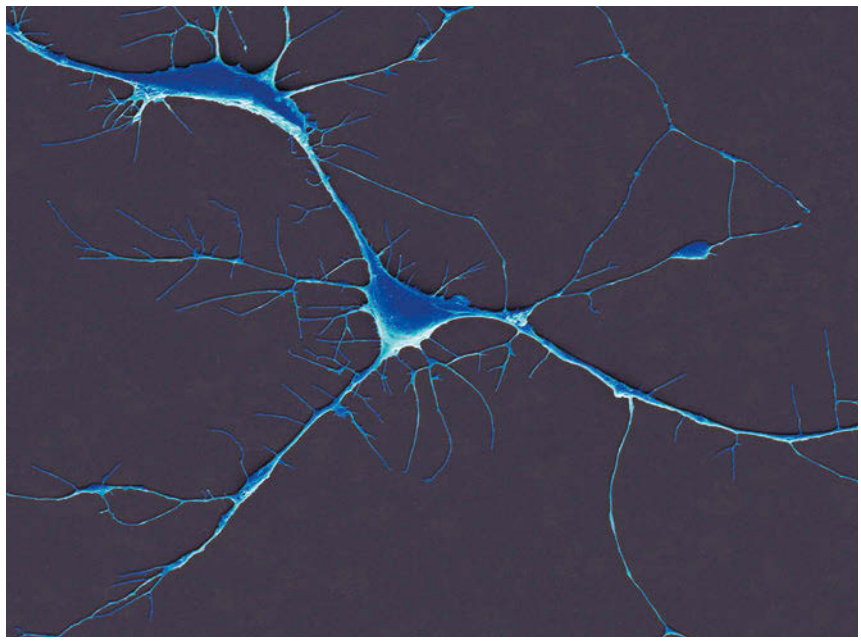


FIGURE 4.2.3 Neurons are specialised cells. The long processes extending from the cell body transmit nerve impulses away from the neuron.

Tissues

Specialised cells are organised into **tissues**. Tissues are groups of similar cells working together to carry out a particular function in a multicellular organism. For some organisms, this level of organisation is sufficient to meet all its needs.

But as organisms become more complex, tissues alone may not be enough to carry out all the tasks required, and it is reasoned that tissues have evolved to group together in distinct structures called organs.

Organs

An **organ** consists of two or more tissues that work together to perform one or more specialised tasks. An organ is commonly recognisable as a distinct structure. Examples of organs are flowers, leaves and roots in vascular plants, and hearts, livers and brains in mammals.

Systems

In multicellular organisms, an organ rarely functions independently of other organs. Instead, organs form an organ system, commonly referred to simply as a system. A system is a group of organs that work together to perform a vital task, such as the circulatory and respiratory systems in humans.

As biological structures and functions become more complex, cells become more and more specialised.

Organisms

The final level of organisation is the organism itself. In a complex animal, systems work together and contribute to the successful functioning and reproduction of the whole organism. Figure 4.2.4 shows the levels of organisation in animals and plants.

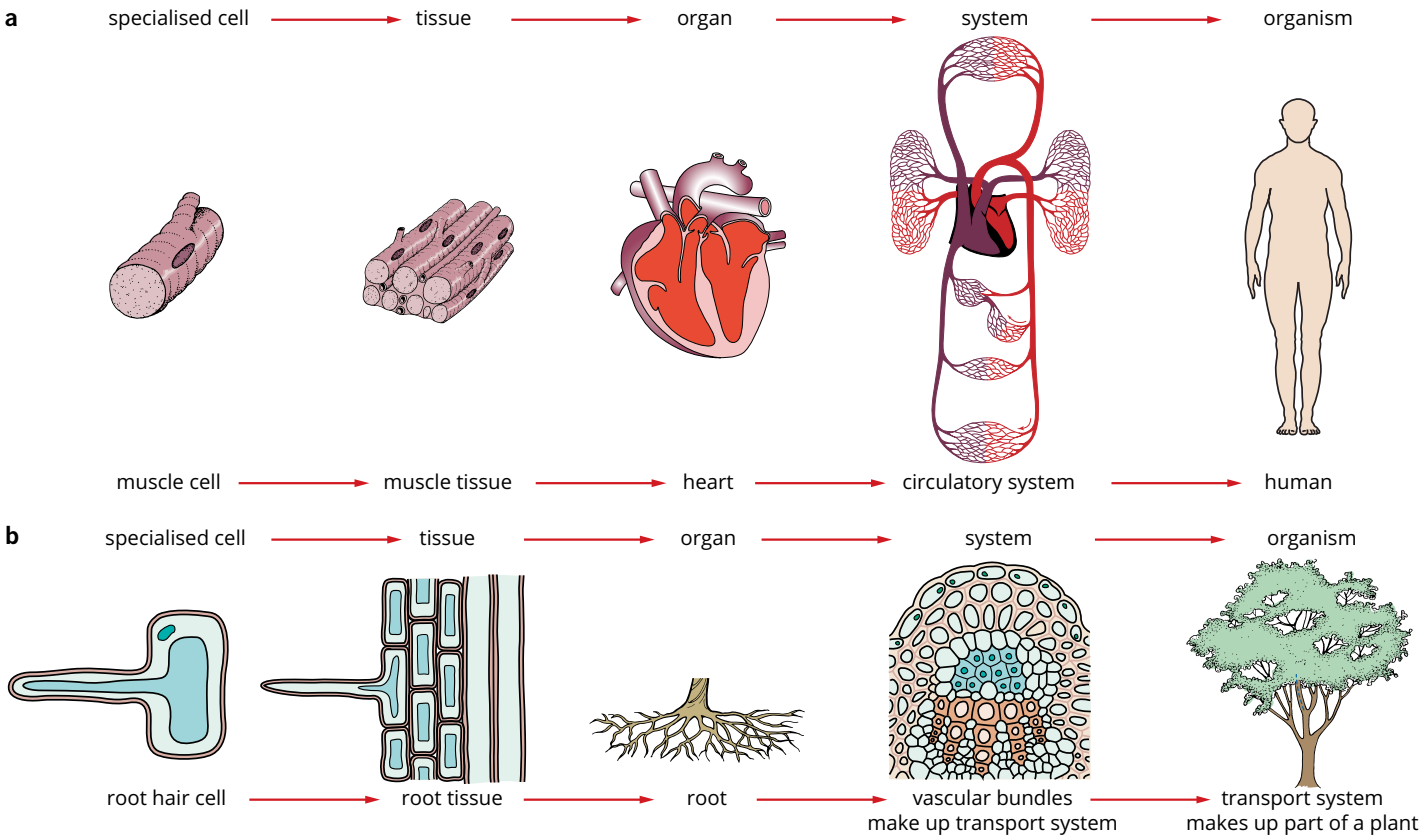


FIGURE 4.2.4 (a) The levels of organisation in a complex multicellular animal: cell, tissue, organ, system and organism. (b) The levels of organisation in a complex multicellular plant: cell, tissue, organ, organ system and organism.

ORGANISATION IN SIMPLE MULTICELLULAR ORGANISMS

Some multicellular organisms are organised only at the cellular level. This includes simple multicellular organisms such as sponges and sea jellies. These animals are considered to be tissue-less multicellular organisms because their cells are not organised into discrete, functioning systems within the organism.

Although simple multicellular organisms are more complex than unicellular organisms such as *Euglena*, simple multicellular organisms can survive without organising their cells into true tissues and organs because they are often only a few cells thick. This means that materials can diffuse easily into and between cells. This lack of organisational complexity also means that many simple multicellular organisms, such as planarians, can regenerate, building new limbs or even an entirely new organism from just a tiny piece of their body or a single cell.

In sponges, such as the azure vase sponge in Figure 4.2.5, the body is hollow and consists of two layers of eukaryotic cells separated by a jelly-like substance. The outer layer protects the sponge and also contains tiny pores through which water and their food can enter. Sponges are filter feeders, filtering plankton, bacteria, dinoflagellates and many other microscopic organisms from the water around them. Digestion is carried out within food vacuoles inside the cells of the sponge. The inner layer consists of a number of cell types, including collar cells and amoebocytes.

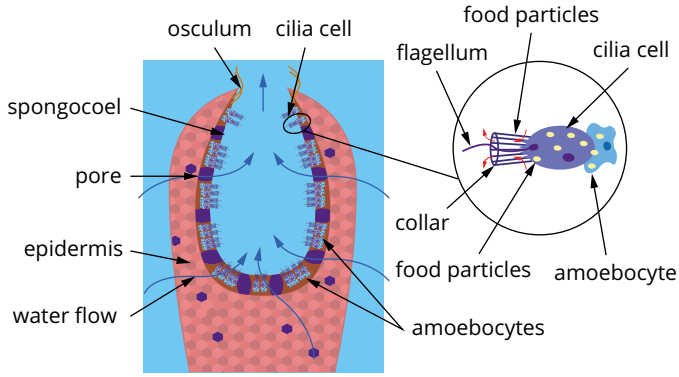


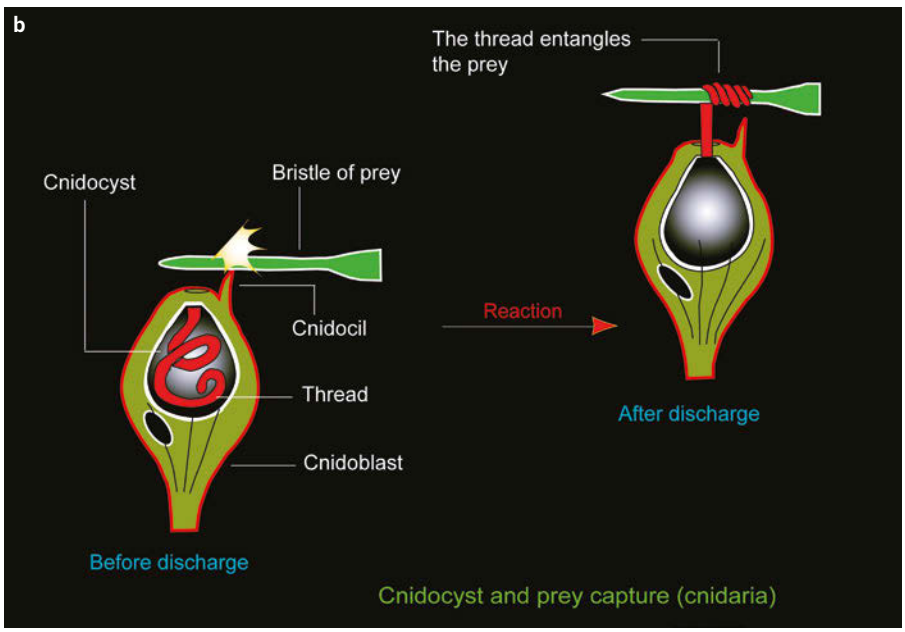
FIGURE 4.2.5 Sponges such as the azure vase sponge (*Callyspongia plicifera*) are organised at the cellular level, with different types of cells performing different functions. Although the cells work together, they do not form true tissues or organs. Sponges are often referred to as tissue-less multicellular organisms.

Despite the simple organisation of these organisms, each of the different cell types found within them has a specialised function that contributes to their survival and reproduction. These functions are outlined in Table 4.2.1. An example of a highly specialised cell in a simple multicellular organism can be seen in Figure 4.2.6.

TABLE 4.2.1 Structure and function of specialised cell types in sponges

Cell type	Function	Structure
epidermal cells	Protect the inner layer of cells	Thin, leathery Closely packed together
collar cells	• Move water through the sponge's pores and into the central cavity (spongocoel), using the motion of their flagella • Absorb nutrients	Flagella Hollow 'collar'
amoebocytes	• Ingest and digest food caught by the collar cells • Transport nutrients to the other cells of the sponge	Mobile and flexible

FIGURE 4.2.6 Simple multicellular organisms often have complex, specialised cells. (a) This cnidarian (*Ectopleura larynx*) is a marine animal with cells along its tentacles called cnidocytes or nematocytes. These cells are specialised to capture prey. (b) A thread is fired from the cnidocyst, a capsule within the cnidocyte, wrapping around and trapping prey. Other cnidarians, such as sea jellies and anemones, have cnidocysts that contain toxins that sting and paralyse prey.



ORGANISATION IN COMPLEX VASCULAR PLANTS

A cellular level of organisation cannot meet the needs of larger and more complex organisms such as vascular plants. Consequently, cells in complex plants such as angiosperms (flowering plants) and conifers are organised into higher levels of organisation: tissues, organs and organ systems.

In comparison, non-vascular plants, such as algae and the moss in Figure 4.2.7, do not have vascular tissue or true organs. Instead, they have simplified tissues and absorb water directly through their cell walls, transporting it between cells by osmosis. The absence of vascular tissue in non-vascular plants also limits their size owing to the lack of structural support and limited area over which they can transport water and nutrients.

FIGURE 4.2.7 Moss is a non-vascular plant, whereas trees are vascular plants. Non-vascular plants lack vascular tissue and true organs, which reduces their ability to transport substances around the entire organism and limits the size to which they can grow. The vascular systems in vascular plants, however, enable trees to grow to great heights.

Specialised cells in vascular plants

Specialised cells are cells that carry out a specific function. Some of the most important functions in vascular plants are involved in the transport of nutrients and water, and acquiring energy via photosynthesis. There are many specialised cells within the vascular tissue of plants for these functions. You will learn more about these specialised cells in Chapter 5.

Tissues in complex plants

The characteristic tissues in vascular plants (and the basis of this type of plant's name) are the vascular tissues, which are involved in the transport of water and nutrients throughout the plant. There are two types of vascular tissue: xylem and phloem.

Organs in complex plants

The major organs of vascular plants are as follows.

- Roots—responsible for absorbing and storing water and nutrients (mineral ions) required by the plant from the soil. Roots also function to support and anchor the plant to the ground. Root systems are often extremely complex and can be much larger than the above-ground structures of the plant. The large root systems of many trees in nutrient-poor rainforest soils do not penetrate deep into the soil layers and instead grow above ground (Figure 4.2.8).
- Leaves—the primary organ of photosynthesis. Photosynthesis is carried out to convert light energy into the chemical energy that fuels the organism's cells. The overall shape and organisation of leaves makes them well suited for their purpose. The major tissues of a leaf are the epidermis, photosynthetic tissue and vascular tissue. The vascular tissue (xylem and phloem) is visible as veins in the leaf structure (Figure 4.2.9).
- Stems—primary functions of the stems are to support the plants leaves, flowers and fruit; store nutrients; transport water and nutrients between the roots and the shoots; and grow new plant tissue. The stem is made up of three tissue types: dermal tissue, ground tissue and vascular tissue. The structure of stems varies widely between different species. The stems of strawberry runners are flexible and fleshy, while the stem or trunk of an oak tree is thick and woody. Some stems are even edible, such as asparagus and celery stalks.
- Flowers—the reproductive structures found in angiosperms. The function of a flower is to facilitate the fertilisation of the ovules (contained within the ovary) by the sperm (contained within pollen). The structures of many flowers are highly specialised to attract pollinators, such as bees, moths and fruit bats, to disperse the pollen from one flower to another. Other flowers produce pollen that is specialised for wind dispersal. After fertilisation, the seeds develop and the surrounding ovary grows into a fruit.

FIGURE 4.2.8 Two major organs of vascular plants are the leaves and roots, both of which are visible in this Amazonian tree with exposed buttress roots.

- Fruits—protect the developing seeds of the plant and help seeds to disperse from the parent plant. Fruits develop from the mature ovaries of flowers and often have a fleshy outer layer that surrounds the seeds. The outer structure of the fruit is often specialised to attract animals that aid in the dispersal of the seeds. Some animals, such as birds, eat the fruit and later excrete the seeds, while other animals disperse seeds that have attached to their fur. Examples of fruits are berries, peaches, tomatoes, nuts and legumes.

FIGURE 4.2.9 Several of the major organs of vascular plants can be seen on this orange tree, including leaves, flowers, fruits and stems. Note the visible veins in the leaf structure.

Systems in complex plants

Vascular plants have two organ systems: the root system and the shoot system. The root system is usually underground and functions to support the structure of the plant and absorb water and nutrients from the soil. The shoot system is made up of two parts: the non-reproductive (vegetative) parts of the plant, such as leaves and stems, and the reproductive parts, such as flowers and fruits. You will learn more about vascular plants in Chapter 5.

ORGANISATION IN COMPLEX ANIMALS

The animal kingdom includes the most complex types of multicellular organisms. An organ level of organisation is not enough to meet the needs of the most complex animals. For this reason, specialised cells of complex animals are organised into tissues, organs and systems.

Specialised cells in complex animals

Most complex animals are made up of hundreds of different cell types that are specialised to perform different functions. The roles of these cells are critical to the healthy functioning of the tissue, organ and organ systems of animals.

Malfunctions in specialised cells: sickle cell disease

Sickle cell disease is an inherited disorder that causes a chemical change in haemoglobin in red blood cells (see Module 7.1). This chemical change makes haemoglobin molecules form long, rigid strands that make the red blood cells sickle-shaped, like those in Figure 4.2.10, and inflexible, blocking small blood vessels. Because of the change to the cell structure, sickle cells cannot transport oxygen effectively (the change affects gas exchange and the carrying capacity; see Chapter 5). Normal red blood cells have a lifespan of about 120 days, but sickle cells often die within 20 days. Sickle-cell disease can result in anaemia, pain, fatigue and joint swelling, and can be fatal if left untreated.

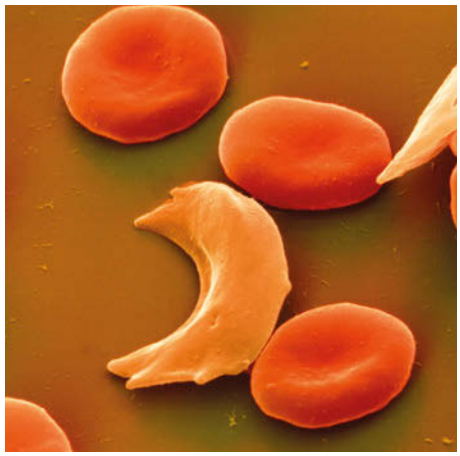


FIGURE 4.2.10 Normal red blood cells (rounded) contrasted with an elongated sickle-shaped cell (at lower centre).

Tissues in complex animals

Specialised cells working together to carry out a specific function are called a tissue. For example, the function of a human red blood cell is to absorb and release oxygen as it travels around the body. However, one red blood cell cannot possibly carry all the oxygen that a human body needs. Billions of red blood cells need to work together to meet the needs of a human.

Cells do not need to be identical to be considered a tissue; they just need to be working together to carry out a particular function. For example, blood is a tissue that consists of red blood cells, white blood cells and platelets all working together.

Tissues in vertebrates are grouped into four basic types. These are shown in Figure 4.2.11.

- Muscle tissue is formed by cells that can contract (for example, skeletal and cardiac tissue).
- Nerve tissue consists of highly specialised cells called neurons that sense stimuli and transmit signals. This is essential for communication and coordination in complex multicellular animals. A motor neuron is shown in Figure 4.2.12.
- Connective tissue forms the supporting and connecting structures of the body (for example, bone and blood).
- Epithelial tissue consists of one or more layers of cells that cover most internal and external surfaces of the organism (for example, skin and intestinal lining).

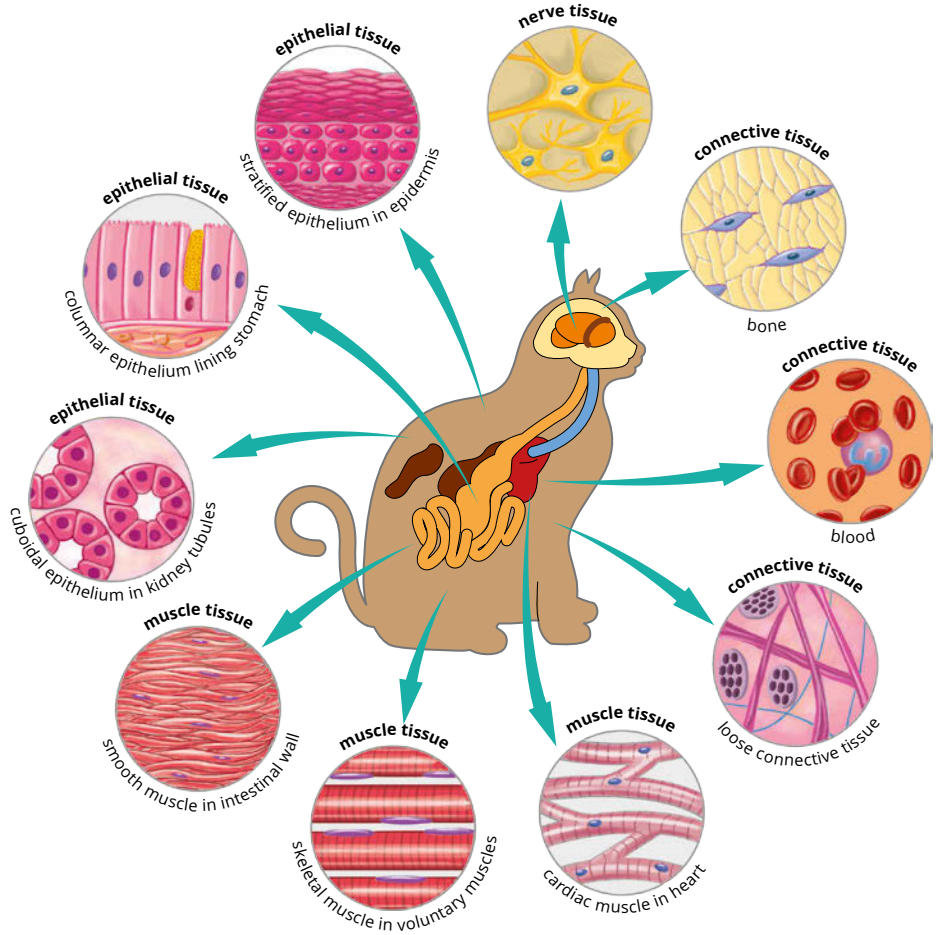


FIGURE 4.2.11 Complex multicellular organisms are made up of a diverse array of tissue types, specialised for many different functions. Vertebrate tissue types are shown here.

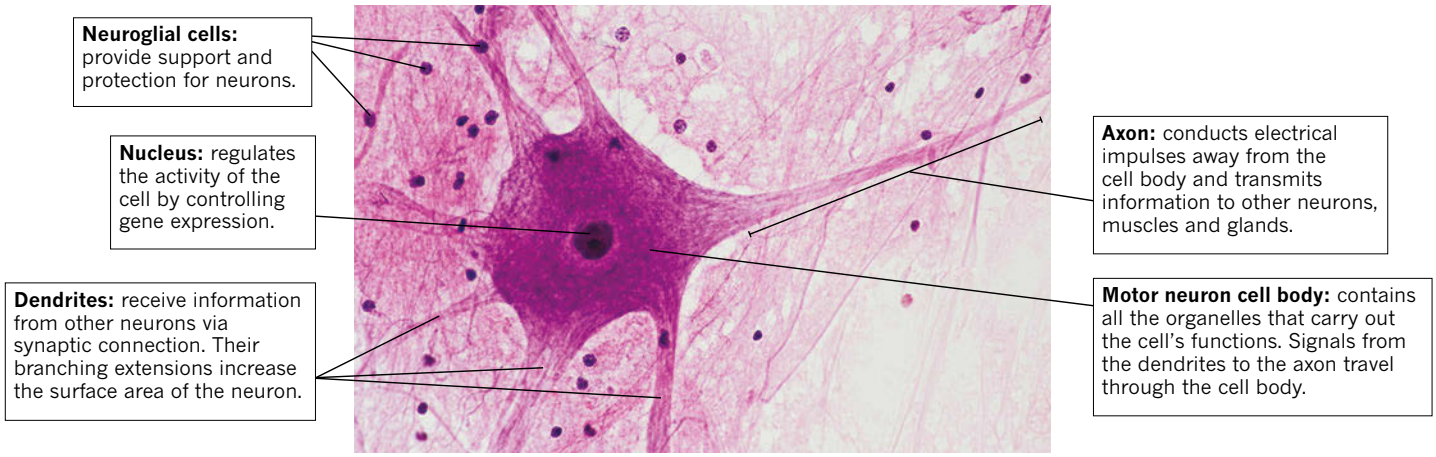


FIGURE 4.2.12 A motor neuron cell and surrounding neuroglial cells from the spinal cord. These specialised structures are part of the tissue of the nervous system that is responsible for communicating signals that regulate and control bodily functions and activity in animals.

Organs in complex animals

An organ is a structure made up of two or more tissues that perform a specific function. Some of the many organs in complex animals include the eye, skin and heart. Below are descriptions of the eye and skin. You will learn more about the heart in Chapter 5.

Eyes

The function of the eye organ is vision. Figures 4.2.13 and 4.2.14 (on page 132) show an insect's eye. Insects have compound eyes that consist of thousands of individual units called ommatidi. Each ommatidium is like a single eye and collectively they are oriented to receive light from different directions, giving an insect a very wide angle of view. Each ommatidium consists of a lens, crystalline cone, light sensitive visual cells and pigment cells. The pigment cells ensure that light hits the visual cells at the correct angle. The visual cells transfer a message to the optic nerve, which transmits information to the brain.

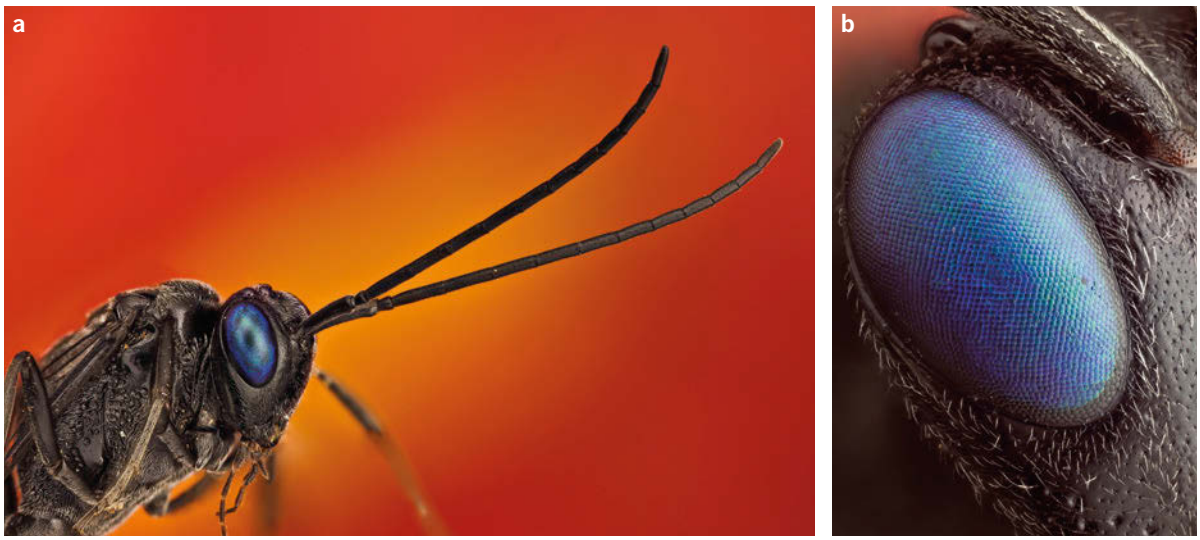


FIGURE 4.2.13 (a) An ensign wasp (*Evania appendigaster*). (b) A magnified view showing the external structure of the compound eye of the ensign wasp.

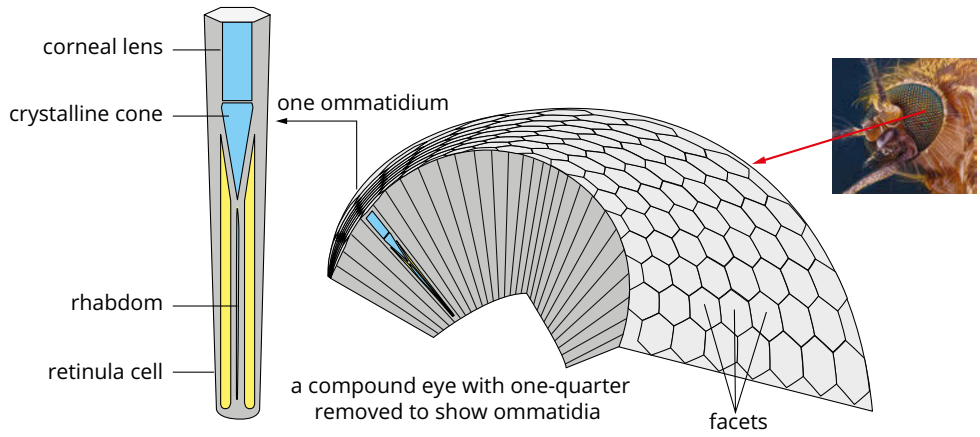


FIGURE 4.2.14 The compound eye of a mosquito, showing the internal structure of the ommatidium typical of insects

Insect vision is different from human vision. The image generated is more like a light and dark mosaic, rather than a sharp image. Insect eyes are also capable of detecting very fast movement from a wide range of directions. This is why insects always seem to react very quickly to danger, such as a human hand.

Skin

The largest organ of the human body is the skin. In an average adult, the skin is more than 1.8 m^2 and makes up 6–10% of the body's total weight. The skin is considered to be an organ because it carries out a number of specific functions, including regulating temperature, preventing water loss and sensing the environment. Skin also provides a protective barrier and contributes to a stable internal environment for the other cells, tissues, organs and systems that make up a human.

Skin in humans is divided into three layers: epidermis, dermis and subcutis (the subcutaneous fatty layer). These layers are shown in Figure 4.2.15.

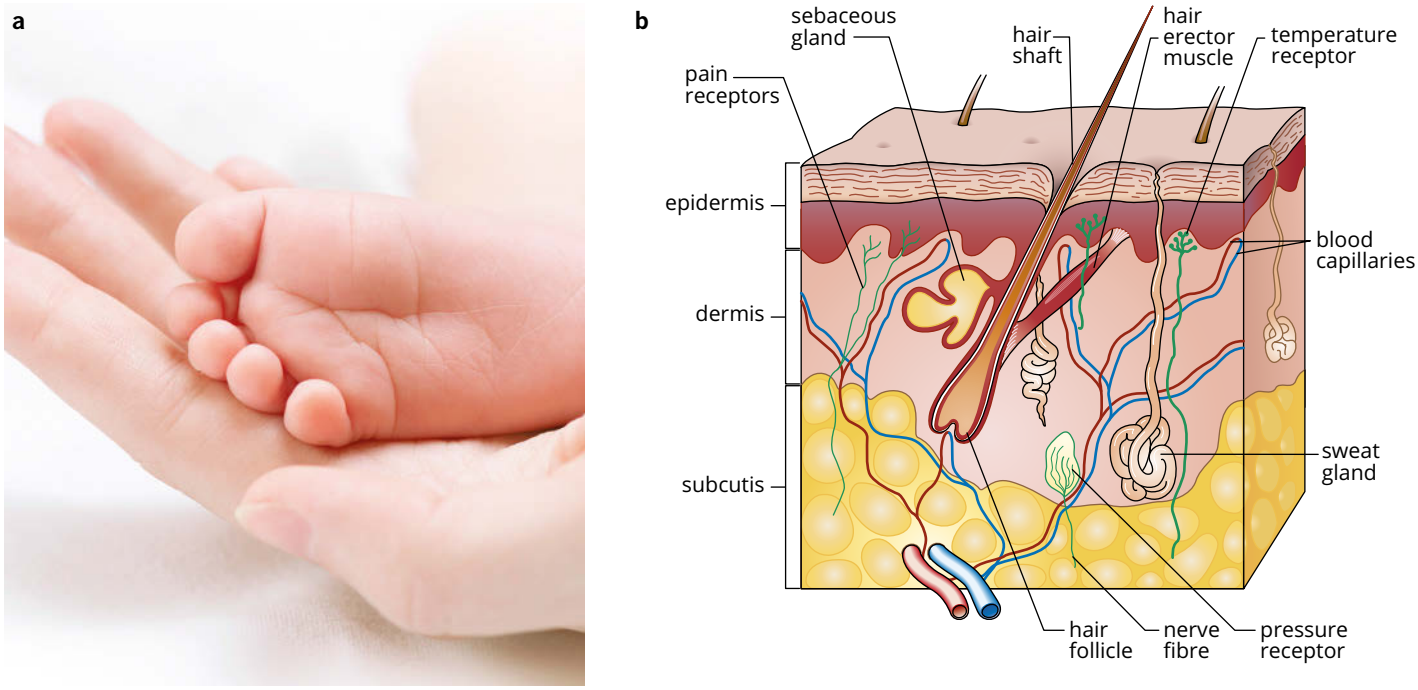


FIGURE 4.2.15 (a) Human skin is a complex organ. (b) Skin consists of many different types of specialised cells and tissues.

The epidermis is the outermost layer and consists mostly of keratinocytes. Keratinocytes are cells that contain keratin and they form a tough, waterproof layer for the body. They also prevent toxins, viruses and bacteria from entering the body. The outer layer of the epidermis consists of dead cells, which are continually replaced by dividing cells below. This layer of dead cells varies enormously over the body and is ten times thicker on the soles of the feet than on the face.

The dermis includes a range of nerves and receptors to sense external stimuli such as temperature, pressure and touch (see Chapter 6 for more details about receptors and stimuli). Some touch receptors are attached to hair cells, while pain receptors are close to the surface of the skin in the dermis or epidermis. Sweat glands aid in cooling by releasing a watery substance onto the epidermis via pores. Sebum is released by the sebaceous glands to help keep the skin and hair cells pliable. Sebum is also thought to have a mildly antiseptic effect on bacteria because of some of the fatty acid molecules present. The dermis has a rich supply of blood vessels that control blood flow through the skin, regulating the body temperature of the whole organism. The dermis also contains fibres of collagen and elastin, which give the skin strength and elasticity.

The deepest layer of human skin, the subcutis, consists mainly of fat cells. These fat cells act as a food reserve for the body and also provide insulation and cushion physical impact.

Systems in complex animals

Complex animals have multiple organ systems that work together to enable the animal to survive. Organ systems include:

- respiratory systems to exchange oxygen and carbon dioxide
- circulatory systems to transport substances throughout the animal's body
- reproductive systems to ensure continuation of the species
- nervous systems which control and coordinate the body, and enable communication throughout the body.

You will learn more about organ systems in complex animals in Chapter 5.

4.2 Review

SUMMARY

- As an organism increases in size and complexity, greater cooperation and coordination is required between its cells.
- Multicellular organisms can be organised into the following levels to provide the needs of the entire organism:
  - specialised cells
  - tissues
  - organs
  - systems.
- Specialised cells are cells that have a specific function. Examples are neurons and red blood cells.
- Tissues are groups of similar cells working together to carry out a particular function in a multicellular organism.
- An organ consists of two or more tissues that work together to perform one or more specialised tasks. Examples are the heart and liver in mammals, and leaves and flowers in flowering plants.
- In multicellular organs, multiple organs work together to form an organ system. Examples in humans are the respiratory system and the circulatory system.

KEY QUESTIONS

Retrieval

1 List the levels of organisation in an organism in descending order, commencing with organism.

2 Describe what is meant by a 'tissue-less' multicellular organism.

3 Recall the name of the two types of vascular tissue in plants.

4 Identify three examples of organs in vascular plants and describe each organ's function.

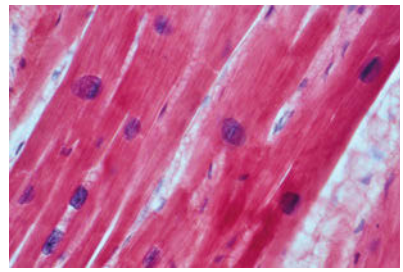
5 Define 'tissue' (as used in biology) and provide an example of a tissue in a mammal.

Comprehension

6 Explain why the cells in multicellular organisms need to act in coordinated and organised ways.

Analysis

7 Identify the level of cellular organisation shown in the following image.

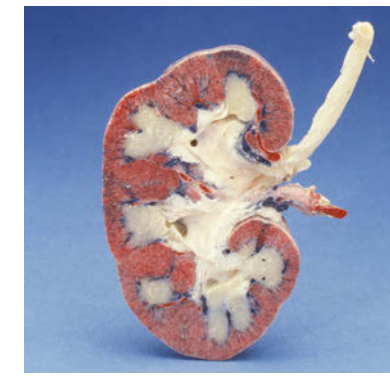


8 Compare unicellular organisms and tissue-less multicellular organisms.

9 Infer why non-vascular plants tend to be smaller than vascular plants.

10 Infer why tissue-less multicellular organisms are often much smaller than more complex multicellular organisms.

11 Identify the level of cellular organisation shown in the following image.

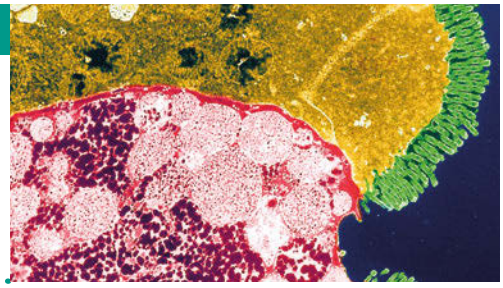


12 Identify the level of cellular organisation of the internal structures shown in the following image.

4.3 Cell specialisation and stem cells

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

- understand how cell specialisation occurs
- recognise the stages of embryo development
- understand the difference between embryonic and adult stem cells
- understand how and from where different stem cells are obtained.



Stem cells, like those in Figure 4.3.1, are cells that are yet to be specialised. In other words, they have the potential to become different types of specialised cells. For this reason, scientists think that in the future stem cells, through innovative medical developments, could replace damaged cells that the human body cannot repair on its own, such as nerve cells. However, stem cell research is often associated with ethical concerns about the use of stem cells from embryos.

In this module, you will learn about how stem cells differentiate to become specialised cells. You will also discover the role and function of different types of stem cells.

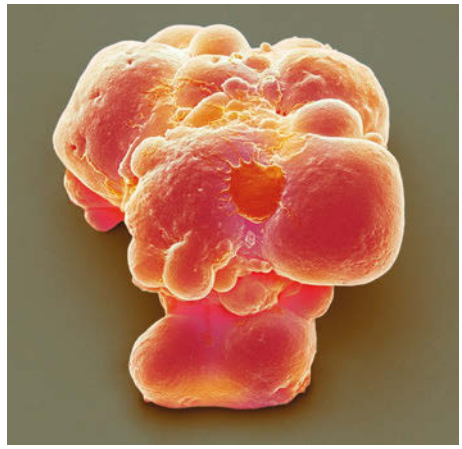


FIGURE 4.3.1 A scanning electron micrograph of a clump of stem cells. This particular type of stem cell can differentiate into any of the cell types in the human body.

CELL SPECIALISATION

All multicellular organisms begin life as a single cell that resulted from the fusion of two highly specialised cells called gametes. Animal gametes are called the egg (or ovum) and sperm. The egg and sperm are shown in Figure 4.3.2. Plant gametes are called the ovule and pollen. Gametes are unique because they can fuse together to form a single cell, called a zygote. This one cell contains all the genetic information required to develop into a fully functional multicellular organism. It is through cell replication and cell differentiation that one single cell can become the trillions of highly specialised cells that make up an organism. Figure 4.3.3 shows a zygote dividing.

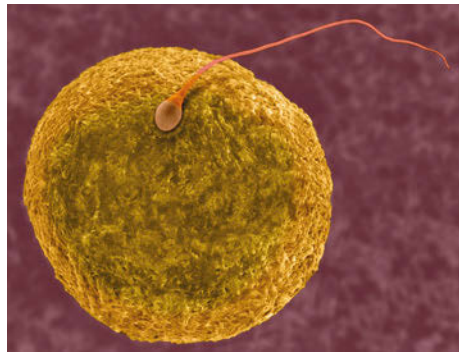


FIGURE 4.3.2 The egg (yellow) and sperm (orange) are two specialised cells. When fertilisation occurs, the egg and sperm form a single cell, called a zygote.

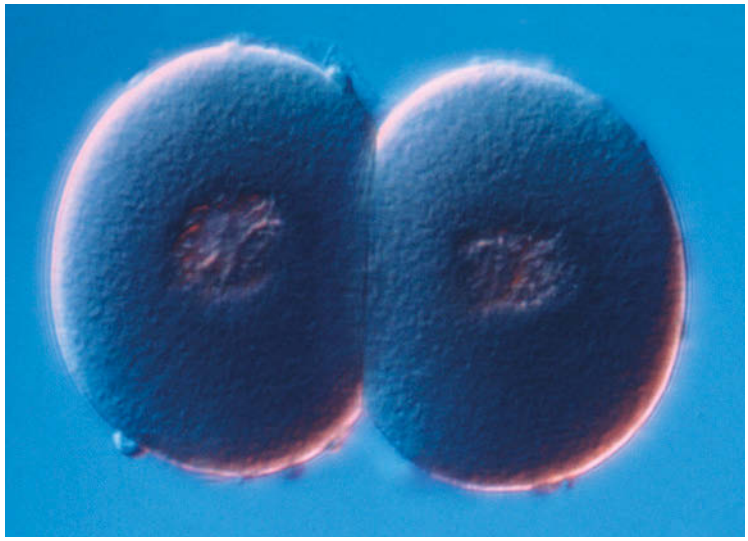


FIGURE 4.3.3 A zygote undergoing cell division, which leads to the development of a multicellular embryo. At this stage, the zygote has undergone one cell division to create two cells.

Cell differentiation

Unlike most animal cells, many cells in a plant's meristem tissue are able to continue differentiating and specialising throughout their entire life.

Cell differentiation is the process by which unspecialised cells, called **stem cells**, become specialised cells. It mostly takes place in all multicellular organisms. Stem cells are present in the embryo and some adult tissues of animals, and in meristem tissue in plants. Stem cells retain the ability to divide indefinitely, while in specialised cells division is slowed or arrested, resuming to repair an injury or replace cells that have died.

In plants, cell differentiation and cell specialisation derives from cells in the meristem tissue. The meristematic cells are fully developed, totipotent embryonic cells at the tips of shoots and roots, as shown in Figure 4.3.4. Organs such as leaves and flowers develop from cells in the shoot apical meristem, while root growth comes from the cells of the root apical meristem.

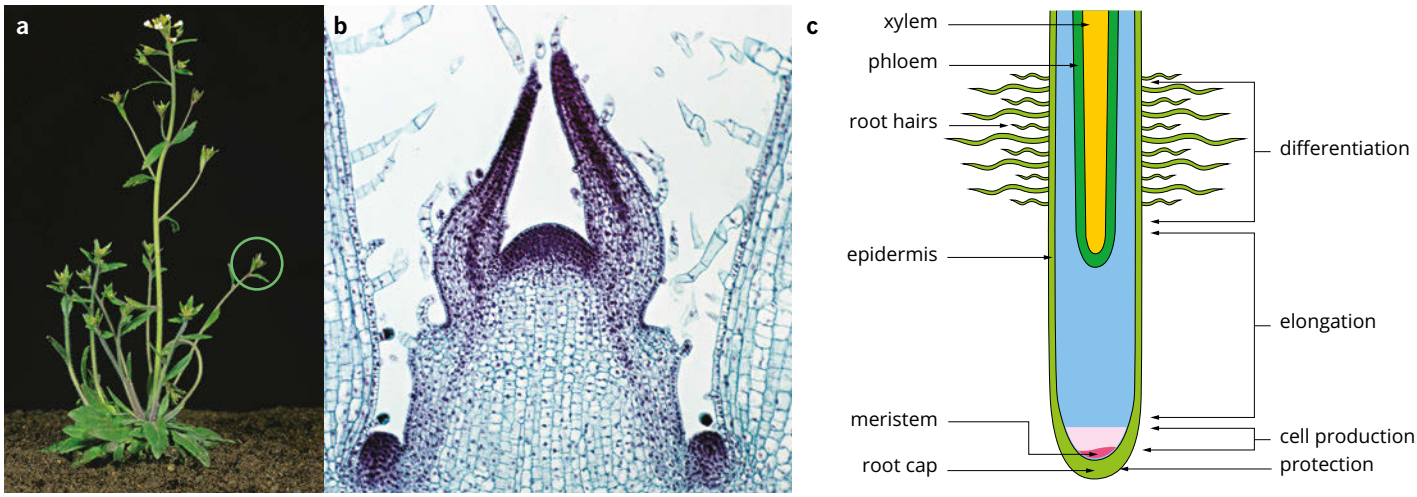


FIGURE 4.3.4 Plant cell production, growth and differentiation derives from developed, totipotent embryonic cells in the meristem. These cells are in the tips of shoots and roots in plants. (a) A thale cress (*Arabidopsis thaliana*) plant with the growing shoot tip highlighted. (b) Magnified image of stem cells in the shoot apical meristem. (c) The structures and regions of cell differentiation in the root meristem.

Gene expression

All of the genes required to produce every type of cell needed by an organism are present from fertilisation. Gene expression is the process in which the information stored in genes is used to build the different structures in a cell. Gene expression determines how a cell differentiates and functions. In specialised cells, only some genes are active or expressed. For example, in developing red blood cells, the genes for haemoglobin are expressed, while in gland cells the genes that code for different hormones, such as insulin, are expressed.

The internal and external structure of a cell is the basis for the functions it performs. Examples of the structures and functions of specialised cells in plants and animals are shown in Table 4.3.1. Cell specialisation is an advantage because cells are more efficient when they have only one function rather than many.

A nerve cell is specialised to carry signals rapidly over long distances. It could not do this if it also had to break down food to obtain nutrients or protect against disease. A red blood cell, which is essentially a bag of haemoglobin that carries oxygen around the body, cannot also protect the organism from invading bacteria, which is the role of white blood cells. In plants, different cells are specialised for photosynthesis, exchange of substances (with other cells or the environment) and fluid transport.

TABLE 4.3.1 The structure and function of some specialised cells in plants and animals

Cell function	Cell specialisation	
	Plant cells	Animal cells
exchange	root hair	gut epithelium cells
transport	companion cell, sieve cell	red blood cells
strength/support	fibres (xylem, phloem)	bone cells, cartilage cells
protection/defence	epidermal cells, cuticle	ciliated epithelium cells, white blood cells
photosynthesis	mesophyll cells	
movement		muscle cells
communication		nerve cell

An example of animal cell specialisation: your skin

One of the highly specialised organs of the human body is the skin, which consists of highly specialised cells. The outer layer of skin (the epidermis) alone consists of four different cell types and these interact with many others. You cans see a diagram of the skin in Figure 4.3.5. Nerve cells, red and white blood cells, muscle cells and gland cells all contribute to the correct functioning of the skin cells in their role of protection, thermoregulation and sensation.

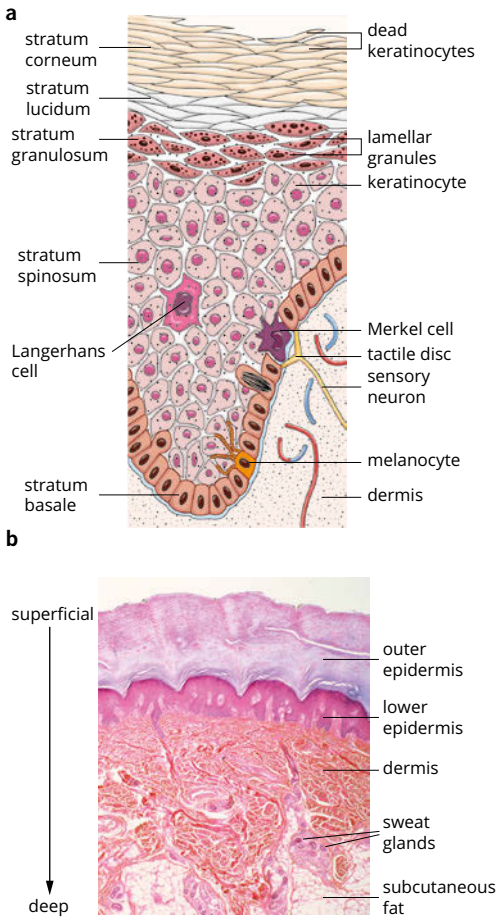


FIGURE 4.3.5 An overview of the different cell types that play a role in the functioning of the highly specialised epidermis, or upper layer, of human skin. (a) The epidermis consists of four principal cell types. (b) A photomicrograph of a portion of the skin.

The structures of the specialised skin cells can give you clues about their function. The keratin-producing keratinocytes are the most common type of skin cell, making up 90–95 % of the epidermis. The flat, scale-like structure of keratinocytes (also called squamous cells) helps them in their role of maintaining the structural integrity of the skin and tight junctions between them form an effective barrier. Keratinocytes also interact with nerve cells, antigen-processing Langerhans cells, sensory-processing Merkel cells and melanin-producing melanocytes.

WS 1.2.3

EMBRYO DEVELOPMENT IN HUMANS

An understanding of embryo development is important to appreciate how and where stem cells form. All humans start life as a single cell—a **zygote**. When the zygote undergoes **mitosis** to become two cells, it is no longer a zygote, but is now known as a **morula**. The morula continues to divide until it consists of 16 cells (after 3–4 days) and then enters the uterus. The morula is an early stage embryo.

In the uterus, mitotic divisions continue, and the morula becomes a **blastocyst** (Figure 4.3.6) as cells begin to specialise. The blastocyst consists of a single layer of surface cells, which enable it to implant in the uterus and eventually develop into the placenta, and an inner cell mass that later gives rise to the embryo. After the blastocyst is implanted, **gastrulation** occurs over approximately 5 days, and the blastocyst becomes a **gastrula**, which has three different layers of cells. This process is shown in Figure 4.3.7. Eventually, the gastrula becomes an **embryo**, and then a **foetus**. These development stages are shown in Figure 4.3.8.

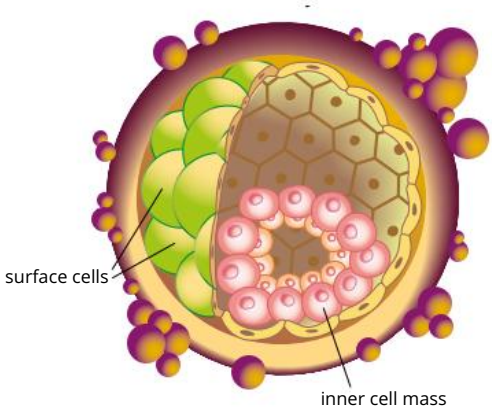


FIGURE 4.3.6 The blastocyst is characterised by an inner and outer cell mass.

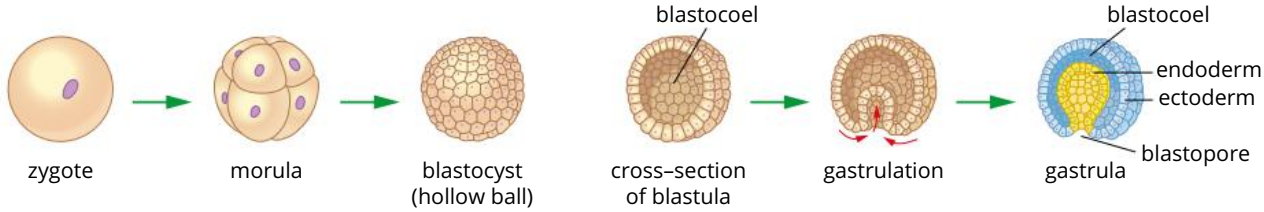


FIGURE 4.3.7 Gastrulation is the process in which the blastula folds in on itself. The resulting product is the gastrula, which has three different layers of cells: ectoderm, endoderm and mesoderm.

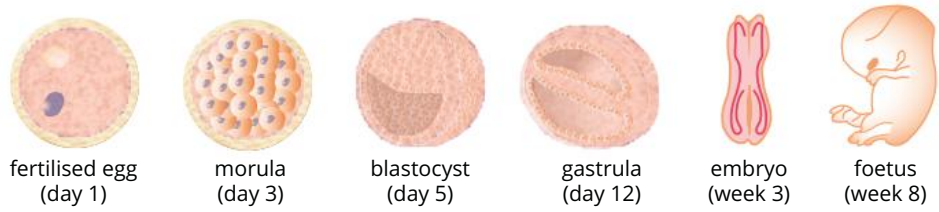


FIGURE 4.3.8 The development of a human zygote (fertilised egg) into a foetus

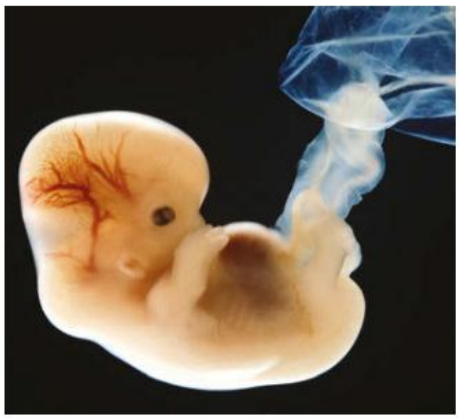


FIGURE 4.3.9 A human foetus at about the eighth week of development.

The difference between each stage of embryo development is determined by the characteristics of the developing individual. As cells continue to specialise, structures and organs become more and more identifiable. For example, at about the eighth week of embryo development, the embryo is recognisable as a human, and is then known as a foetus, as shown in Figure 4.3.9. By the foetal stage, some of the internal and external organs and structures can be distinguished.

- The brain, spinal cord and heart, which began development in the fifth week, continue to grow, the heart beats at about 150 beats per minute now and the lungs begin to form.
- Tissues grow that will become the spine and other bones.
- Eyes and ears begin to form.

Embryonic germ layers and cell specialisation

After implantation in the uterus, the blastocyst undergoes gastrulation, folding in on itself to form a gastrula with three primary layers of cells: ectoderm, mesoderm and endoderm. These primary layers are known as **germ layers** and are shown in Figure 4.3.10. The germ layers are also supported by two membranes:

- the yolk sac, which surrounds the egg yolk. It has a well-developed vascular system that transports nutrients from the egg yolk to the developing embryo
- the amnion, which surrounds the developing embryo, and is filled with fluid. Its main role is as a shock absorber to protect the embryo against any impacts or movements.

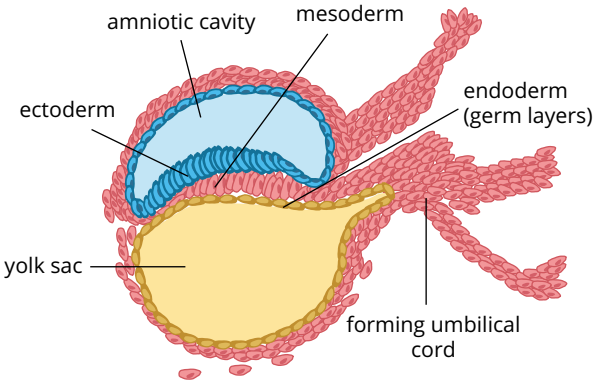
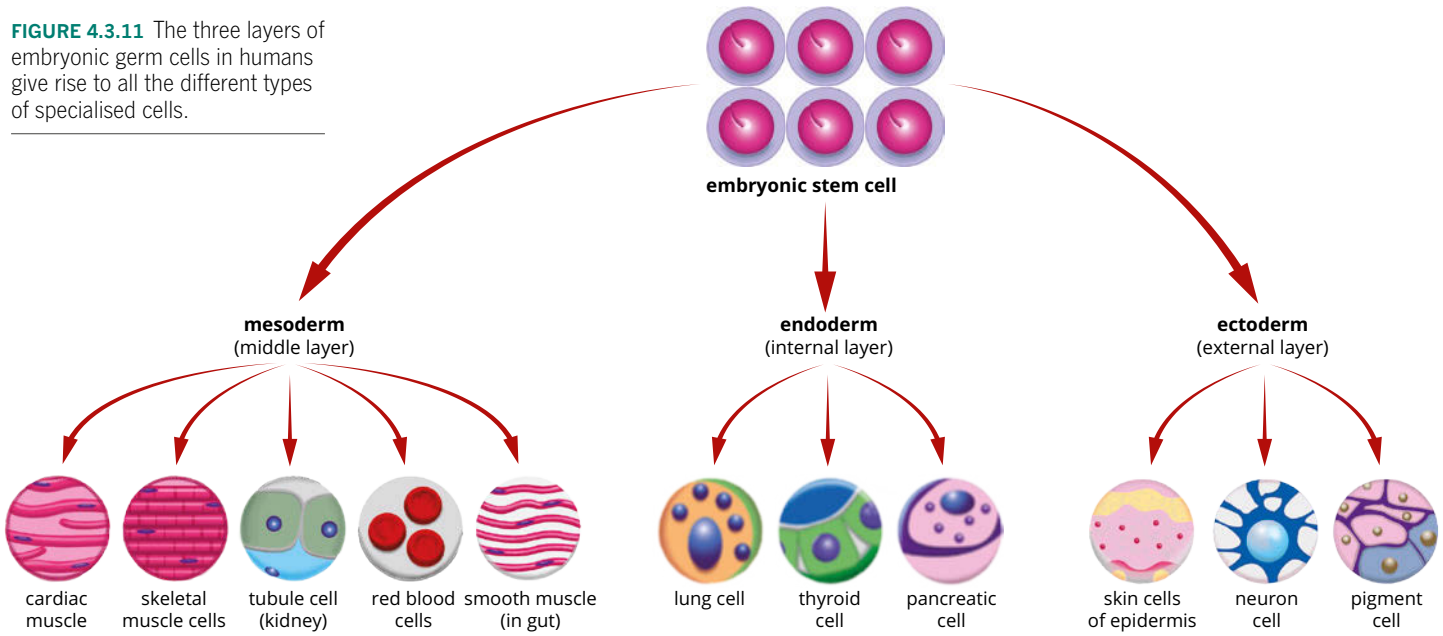


FIGURE 4.3.10 A gastrula approximately 16 days after fertilisation, showing the three primary germ layers: ectoderm, mesoderm and endoderm

The three embryonic germ layers that form will eventually give rise to the different types of specialised cells that make up the tissues and organs in humans (Figure 4.3.11). These are the:

- ectoderm (outermost layer of the embryo), which forms epidermis, hair, peripheral nervous system, brain and spinal cord cells
- mesoderm (middle layer of the embryo), which forms muscle, cartilage, kidney and gonad cells
- endoderm (innermost layer of the embryo), which forms the lungs, bladder and lining of the digestive system, including the stomach, colon, liver and pancreas.

FIGURE 4.3.11 The three layers of embryonic germ cells in humans give rise to all the different types of specialised cells.



STEM CELLS

Stem cells are capable of self-renewal; that is, replicating themselves as new stem cells, as well as differentiating into distinct cell types. Certain stem cells can divide indefinitely in order to replace cells. There are two types of stem cells, each of which come from different sources and have different properties. It is important to note the distinction between the two.

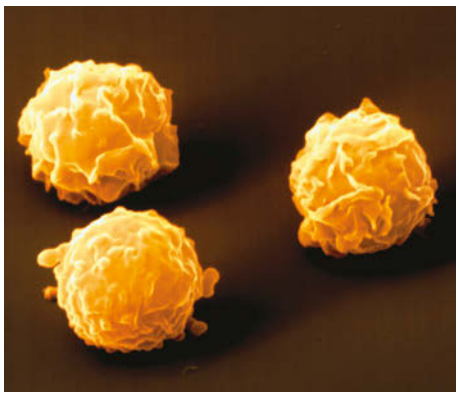


FIGURE 4.3.12 A scanning electron micrograph of human bone marrow stem cells. These adult stem cells can give rise to different types of blood cells only.

Embryonic stem cells

Embryonic stem cells are the undifferentiated or relatively undifferentiated cells of embryos (from the blastocyst stage). They can be obtained from surplus 3-day-old to 5-day-old embryos from IVF programs. Embryonic stem cells can become many types of cells and can replicate indefinitely.

Adult stem cells

Adult stem cells are present in small numbers in some adult tissues, such as hair follicles, bone marrow, the spinal cord and germ cells, and remain as stem cells throughout an individual's life. Adult stem cells can give rise to only a limited range of cells. For example, bone marrow (haemopoietic) stem cells, such as those in Figures 4.3.12 and 4.3.13, can only produce blood cells. The biological purpose of adult stem cells is to repair and regenerate damaged and aged tissue, such as skin and liver cells. Adult stem cells cannot replicate indefinitely.

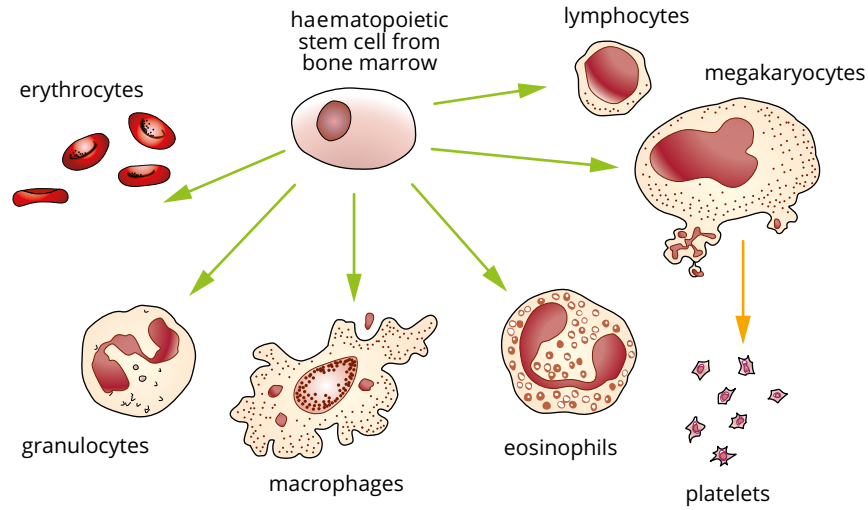


FIGURE 4.3.13 Haematopoietic cells (blood-forming) stem cells are set apart very early in development. They are found in bone marrow and are responsible for the continued production of a number of distinct cell types.

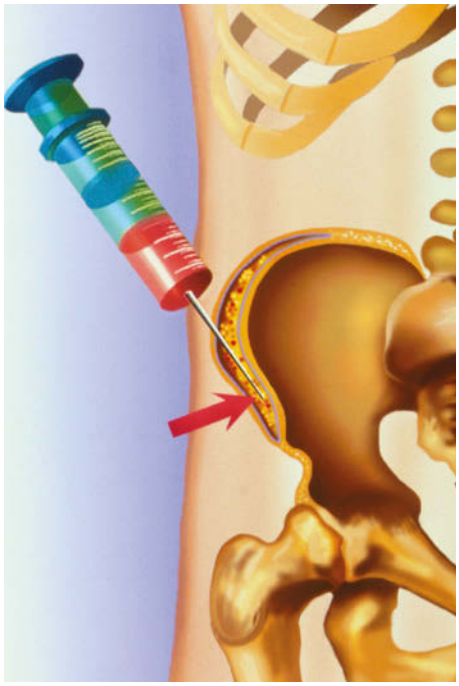


FIGURE 4.3.14 Harvesting bone marrow. The donor's bone marrow, which produces blood cells, is removed from the pelvis by syringe. The collected marrow is then filtered and treated before it is infused into the recipient.

There are several sources of adult stem cells in the human body, including bone marrow and blood, cord blood, the intestines and the epidermis.

Bone marrow and blood stem cells

Bone marrow is the soft, fatty tissue found within bones. Bone marrow contains multipotent stem cells (called haematopoietic stem cells) that differentiate to give rise to all of your blood cells. Harvesting bone marrow or blood stem cells involves collecting the stem cells from a healthy patient. For bone marrow transplants, the bone marrow is taken from the pelvic region by inserting a large needle into the bone and withdrawing the marrow with a syringe. This procedure, which is shown in Figure 4.3.14, can be painful for the donor.

An easier and less painful procedure is to collect stem cells that are circulating in the blood. Peripheral blood stem cells are different from bone marrow stem cells, but the two stem cell types have similar degree of potency. To collect peripheral blood stem cells, a patient is connected to a machine and their blood is filtered to collect the stem cells, while the rest of the blood is returned to the patient, as shown in Figure 4.3.15.

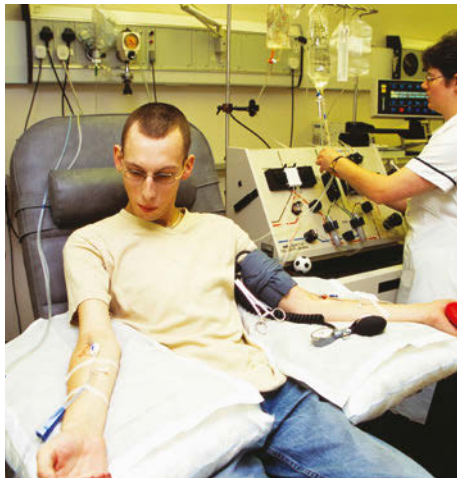


FIGURE 4.3.15 Harvesting stem cells from the blood of a patient. Blood is being taken from one arm, passed through the machine to retrieve the stem cells, and then returned to the other arm.

Cord blood stem cells

Blood stem cells can also be taken from **cord blood**, which is blood taken from the umbilical cord after the birth of a baby (Figure 4.3.16). This blood contains 'adult' stem cells for the blood and immune systems in the body. The stem cells in cord blood are younger and healthier than stem cells from adult bones.

FIGURE 4.3.16 A donated human placenta being prepared for the harvesting of umbilical cord stem cells

Intestinal stem cells

The lining of the intestines is a vital tissue in humans because it is the layer across which nutrients are absorbed into the body. The epithelial lining of the intestines has a remarkable ability to repair and renew itself because it contains adult stem cells. Scientists in the USA first harvested viable stem cells from the human intestine in 2013, and research into the possible uses of intestinal stem cells is continuing. Figure 4.3.17 shows a section of the small intestine with epithelial cells.

Epidermal stem cells

The skin is a very important organ because it regulates body temperature and acts as a barrier against pathogens. Like the intestines, it also has a remarkable ability to repair and renew itself after damage, using adult epidermal stem cells.

Skin stem cells are already being used to treat patients. Epidermal skin cells harvested from a person can be used to grow epidermis in a laboratory, as shown in Figure 4.3.18. These new layers of epidermis can then be grafted onto patients who have lost significant amounts of skin through, for example, third-degree burns.

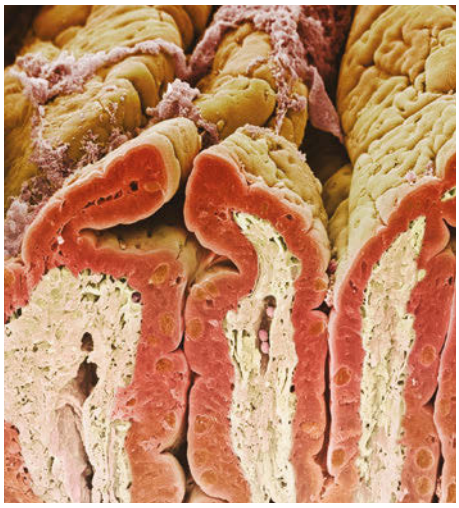


FIGURE 4.3.17 A scanning electron micrograph of a section of the small intestine. The surface consists of deep folds, and the surface (epithelial) cells are shown in red. These cells are able to repair and renew very rapidly with the help of the adult stem cells present.

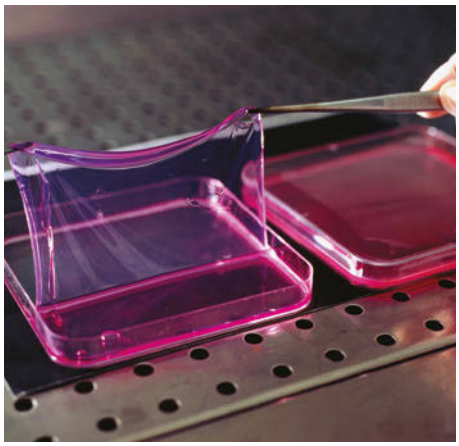


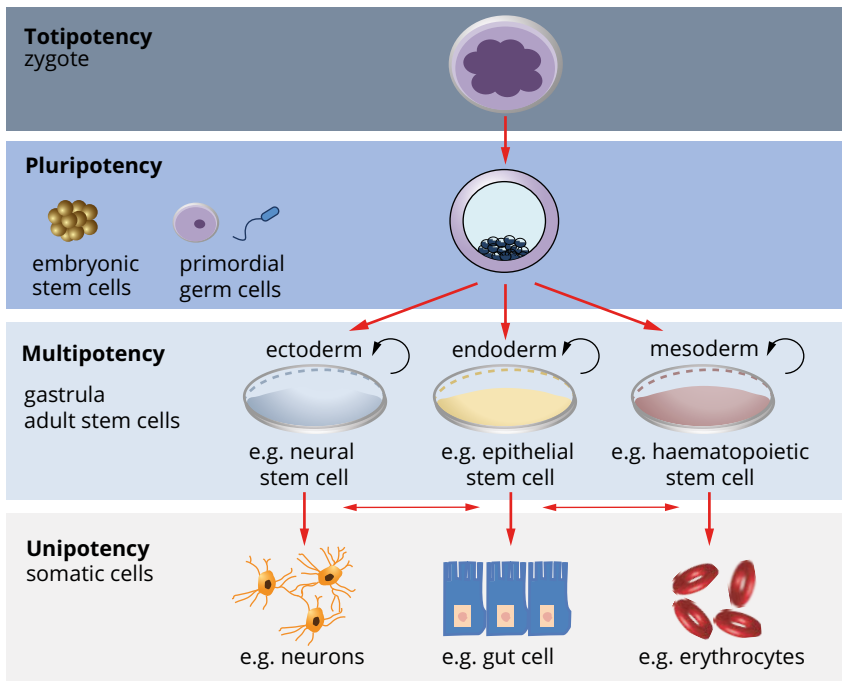
FIGURE 4.3.18 Artificially grown human skin being removed from a culture dish to make a skin graft. The cultures are made by transferring epithelial skin cells onto fibrin gel. The gel contains the nutrients needed by the cells to multiply and form skin. It takes only 3 weeks to grow a square metre of cultured skin.

Potency

Scientists also characterise stem cells by their cell potency. **Cell potency** is a cell's ability to differentiate into other cells types. The more cell types into which a cell can differentiate, the greater its potency. Stem cells are classified as totipotent, pluripotent, multipotent or unipotent, depending on what sort of cells they can become:

- **totipotent** stem cells, which are capable of giving rise to any cell type and a complete organism. A zygote and its divisions up to the 16-cell morula stage are the only stem cells that are totipotent
- **pluripotent** stem cells, which can differentiate into any of the three germ layers: endoderm (e.g. lungs and gut lining), mesoderm (e.g. muscle, bone, blood), or ectoderm (e.g. skin and nervous system). Pluripotent stem cells cannot develop into a complete organism. These cells are present in the blastocysts. The primordial germ cells that give rise to gametes are also pluripotent
- **multipotent** stem cells, which have the ability to give rise to multiple, but limited, cell types. Haematopoietic (blood-forming) stem cells from red bone marrow are an example of this cell type, as they can give rise to lymphocytes, macrophages, platelets and other blood cells
- **unipotent** stem cells, which can only differentiate into one cell type found in a specific tissue but can divide repeatedly. Skin epidermal stem cells are examples of unipotent cells that give rise only to new skin cells.

Embryonic stem cells are pluripotent. Adult stem cells are multipotent or unipotent. The four potencies of stem cells and the life stages in which they are found are outlined in Figure 4.3.19.



WS 1.2.4

FIGURE 4.3.19 Stem cell potency is determined by how many cell types the stem cell can differentiate into. Totipotent cells have the greatest cell potency, followed by pluripotent cells, then multipotent cells.

Stem cells in other organisms

Stem cells are found in most adult organisms. Some organisms, such as the free-living planarians shown in Figure 4.3.20 and sea stars, retain a population of pluripotent stem cells throughout their life. These stem cells can develop into specific tissues, giving these organisms the remarkable ability to regenerate a body part that is completely lost through injury. This process is illustrated in Figure 4.3.21. While stem cells are found in many different organisms, this section will focus on human stem cells.

FIGURE 4.3.20 This marine planarian, or flatworm, has a population of stem cells that enables it to regenerate if severed.

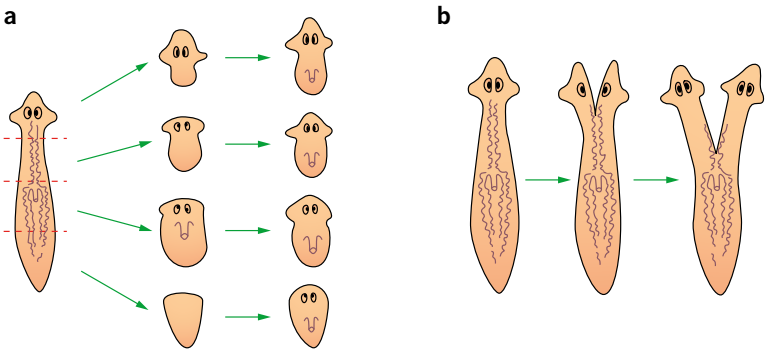


FIGURE 4.3.21 Planarians can regenerate completely after being cut in half. (a) A planarian that has been cut transversely. (b) A planarian that has been cut longitudinally. Anterior regions are able to regenerate a new head faster than more posterior regions.

Stem cell therapy

Stem cell research has the potential to revolutionise medicine through stem cell therapy. In the first instance, the ability to control cell division and differentiation would mean the ability to generate healthy laboratory-cultured tissues and organs to replace damaged ones. Stem cell research to date has also shown limited results from injecting either embryonic or adult stem cells directly into an individual to assist with repairing damage within the body. For example, engineered adult stem cells have been injected into individuals with cardiovascular disease, which has led to some regeneration of heart tissue.

For stem cell therapy to be considered successful:

- stem cells must be able to replicate themselves in cultures within a laboratory
- stem cells must be able to differentiate into the particular cells required to treat the disease or disorder
- stem cells must not remain as self-renewing stem cells with the potential to grow out of control
- the immune system must not reject the stem cells or tissue formed from stem cells. There is evidence that the immune system may tolerate embryonic stem cells better than foreign adult stem cells.

However, several ethical considerations need to be resolved before stem cell therapy becomes widely accepted. The primary ethical considerations of embryonic stem cell therapy relate to the destructive use of embryos. The first harvesting techniques for embryonic stem cells involved the destruction of embryos at the blastocyst stage. While stem cell research has the potential to prevent or alleviate suffering through the treatment of various diseases and disorders, some people consider the destruction of embryos as the destruction of human life or, at least, the potential for human life.

Consequently, new harvesting techniques that do not damage the embryo are being developed. One current area of interest in cell biology is the development of induced pluripotent stem cells (iPSCs).

iPSCs are adult cells that have been genetically reprogrammed to an embryonic stem cell-like state. This forces the cell to express genes and factors that are characteristic of embryonic stem cells. Although iPSCs by definition are pluripotent stem cells, it is not known whether there are clinical differences in these two stem cell types.

In 2015, researchers from the University of California, USA, published the results of a study in which they used human iPSCs to grow miniature 'beating hearts'. These were nothing like the four-chambered heart inside your chest, but the cells did form hollow, pulsating chambers rather than simple layers of cells. Previously, stem cells had been grown in wells that were about 2.5 cm in diameter, such as those shown in Figure 4.3.22, and under these conditions they only grew into flat sheets of cells.

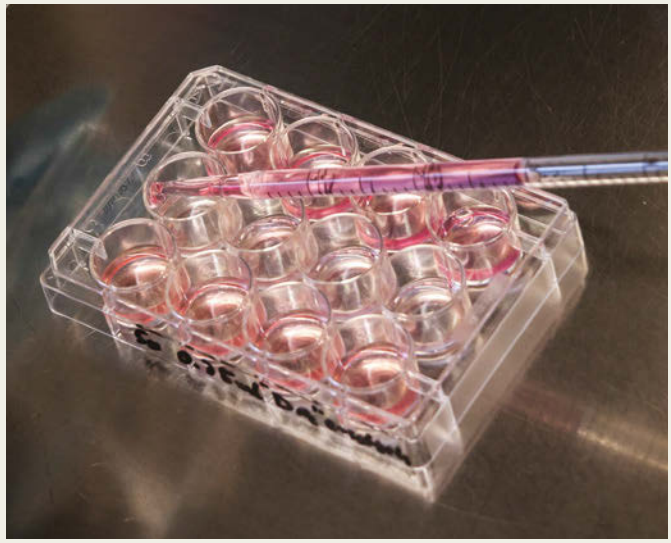


FIGURE 4.3.22 A standard 12-well culture dish containing human stem cells

To create the beating chambers, the researchers created tiny wells in the bottom of a petri dish only 200–600 µm wide—the thickness of a few strands of human hair. They then took iPSCs that had been genetically reprogrammed from human skin tissue and grew them in the tiny wells. The stem cells formed 'microchambers' because the mechanical pressure on the cells on the outside caused them to develop into cells that produced collagen, while the cells on the inside developed into heart muscle cells.

Once they had produced the beating microchambers, the researchers added thalidomide, a drug that causes heart defects and deformities in foetuses. The drug made it difficult for the microchambers to contract, which resulted in them beating slower than ones that had not been exposed to thalidomide.

Stem cells will not be used to produce replacement hearts for people in need of heart transplants any time soon, but thanks to this new research, the creation of beating heart microchambers that can then be used to test drugs for any side effects on heart chamber formation is now a reality.

Review

1. Describe what is meant by an iPSC (induced pluripotent stem cell).
2. Outline a benefit of using iPSCs rather than embryonic stem cells.
3. Explain the benefit of using beating heart microchambers to test drugs for side effects on the heart.

4.3 Review

SUMMARY

- All multicellular organisms start life as a single cell, known as a zygote.
- Cell replication and differentiation enable a single cell to produce all of the highly specialised cells in a multicellular organism.
- Cell differentiation is the process by which unspecialised cells, called stem cells, become specialised cells.
- Specialised cell function results from expression of particular sets of genes.
- There are two main types of stem cells: embryonic stem cells and adult stem cells.
- Embryonic stem cells can be thought of as 'all-purpose' cells that have the potential to develop into many different kinds of cells; stem cells are relatively undifferentiated cells.
- Stem cells can also be defined according to their potency, which refers to the number of different types of cells a stem cell can give rise to.
- Embryonic stem cells are pluripotent, which means they can differentiate into any of the three germ layers: endoderm (e.g. lungs and gut lining), mesoderm (e.g. muscle, bone, blood) or ectoderm (e.g. skin and nervous system). However, they can not develop into a complete organism.
- Adult stem cells are classified as either multipotent or unipotent.
- Multipotent stem cells can give rise to multiple, but limited, cell types (e.g. haematopoietic stem cells can only give rise to blood cells).
- Unipotent stem cells can only give rise to one cell type in a specific tissue but can divide repeatedly.

KEY QUESTIONS

Retrieval

1 Recall the three germline layers in a blastocyst.

2 Recall the name of an undifferentiated cell that has the potential to become any cell type.

3 Recall where stem cells are present in:
   a plants
   b mammals.

4 Classify the following cell types with their correct potency.
   a zygote
   b embryonic stem cell
   c adult stem cell

Comprehension

5 Explain the role of gene expression in cell differentiation.

6 Describe how embryonic stem cells differ from adult stem cells.

7 Explain the role of adult stem cells in the lining of the human intestines.

Analysis

8 Refer to Table 4.3.1 on page 137. Select a cell type and assess how its structure assists its function.

9 Differentiate between a zygote and a foetus.

Chapter review

04

KEY TERMS

adult stem cell
blastocyst
cell differentiation
cell potency
colony
cord blood
embryo
embryonic stem cell
epidermis
foetus
gastrula
gastrulation
germ layer
mitosis
morula
multipotent (cell)
organ
pluripotent (cell)
specialised cell
stem cell
tissue
totipotent (cell)
unicellular
unipotent (cell)
zygote

KEY QUESTIONS

Retrieval

1 Name the kingdom that consists solely of unicellular organisms.
- **A** Animalia
- **B** Archaebacteria
- **C** Fungi
- **D** Protista

2 Recall which organ in flowering plants is primarily responsible for reproduction.
- **A** leaves
- **B** flowers
- **C** roots
- **D** stems

3 A fertilised egg is also known as:
- **A** a blastocyst.
- **B** an embryo.
- **C** a gastrula.
- **D** a zygote.

4 Embryonic stem cells are:
- **A** totipotent.
- **B** pluripotent.
- **C** multipotent.
- **D** unipotent.

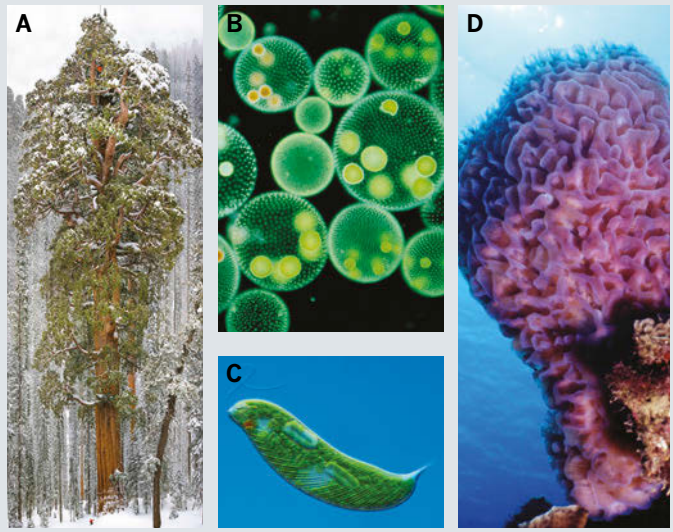
Comprehension

5 The stomach is an example of:
- **A** a specialised cell.
- **B** a tissue.
- **C** an organ.
- **D** a system.

6 Explain the difference between a tissue and an organ.

7 Planarians (flatworms) retain a population of totipotent stem cells throughout their life. Describe how this observation explains why a planarian, when cut in half, can regenerate.

8 Identify the image that represents a:
- **a** unicellular organism
- **b** simple colony of unicellular organisms
- **c** tissue-less multicellular organism
- **d** complex multicellular organism.

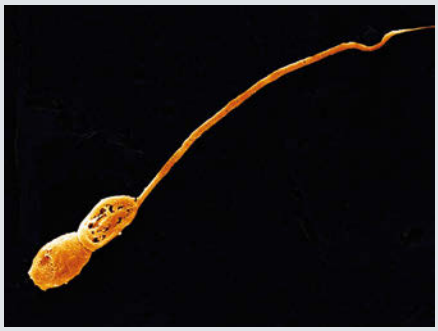


9 Construct a flowchart that shows the levels of organisation in complex plants and animals, indicating how these groups of organisms are similar.

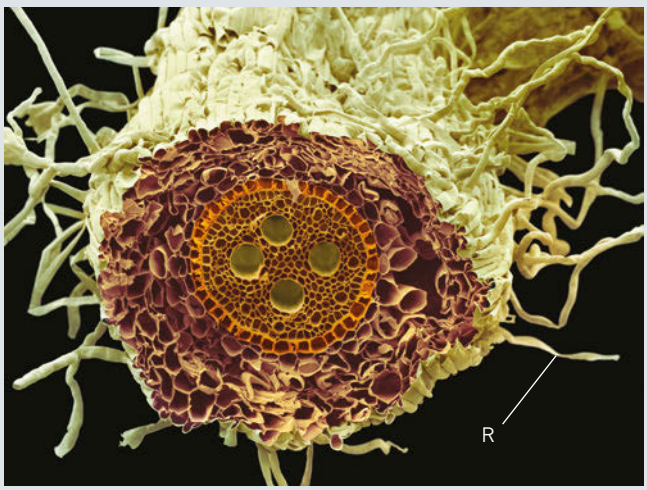
10 Explain the role of gene expression in cell specialisation.

Analysis

11 Determine which level of cellular organisation best characterises the following image.



12 The following image shows a scanning electron micrograph of a root.



a Explain how cell R is specialised in its function.

b The root is an organ. Using the root as an example, outline how the cells are organised from an organ.

13 Organ transplant is the process of removing an organ from a donor and inserting it into a recipient. According to Australia's 2015 donor records, 435 deceased organ donors donated to a total of 1239 transplant recipients.

a Deduce how it is possible for there to be more recipients than donors.

b Assuming each transplant recipient received one organ, calculate the average number of organs donated by a deceased organ donor.

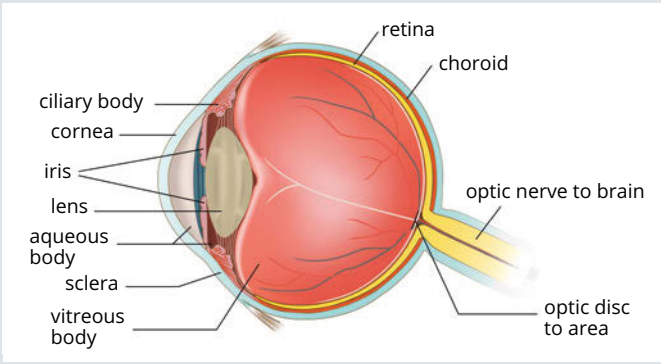
14 This table outlines the various organ transplants that occurred in Australia in 2015.

Organ	Number
Kidney	718
Liver	247
Heart	95
Lung	375
Pancreas	45
Intestine	1
Total	1481

Data source: *Organ Donation in Australia and New Zealand 2016 Annual Report*, Australian and New Zealand Organ Donation Registry, http://www.anzdata.org.au/anzod/ANZODReport/2016/2016-anzod-01-organdonation-v3.0_20160820.pdf

Calculate what percentage of donated organs were kidneys.

15 The following image shows some of the parts of the human eye.

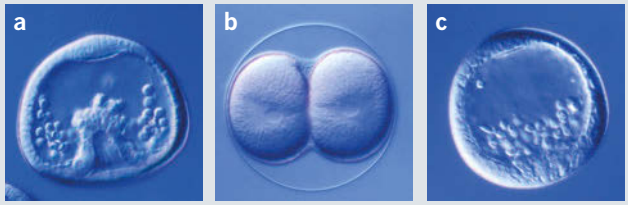


Corneal transplants enable the cornea to be replaced if it is diseased or damaged. Only the cornea can be transplanted, not the entire eye.

Categorise the level of cellular organisation of the cornea.

16 There are many types of stem cells and ways for them to be obtained. Determine which type of stem cell and which method of obtaining them you have the fewest ethical objections to.

17 Determine with reason why the order of embryonic development is from diagram **b** to **c** then **a**.



Knowledge utilisation

18 A student stated that complex multicellular organisms were the most successful forms of life. Critique the student's assertion.

19 Research a multicellular organism indigenous to your area and identify three specialised cell types. For each cell type:

- **a** explain how its structure relates to its function
- **b** list the tissue, organ and system the cell belongs to
- **c** identify the germ line from which the specialised cell orginated.

CHAPTER

05 Organ systems

In this chapter, you will learn how multicellular organisms conduct the complex tasks of moving substances into and out of their bodies. The mechanisms via which products enter and leave an organism demonstrate not only the organism's level of complexity, but also the particular demands of the environmental niche in which the organism lives.

Gas exchange is a fundamental process for all organisms. It is a limiting factor and one that determines where and how an organism lives. The attainment of nutrients is also a fundamental process for organisms. Once inside an organism, nutrients, products of metabolism and wastes all need to be transported, usually from the point of manufacture or acquisition, to the point of use, storage or elimination from the body. While these processes vary between species, they each are suited to the environment in which the species resides, which enables them to compete successfully for resources.

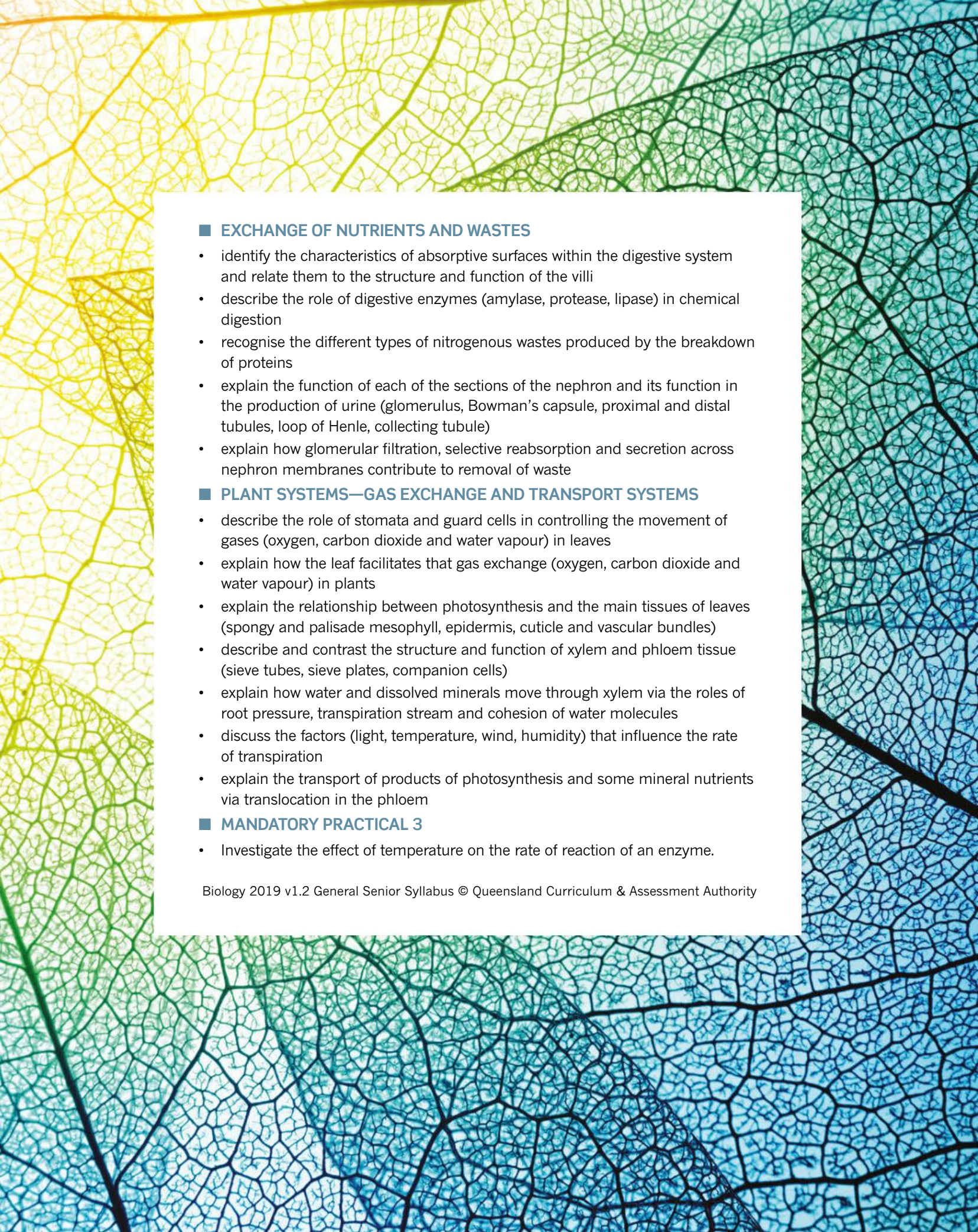
You will learn how plants and animals exchange gases with their environment. You will also explore how plants and animals move substances around their bodies, and you will discover how organisms access and assimilate nutrients as well as removing substances from the body. While various systems are discussed separately, it is important to remember that many of their functions overlap and that they work in a coordinated way for the survival of the organism as a whole.

Syllabus subject matter

Topic 2 • Multicellular organisms

GAS EXCHANGE AND TRANSPORT

- explain the relationship between the structural features (large surface area, moist, one or two cells thick and surrounded by an extensive capillary system) and function of gaseous exchange surfaces (alveoli and gills) in terms of exchange of gases (oxygen, carbon dioxide)
- explain how the structure and function of capillaries facilitates the exchange of materials (water, oxygen, carbon dioxide, ions and nutrients) between the internal environment and cells
- use data presented as diagrams, schematics and tables to predict the direction in which materials will be exchanged between:
  - alveoli and capillaries
  - capillaries and muscle tissue



EXCHANGE OF NUTRIENTS AND WASTES

- identify the characteristics of absorptive surfaces within the digestive system and relate them to the structure and function of the villi
- describe the role of digestive enzymes (amylase, protease, lipase) in chemical digestion
- recognise the different types of nitrogenous wastes produced by the breakdown of proteins
- explain the function of each of the sections of the nephron and its function in the production of urine (glomerulus, Bowman's capsule, proximal and distal tubules, loop of Henle, collecting tubule)
- explain how glomerular filtration, selective reabsorption and secretion across nephron membranes contribute to removal of waste

PLANT SYSTEMS—GAS EXCHANGE AND TRANSPORT SYSTEMS

- describe the role of stomata and guard cells in controlling the movement of gases (oxygen, carbon dioxide and water vapour) in leaves
- explain how the leaf facilitates that gas exchange (oxygen, carbon dioxide and water vapour) in plants
- explain the relationship between photosynthesis and the main tissues of leaves (spongy and palisade mesophyll, epidermis, cuticle and vascular bundles)
- describe and contrast the structure and function of xylem and phloem tissue (sieve tubes, sieve plates, companion cells)
- explain how water and dissolved minerals move through xylem via the roles of root pressure, transpiration stream and cohesion of water molecules
- discuss the factors (light, temperature, wind, humidity) that influence the rate of transpiration
- explain the transport of products of photosynthesis and some mineral nutrients via translocation in the phloem

MANDATORY PRACTICAL 3

- Investigate the effect of temperature on the rate of reaction of an enzyme.

5.1 Animal transport systems

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

- understand how the structure and function of capillaries enables efficient exchange of substances.

The function of transport systems is similar in all organisms: to transport nutrients to cells and remove wastes from them. In simple multicellular organisms, nutrients are transported by diffusion between cells. However, diffusion only works over short distances from cell to cell. In large, complex animals, diffusion is not sufficient to deliver essential nutrients to all of the organism's cells. Moreover, not every cell in a multicellular organism has equal access to the external environment. It is for these reasons that specialised circulatory systems, with networks of pipes and chambers, have evolved to transport vital nutrients to all cells in complex multicellular organisms.

OPEN AND CLOSED CIRCULATORY SYSTEMS

There are two broad types of transport systems for multicellular organisms: **open circulatory systems** and **closed circulatory systems**.

Arthropods, including insects, have an open circulatory system. The primary function of open circulatory systems is to provide nutrients and remove wastes.

An open circulatory system has a heart or heart-like structure but no blood vessels (Figure 5.1.1). The blood-like fluid in an open circulatory system is called haemolymph. Haemolymph mostly consists of water and usually carries biomolecules such as proteins, lipids and carbohydrates, as well as wastes such as nitrogenous wastes.

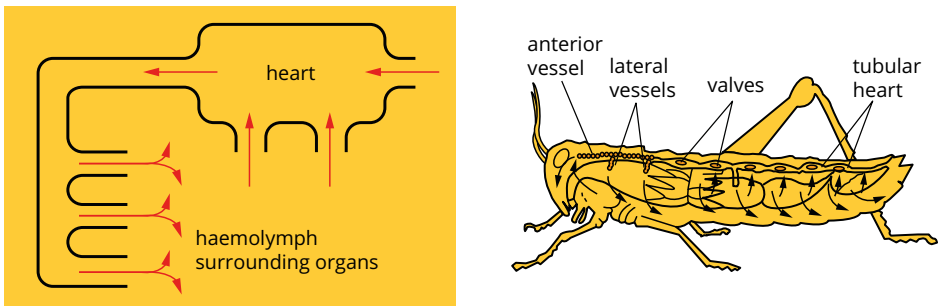


FIGURE 5.1.1 The open circulatory system of a grasshopper supplies the body cells with nutrients and oxygen and transports wastes away from the cells to the organs that excrete them.

In humans and all other vertebrates, the circulatory system is a closed system, as shown in Figure 5.1.2. In a closed circulatory system, the blood is enclosed within a system of blood vessels and the heart. In other words, unlike open circulatory systems, blood never leaves the vessels in which it is carried. Typically, a closed system involves:

- a multi-chambered heart
- vessels that carry the blood away from the heart
- specialised vessels called capillaries, which allow the exchange of substances between the blood and the tissues it is servicing
- vessels that return the blood to the heart.

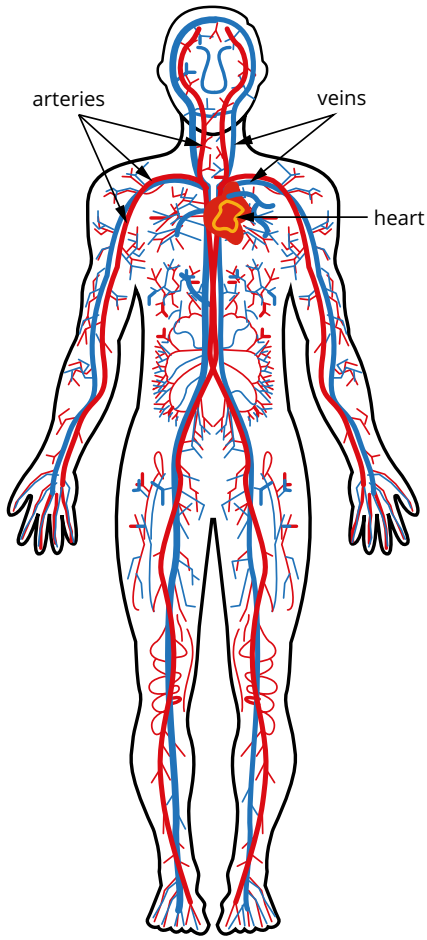


FIGURE 5.1.2 The human circulatory system is an example of a closed circulatory system. The blood in a closed circulatory system is always contained within a system vessels and a heart.

DISTRIBUTING MATERIALS: MAMMALIAN TRANSPORT SYSTEMS

The structure and function of transport systems are similar in all mammals. Mammals have two transport systems: the blood circulatory system and the lymphatic system (Table 5.1.1).

TABLE 5.1.1 Mammalian transport systems

Blood circulatory system	Lymphatic system
• is a closed circulatory system	• is an open circulatory system
• uses blood as the circulatory fluid	• circulates colourless **lymph** fluid
• transports the majority of substances to and from cells in mammals	• plays vital roles in maintaining osmotic and fluid balance in tissues and supporting immune defences

THE CIRCULATORY SYSTEM

The mammalian circulatory system is a closed system that transports substances throughout the body (Figures 5.1.2 and 5.1.3). The vital metabolic products of the body are transported via the blood. The blood and the circulatory tissues and organs ensure that all cells have a ready supply of nutrients and oxygen and a means to transport away metabolic wastes. In mammals, the highly branched network of the circulatory system means that no cell is more than 1 mm from a capillary. This ensures there is efficient nourishment and waste removal for all cells in the body.

Circulation pathways

Blood circulates around the body via two sequential pathways, as shown in Figure 5.1.3.

- Pulmonary circulation transports blood to and from the lungs. Deoxygenated blood is pumped from the heart to the lungs, where it is oxygenated before returning to the heart.
- Systemic circulation transports blood to and from the rest of the body. This system is larger than the pulmonary circulatory system because the heart must pump blood to all the organs in the body. Oxygenated blood is pumped from the heart to the organs, where it gives up its oxygen to the cells, before returning to the heart.

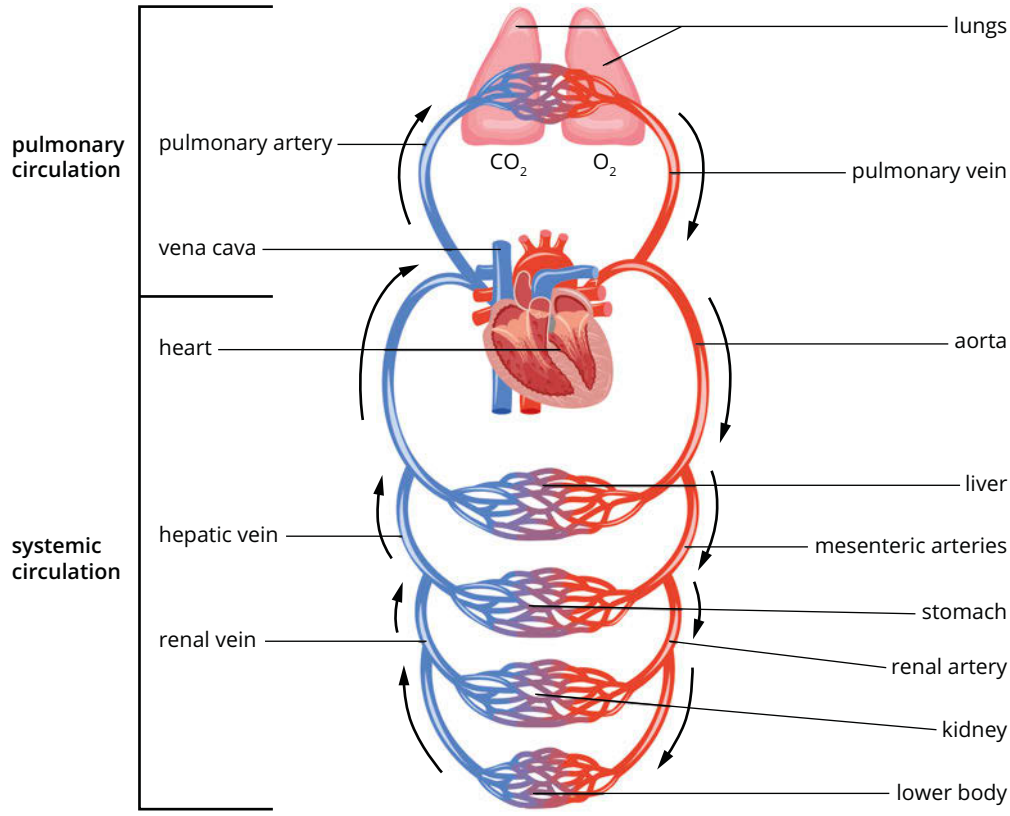


FIGURE 5.1.3 Pulmonary circulation transports blood to and from the lungs. Systemic circulation transports blood to and from all the systems in the mammalian body.

Components of the circulatory system

The key components of the circulatory system are:

- the heart, which in humans is a four-chambered muscular pump with two pumping chambers (ventricles) and two receiving chambers (atria). It is responsible for moving blood throughout the circulatory system. The right side of the heart pumps deoxygenated blood, while the left side pumps oxygenated blood
- veins and arteries, a network of muscular vessels carrying blood to and from the heart, are divided into:
  - pulmonary vessels, which carry blood to and from the lungs
  - systemic vessels, which carry blood to and from all other parts of the body
  - capillaries, which are numerous very fine vessels with thin walls that provide a large surface area across which exchange of substances occurs and which connect the arteries and the veins
- blood, which is the circulating fluid and is highly specialised for transport and immune defence.

The heart

The mammalian heart is in the centre of the chest, between the lungs, surrounded by the protective rib cage. It consists of a number of tissues including cardiac muscle (Figure 5.1.4), **connective tissue** and nerve tissue. Connective tissue makes up the **valves**, and nerve tissue controls the heart rate.

The mammalian heart has four chambers, as shown in Figure 5.1.5. The upper receiving chambers, which have thinner walls, are the atria. Each **atrium** opens into one of the lower, thicker-walled chambers, called **ventricles**. Blood moves through the heart in one direction because of the presence of four one-way valves: one between each atria and the ventricle below, and one between each ventricle and its outgoing artery.

Both sides of the heart function in a coordinated way: first, both atria contract; then, both ventricles contract.

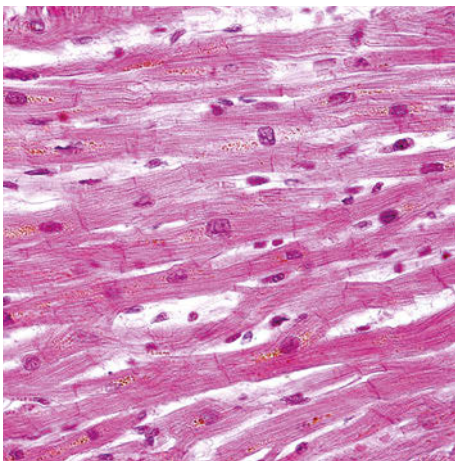


FIGURE 5.1.4 Cardiac muscle tissue is made of highly specialised muscle cells that are found only in the heart. The dark bodies are nuclei.

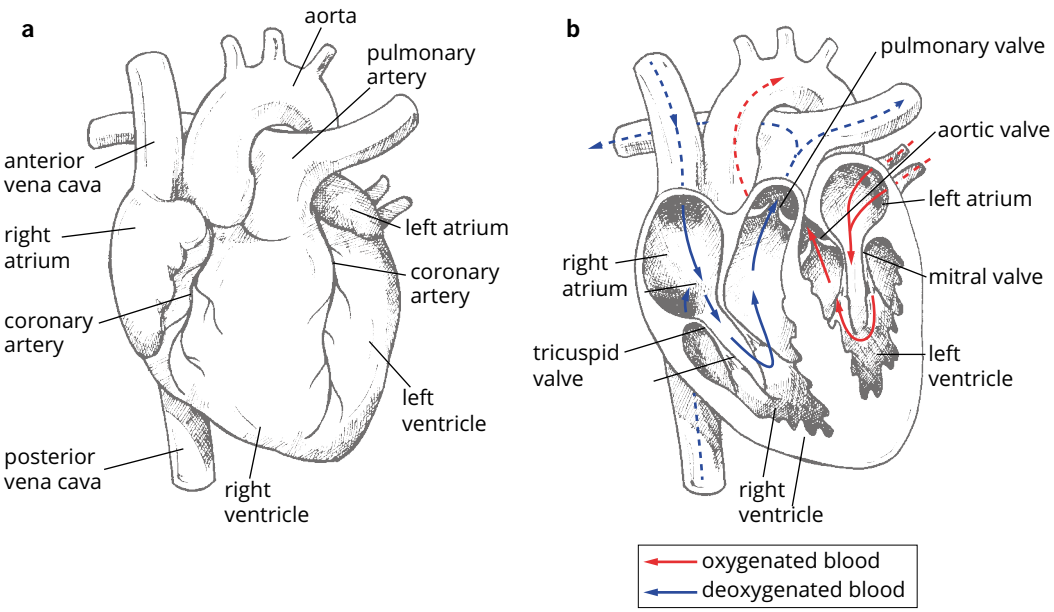


FIGURE 5.1.5 The human heart. (a) View of the ventral surface of the heart. (b) Ventral surface opened to show the major vessels, valves and the greater thickness of the left ventricle.

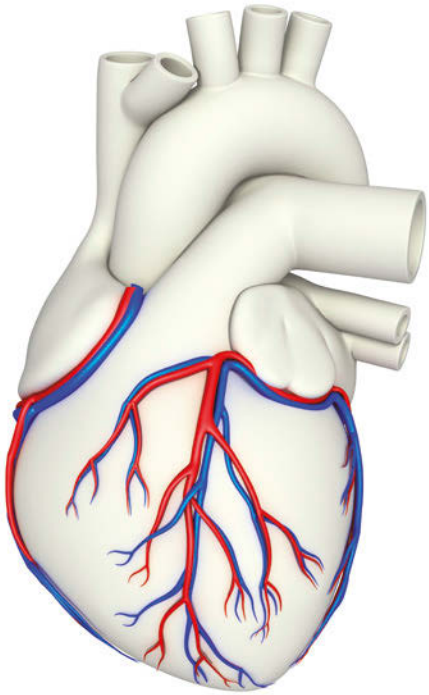


FIGURE 5.1.6 The coronary system, showing the coronary arteries (red) and cardiac veins (blue)

Deoxygenated blood (blood with a low oxygen concentration), returns from the body through the venae cavae (singular, vena cava), flowing into the right atrium and through the tricuspid valve into the right ventricle as both chambers relax between contractions. The atrium contracts first, further filling the right ventricle. As the ventricle contracts, the rising ventricular pressure closes the tricuspid valve (between the right atrium and right ventricle) and opens the pulmonary valve (between the right ventricle and the opening of the pulmonary artery), causing blood to be ejected into the pulmonary artery towards the lungs.

In the lungs, blood loses carbon dioxide and gains oxygen by diffusion as blood flows through the narrow capillaries around the alveoli. Oxygenated blood (blood with a high oxygen concentration) returns from the lungs to the left atrium through the **pulmonary veins**. The contraction of the atrium forces the blood into the left ventricle. When the left ventricle contracts, oxygenated blood is pumped out of the left ventricle to the rest of the body via the **aorta**. The mitral valve also closes, preventing backflow into the atrium.

During a complete circuit around the body, blood passes through each side of the heart. In humans, one complete circuit takes about 45 seconds.

The coronary system

The heart is a continuously active muscular organ, so it has a high requirement for nutrients and oxygen. The cells of the heart have their own rich blood supply via the **coronary circulation**.

The coronary system begins at the base of the aorta and consists of vessels that spread across the surface of the heart and penetrate into the heart tissue (Figure 5.1.6).

Arteries, veins and capillaries

Blood vessels (Figure 5.1.7) are named according to their structure and position in the circulatory system:

- **arteries** (and smaller **arterioles**) transport blood away from the heart
- **veins** (and smaller **venules**) transport blood towards the heart
- **capillaries** are the narrow exchange vessels between arteries and veins.

Arteries and veins are composed of the same layers of tissue, but arteries have more muscular walls to withstand the pressure of the blood as it is pumped out of the heart. Veins are more easily stretched and also contain valves, to prevent blood from flowing backwards. Capillaries have very thin walls consisting of only a single layer of flattened epithelial cells.

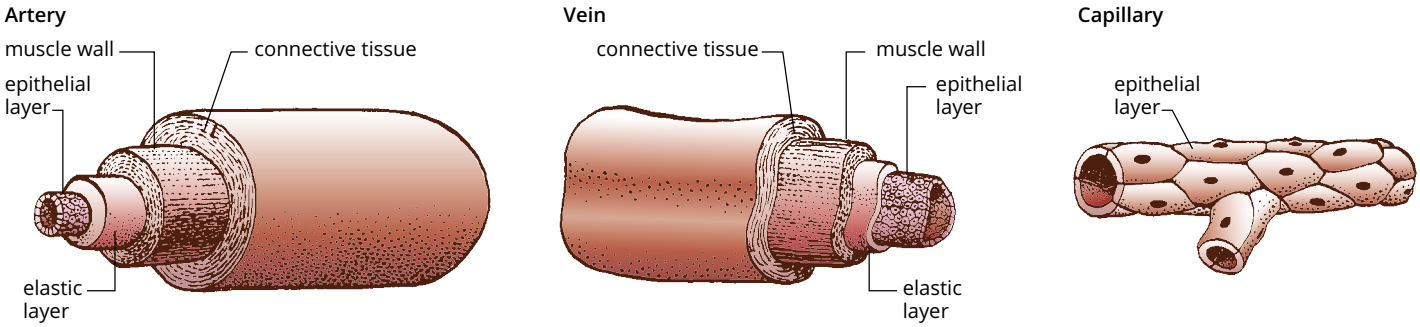


FIGURE 5.1.7 Wall structures of an artery, a vein and a capillary.

The structure, function and other features of the blood vessels in the circulatory system are summarised in Table 5.1.2.

TABLE 5.1.2 Structure and function of the blood vessels in the circulatory system

	Arteries	Veins	Capillaries
Structure	• consist of an epithelial layer of cells, an elastic layer, muscle wall and connective tissue • same structure as veins but thicker muscular walls	• consist of an epithelial layer of cells, an elastic layer, muscle wall and connective tissue • same structure as arteries but thinner muscle walls	• consist of a single layer of flattened epithelial cells • very thin walls
Function	• transport blood away from the heart	• transport blood towards the heart	• connect arteries to veins • deliver nutrients and other substances to extracellular fluids, and receive wastes
Other features	• higher blood pressure than veins	• contain many one-way valves • lower blood pressure than arteries	• very numerous • form a network within tissues to be near most cells

PA 1.2.1

Capillaries

Capillaries are the smallest of the blood vessels; their internal diameter is so small that blood cells have to travel through them in a single file (Figure 5.1.8). A capillary has a diameter of 5–10 μm, so red blood cells (about 7–10 μm in diameter) pass very close to the capillary walls. When the wall of a red blood cell presses against a capillary wall, there is an exchange of oxygen and carbon dioxide. The flattened shape and lack of a nucleus in red blood cells are believed to enhance their transport capability by increasing the surface area available for exchange. Their membrane structure makes them very flexible, allowing them to fold and squeeze through the narrow capillaries.

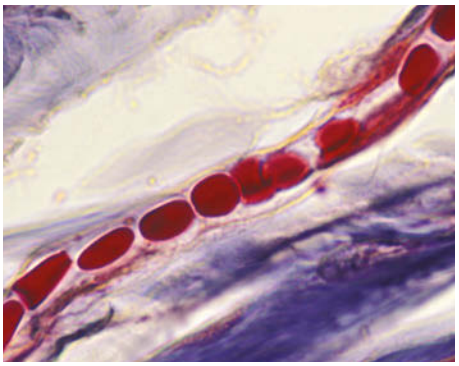


FIGURE 5.1.8 Red blood cells flowing in single file through a capillary

The capillaries connect arteries to veins, deliver oxygen, nutrients and other substances to extracellular fluids via diffusion, and receive carbon dioxide and other wastes. Capillary walls are extremely thin (just one epithelial cell thick) and porous, which allows substances to pass in and out of the circulatory system into **interstitial spaces**, tissue and cells. Because of their important role in the transport of oxygen and nutrients to tissues, capillaries are most abundant in metabolically active tissues and organs, such as muscle tissue.

Capillaries are distributed throughout the body as an enormous branched network, providing a vast surface area for the exchange of materials between the blood and extracellular fluid. The interwoven network of blood vessels is known as a capillary bed. To ensure that materials are transported rapidly and efficiently, most cells are no more than 1 mm away from the nearest capillary.

Exchange between blood plasma and extracellular fluid occurs by diffusion and filtration across capillary walls. Ions and small molecules such as glucose and amino acids diffuse through the capillary wall, along concentration gradients. **Filtration** occurs because of two opposite forces: hydrostatic pressure (or blood pressure) and osmotic pressure (Figure 5.1.9 on page 156). The pressure from these two forces pushes fluid into and out of the capillaries. Hydrostatic pressure is a result of blood pushing outwards on the capillary walls. Osmotic pressure results from the differing solute concentrations between the blood and the extracellular fluid.

Capillaries are one cell thick, allowing efficient exchange of materials via diffusion and filtration between the blood and interstitial spaces, tissues and cells.

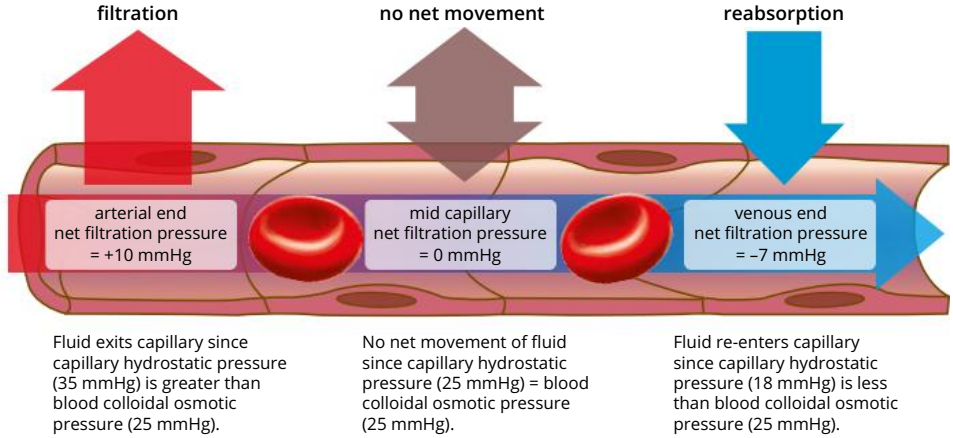


FIGURE 5.1.9 Filtration of fluid across capillary walls is a result of capillary hydrostatic pressure (blood pressure) pushing outwards and blood colloid osmotic pressure pushing inwards. Overall hydrostatic pressure is greater and so fluid leaks into the extracellular environment.

FIGURE 5.1.10 Centrifuged blood separates into plasma (clear yellow fluid) and the cellular elements (dark red solids).

Because blood is hypertonic (more concentrated) than the extracellular fluid, water tries to move through the capillary walls into the blood, putting an inward pressure on the capillaries. The pressure varies along the length of a capillary, but overall the hydrostatic pressure is greater than the osmotic pressure, so more fluid filters out of the capillary than filters in. You can see this in Figure 5.1.9. This pressure results in a small amount of protein leakage through the capillary wall cells. When blood pressure increases, this leakage is higher and can result in fluid loss to tissues, causing swelling. Reabsorption allows around 85% of the fluid to return to the capillaries, while the remaining 15% enters the lymphatic system.

In some tissues, such as the gut and **liver**, the capillaries are more permeable and allow large molecules to cross. This helps the absorption of digested foods from the gut and enables the liver to take in materials to be broken down. In contrast, capillaries in the brain have very low permeability, and access of substances to brain tissue is tightly controlled. Nerve tissue is very sensitive to its environment, so it is important that the composition of the extracellular fluid surrounding the brain and spinal cord is carefully regulated.

Blood

Mammalian blood is a fluid containing cells and cellular fragments. The fluid portion of blood is plasma, which is a pale yellow liquid, largely water by volume, and contains ions, dissolved gases, proteins, hormones, nutrients and wastes. The cellular elements of blood include red blood cells (erythrocytes), white blood cells (leukocytes) and platelets, as shown in Figure 5.1.10. They are produced by cells located in the red bone marrow, found in the upper ends of long bones and in flat bones like the skull, ribs and pelvis. Blood is a tissue because it is made up of many similar cells working together.

Red blood cells

In humans, red blood cells make up around 40% of the blood in females and 45% of the blood in males. A single drop of human blood contains about 5 million red blood cells. Mature red blood cells are concave on each side and highly flexible. They lack a nucleus and are full of the protein **haemoglobin**. Unlike carbon dioxide, oxygen is relatively insoluble. The function of haemoglobin is to bind the oxygen and transport it to the cells (see Module 5.2). Haemoglobin is also what gives red blood cells their red colour.

White blood cells

White blood cells are slightly larger than red blood cells, but there are far fewer of them (Figure 5.1.11a). A drop of blood contains 5000–10 000 white blood cells, but more are held in reserve in organs such as the spleen, kidney, thymus, thyroid gland and lymphatic tissue.

There are several different types of white blood cells. The two most numerous types are phagocytes (neutrophils) and lymphocytes, both of which are involved in defence against microorganisms (see Chapter 8 for more detail).

- Phagocytes remove debris and fight infections. They are attracted to a site of infection, squeeze through tiny gaps in capillary walls and engulf harmful bacteria and damaged cells.
- Lymphocytes are responsible for the production of antibodies and the development of immune responses.

Platelets

Platelets are fragments of cells. They are much smaller than red and white blood cells and contain substances that are important in preventing blood loss and promoting blood clotting. You can see platelets in Figure 5.1.11b.

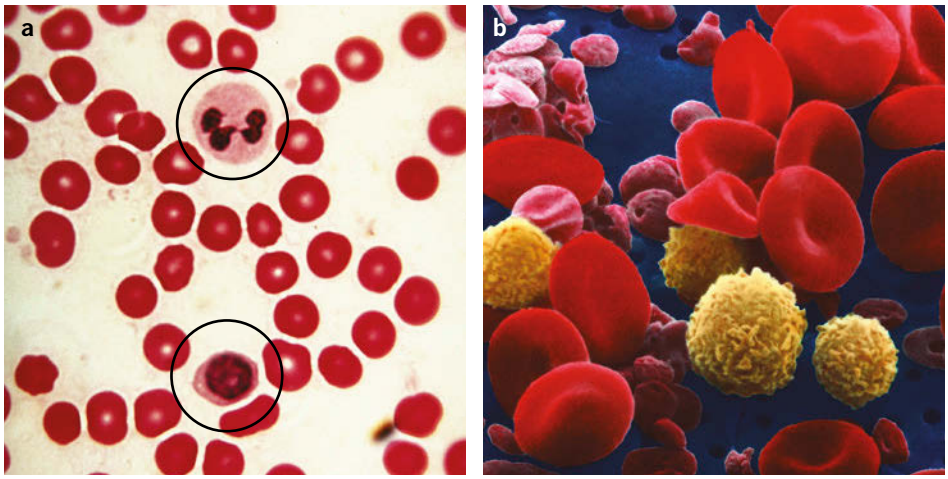


FIGURE 5.1.11 (a) Many red blood cells and two white blood cells (circled) viewed by light microscopy. (b) A coloured scanning electron micrograph showing human blood tissue. The red concave discs are red blood cells, the yellow spheres are white blood cells and the smaller pink cells are platelets.

WS 1.2.5

THE LYMPHATIC SYSTEM

The lymphatic system is the second transport system in mammals. The lymphatic system:

- is an open system
- consists of lymph vessels, lymph nodes and organs such as the thymus and spleen
- transports a colourless liquid called lymph
- transports lymph in one direction, from the tissues to the heart.

The lymphatic system has several roles. One of its main roles is to return extracellular fluid containing proteins that have leaked out of the capillaries back into the circulatory system. Without the constant removal of leaked proteins from the extracellular fluid by the lymph capillaries, fluid would accumulate in the tissues. Once inside the lymphatic system, this fluid is called lymph.

The structure of the lymphatic system is similar to the venous part of the circulatory system (Figure 5.1.12). Fine lymphatic capillaries join to form increasingly larger vessels that eventually empty into the large veins near the heart. The structures of lymph capillaries and vessels are similar to the capillaries and veins of the blood vascular system.

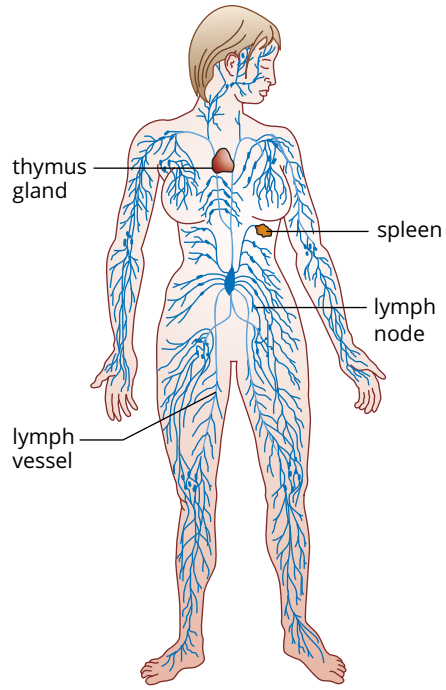


FIGURE 5.1.12 The distribution of lymph vessels throughout the body. The blood circulatory system loses around 3 litres of fluid into the extracellular fluid every 24 hours. The lymphatic system collects and returns this fluid to the circulatory system.

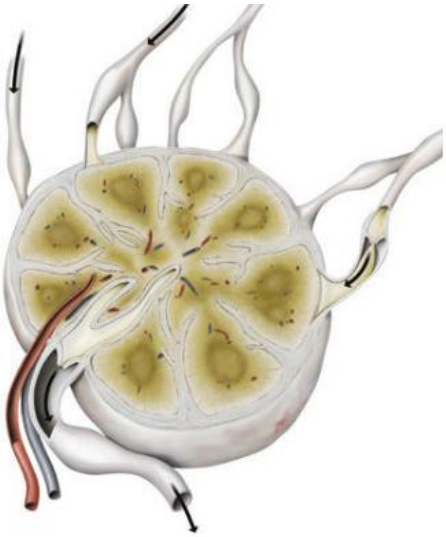


FIGURE 5.1.13 A cross-section of a lymph node. The lymphatic fluid enters the lymph node through lymph vessels where pathogens and cancerous cells are destroyed.

Some of the larger lymph vessels can contract, but most lymph flow results from the external compression of lymph vessels by muscular activity, such as during movement and breathing. When vessels are compressed, the lymph fluid is forced in one direction because of numerous one-way valves, like those in veins, located along the vessels. When a person is inactive (such as standing still or sitting) for a long time, the fluid drainage from tissues decreases and causes swelling. This is especially so in the legs, because fluid drainage must work against gravity.

The lymphatic system also plays a vital role in the immune system. Invading pathogens are transported in the lymph to the lymph nodes (Figures 5.1.12 and 5.1.13), where bacteria, viruses and cancer cells are trapped and destroyed by phagocytes and lymphocytes (see Chapter 8). This is why your lymph nodes swell when you have an infection.

Malfunction of the lymphatic system: deep vein thrombosis

People who sit for long periods of time, such as passengers on a long flight, are encouraged to stretch and exercise regularly to assist the movement of lymph and venous blood back to the heart. Failure to do this can result in swelling in the feet, ankles and legs because fluid accumulates in these areas. This can lead to a condition called deep vein thrombosis (DVT), a blood clot that forms in the veins of the leg. DVT can result in pulmonary embolism, a blockage of the main artery of the lungs, if the clot breaks away and is carried by the bloodstream to a lung and lodges there (Figure 5.1.14). A pulmonary embolism can cause difficulty in breathing, chest pain, heart palpitations and, if the clot completely blocks an artery, death. Regular exercise, a healthy diet and not smoking all reduce the risk of DVT.

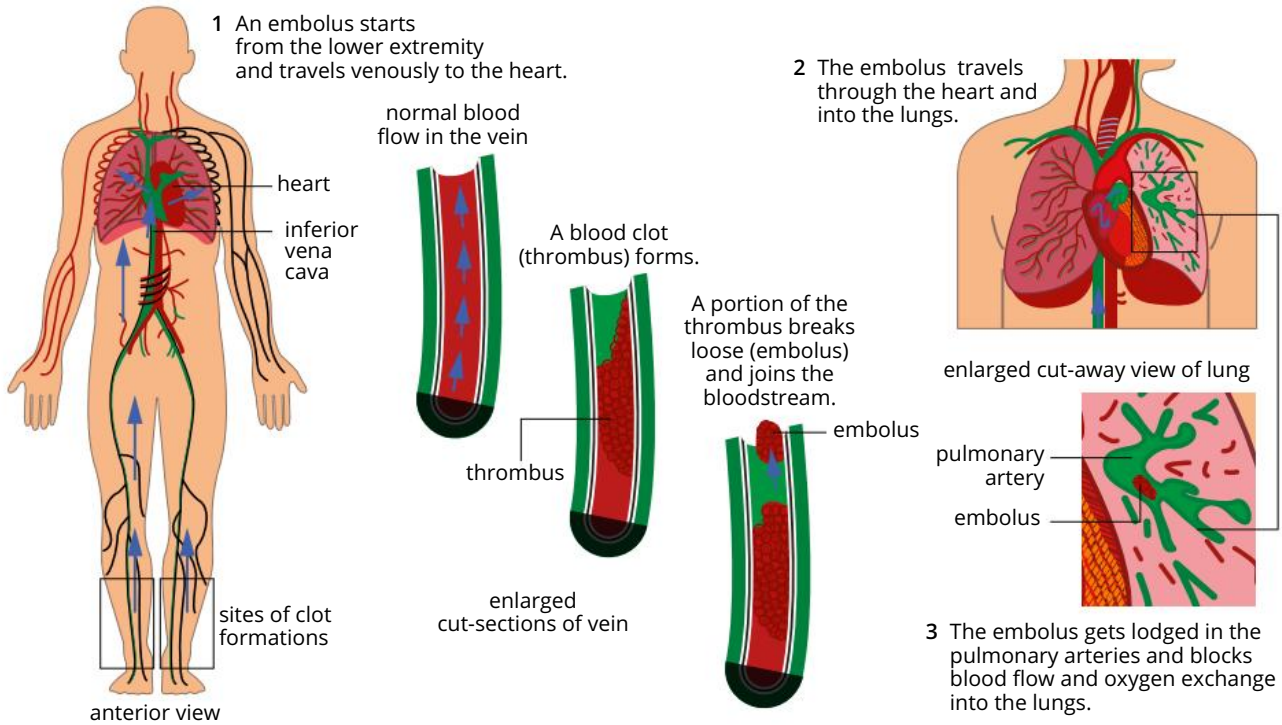


FIGURE 5.1.14 The mechanism of pulmonary embolism resulting from deep vein thrombosis (DVT). A pulmonary embolism can occur when a blood clot (embolus) breaks off and lodges in a lung, blocking oxygen exchange.

5.1 Review

SUMMARY

- There are two types of circulatory systems in animals: open circulatory systems and closed circulatory systems
- In closed circulatory systems, the blood is enclosed within a system of blood vessels and the heart.
- Mammals have two transport systems: the blood circulatory system and the lymphatic system.
- The blood circulatory system:
  - consists of the heart, veins, arteries, capillaries and blood
  - transports nutrients and oxygen to all cells in the body and transports metabolic wastes away from all cells in the body
  - has two sequential circulation pathways: pulmonary circulation (transports blood to and from the lungs) and systemic circulation (transports blood to and from the rest of the body).
- The lymphatic system:
  - consists of lymph vessels, lymph nodes and organs, such as the thymus and spleen
  - transports a colourless liquid called lymph
  - transports lymph in one direction, from the tissues to the heart
  - has several functions, one of which is returning extracellular fluid containing proteins that have leaked out of the capillaries back into the circulatory system.

KEY QUESTIONS

Retrieval

1 Describe the two pathways through which blood is circulated in mammals.

2 List the fluid and cellular components of blood.

3 Name the protein that binds with oxygen in red blood cells.

4 Recall the name of the condition that can be caused by excess fluid accumulating in the feet and legs during a long flight.

Comprehension

5 Describe the function of circulatory systems.

6 Name the two forces that are responsible for pushing fluid into and out of capillaries. Describe in which direction each of these exert pressure.

7 Explain the functions of the lymphatic system.

Analysis

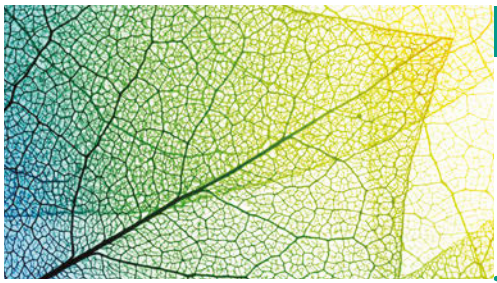
8 Compare open and closed circulatory systems.

9 A patient has extremely low blood pressure. Her colloid pressure is normal. Predict, using estimated values, the effect on net filtration pressure through her capillaries.

10 People with high blood pressure can have excess fluid accumulate in their tissues. This condition is known as oedema. Compare and distinguish the capillary filtration of healthy people and of people with oedema.

11 Compare the features of the circulatory system and the lymphatic system.

5.2 Gas exchange in complex animals



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

- understand the properties of efficient gas exchange surfaces
- understand the components of the mammalian respiratory system
- understand how complex animals obtain oxygen from their environment
- understand how the partial pressure of gas influences the rate and direction of gas exchange.

Gas exchange is a fundamental process for all organisms. As you will recall from Chapter 3, all organisms need to exchange oxygen and carbon dioxide with their environment to maintain the important energy-transforming process: cellular respiration. Disruption of this exchange—for example, by respiratory illness in humans—can have serious consequences.

Animals generally have active lifestyles and high energy demands. Their systems are specialised to suit the demands of the environment in which they exist. The respiratory system is responsible for gas exchange in complex animals. It is important to distinguish the organ system of respiration from cellular respiration. Cellular respiration functions to convert nutrients to energy within a cell, while the organ respiratory system in complex animals transports carbon dioxide and oxygen between cells and the external environment.

EFFICIENT GAS EXCHANGE SURFACES

FIGURE 5.2.1 The smallest bat, *Craseonycteris thonglongyai* shown here with a baby attached, is too large to exchange gases directly with its environment. Like all mammals, it has a complex respiratory system to obtain oxygen from the air and expel carbon dioxide.

In **aerobic** (oxygen-dependent) organisms, a constant supply of oxygen to cells is required for cellular respiration to occur. Carbon dioxide, which is a waste product of cellular respiration, forms a weak acid in solution with water. If carbon dioxide is allowed to accumulate in body fluids, the pH decreases (i.e. acidity increases), with damaging effects on the structure and function of many important molecules. So it is important that carbon dioxide is removed efficiently.

In single-celled and very small organisms with high surface area to volume ratios, adequate levels of gas exchange occur directly with the environment. In larger animals that have a high metabolic rate and a need for highly efficient gas exchange, well-developed mechanisms to ventilate their gas exchange surfaces are required (Figure 5.2.1). This surface is linked closely to blood transport systems so that gases move efficiently between cells and the environment.

Gas exchange always takes place by diffusion across a moist plasma membrane. Diffusion is the passive movement of a substance along its concentration gradient from a region of high concentration to a region of low concentration (see Chapter 2). The immediate environment of cells is the layer of fluid that surrounds them. Even for organisms that get their oxygen from air, oxygen must first dissolve in the layer of extracellular fluid covering the gas exchange surface before it can cross cell membranes and enter the body.

Small, uncharged molecules, such as oxygen and carbon dioxide, pass directly through the phospholipid bilayer of the cell membrane. Therefore, they diffuse into or out of cells along their concentration gradient. In contrast to the many nutrients that are actively taken up by organisms, neither oxygen nor carbon dioxide is actively pumped across membranes.

The rate of diffusion of a molecule across a membrane depends on the size and maintenance of the concentration gradient, and also on properties of the membrane itself. The amount of a particular molecule transferred per unit time depends on the membrane's permeability to the molecule, the available surface area of the membrane, and the thickness of the membrane (the distance of diffusion).

For efficient gas exchange:

- the surface area should be as large as possible. This increases the surface area to volume ratio, enabling faster rates of diffusion to occur
- the barrier to be crossed (such as cell membranes and fluid layers) should be as thin as possible and should consist of a material that allows the gas to pass through the barrier easily
- there should be an adequate supply of the gas being transferred. If the respiratory surface is not adequately ventilated, the rate of exchange drops
- there should be efficient removal of the substance after transfer. Oxygen is carried away from the respiratory surface, usually by blood. Inadequate blood flow past the respiratory surface allows oxygen to accumulate, so that further transfer is slowed down.

In most large animals, energy is used to ventilate the respiratory surface and to circulate blood past its inner surface. The efficient supply and removal of oxygen maintains a high concentration gradient across the exchange surface, and, therefore, a high rate of diffusion. Energy expenditure is most economical when the rates of **ventilation** and blood flow to the respiratory tissue are matched. For example, when you begin to exercise, you need more oxygen. You breathe more heavily and your heart rate increases. Ventilation and blood flow to the lungs are still matched, but each is at a higher level in order to supply more oxygen.

i Ventilation (breathing) is the active movement of the respiratory medium (air or water) across a gas exchange surface.

MAMMALIAN RESPIRATORY SYSTEMS

All mammals obtain their oxygen by breathing air. Oxygen is absorbed from the environment by the respiratory system and is then transferred to cells via the circulatory system.

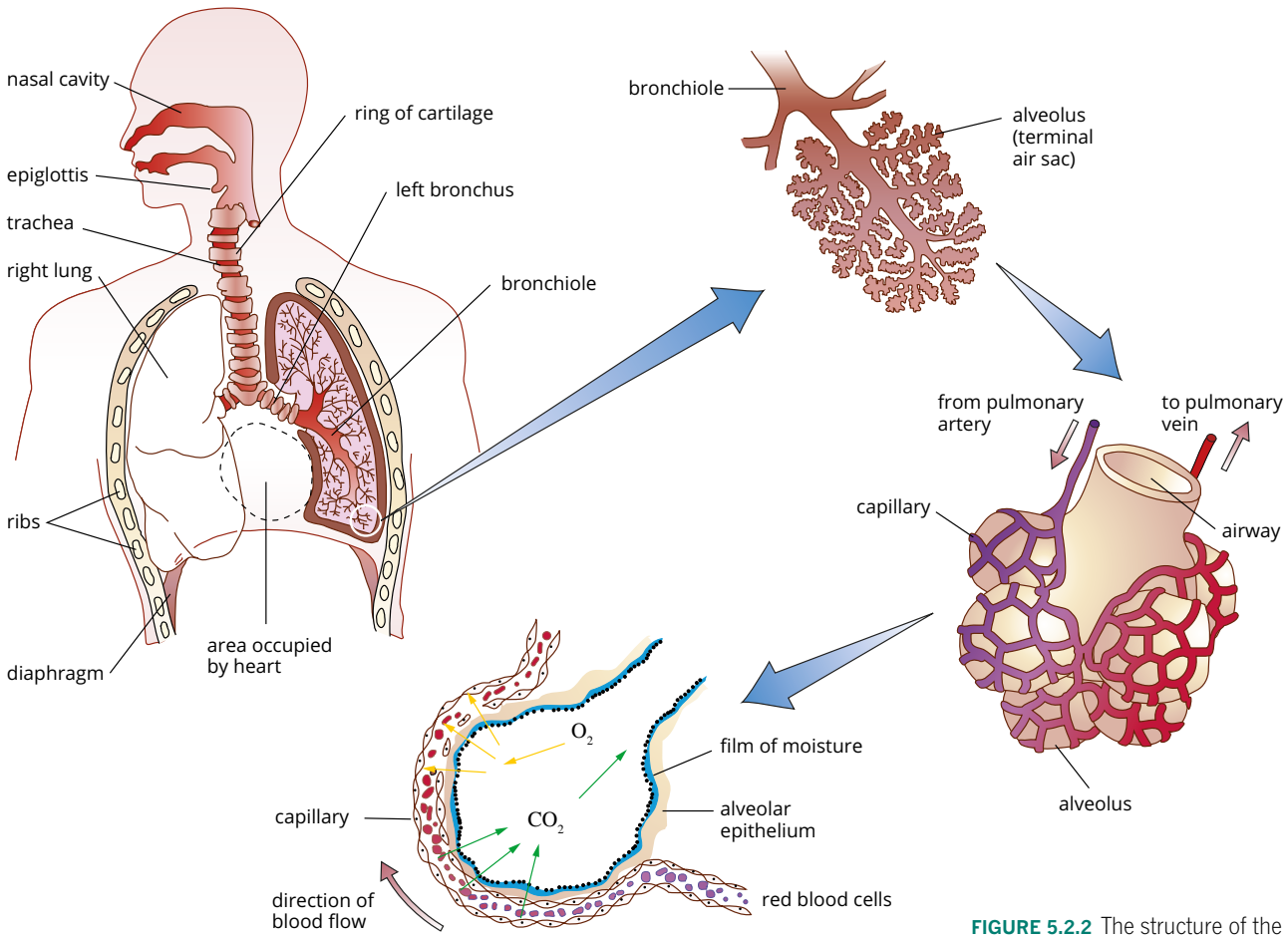


FIGURE 5.2.2 The structure of the human respiratory system

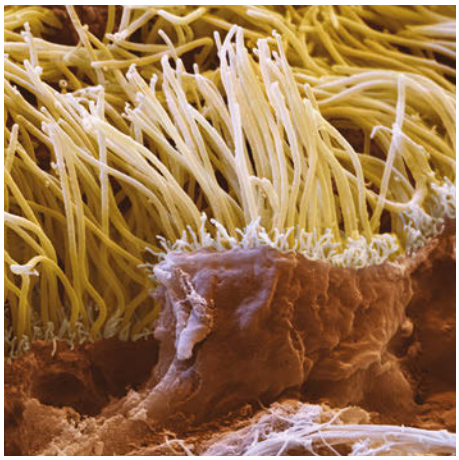


FIGURE 5.2.3 A cross-section through the cilia-covered epithelial cells of the bronchus (lung airway). The cilia are microscopic hairs that sweep trapped particles and mucus away from the gas-exchanging parts of the lungs and towards the throat, where the particles can be swallowed or coughed up.

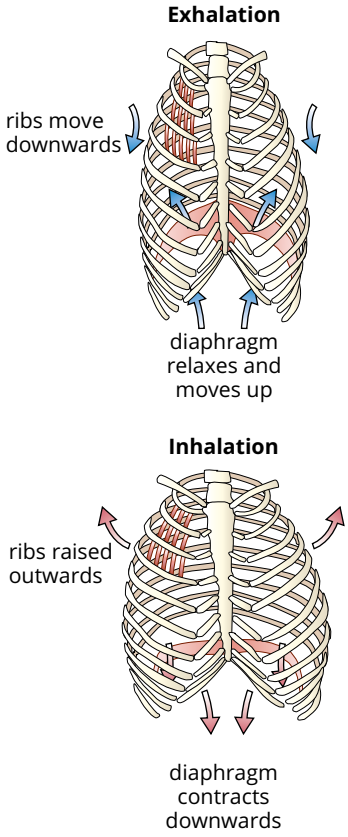


FIGURE 5.2.4 Mammals breathe by negative pressure ventilation. Raising the ribs and contracting the diaphragm increases the volume of the chest cavity and draws air into the lungs (inhalation). Relaxing these muscles causes the volume of the chest cavity to reduce and air is forced out again (exhalation).

The key steps in the process of mammalian respiration occur at the following sites, shown in Figure 5.2.2 on page 161:

- nose and throat—air is drawn in through the nasal cavity and passes into the **pharynx** (the back of the throat). Breathing through the nose is preferable to breathing through the mouth because the air is filtered, moistened and warmed in the nasal passages
- airways—from the pharynx, air passes into the airways: the **trachea**, paired **bronchi** and branching bronchioles. The trachea and bronchi are lined with cells covered in **cilia** and secrete mucus (Figure 5.2.3). Particles of dust or bacteria are trapped by this mucus and swept by the cilia back up to the pharynx and swallowed. The **larynx**, containing the vocal cords responsible for speech, is located at the upper end of the trachea
- **alveoli**—air enters the terminal **air sacs**, called alveoli, where gas exchange takes place. A constant supply of oxygen to cells is the most critical input for endotherms, such as mammals and birds, because they use energy to warm their bodies, and therefore need oxygen at a great rate for cellular respiration.

The tissue of the alveoli shows all the features of efficient exchange structures. It provides a large surface area for gas exchange; the total surface area in most adults is 30–70 m^2. Each alveolus is lined with a very thin layer of flattened cells, called the alveolar **epithelium** (Figure 5.2.3). This thin layer of cells is richly supplied with blood through numerous capillaries, facilitating diffusion of gases between the alveoli and the capillaries (Figure 5.2.2). Once oxygen enters the capillaries, it has entered the circulatory system, and the oxygenated blood is transported throughout the body.

Organisms can obtain oxygen either by breathing air (e.g. mammals) or from water (e.g. fish). However, there are two great advantages of obtaining oxygen from air. First, ventilation with air requires much less energy than breathing water, which is heavy. Second, much more oxygen is available in air than in water. But animals that breathe air must have a large, moist gas exchange surface. The disadvantage of breathing air is that water evaporates continuously from this large, moist surface area. Respiratory surfaces are therefore a major site of water loss for all terrestrial organisms.

Enclosing the respiratory surface inside the body provides physical protection from the external environment and support for the respiratory membrane, and reduces water loss. However, it means that specialised systems must aid in the ventilation of gas to and from the enclosed gas exchange surface.

Lung ventilation

Mammalian lungs are contained in the chest cavity (the thorax), which is completely enclosed and under a small negative pressure that keeps the lungs expanded within the thorax. The floor of the chest cavity is the muscular diaphragm.

Mammals use a 'suction pump' mechanism to ventilate their lungs. The chest cavity is expanded by contracting the diaphragm downwards and raising the ribs. This expands the lungs and draws air in through the airways (Figure 5.2.4). **Inhalation** is always an active process (it requires energy). However, **exhalation** is normally the result of the elastic recoil of the thorax as it returns to its relaxed state. Forceful exhalation involves an active compression of the rib cage.

Tidal volume

Tidal volume is the volume of air moved in and out at each breath. Normal resting levels of inhalation and exhalation are much less than our **vital capacity**, which is the maximum volume of air that we can move into and out of our lungs. Tidal volume varies according to the need for oxygen.

Air moves tidally into and out of mammalian lungs through the same airways. This is not as efficient as one-way flow, because at the end of an exhalation there is still some 'stale' air left in the airways and in the alveoli. The next inhalation draws this stale air back into the lungs, so it is impossible to fill our lungs completely with fresh air. The volume of air left in the respiratory system at the end of exhalation is referred to as the residual volume. Figure 5.2.5 graphically represents lung ventilation in humans.

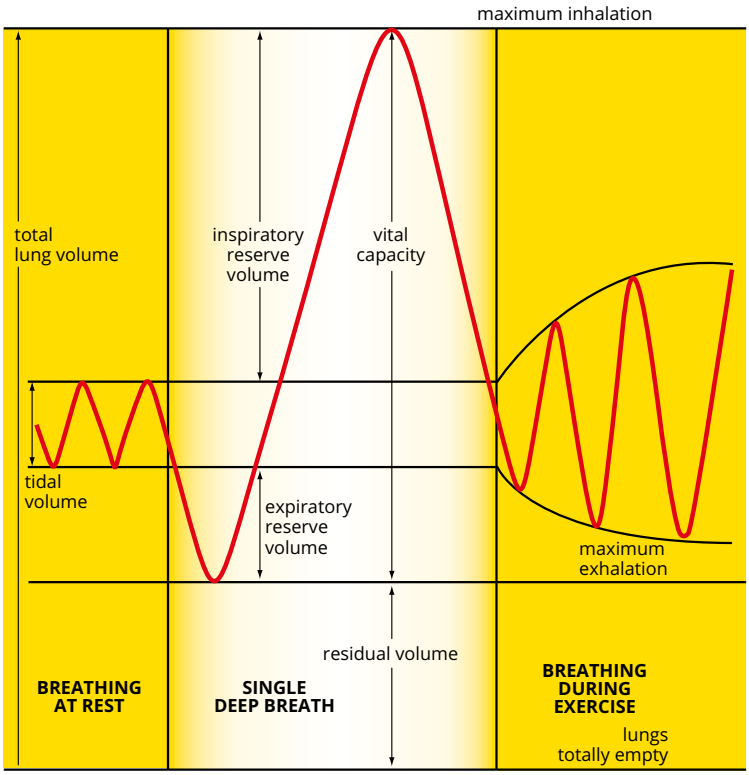


FIGURE 5.2.5 Lung ventilation in humans. During exercise, tidal volume increases. The extent of this increase is directly related to the increased use of oxygen, and is matched by an increased blood flow to the lungs.

EXCHANGING AND TRANSPORTING GASES

The exchange and transporting of the two gases, oxygen and carbon dioxide, is possible because of the coordination between the circulatory and respiratory systems. Gas exchange always occurs in the capillaries, whether at the alveoli or in body tissue. Both gases are also transported by the blood.

Gas exchange

Gas exchange, whether in the alveoli or tissues, occurs by diffusion. The rate of diffusion is influenced by the **partial pressure** of gases at the sites of gas exchange. Partial pressure is the pressure a particular gas contributes to the total pressure of a gas mixture. The partial pressure of gas X is written as P_X.

For example, air is a gas mixture that is approximately made up of 78% nitrogen, 21% oxygen and 1% other gases. At sea level, the pressure of air is 760 mmHg.

The partial pressure of the gases that make up air at sea level is:

P_N = 78% of 760 mmHg = 592.8 mmHg

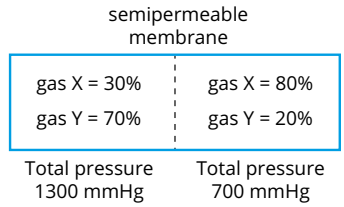
P_{O_2} = 21% of 760 mmHg = 159.6 mmHg

$P_{\text{other gases}}$ = 1% of 760 mmHg = 7.6 mmHg

Worked example 5.2.1

CALCULATING PARTIAL PRESSURE

Consider the following diagram. Calculate the partial pressure of the gases in each side of the container to determine in which direction the gases diffuse.

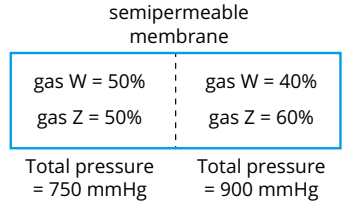


Thinking	Working
Calculate the partial pressure of the gases in the left side of the container.	P_{Xleft} = 30% of 1300 = 390 mmHg P_{Yleft} = 70% of 1300 = 910 mmHg
Calculate the partial pressure of the gases in the right side of the container.	P_{Xright} = 80% of 700 = 560 mmHg P_{Yright} = 20% of 700 = 140 mmHg
Compare partial pressures of gas X. Recall that gases move down partial pressure gradients.	P_{Xleft} = 390 mmHg, P_{Xright} = 560 mmHg Gas X moves from right to left.
Compare partial pressures of gas Y. Recall that gases move down partial pressure gradients.	P_{Yleft} = 910 mmHg, P_{Yright} = 140 mmHg Gas Y moves from left to right.
Answer	Gas X moves from right to left, while gas Y moves from left to right.

➤ Try yourself 5.2.1

CALCULATING PARTIAL PRESSURE

Consider the following diagram. Calculate the partial pressure of the gases in each side of the container to determine in which direction the gases diffuse.



Gas partial pressure in the human circulatory system

As air enters the lungs, water vapour is added to it and oxygen is continually taken up by the body, while carbon dioxide is added. By the time inhaled air reaches the alveolus, the partial pressure of oxygen is 104 mmHg and the partial pressure of carbon dioxide is 40 mmHg.

Gas exchange occurs because gases diffuse down partial pressure gradients.

In the deoxygenated blood in the pulmonary arteries, the partial pressure of oxygen is 40 mmHg and carbon dioxide is 45 mmHg. Consequently, oxygen moves down its partial pressure gradient from the alveoli into the blood. Carbon dioxide also moves down its concentration gradient, but moves from the deoxygenated blood to the alveoli. After gas exchange at the alveoli, the partial pressures of gases in the oxygenated blood leaving the lungs are: P_{O_2}= 104 mmHg, P_{CO_2} = 40 mmHg.

The cells in your body use oxygen for cellular respiration and produce carbon dioxide as waste. The partial pressures of gases in tissue cells are: $P_{O_2} = 20$ mmHg, $P_{CO_2} = 46$ mmHg. Again, because of the differences in gas partial pressures, oxygen diffuses into the tissue cells while carbon dioxide diffuses into the blood. The deoxygenated blood then returns to the right side of the heart and then to the lungs, via the pulmonary system.

Figure 5.2.6 shows the partial pressure of oxygen and carbon dioxide at the sites of gas exchange and in the blood in the body. The direction in which the gases diffuse is also shown.

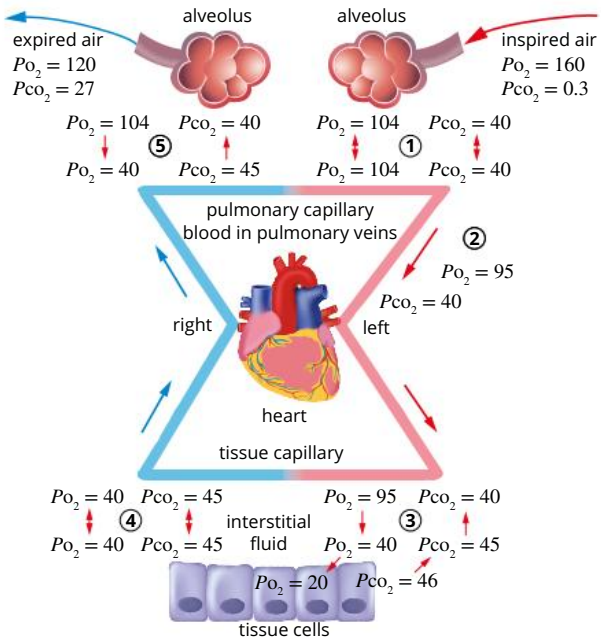


FIGURE 5.2.6 Partial pressure of gases (mmHg) in the respiratory and circulatory systems. Gas exchange occurs down partial pressure gradients.

Carrying oxygen

Maintaining an oxygen concentration gradient across the lung surface requires efficient supply (through ventilation) and removal (by circulation) of the oxygen. But the amount of oxygen that dissolves in water (or blood, which is about 90% water) is very small.

The oxygen-carrying molecule haemoglobin increases the **oxygen-carrying capacity** of the blood; that is, the amount of oxygen that it can carry. The most important feature of haemoglobin is that it can combine reversibly with oxygen.

Haemoglobin increases the oxygen-carrying capacity of blood and reduces the amount of energy that must be spent pumping blood. Because haemoglobin enables each millilitre of blood to carry much more oxygen, an animal can have a much smaller volume of blood, and pump it around the body more slowly, while still supplying the same amount of oxygen to its cells.

Haemoglobin

Oxygen is relatively insoluble in blood: only 0.2 mL of oxygen gas dissolves in 100 mL of blood. The carrying capacity of mammalian blood is increased 100 times by the presence of the red respiratory protein haemoglobin, which is carried in red blood cells.

Haemoglobin is a complex protein containing iron. Four oxygen molecules can combine with each haemoglobin molecule (Figure 5.2.7). In areas of high oxygen concentration, such as in the blood in vessels in the lungs, haemoglobin combines with oxygen to form **oxyhaemoglobin**. In areas of low oxygen concentration, such as in exercising muscles, oxygen is released (dissociated) from the oxyhaemoglobin. Therefore, the percentage of oxygen concentration in exercising muscles, tissues and lungs varies. This relationship can be seen in Figure 5.2.8.

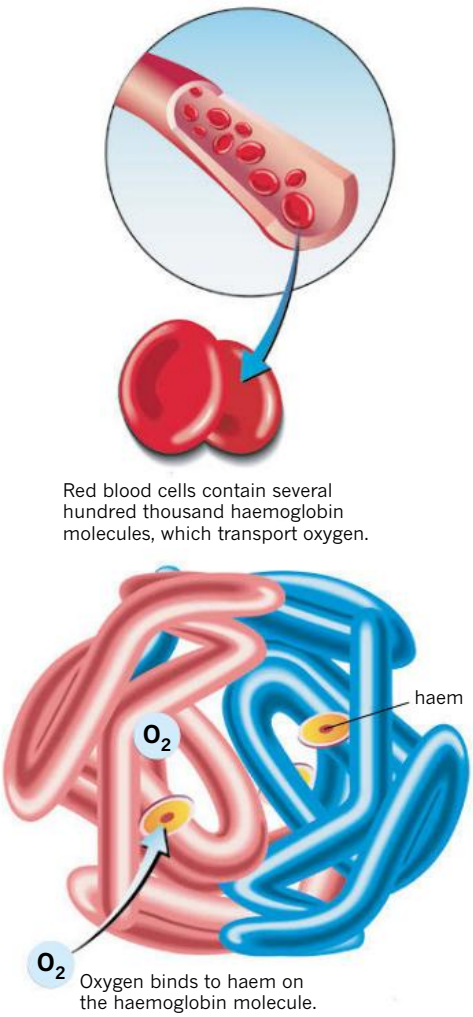


FIGURE 5.2.7 The 3D structure of a haemoglobin molecule. This molecule is responsible for binding oxygen molecules in red blood cells.

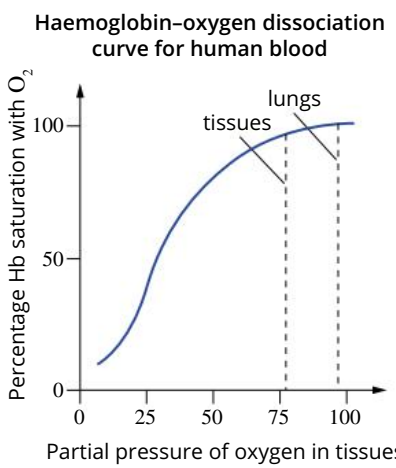


FIGURE 5.2.8 The haemoglobin–oxygen dissociation curve for human blood. It shows how the partial pressure of oxygen effects the extent to which oxygen binds to haemoglobin molecules in the body.

Oxygen in the tissues

In resting humans, haemoglobin is almost 100% saturated with oxygen in the lungs and about 75% saturated in tissues of other organs (Figure 5.2.8). In the lungs, the high partial pressure of oxygen means that haemoglobin has a high affinity to oxygen, and is 98% saturated. However, in the tissues of other organs, the partial pressure of oxygen is around 40 mmHg. At this pressure, haemoglobin has a lower affinity for oxygen. This means that oxygen is released from the haemoglobin molecule and diffuses into cells in the body tissues.

Our muscles are red because they also contain a form of haemoglobin called **myoglobin**. Myoglobin carries a reserve store of oxygen that muscles can use for a limited period if the amount of oxygen in the blood suddenly decreases to a very low level. This situation could arise if a blood vessel were temporarily blocked, or during strenuous exercise. When blood supply is restored, the myoglobin oxygen store is immediately refilled from the blood. Myoglobin has a higher affinity for oxygen than haemoglobin and therefore can take oxygen from it. This also means that haemoglobin releases large amounts of its bound oxygen to exercising muscle before the myoglobin releases its store, making it an emergency resource.

Anaemia

Anaemia is a condition in which there are insufficient red blood cells, or the quality of the red blood cells or the haemoglobin is low. The most common cause of anaemia is a deficiency of iron in the diet. Other causes include failure to absorb iron because of disease, heavy menstruation and inherited disorders such as sickle-cell anaemia.

People with anaemia may have a normal blood oxygen saturation reading, but because they have less functioning haemoglobin in their blood, less oxygen may be getting to the cells in their body. Consequently, anaemia results in pale skin, tiredness, muscle weakness, headaches and problems with concentration. Treatment is determined by the underlying cause, but can involve a change in diet, iron supplements, surgery, or (in extreme cases) oxygen therapy and blood transfusions.

Carrying carbon dioxide

Carbon dioxide, produced by cellular respiration, must be carried in body fluids to an external surface where it can be released to the environment. Because carbon dioxide combines with water to form an acid (carbonic acid) and causes a decrease in pH, it can be carried in solution only in limited amounts.

In mammals, about 7% of the carbon dioxide carried by blood is dissolved in the plasma. About 23% combines with haemoglobin molecules (forming carbamino-haemoglobin), but at a different site on the haemoglobin molecule to the site where oxygen binds. Carbamino-haemoglobin is still able to combine with oxygen. The remainder of the carbon dioxide produced in working tissues passes into red blood cells, where it is converted to hydrogen carbonate ions, and then passes out to be transported in the plasma.

When the blood reaches the lungs, the hydrogen carbonate moves back into the red blood cells where it is converted to carbon dioxide for release during breathing.

OTHER ANIMAL RESPIRATORY SYSTEMS

Like mammalian respiratory systems, the respiratory systems of other animals demonstrate the structural features for efficient gas exchange to occur: the surface area is as large as possible and moist, and the barrier to be crossed is one or two cells thick and supplied by an extensive capillary system (except for insects).

Insect respiratory system

Insects exchange oxygen and carbon dioxide between the atmosphere and their cells directly. There is no circulatory system involved. Gas exchange takes place across a network of fine internal air-filled tubes—the tracheae and the finer **tracheoles**—that open to the atmosphere through spiracles that can open and close (Figure 5.2.9). The tracheoles branch into smaller and smaller tubes, reaching all tissue. Oxygen moves into the tissues and carbon dioxide enters the tracheae to be expelled from the body.

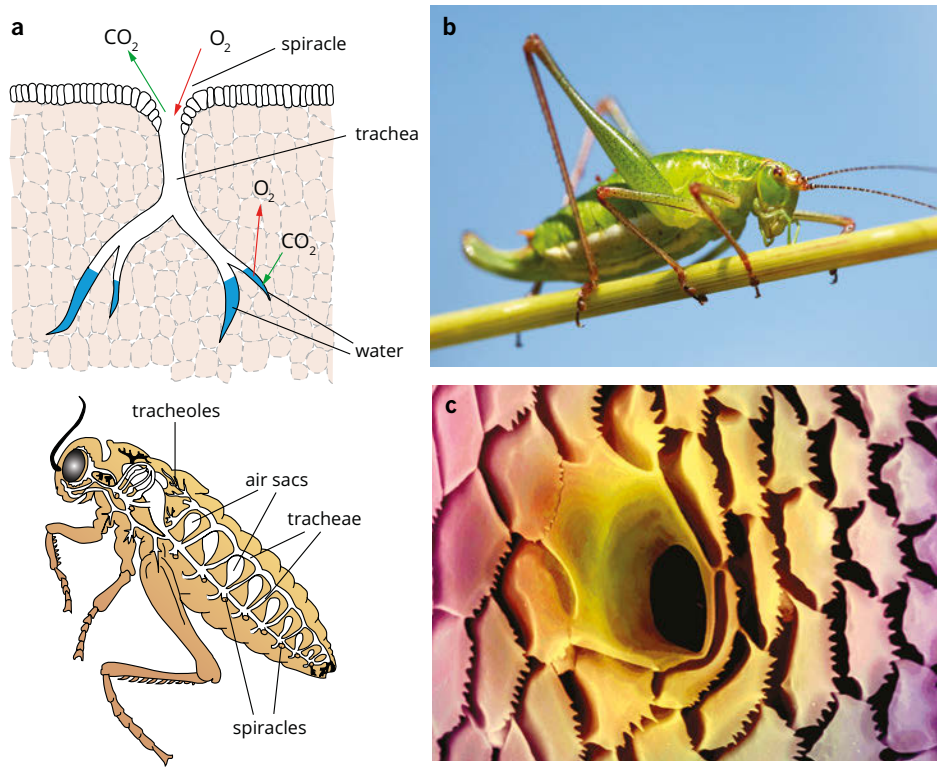


FIGURE 5.2.9 (a) Insects have a system of air-filled tracheae and tracheoles that penetrate every tissue, bringing air into close contact with their cells. (b) Some insects, such as this grasshopper, also have air sacs that can be pumped like bellows to move air through the system. (c) A coloured scanning electron micrograph of an ant spiracle.

This process of gas exchange is quite slow, so some larger insects pump their abdomens to help speed up the movement of these gases. Some insects, such as grasshoppers, also have air sacs that can be pumped like bellows to move air through the system.

The structure of this type of respiratory system is one of the factors that limits the size of insects.

Fish respiratory system

FIGURE 5.2.10 The gill arches of this juvenile Mediterranean dusky grouper (*Epinephelus marginatus*) can be seen along the side of its pharynx.

Gills are the principal organs of the respiratory system in fish. Oxygen is not very soluble in water, so the respiratory system needs to be very efficient. Fish gills are composed of several gill arches on either side of the pharynx (throat) (Figures 5.2.10 and 5.2.11).

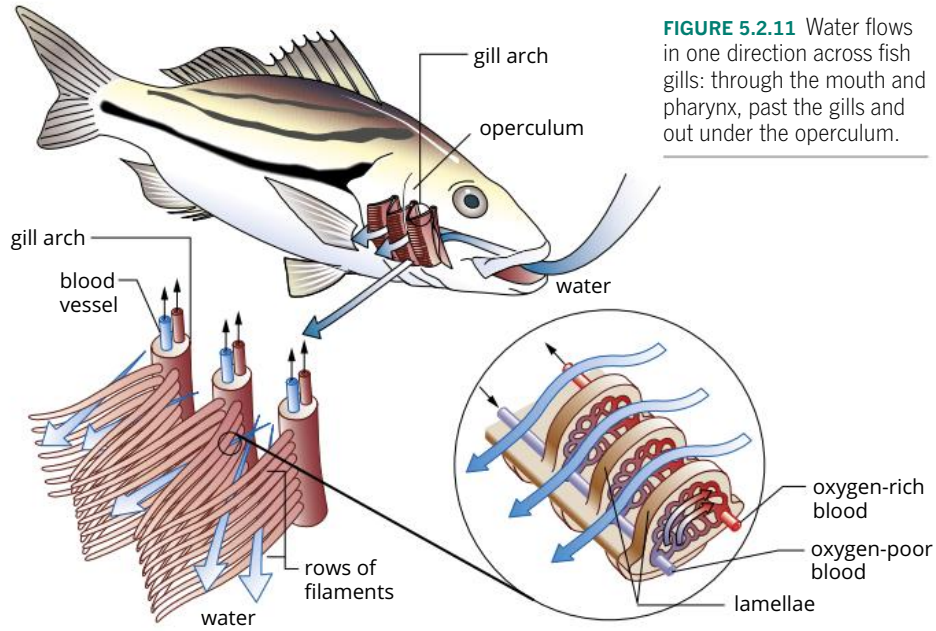


FIGURE 5.2.11 Water flows in one direction across fish gills: through the mouth and pharynx, past the gills and out under the operculum.

Each gill arch is composed of rows of filaments, which in turn are composed of lamellae. The **lamellae** are closely packed rows of leaf-like structures where oxygen diffuses into the blood and carbon dioxide diffuses from the blood into the surrounding water.

Water is drawn into the pharynx through the mouth and then pushed between the gill arches by compressing the pharynx with the mouth closed. This forces water between individual gill lamellae. The lamellae provide a large surface area for gas exchange and are visibly red because they contain many blood vessels. Water then passes out under the operculum, which covers and protects the fragile gills.

To maximise gas exchange, oxygenated water flows across the gills in the opposite direction in relation to blood flow. This is known as **counter-current exchange**. The benefit of counter-current exchange is that it maintains the diffusion gradient across the entire length of the gill lamellae (Figure 5.2.12). This means that a far greater amount of diffusion occurs compared with a unidirectional flow.

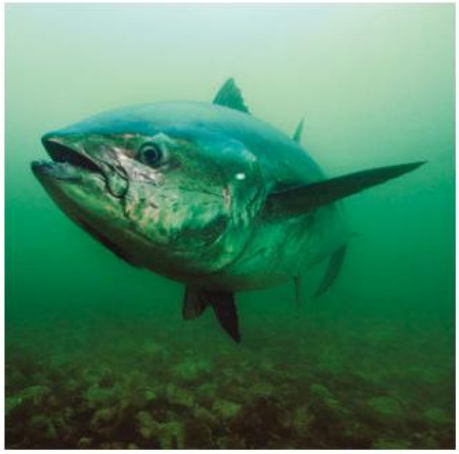


FIGURE 5.2.13 Fish such as this Atlantic bluefin tuna (*Thunnus thynnus*) often swim with their mouths open to create a fast, continuous flow of water across their gills.

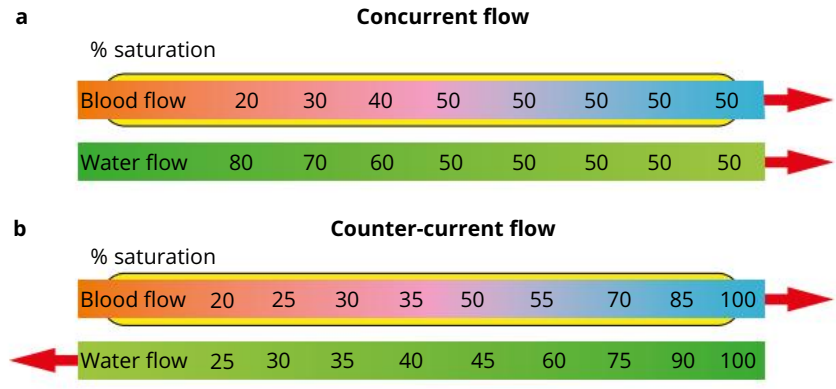


FIGURE 5.2.12 A comparison of concurrent versus counter-current flow. Note the difference in percentage saturation between the two flows.

To increase water flow across the gills and improve the efficiency of gas exchange, some very active fish such as tuna use a technique called ram ventilation. In this process the fish swims in a straight line with its mouth open, thus increasing water flow across the gills (Figure 5.2.13).

Amphibian respiratory system

Amphibians have two life-stages: juvenile and adult. Juvenile amphibians, such as tadpoles, live in water and use gills for gas exchange. Most adult amphibians, on the other hand, live on land and breathe air. As the amphibian develops, the gills are replaced by lungs. The axolotl shown in Figure 5.2.14 retains its gills as an adult.

Amphibian lungs are not as complex as the mammalian respiratory systems. Amphibians have a reduced or absent diaphragm, and they lack ribs. Consequently, the inhalation and exhalation of air into the lungs of an amphibian is forced through the opening and closing of its nostrils and mouth (Figure 5.2.15).

As well as in the lungs, gas exchange in amphibians can occur directly across the skin. The skin of amphibians is highly permeable and serviced by a large network of blood vessels, which enable gas exchange to occur. When submerged, gas exchange can occur directly through the skin of an amphibian. While on land, the skin of an amphibian is kept moist by secretions from the mucus glands in their skin.

The final way amphibians can exchange gas with their environment is through the lining of their mouths.

Reptile respiratory system

There are three classes of reptiles, each of which have a unique respiratory system.

Snakes and lizards, known as squamates, lack a diaphragm. Similar to amphibians, some squamates use their mouths to force air into and out of the lungs. Unlike amphibians, reptiles have ribs. The bodily movements of squamates can also cause their ribs to expand and contract, which causes air to move into and out of the lungs.

Crocodilians have a diaphragm that works in a similar way to the mammalian diaphragm to expand and contract the lungs. Unlike the mammalian diaphragm, the crocodilian diaphragm is attached to the liver and pelvis, rather than to the ribs, as shown in Figure 5.2.16. The liver compresses the lungs during exhalation, forcing air out. During inhalation, the pelvic bone rotates downwards, stretching the crocodile's abdomen, letting the diaphragm muscles pull the liver backwards, expanding the lungs.

The final class of reptiles is testudines (turtles and tortoises). The hard shell of testudines means that they cannot expand their ribs to ventilate their lungs. Testudines have a sheet of muscle within the shell that contracts and relaxes to force air into and out of the lungs. Moreover, the movement of their limbs can also change the pressure inside their bodies, which causes air to move into and out of their lungs.

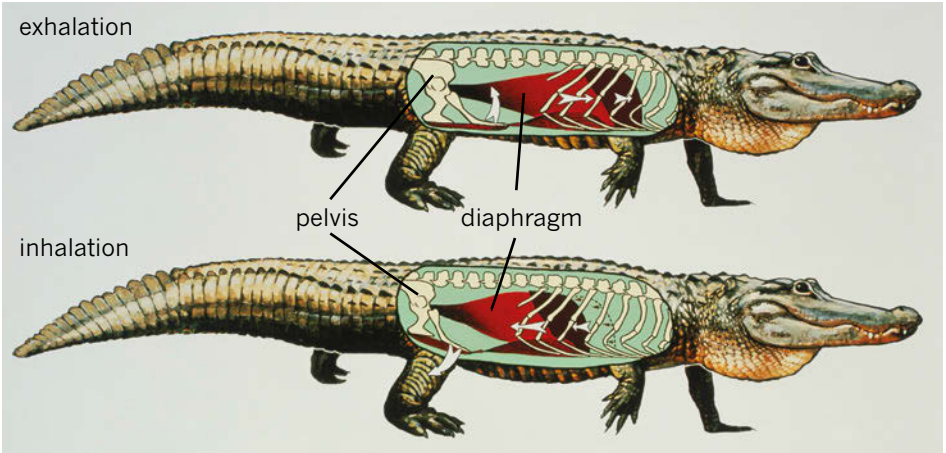


FIGURE 5.2.16 The actions of crocodilian exhalation and inhalation on internal movements

FIGURE 5.2.14 The axolotl (*Ambystoma mexicanum*) is one amphibian that retains its external gills as an adult. Amphibians that do not undergo metamorphosis are collectively known as neotenic amphibians.

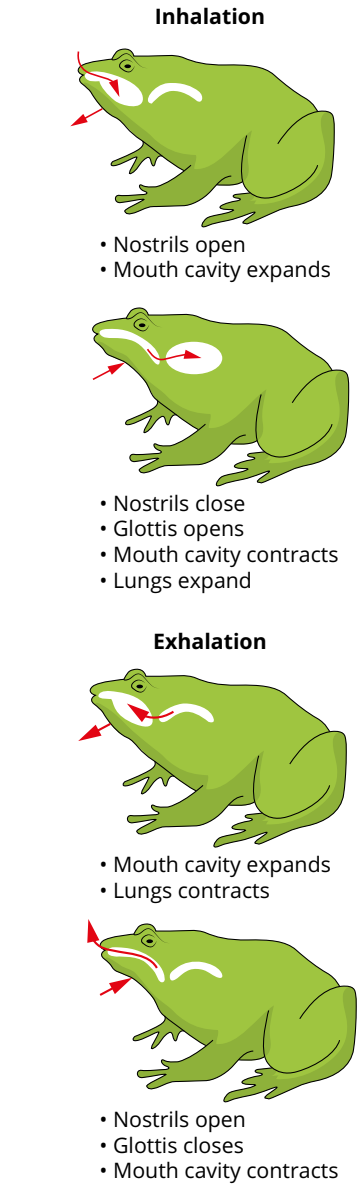


FIGURE 5.2.15 Inhalation and exhalation in a frog

Bird respiratory system

Birds have the most efficient respiratory system of all animals. Most birds can fly and are usually very active. This means a bird has a high demand for oxygen and needs to be light.

As with mammals, gas exchange for birds takes place in the lungs. Bird lungs are similar to those of mammals, but instead of alveoli they have a system of microscopic tubules called air capillaries. In the air capillaries, oxygen moves into the blood and carbon dioxide moves from the blood into the lungs to be exhaled.

Birds have relatively small lungs that do not expand and contract like those of a mammal. Unlike mammals, birds do not have a diaphragm, but instead rely on pressure changes in air sacs to move air in and out of their respiratory system (Figure 5.2.17). The respiratory system of a bird has seven, eight or nine air sacs, depending on the species. During inhalation, air is drawn into the posterior air sacs and air from the lungs moves into the anterior air sacs. During exhalation the air sacs collapse, which pushes air from the posterior air sacs into the lungs. At the same time the air in the anterior air sacs is expelled via the trachea. This process of exhalation creates a one-way flow of fresh air through the bird's lungs, which is extremely efficient. The large number of air sacs also helps to make the bird very lightweight.

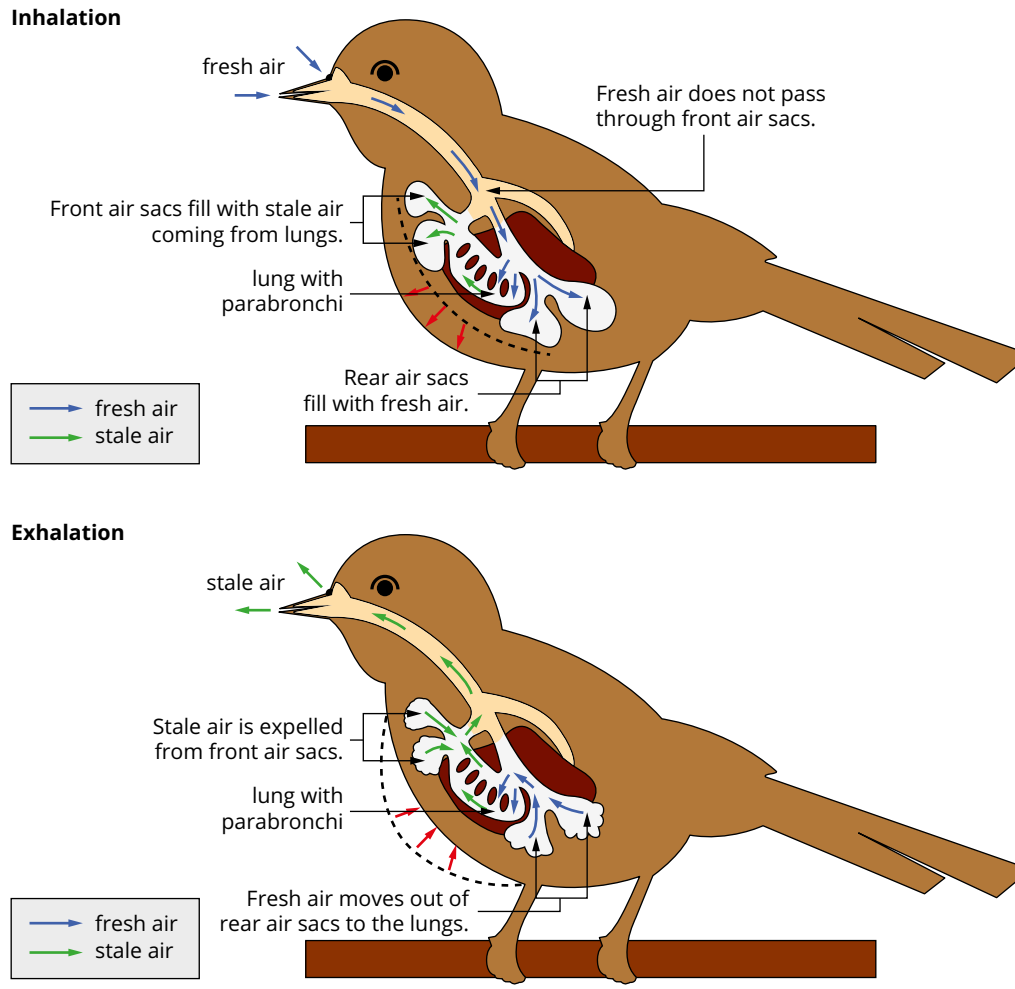


FIGURE 5.2.17 The respiratory system of birds consists of small lungs and several air sacs. This system is extremely efficient and light to meet the demands of flight.

5.2 Review

SUMMARY

- Gas exchange is a fundamental process for all organisms.
- Single celled organisms can rely on diffusion as the only mechanism of gas exchange
- Complex animals have respiratory systems to ensure adequate ventilation.
- Gas exchange always takes place by diffusion across a moist plasma membrane.
- Features of an efficient gas exchange surface are:
  - a large surface area to volume ratio
  - moist
  - one to two cells thick
  - adequate supply of the gas being transferred
  - efficient removal of the substance after transfer.
- Mechanisms of gas exchange reflect the environment in which the organisms are found.

KEY QUESTIONS

Retrieval

1 Name the fundamental process that all organisms rely upon for gas exchange.

2 Recall the advantages of breathing air over water.

3 Recall the name given to the volume of air that is moved in and out at each breath.

4 Recall how many oxygen molecules bind to one molecule of haemoglobin.

5 Recall the name of the principal organs of fish respiratory systems.

Comprehension

6 Explain the function of respiratory systems.

7 Describe the features of the alveoli that make them highly effective for gaseous exchange.

8 Describe the concept 'partial pressure of a gas'.

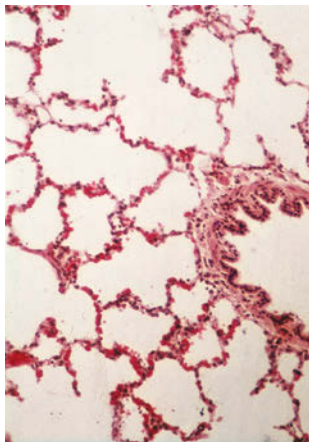
Analysis

9 Infer why terrestrial organisms do not have gills.

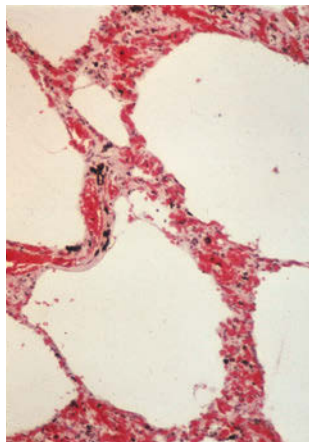
10 Differentiate between cellular respiration and respiration that occurs in a respiratory system.

11 Pneumonia is an infection of the lungs where the air sacs fill with fluid or pus. Predict how pneumonia would impact the efficiency of gas exchange.

12 Emphysema causes the breakdown of alveoli. The following images show the difference between lung tissue in a normal person and a person with emphysema. Deduce how emphysema reduces the efficiency of gas exchange in a diseased person.



Normal lung tissue has large air spaces.



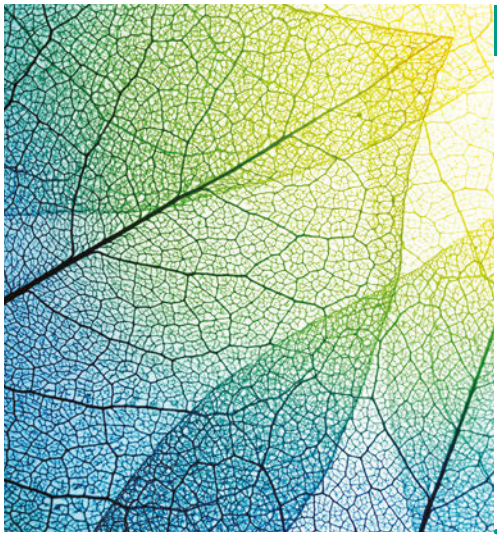
In emphysema, the air sacs break down.

13 A gas mixture comprises 40% oxygen, 25% carbon dioxide and 35% nitrogen. Calculate the partial pressure of the three gases if the total gas pressure is 1250 mmHg.

14 The base camp on Mount Everest is at 5000 m altitude, where the atmospheric pressure is 420 mmHg. Assuming that the air comprises 21% oxygen in the air, and partial pressure of O_2 reduces by 40% by the time it reaches the alveoli, deduce the effect high altitude has on the rate of alveolar gas exchange.

15 Compare a frog respiratory system with a mammalian respiratory system.

5.3 Exchange of nutrients and wastes in complex animals



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

- understand that the purpose of digestion is to break down organic food into smaller molecules that the body can absorb
- understand the role of the various organs of the mammalian digestive system
- be able to distinguish between foregut and hindgut fermenters
- understand that food is digested by both physical and chemical means
- understand that excretion is the removal of wastes from the body of an organism
- understand that the nephron is the functional unit of the mammalian kidney
- understand that the three main stages of urine formation in mammals are filtration, reabsorption and secretion.

Mammals are heterotrophs; unlike plants, they cannot make organic molecules from inorganic materials. Consequently, they must consume other organisms or their products to obtain organic molecules. As well as needing organic molecules to provide chemical energy, heterotrophs also require other organic molecules such as vitamins, amino acids and fatty acids. Their diet must also contain minerals and water.

DIGESTION OF FOOD

Organisms are composed of many different types of complex organic molecules. When eaten as food, these molecules are too large to be simply absorbed into an animal's body. Regardless of the type of animal, food molecules must be small enough to pass across plasma membranes into the cells lining the gut. This is the purpose of digestion—to rapidly break down organic food into molecules small enough to be able to pass through membranes and into cells.

The food you eat does not become part of your body until it has been absorbed by the cells lining the walls of your intestine. The digested food then passes into the bloodstream and is carried throughout the body. If food is not absorbed, it continues through the intestine and is passed out again as faeces (**egestion**).

Digestion is the breakdown of food into a form that can be used by an organism for **metabolism**. This involves physical and chemical breakdown.

Do not confuse egestion with **excretion**. Excretion refers to the removal of substances that were once part of the body, and occurs largely in the kidneys.

Physical breakdown

Digestive enzymes can only act on the outside surface of food. If food is swallowed in large pieces, the enzymes have a relatively small surface area to work on. Unless the digestive system is extraordinarily long, most of the food would remain undigested. Given the relationship between surface area and volume (see Module 2.3), digestion is much faster if food is in small pieces and the enzymes have a proportionally larger area to act upon.

Therefore, it is important to have a mechanism for breaking down large food into smaller pieces to increase its surface area. Animals have developed a variety of structures to break down food physically. For example, the teeth of vertebrates break food into pieces small enough to be swallowed (Figure 5.3.1). Other organisms, such as birds, reptiles and fish, use the gizzard, an organ in their digestive system, to digest food.

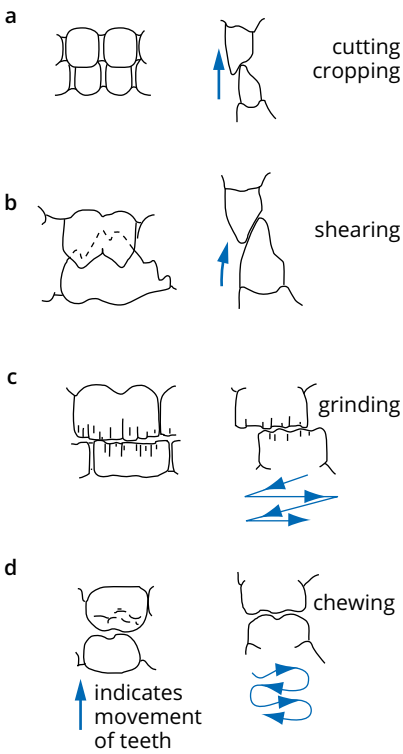


FIGURE 5.3.1 In mammals, the tooth structure is adapted for the mechanical breakdown of different types of foods. (a) Incisors are typically used for cutting and tearing. (b) Carnivores have large powerful cheek teeth that shear through tough tissues and bones. (c) Herbivores have molars that grind fibrous plant foods. (d) Omnivores, such as you, have molars that roll and crush a variety of foods.

Sometimes hard objects, such as stones, are swallowed to assist the grinding process in gizzards (Figure 5.3.2).

To improve the efficiency of digestion, this physical breakdown should take place before **chemical digestion** is completed. In contrast to chemical digestion, physical breakdown does not chemically change food molecules.

Bile is important in the physical breakdown of fats, but it is not an enzyme. Bile is produced by the liver and released into the small intestine where it acts like a detergent to emulsify fats—breaking up large fatty masses into small droplets. This increases the surface area of fats available for digestion by lipases.

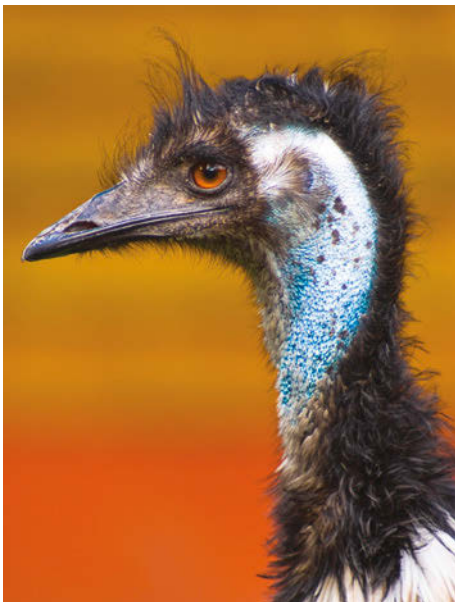


FIGURE 5.3.2 Emus (*Dromaius novaehollandiae*) swallow stones, which stay in the gizzard, to aid physical digestion of food.

Chemical digestion

The process of breaking apart complex molecules into simple molecules is called chemical digestion, and is carried out by the action of enzymes. Enzymes are important in digestion because they greatly increase the rate of breakdown of food molecules.

Most digestive enzymes split food molecules by the process of **hydrolysis** (from Greek *hydro*, meaning 'water', and *lysis*, meaning 'to split'). This means they split the food molecule at a particular point by adding a water molecule. There are three main kinds of digestive enzymes, as shown in Figure 5.3.3:

- **amylases**, which act on carbohydrates
- **proteases**, which act on proteins
- **lipases**, which act on lipids.

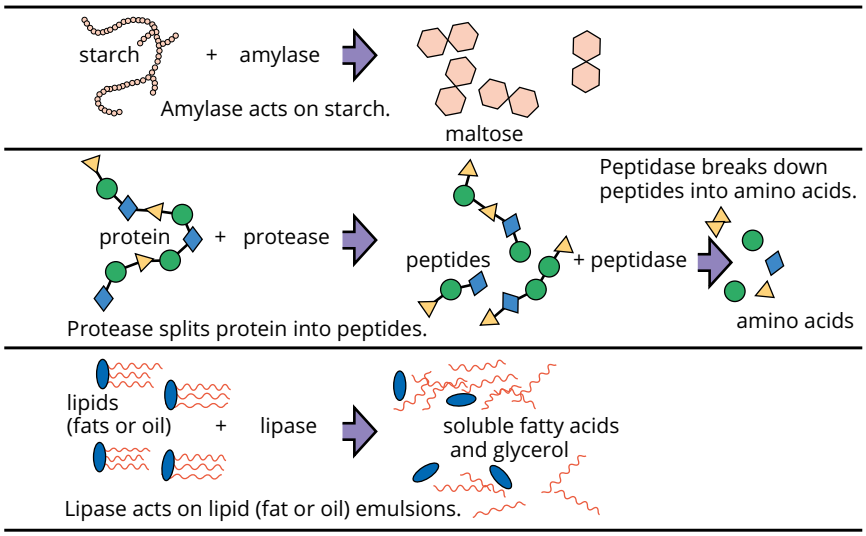


FIGURE 5.3.3 Digestion involves the splitting of food molecules into components small enough to pass across plasma membranes and into the body. Enzymes used in digestion are often named according to the substance on which they act, with the common ending -ase. For example, protease digests proteins and lipase digests lipids.

Humans secrete more than 20 different digestive enzymes into the digestive tract. Digestive enzymes are manufactured by specific cells in the gut wall, and by the salivary glands and the pancreas. Many very large food molecules can be broken down only by several enzymes acting one after the other. In this case, the different enzymes are produced at appropriate sites along the digestive system.

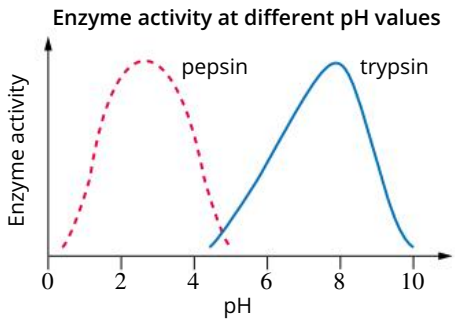


FIGURE 5.3.4 Pepsin and trypsin are both enzymes that digest proteins, but they have very different pH requirements. Pepsin is released in the stomach and is most active in its acidic environment. Trypsin is most active in the slightly alkaline small intestine.

FIGURE 5.3.5 A bat star (*Asterina miniata*) feeding with its stomach everted.

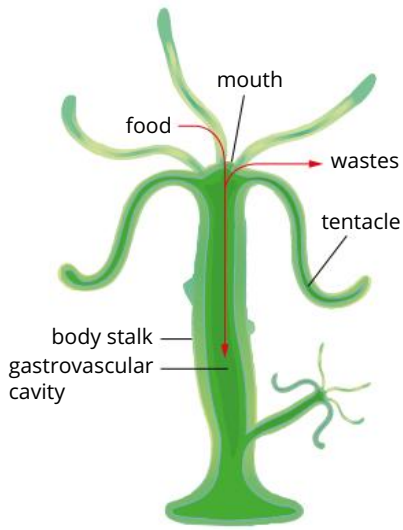


FIGURE 5.3.7 The hydra has a two-way digestive tract. Food enters and waste exits the gastrovascular cavity through the mouth.

The importance of pH

Because enzymes are proteins, they are sensitive to changes in the pH of a solution (Figure 5.3.4). Altering the pH changes the shape of protein molecules, which in turn alters their chemical properties. The change in shape alters the way that an enzyme binds with the molecule upon which it acts. Enzymes, therefore, have certain pH ranges over which they operate best. Different regions of the gut have different pH values that are most suitable for enzymes found in that region.

Extracellular digestion

Chemical digestion can be extracellular or intracellular. **Extracellular digestion** occurs when, for example, cells release enzymes into the **lumen** (central cavity) of the small intestine. There, enzymes split the food molecules and the resulting smaller molecules are absorbed. Sea stars turn their stomach inside out and release enzymes directly onto the animal they have trapped. You can see this in Figure 5.3.5.

Carnivorous plants and fungi also release enzymes to break down their food before absorbing it. In each of these examples, digestion is extracellular because it takes place outside cells. Sometimes, digestive enzymes are located on the actual surface of cells. As the food is digested into smaller molecules, the molecules pass immediately into the cells. Mammals and most other animals rely on some form of extracellular digestion.

In contrast, many protozoans and invertebrate animals, such as mussels, sea jellies and free-living flatworms, use **intracellular digestion**. Their cells engulf small pieces of food into a membrane-bound food vacuole within the cell (Figure 5.3.6). Lysosomes fuse with the vacuole and release enzymes into it to digest the food. The resulting small molecules from the digestive process pass through the vacuole membrane and into the cytosol.

FEATURES OF EFFECTIVE DIGESTIVE SYSTEMS

In one sense, the digestive systems of all animals must be effective; otherwise, the animals would not exist. For each animal, their digestive system adequately provides for their needs. Cnidarians, such as sea jellies, hydra and anemones, have a two-way digestive system, as shown in Figure 5.3.7. In a two-way digestive system, food is taken in and waste is excreted through the one opening. Although food is always being mixed in some way with waste products, the two-way digestive system provides sufficient nutrients for cnidarians to function.

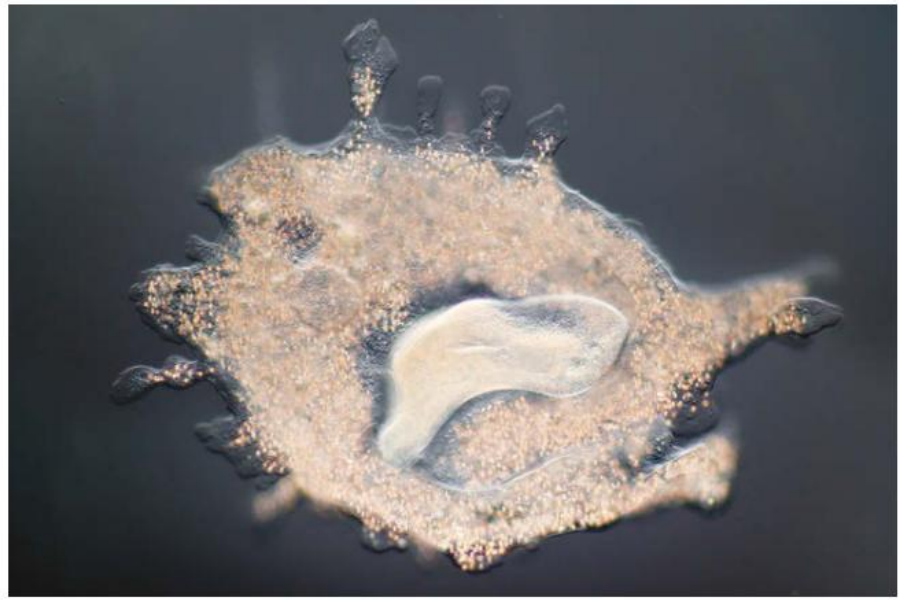


FIGURE 5.3.6 An example of intracellular digestion. This amoeba proteus is engulfing a *Paramecium caudatum* protozoan. Once ingested, the protozoan is contained inside a food vacuole into which lysosomes release digestive enzymes.

Large animals, including vertebrates, require higher levels of energy and nutrients for their normal activities. Because mammals are endothermic (they maintain a stable body temperature, usually higher than their environment), they require a lot of energy to maintain their body temperature. Therefore, they need digestive systems that can efficiently extract large amounts of energy and nutrients from food resources, and these systems are found in more active animals. Characteristics of these highly efficient digestive systems include:

- effective mechanisms for capture and preliminary handling of food
- appropriate physical breakdown of food
- a one-way gut with separation of tasks along its length
- efficient transport and storage of ingested food
- efficient sequential release of digestive enzymes
- an adequate surface area for maximal absorption of nutrients and water
- efficient egestion of unwanted materials.

DIGESTIVE SYSTEMS IN MAMMALS

All mammals need food and water, but different species (such as cows and dogs) have different food requirements, feeding behaviours and digestive systems. Cows are slow-moving and spend much of the day eating grass and chewing. In contrast, dogs are energetic and active, and may spend only 5–10 minutes each day gulping down food. Dogs and cows have many other differences that relate to their eating habits. Their teeth are very different, and cows have much larger and more complex intestines than dogs (Figure 5.3.8).

The feeding behaviour, teeth and digestive systems of cats and dogs are similar, but in guinea pigs and rabbits they are more like those of cows. One common factor is diet: cats and dogs eat meat, whereas cows, guinea pigs and rabbits eat plants.

Humans are different again. Our teeth are unlike those of dogs or cows—we are not very good at chewing bones or grass! Our preferred foods include both meat and plant material, and we often cook our food first.

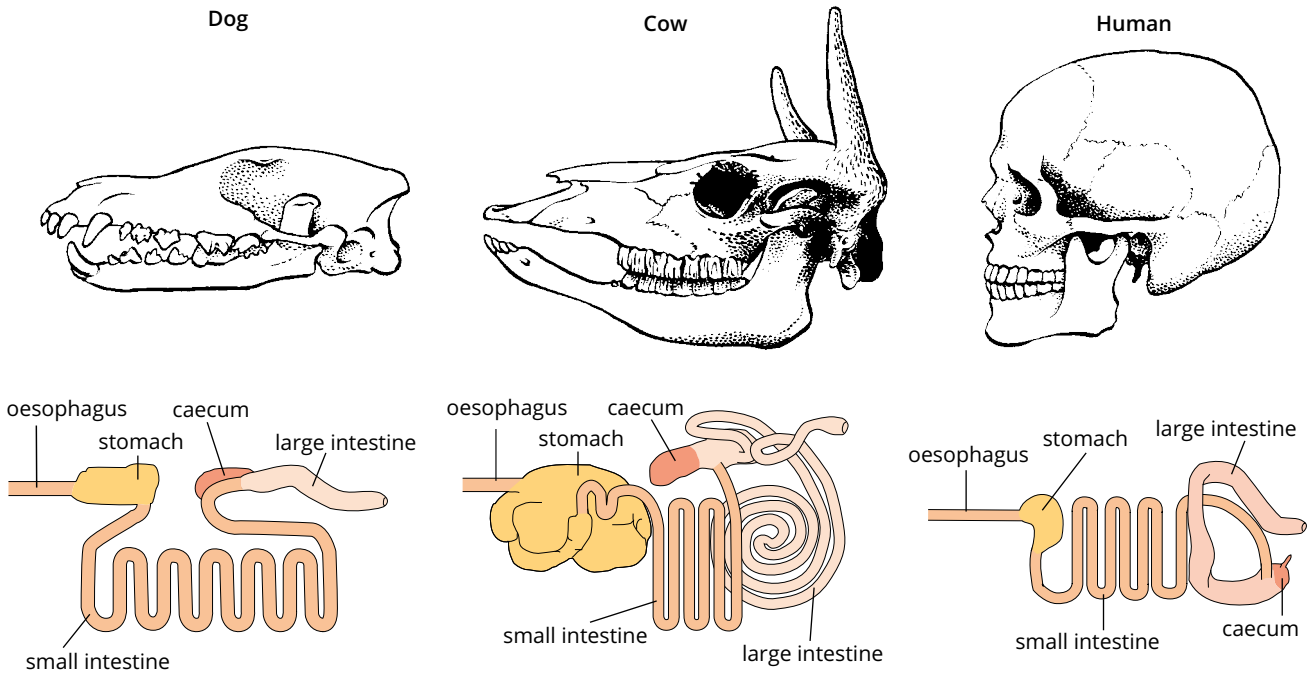


FIGURE 5.3.8 Skulls and digestive systems of the dog (a carnivore), the cow (a herbivore) and the human (an omnivore). Scientists studying fossil jaws, or even a few fossil teeth, can suggest the likely feeding behaviour and diet of the particular mammal species because teeth are modified in different species to suit the type of food that is eaten.

Humans spend 30–90 minutes each day eating, although the social aspects of eating may extend this time. The human digestive system is proportionally longer than that of a dog, but shorter than that of a cow.

Cows, dogs and humans are examples of animals with three different dietary patterns. Animals that eat only plants, such as cows, rabbits, kangaroos and koalas, are **herbivores** (Figure 5.3.9a). Herbivores typically spend much of the day eating. **Carnivores**, including dogs and cats, consume animals (Figure 5.3.9b). They spend much less time eating; sometimes animals in the wild, such as lions, may not eat for days between meals. Humans, on the other hand, are **omnivores** (from the Latin *omnivorus*, meaning 'eating everything'), because they can eat both plant and animal foods.

Animal matter has a much higher proportion of extractable energy per gram than plant matter. The carnivore gut produces all the enzymes needed for the complete digestion of meat. Digestion is quicker and more efficient. Digestive systems are shorter and simpler in carnivores than in herbivores.

The reason for the difference in feeding behaviour between herbivores and carnivores is clear. Plant material must be repeatedly ground by the teeth to expose as much surface area as possible for enzyme action and to release the contents from broken cells. As a food, plant material provides much less energy than meat and it takes a long time to extract that energy.

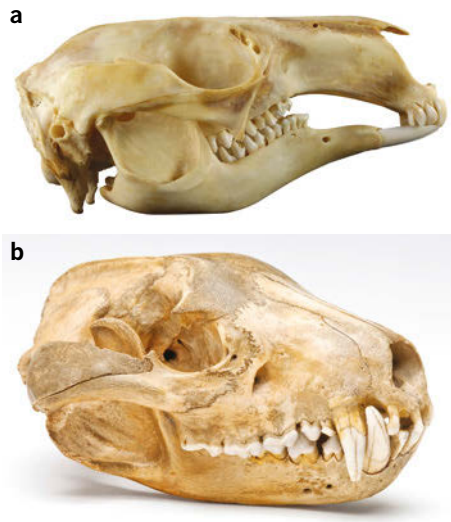


FIGURE 5.3.9 The skull of (a) a kangaroo, a herbivore, and (b) a Tasmanian devil, a carnivore.

Human digestion

The digestive system in mammals has the principle function of digesting and absorbing food. In other words, the digestive system breaks down food, making it simple enough to pass across cell membranes and be useful to cells.

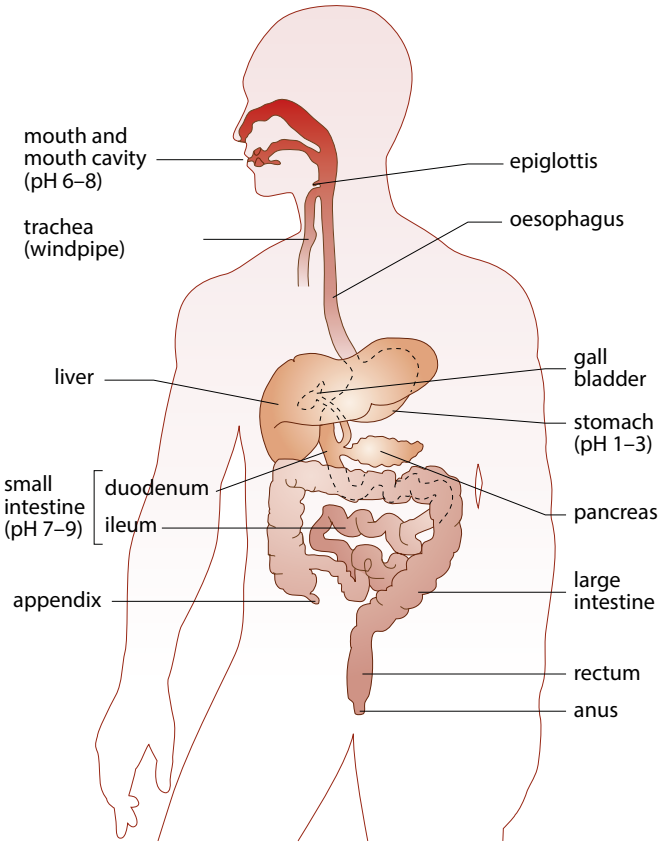


FIGURE 5.3.10 Components of the human digestive system

Before food passes into the digestive system of a mammal, it is physically broken into pieces by the teeth. Mucus is secreted to protect the lining of the gut and to lubricate food for easier passage. The food then moves along the gut past a series of digestive enzymes that sequentially break down the various compounds for absorption. Proteins are broken down to amino acids, fats and lipids to fatty acids and glycerol and complex carbohydrates such as starch to simple sugars. Useful substances, such as water, are absorbed, leaving unwanted and undigested substances to be eliminated in the faeces.

The main regions of the human digestive system are the mouth and mouth cavity, oesophagus, stomach, small intestine, large intestine, rectum and anus. These components are shown in Figure 5.3.10. The salivary glands, pancreas and liver are digestive glands that develop as outgrowths (accessory organs) of the digestive system.

Key steps in the process of digestion in humans occur at the:

- mouth, where teeth mechanically break food into small pieces. Saliva lubricates food and the enzyme amylase digests **starch** into **maltose**
- **epiglottis**, which is a flap, at the entrance to the larynx, prevents food from entering the trachea and respiratory system, directing it down the oesophagus. The epiglottis is also associated with the gag and cough reflex
- oesophagus, a tube down which food travels to the stomach, aided by muscular contractions (**peristalsis**)
- stomach, where protein-digesting enzymes (proteases) and gastric juices are secreted to aid in food digestion. Peristalsis of the stomach muscles further breaks the food down and pushes it through the digestive system

- liver, which has important roles in regulating metabolism, toxin removal and processing nutrients. It stores excess glucose as glycogen (a polysaccharide or carbohydrate) for later conversion back to glucose when needed for energy. The liver is also the site of bile production, for the breakdown of fats
- gall bladder, which stores and concentrates bile before releasing it into the small intestine
- pancreas, where digestive enzymes are produced and activated when the food reaches the duodenum (first part of the small intestine). The pancreas also produces the hormones insulin and glucagon, which regulate sugar levels in the blood, and sodium hydrogencarbonate, which neutralises stomach acids in the food
- small intestine, the primary function of which is to absorb nutrients and minerals from food. Enzymes produced in the pancreas and the small intestine and bile from the liver and gall bladder further process food products to facilitate nutrient and water absorption. The small intestine's many blood vessels absorb the nutrients and waste products of digestion and deliver them to adjacent vessels of the circulatory system
- large intestine, where water is absorbed with soluble compounds like vitamins and minerals; undigested food leaves the body as faeces.

Structure of the small intestine

The principal organ of absorption is the small intestine. 'Small' refers to the diameter of this part of the intestine. The small intestine is long and has a large surface area, making it well suited for absorption. The internal surface area is further increased by millions of tiny folds called villi, and also by the presence of many microvilli on the exposed surface of the epithelial cells lining the lumen (Figures 5.3.11 and 5.3.12).

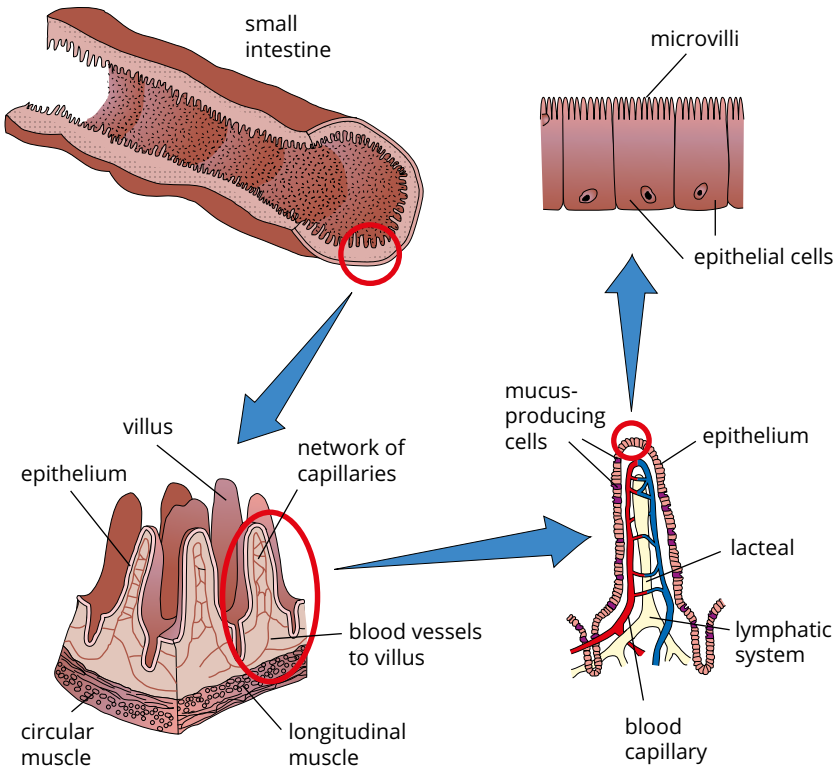


FIGURE 5.3.11 The internal surface of the human intestine, showing the villi and microvilli.

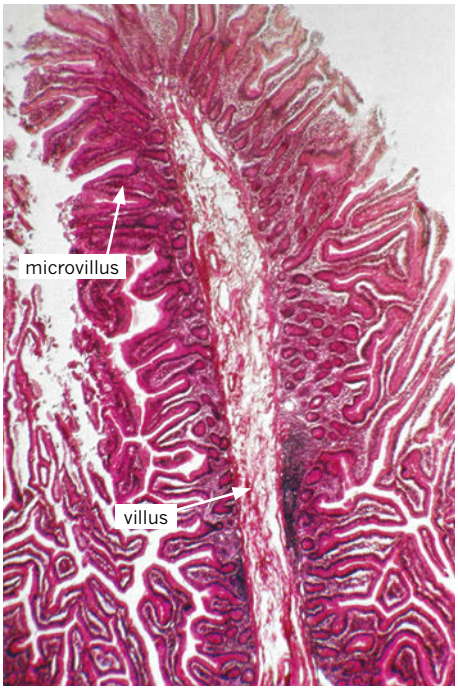


FIGURE 5.3.12 A cross-section of a villus (plural villi) from the small intestine. Villi are finger-like projections from the wall of the small intestine that increase the surface area for more efficient absorption of nutrients. Villi are covered in microvilli, which further increase the surface area for absorption.

Absorption in the small intestine

The epithelial lining in the small intestine is only one cell thick, allowing a rapid transfer of nutrients to the many blood and lymphatic vessels beneath the surface, which transport nutrients away to the body tissues. Nutrients pass through the lining of the small intestine by facilitated diffusion or active transport, along or against the concentration gradient.

Lipid-soluble molecules, which are the products of fat digestion (mainly fatty acids and glycerol), diffuse easily through the membranes of the epithelial cells along a concentration gradient. They then reassemble into fats before passing into the **lacteals**. Lacteals are capillaries of the lymphatic system near the intestine and have a milky appearance because of their high fat content after a fatty meal. Lipid-soluble vitamins also pass through the intestinal epithelium by passive diffusion.

Water-soluble molecules, including amino acids, simple sugars (monosaccharides such as glucose), and water-soluble vitamins and minerals pass through the membranes of the epithelial cells by active transport and facilitated diffusion. This can occur down or against a concentration gradient, ensuring that these essential nutrients are absorbed quickly.

Most of the water (90–95%) that enters the small intestine is also absorbed. This absorption is passive. Water diffuses across the lining of the intestine osmotically as the products of digestion are absorbed.

Blood leaving the intestine passes first into the liver through the hepatic portal vein, where absorbed nutrients can be removed and stored in the liver, before passing into the general venous circulation.

Herbivores utilise cellulose

Cellulose is the main component of plant cell walls, but its molecules are too large to be absorbed without digestion. Although many species of animals are herbivores, only a few can make the enzyme cellulase that is needed to digest cellulose. To get around this problem, herbivores have a symbiotic partnership, called mutualism, with bacteria that can produce cellulase. The bacteria live in the gut of the animal. They receive shelter and nutrients, and in return convert cellulose into simpler molecules that can be absorbed by the gut. The bacteria also supply important vitamins such as the B group and vitamin K.

The environment inside the gut is warm and wet but there is little or no oxygen, so the breakdown of cellulose must occur anaerobically by fermentation. Because of this, the part of the intestine in which the breakdown of cellulose occurs is sometimes called a fermentation chamber.

In herbivorous mammals, fermentation takes place in different parts of the intestine in different species, with varying degrees of efficiency. Generally, herbivorous mammals belong to either of two groups—hindgut or foregut fermenters.

Hindgut fermenters

In hindgut fermenters, fermentation occurs in the caecum (an enlarged pouch where the small and large intestines join), or the first part of the large intestine (the wombat in Figure 5.3.13), or both (the koala in Figure 5.3.13). Both of these are located after the small intestine, which is the region where most absorption takes place. This arrangement limits the advantage obtained from the symbiotic relationship, because the products of their digestion are not completely absorbed.

Horses are hindgut fermenters, and the relative inefficiency of their system can be seen by the fact that horse faeces contain large amounts of undigested plant material. Some hindgut fermenters, such as possums and rabbits, overcome this problem by producing two types of faeces. One of these comes directly from the **caecum** at night and is reingested so that it can go through the intestine again. This means that the vitamins and products of cellulose digestion from the bacteria are available for absorption from the small intestine.

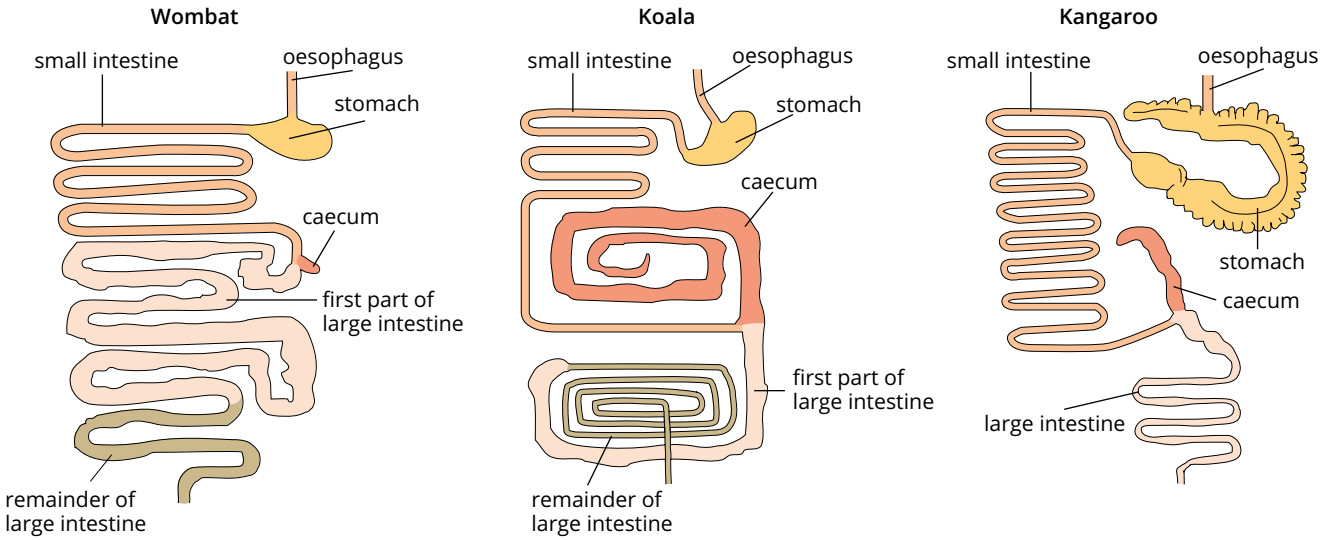


FIGURE 5.3.13 Wombats, koalas and kangaroos are herbivores and use symbiotic bacteria for the digestion of cellulose. Wombats and koalas are hindgut fermenters whereas kangaroos are foregut fermenters.

Foregut fermenters

In the foregut fermenters (such as the kangaroo in Figure 5.3.13), the fermentation chamber is located before the stomach. In ruminants such as cattle and sheep, it is called the **rumen**. Food can be regurgitated back into the mouth for further physical breakdown (rumination), then returned to the rumen for continued chemical breakdown by bacteria. This regurgitated food is called cud.

Foregut fermentation has the obvious advantage that the products of digestion by microorganisms are available for absorption along the entire length of the small intestine. Kangaroos and wallabies are the only marsupial foregut fermenters.

Ruminant digestion has some drawbacks. The complete digestion of plant material in the rumen by microorganisms can take a long time—hours or even days, with constant regurgitation and chewing of the cud. If the quality of food is very low (i.e. mostly cellulose and not much fresh, young plant growth), an animal may be starved of food that is digested enough for absorption, even though the animal has a very full rumen.

Food and energy storage in mammals

When food is not available, an animal's body draws on its own stores to meet its nutritional and energy needs. Energy storage is clearly essential for carnivores, which eat intermittently depending on the availability of prey.

Herbivores often have to travel considerable distances to find new and adequate supplies of the plants that they eat, when seasons change or if they have overgrazed an area. In winter, food generally becomes scarce for both herbivores and carnivores. In very cold climates, some mammals (usually small species) resort to hibernation to survive the winter (Figure 5.3.14). In each of these situations, the ability to store nutrients and energy reserves is essential for survival.

PA 1.2.2

FIGURE 5.3.14 The mountain pygmy-possum (*Burramys parvus*) is Australia's only hibernating marsupial. They accumulate fat stores before entering hibernation for 5–7 months every year.

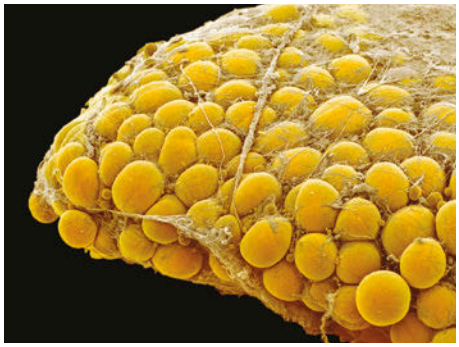


FIGURE 5.3.15 A coloured scanning electron micrograph of a sample of fat tissue, showing fat cells (adipocytes) surrounded by fine strands of supportive connective tissue. Adipocytes are among the largest cells in the human body, each cell being 100–120 µm in diameter.

When needed, carbohydrate stores in the liver and muscles (glycogen) are used first and most easily, but their capacity is limited. Humans usually have enough glycogen stored to last for 12–48 hours of moderate activity. The capacity for storage in fat tissue (adipose tissue) is virtually unlimited (Figure 5.3.15). In a person of healthy weight, there is enough fat stored in tissues to allow normal energy consumption to continue for 3–7 weeks. As a last resort, the more limited protein stores of body tissues are used to provide energy after other stores are depleted.

Unlike carbohydrates and fats, amino acids cannot be stored in animal tissues, so animals need the full range of amino acids needed for building proteins in their diet. Proteins are assembled in cells by linking amino acids in a specific order. If the next amino acid required is not available, the synthesis of that protein molecule cannot continue until the required amino acid arrives.

This has consequences for strict vegetarians because, unlike meat, individual plants do not normally contain the full range of essential amino acids. However, by eating an appropriate combination of plant foods at the same meal, such as beans (which are a good source of the amino acids isoleucine and lysine, but deficient in tryptophan) and rice (which is deficient in isoleucine and lysine, but a good source of other essential amino acids), a balanced diet can be obtained. A meal of rice and beans together is as good a source of protein as eggs or meat.

Energy reserves

In contrast to plants, animals have only a limited capacity to store carbohydrates. Carbohydrates are stored in animals as **glycogen**, which, like starch, is a large molecule made from glucose subunits. In humans about 300 g of glucose is stored as glycogen in the liver and muscles. The remainder of our energy reserves is stored as fats.

Unlike plants, animals use fats rather than carbohydrates as their main form of energy reserves because:

- almost 25% more ATP is produced (per carbon atom) from fats than from carbohydrates
- fat is almost 50% lighter (per carbon atom) than carbohydrate
- stored carbohydrates attract and bind water molecules, increasing their weight by 200–500%; fats do not
- 1 gram of carbohydrate or protein provides up to 17 kJ of energy; 1 gram of fat provides 39 kJ of energy.

An average 70 kg male human stores about 11 kg of fat; the same amount of energy stored as carbohydrate could weigh more than 100 kg.

Some of the chemical processes that take place in living organisms use up energy, while other processes release energy. For energy balance, energy input (eating) must equal energy output (usage). If the amount of food eaten provides more energy than is used, the excess energy is stored as chemical energy (e.g. in fat or glycogen). If the energy content of food is less than required, the balance is made up from stored energy reserves or by breaking down body tissues.

Energy requirements in humans

In animals, the amount of energy that is needed each day depends on factors such as **basal metabolic rate**, body size, activity level and environmental temperature. Metabolism is the name for the sum of all these processes, and metabolic rate is a measure of the overall energy requirements of an organism. Basal metabolic rate refers to the amount of energy required to maintain basic functions in a resting, unstressed animal per unit time. Basal metabolic rate varies greatly between species. Mammals have a much higher basal metabolic rate than some other vertebrates because they use energy to maintain a constant body temperature. Basal metabolic rate does not include the extra energy required for activity or for maintaining a warm body temperature in a cold climate.

In humans and other mammals, metabolic rate is affected by:

- body composition (the proportion of fat or bone to muscle). Muscle tissue uses energy at a faster rate than does fat tissue, so more muscle means a greater energy requirement
- level of activity. Different levels of physical activity account for large differences in metabolic rate. Individuals also vary in the amount of energy they use to carry out a particular activity
- gender. Men use energy at a higher rate than women, mainly because on average they have a lower fat-to-muscle ratio than women
- age. **Metabolic rate** increases during periods of growth, such as childhood and adolescence, levels off during adulthood (except during pregnancy and breastfeeding when it increases by about 25% and 60% respectively) then declines during later years, mainly because of decreased physical activity and changes in body composition.

REMOVING WASTES: THE EXCRETORY SYSTEM

As cells function using the nutrients provided, they produce substances that are no longer useful to them. The accumulation of these waste substances, such as carbon dioxide from respiration and **nitrogenous wastes** from protein breakdown, can prevent cells from functioning properly.

In mammals, the function of the kidneys is to excrete nitrogenous wastes. Excretion usually involves the loss of water and is therefore closely linked to water balance in terrestrial animals. This system works closely with the circulatory system, filtering waste products from the bloodstream and collecting them in urine.

For heterotrophs, it is sometimes inevitable that toxic substances are absorbed from the food they eat; these toxic substances must also be excreted. Excretion is the removal of substances that once formed part of the body of the organism. (This is different from egestion, which is the removal of undigested food from the gut in faeces.)

The internal environment of animals is extracellular fluid, which is quite separate from the external environment and has a highly regulated composition. Salts form ions in solution. The concentrations of certain ions in cells are held within narrow limits. Some of these ions are also important for regulating the pH of body fluids, which must be at a suitable pH for enzymes and other molecules to function efficiently.

In animals, the removal of wastes and toxic substances, and the control of pH, ion concentrations and water balance, are carried out mainly by excretory organs. These processes vary with the activity of the animal and the external conditions.

The nature of wastes

During normal activity, animal cells break down and replace carbohydrates, lipids and proteins, producing waste products that usually cannot be used by the body.

Carbon dioxide

When carbohydrates or lipids are broken down during cellular respiration to release energy, carbon dioxide and water are produced (see Module 3.2). These are released into the surrounding environment across respiratory membranes, which in mammals are in the lungs. Water produced during cellular respiration is incorporated into body fluids, and excess water is expelled from the body.

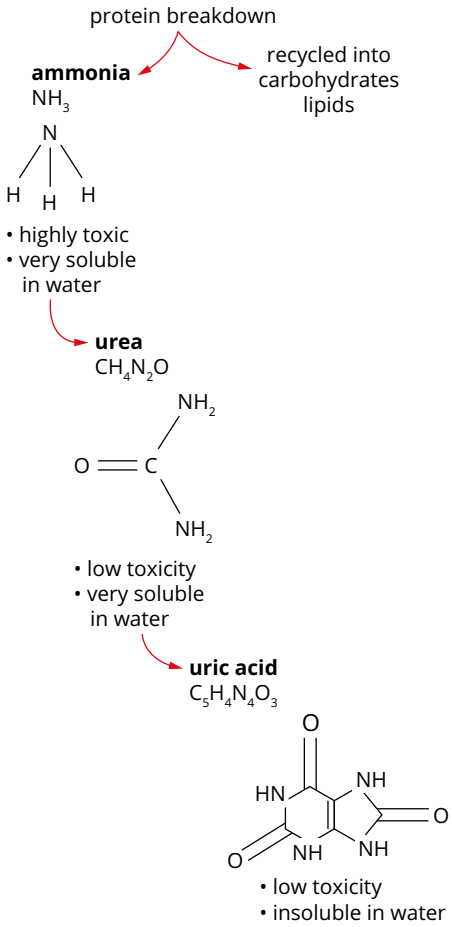


FIGURE 5.3.16 Three important nitrogenous wastes produced from the breakdown of proteins in animals. Mammals excrete their nitrogenous wastes in the form of urea.

FIGURE 5.3.17 Desert-dwelling animals such as the bilby (*Macrotis lagotis*) can produce highly concentrated urine, which minimises water loss.

Nitrogenous wastes

Protein consists of amino acids, which contain nitrogen. When proteins are broken down, the nitrogenous parts are split off and the remainder of the molecule is converted into carbohydrates or lipids, which can be used for energy. The remaining nitrogenous wastes must be removed from the cell, because they can become toxic.

The first nitrogenous waste to be formed from the breakdown of protein is **ammonia**. Ammonia is highly soluble in water, and many aquatic organisms take advantage of this solubility to effectively remove nitrogenous wastes from the body, often through the gills. One problem with ammonia is its toxicity to cells, even at low concentrations; ammonia cannot be stored in the body for any length of time.

Ammonia can be converted into two less toxic forms, **urea** and **uric acid** (shown in Figure 5.3.16), but this process requires energy. Neither urea nor uric acid is of any further use to most animals; however, because urea and uric acid are less toxic than ammonia, they can be stored in the body before being excreted. Mammals excrete nitrogenous waste in the form of urea, which is in urine. Reptiles and birds excrete nitrogenous waste in the form of uric acid. The white component of bird droppings contains uric acid crystals.

Excretory mechanisms in mammals

Kidneys

The kidneys of all vertebrates, from fishes to mammals, function by filtering blood, then reabsorbing useful substances and secreting unwanted ones. Blood is filtered through blood vessel walls to form a primary filtrate that has the same composition as plasma, except that the large proteins have been filtered out. Most of the useful substances in the primary filtrate are reabsorbed as it passes through the kidney tubule. Some unwanted substances may be secreted into the fluid in the tubule before it passes out of the kidney to the bladder. These processes regulate the concentration of different salts in the blood, including those salts that are responsible for maintaining the pH of body fluids within closely controlled limits.

Mammals conserve water by producing urine that is more concentrated than body fluids. The ability to produce concentrated urine is related in some mammals to the degree of water stress experienced in their normal environments. Desert-adapted mammals, such as the bilby in Figure 5.3.17, are able to excrete highly concentrated urine.

The liver prepares wastes

The liver performs many different functions and has a central role in the maintenance of a stable internal environment. In addition, it is responsible for preparing various substances for excretion. It detoxifies a variety of harmful chemicals such as alcohol and some drugs. It is also responsible for breaking down amino acids to release ammonia, which it then converts largely into urea. The waste products from these processes travel in the bloodstream to the kidneys for excretion.

The liver also destroys worn-out red blood cells, producing bile pigments from the breakdown of haemoglobin. Bile pigments, along with bile salts, which emulsify fats as part of digestion, are stored in the gall bladder before they are released into the lumen of the intestine. Bile pigments are one of the few substances excreted into the gut.

THE MAMMALIAN KIDNEY

Mammals have two kidneys at the back of the abdominal cavity. Blood flow to the kidneys is always kept high, because they are so important in maintaining the stability of the internal environment. Although kidneys are only about 1% of body tissue, they receive approximately 25% of the body's blood flow.

Blood enters the kidney from the aorta through the renal artery, and leaves through the renal vein. Blood vessels branch throughout the kidney in a complex fashion (Figure 5.3.18). Urine, formed in the kidneys, drains via the **ureters** into the **bladder**, for storage, until an appropriate time for release through the **urethra**.

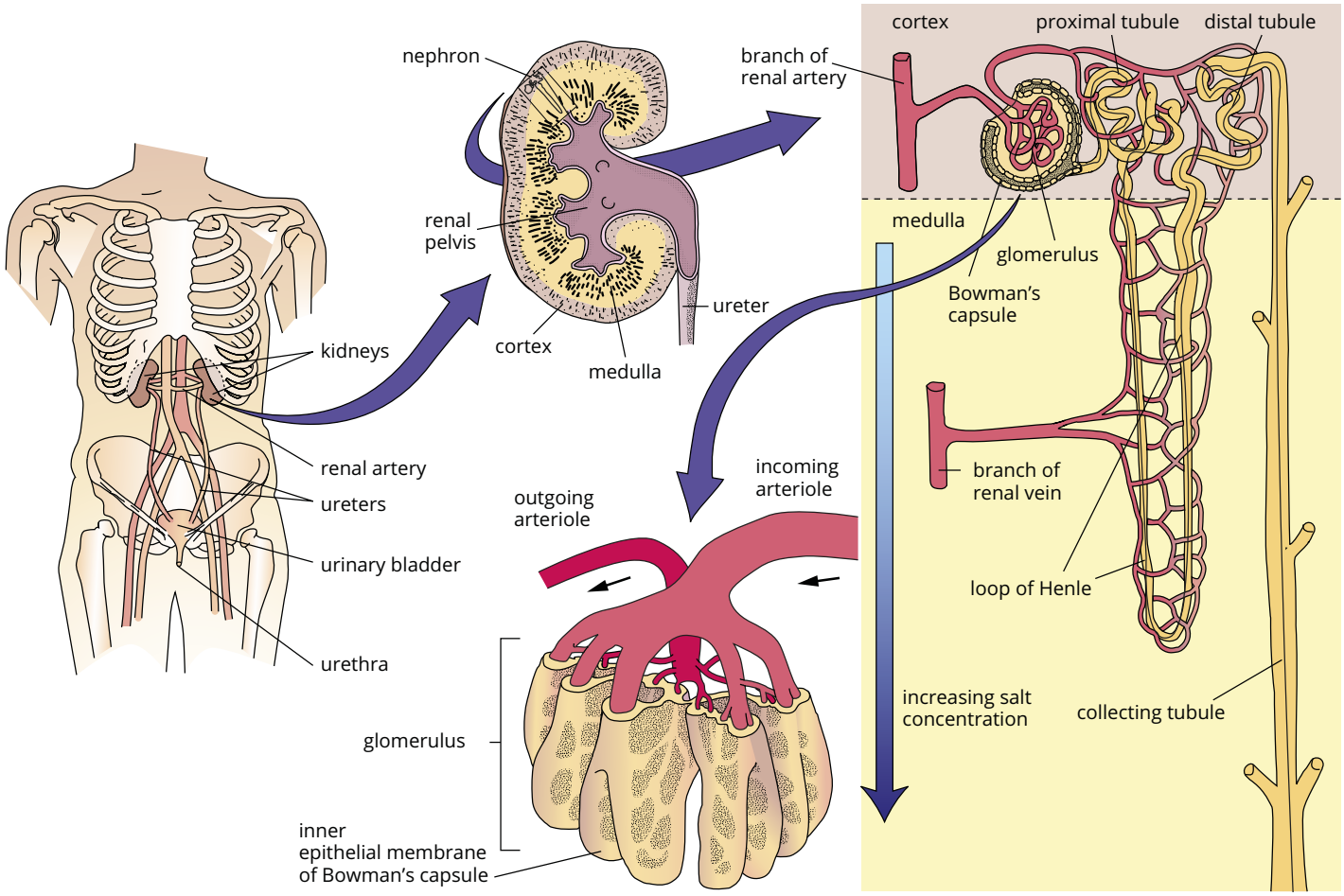


FIGURE 5.3.18 The structure of the human excretory system

The functions of the mammalian kidney are carried out by **nephrons**, which are the functional units of the kidney. There are approximately one million nephrons in a human kidney, and their combined function carries out the work of the kidney. A nephron is composed of a **Bowman's capsule** surrounding a **glomerulus**, and a tubular region consisting of the proximal convoluted tubule, **loop of Henle** and distal convoluted tubule that leads into a collecting tubule (Figure 5.3.19). The formation of urine involves passive filtration, selective **reabsorption** and **secretion**, and the passive removal of water.

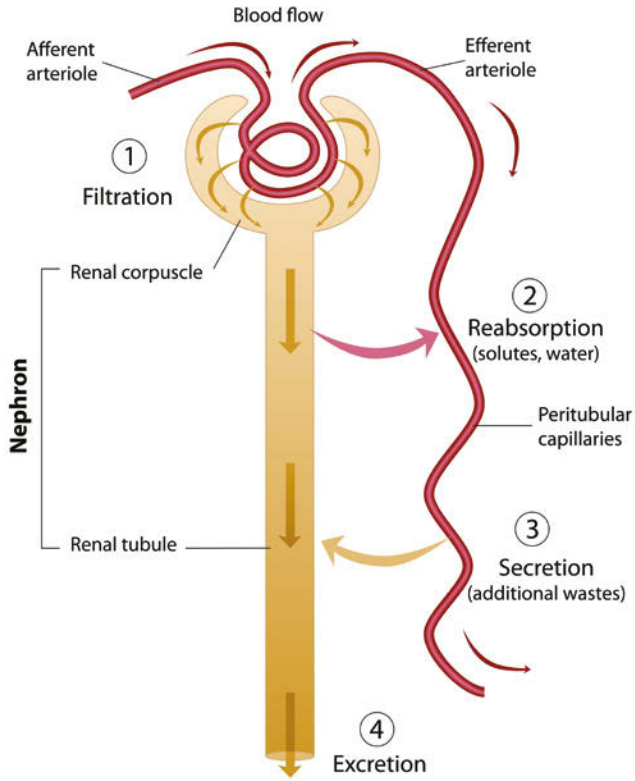


FIGURE 5.3.19 The stages of urine formation involve filtration, reabsorption, and secretion. Urine is stored in the bladder before it is finally excreted.

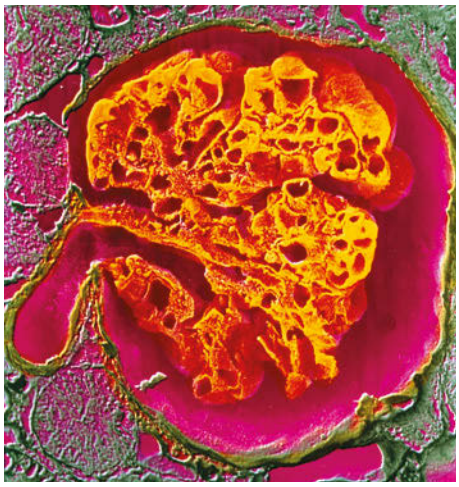


FIGURE 5.3.20 A coloured scanning electron micrograph of a glomerulus—a tight knot of blood capillaries (yellow) inside the Bowman's capsule (pink)

WS 1.2.8 PA 1.2.3

The nephron is very closely associated with blood vessels, particularly the glomerulus, which is a clump of looping capillaries embedded in the Bowman's capsule, and networks of capillaries wrapped around the remainder of the tubule.

There are two distinct regions in the kidney: the outer cortex and the inner medulla. Glomeruli are located in the cortex (Figure 5.3.19).

Filtration

Filtration occurs across the glomerulus into the Bowman's capsule, as shown in Figure 5.3.20. The high pressure of blood in the glomerular blood vessels forces fluid through the walls of glomerular capillaries and into the Bowman's capsule.

Only small molecules and water can pass through the wall membranes; blood cells and large blood proteins remain behind in the glomerular capillaries. This primary filtrate has the same composition as blood plasma, without large proteins.

If red blood cells or large proteins are found in urine, this indicates that the normal filtration mechanism has broken down and blood is leaking from the glomerulus into the Bowman's capsule. This may occur as a result of damaged glomerular blood vessels, or very high blood pressure.

Reabsorption

Approximately 99% of the primary filtrate—including salts, glucose, amino acids and water, but only half or less of the urea—undergoes reabsorption along the length of the nephron (Figure 5.3.19). Virtually all amino acids and glucose are reabsorbed in the proximal convoluted tubules by active transport against a concentration gradient. The presence of glucose or amino acids in urine therefore indicates a possible kidney malfunction. Specific salts, particularly sodium chloride, are also actively reabsorbed. These active processes consume a lot of energy.

Water is reabsorbed from the urine passively, along an osmotic gradient. The mechanism by which the kidney is able to produce concentrated urine involves the loop of Henle (Figure 5.3.18). A large amount of sodium chloride pumped out of the loop of Henle is retained in the medullary region of the kidney, producing a very high salt concentration. The osmotic concentration within the kidney therefore increases considerably from the outer cortex to the medulla. When the urine finally passes down the collecting tubules towards the ureter, it passes through this region of high salt concentration. Because the collecting tubule is permeable to water, but not to salt, water passes from the collecting tubule back into the kidney and into blood vessels. As a result, the urine becomes concentrated. Antidiuretic hormone (ADH) from the pituitary gland increases the permeability of the collecting tubule to water, increasing reabsorption of water and causing urine to become concentrated.

Secretion

Secretion is the active removal (excretion) of particular substances by the cells of the tubule wall (Figure 5.3.19). Ammonium, potassium and hydrogen ions are actively secreted into the distal convoluted parts of the tubules. Various dyes and drugs such as penicillin and aspirin are also eliminated by tubular secretion. These substances are added to the filtrate as it passes through the nephron.

5.3 Review

SUMMARY

- Mammals are heterotrophs. They must consume other organisms or their products to obtain organic molecules.
- The purpose of digestion is to rapidly break down organic food into molecules small enough to be able to pass through membranes and into cells.
- Chemical digestion involves breaking apart complex molecules into simple molecules by the action of enzymes (amylase, protease and lipase).
- Physical breakdown of large food into smaller pieces increases the surface area available for enzyme action and therefore increases the efficiency of digestion.
- When food is not available, an animal's body draws on its own stores to meet its nutritional and energy needs.
- Mammals can store excess carbohydrates and fats, but not amino acids. Lipids store more energy by weight than carbohydrates.
- For energy balance, energy input (eating) must equal energy output (usage).
- The amount of energy that is needed each day depends on factors such as basal metabolic rate, body size, activity level and environmental temperature. In mammals, body composition, activity levels, sex and age also affect basal metabolic rate.
- Excretion is the removal of substances that once formed part of the body of the organism.
- In animals, removal of waste and toxic substances, and control of pH, ion concentrations and water balance, are carried out largely by excretory organs, such as the kidney.
- Proteins are broken down and converted into carbohydrates or lipids, which can be used for energy, and nitrogenous wastes, which must be removed from the cell, because they can become toxic.
- The nephron is the functional unit of the mammalian kidney.
- The three main stages of urine formation are filtration, reabsorption and secretion.
- A nephron consists of a Bowman's capsule (surrounding a glomerulus) leading into a tubular region (proximal convoluted tubule, loop of Henle and distal convoluted tubule) and then into the collecting tubule.

KEY QUESTIONS

Retrieval

1 Define 'digestion'.

2 Recall three characteristics of an efficient digestive system.

3 Name the two main types of wastes produced by mammals.

4 Recall the name of the functional unit of the mammalian kidney.

Comprehension

5 Explain the main differences between chemical and physical digestion.

6 Describe two ways, with examples, that surface area is maximised in mammalian digestive systems.

7 Demonstrate an advantage of a one-way digestive system compared to a two-way digestive system.

8 Explain why ammonia must be converted to urea and uric acid in some animals.

9 Explain why it is important that the permeability to water of the collecting tubule of the mammalian kidney can be regulated.

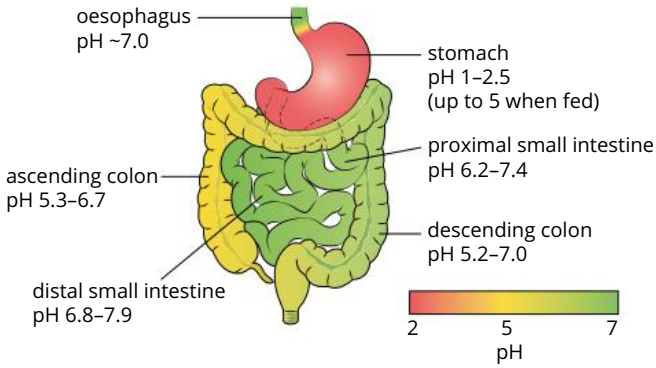
Analysis

10 Organise the following to show the path of filtrate through a renal tubule: ascending limb of loop of Henle, descending limb of loop of Henle, distal convoluted tubule, proximal convoluted tubule.

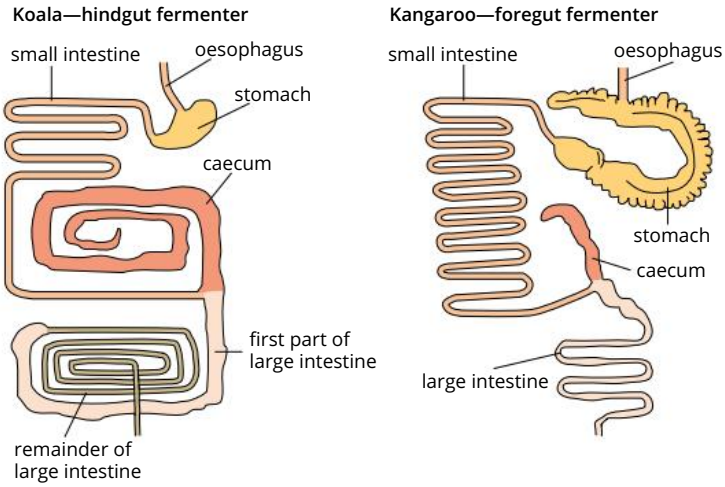
continued over page

5.3 Review *continued*

11 The following diagram shows the pH of the human digestive tract. Pepsin is an enzyme that is released into the stomach to break down protein. Deduce what happens to pepsin once it leaves the stomach.



12 Consider the figure below. In comparison to hindgut fermenters, foregut fermenters are considered to be far more efficient at digesting their food. Identify reasons why this may be the case.



13 Compare the excretory functions of the mammalian kidney and liver.

14 This table shows the urine concentration of four different mammals. The unit used is milliosmole (mOsm) per litre. Determine which animal would live in a desert habitat.

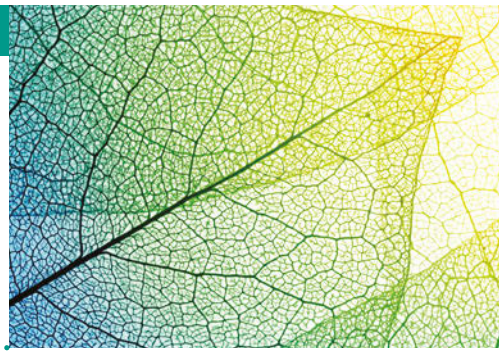
Organism	Urine concentration (mOsm L^{-1})
Organism A	2900
Organism B	5500
Organism C	520
Organism D	1400

15 Dialysis is used by patients with kidney failure. During dialysis, small solute molecules pass through a partially permeable membrane, but larger proteins and cells do not. Identify which state of normal kidney function dialysis replicates.

5.4 Gas exchange and transportation in vascular plants

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

- understand how vascular plants exchange gases with their environment
- understand the role of stomata in gas exchange and water regulation in plants
- understand how xylem vessels transport water and nutrients from the roots to the leaves of plants
- understand how phloem vessels transport sugars produced during photosynthesis from the leaves to the roots.



Plants carry out two energy-transforming processes. Cellular respiration occurs throughout all of the cells in vascular plants, requiring oxygen and producing carbon dioxide. However, photosynthesis occurs primarily in cells in the leaves, where chloroplasts in the cells convert water and carbon dioxide, in the presence of sunlight, into glucose, water and oxygen.

Vascular plants include ferns, cycads, conifers and flowering plants and usually grow in terrestrial environments. Like complex animals, vascular plants have specialised tissues and organs to exchange gases and move substances, such as nutrients and wastes, around the organism. Vascular plants are characterised by the presence of vascular tissue, which is tissue that is specialised for transporting fluids. Two of the major organs in plants are leaves and roots. In vascular plants, vascular tissue is found within both of these organs.

In vascular plants, gas exchange occurs in the leaves, stems and roots, while transport occurs inside closed vessels organised into **vascular bundles** that move water, mineral ions and sugars around the plant. They consist of:

- **xylem** vessels, which transport water and nutrients to the leaf from the roots
- **phloem** vessels, which transport sugars produced during photosynthesis from the leaves to the roots
- a sheath of **lignin**, which strengthens and supports the tissue.

In this module, you will learn about the tissues and organs in **vascular plants** that exchange gases, and transport water and mineral ions.

GAS EXCHANGE IN VASCULAR PLANTS

Most plants do not have specialised organs for gas exchange. Simple plants, such as mosses, have leaves that are small and extremely thin, only one cell thick, so each cell is in direct contact with the surrounding environment. Gases such as oxygen and carbon dioxide can easily diffuse directly between the air and the contents of each cell. In vascular plants (plants with conducting tissue), the exchange of oxygen and carbon dioxide in the leaves, stems and roots occurs by diffusion through special openings in the epidermis called **stomata** (singular *stoma*).

The rate of movement of gases between air spaces and the atmosphere is regulated by the stomata, the main route through which gas exchange occurs. When the stomata are closed, the exchange of oxygen, carbon dioxide and water vapour between the plant and its environment virtually stops. Only small quantities of gases are able to pass directly through the epidermis and the overlying cuticle (the outer waxy layer).

Plant cells are loosely packed, allowing rapid diffusion of gases through intercellular spaces, which are filled with air (Figure 5.4.1). During gas exchange, oxygen and carbon dioxide diffuse from these air spaces through the water film covering the cells and into the cells along concentration gradients. Diffusion also occurs in the reverse direction.

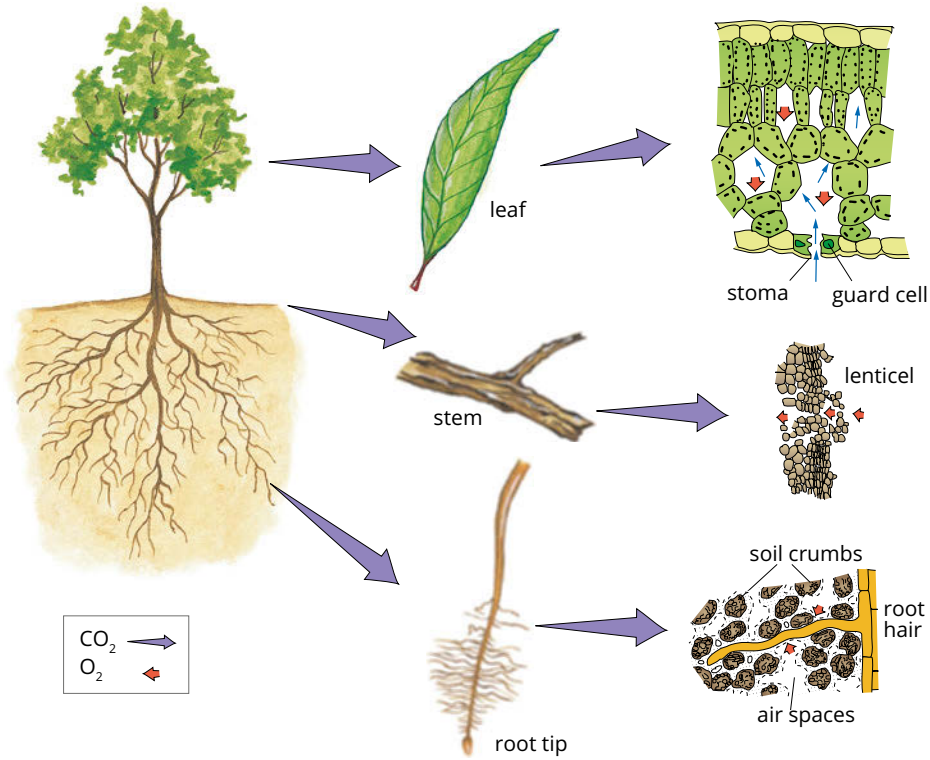


FIGURE 5.4.1 Routes of gas exchange with cells of leaves, stems and roots

Because diffusion distances are not great, and cells are organised in thin layers near the surface (even in large plants), gases do not generally have to be transported from one part of a plant to another.

Stomata

Stomata are tiny pores in the epidermis, bordered by two highly specialised epidermal cells called **guard cells** (Figure 5.4.2). Unlike other epidermal cells, guard cells contain chloroplasts. Stomata can occur on any part of a plant except the roots, but in most species they are most abundant on the surface of the leaves.

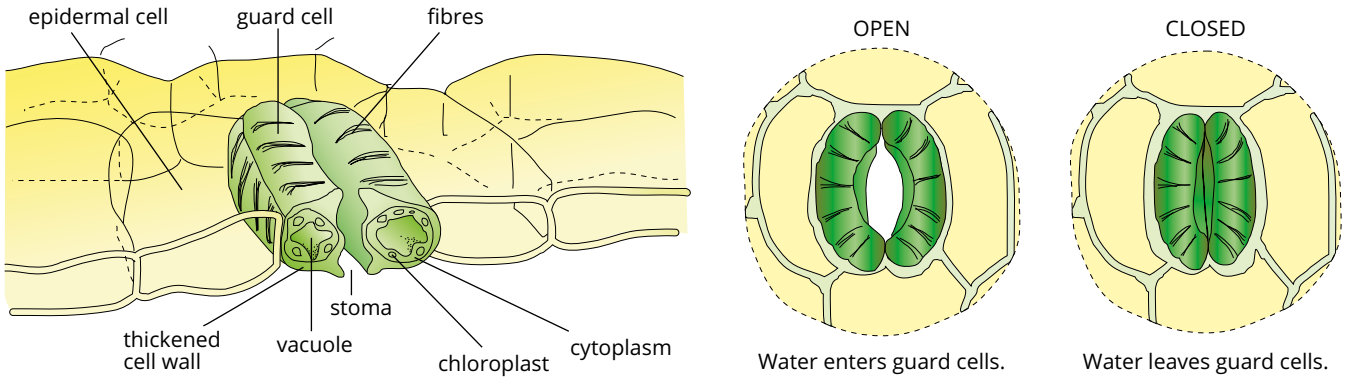


FIGURE 5.4.2 Gas exchange in leaves occurs through stomata. When water enters guard cells, they expand, opening the stoma. Guard cells expand lengthwise because they have a thickened inner cell wall with cellulose fibres that prevent the cells expanding in width.

The number and size of stomata on a leaf vary according to the plant species and the environmental conditions under which it has grown.

In a typical plant, most stomata are on the underside of the leaves, away from the drying effect of the sun's rays. In contrast, stomata in floating aquatic plants, such as water lilies, are confined to the upper epidermis. In plants such as eucalypts, which are adapted to dry conditions, stomata are often in sunken pits in the surface of the leaves. This reduces direct flow of air across them and so reduces water loss.

Controlling guard cells

Guard cells (Figures 5.4.2 and 5.4.3) have the following structural features relating to their function.

- They are joined at their ends in pairs.
- Their cell walls are thicker on the side adjacent to the stoma.
- Bands of inelastic fibres run around each cell wall.

When water passes into the guard cells, their internal fluid pressure, or **turgor**, increases. This causes them to expand in the only direction possible: lengthways. The guard cells buckle and open the stoma. Conditions favouring the opening of stomata are abundant water, light and low internal carbon dioxide concentrations.

Terrestrial plants, like terrestrial animals, must reduce loss of water by evaporation. The moist surfaces that they use for gas exchange are the major site of water loss. Therefore, the stomata act to balance the plant's need to obtain carbon dioxide for photosynthesis against the dangers of drying out due to the loss of water from the leaves.

During daylight, when plants are photosynthesising, large volumes of carbon dioxide and oxygen are exchanged with the environment through open stomata. At night, when photosynthesis is not occurring, stomata are usually closed. Stomata also close during the day if it is very hot and dry. This prevents excessive water loss, but also drastically reduces the rate of photosynthesis.

Thus, conditions that usually favour the opening of stomata are abundant water, bright light and low internal carbon dioxide concentrations.

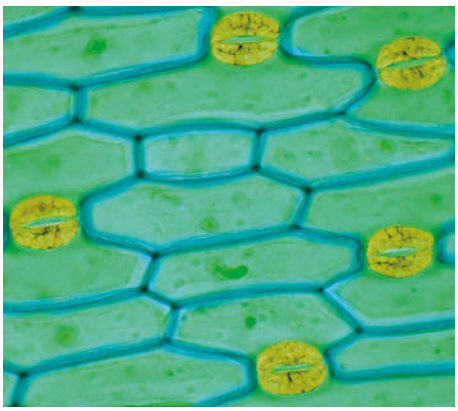


FIGURE 5.4.3 A light micrograph of stomata on the surface of a plant. Guard cells (yellow) either side of the opening regulate the exchange of gases and water vapour into and out of the plant.

Stems and roots

In the epidermis of green stems, as in the leaf epidermis, there are stomata through which gas exchange takes place. In woody stems and mature roots, the epidermis is replaced by a layer of cork cells that are waterproof and airproof. Air passes freely through groups of these loosely packed cells to the cells beneath. Each group of loosely packed cells is called a **lenticel** (Figure 5.4.4).

Roots exchange gases with the air in spaces in the soil. Oxygen readily diffuses into the film of moisture surrounding **root hairs**, and then into the roots themselves. When soil is waterlogged due to excessive rain or poor drainage, the spaces in the soil are filled with water instead of air. Because the amount of oxygen dissolved in water is so much less than the amount of oxygen in air, the roots may not be able to get enough oxygen for their needs. The root cells may die, killing the plant. Many indoor plants are 'killed with kindness' by over-watering.

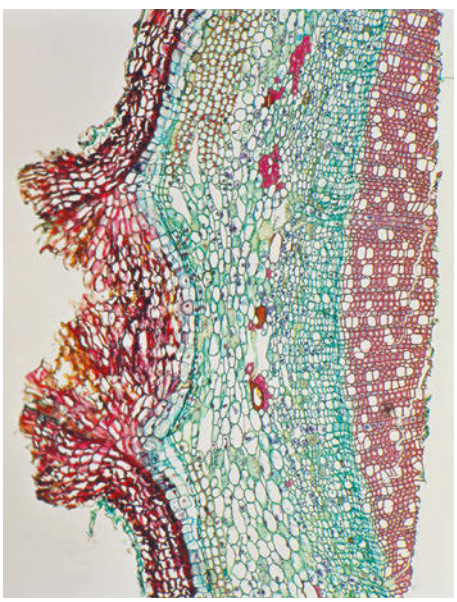


FIGURE 5.4.4 A cross-section through the surface of a woody stem showing a loosely packed lenticel on the left bordered by layers of waterproof cork cells

Aquatic plants

In aquatic plants, roots are often continuously submerged. In some of these species, oxygen diffuses from aerial parts of the plant into the submerged organs. Some aquatic plants have adaptations that help in gas exchange. Pondweeds and water hyacinths float on water because the leaf stalks are swollen with large, air-filled intercellular spaces (Figure 5.4.5a on page 190). Mangroves, which live in salty, waterlogged mudflats, have specialised roots called pneumatophores that assist in gas exchange (Figure 5.4.5b on page 190). Pneumatophores also contain large intercellular spaces.

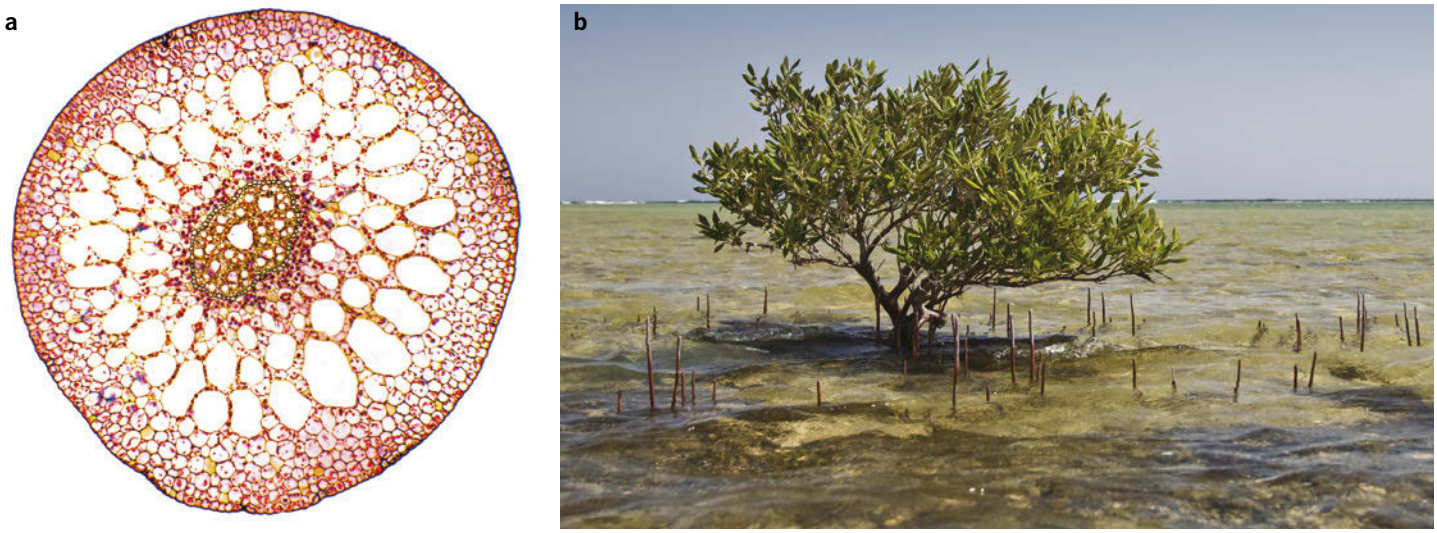


FIGURE 5.4.5 (a) The pondweed *Potamogeton* has long stems and broad floating leaves. This cross-section of its stem shows many air-filled intercellular spaces. (b) Mangroves send up specialised roots (pneumatophores) to help with gas exchange.

TRANSPORTATION IN VASCULAR PLANTS

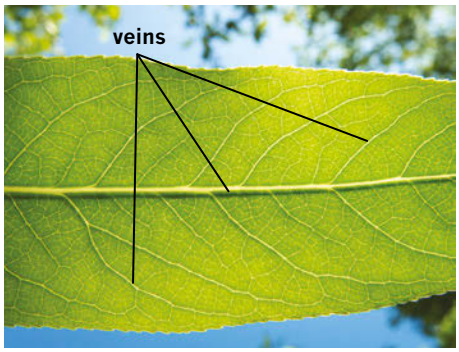


FIGURE 5.4.6 The veins in a leaf are vascular tissue that is specialised for transporting water and organic solutes throughout the plant. Each vein is made up of a vascular bundle of xylem, phloem and a lignin sheath.

Like all plants, vascular plants are autotrophs or producers, manufacturing their food from light energy by photosynthesis. For photosynthesis, plants need water, carbon dioxide and sunlight for energy. Water is absorbed through the roots, and carbon dioxide is absorbed via the leaves. Photosynthesis occurs in the leaves and produces the sugars that are needed by all active cells of the plant. Transport of these substances to the locations where they are needed is made possible by the presence of **vascular tissue** (Figure 5.4.6).

In large vascular plants, the leaves can be a long way from where water is absorbed via the roots, and the active cells in the roots requiring sugars for the energy requirements of nutrient uptake can be a long way from where photosynthesis occurs in the leaves. In tall trees such as the Californian redwoods pictured in Figure 5.4.7, water and nutrients need to be transported more than 100 metres from the roots to the upper branches! Their root system is relatively shallow but water still needs to travel a great distance from where it is absorbed via the roots and root hairs to the leaves, where it is used during photosynthesis.

FIGURE 5.4.7 The tallest trees in the world are the giant sequoias (*Sequoiadendron giganteum*) of California. These trees can reach a height of more than 115 metres above the ground.

Vascular tissue transports:

- water and mineral ions obtained from the soil by the roots throughout the plant
- sugars made in the leaves to other parts of the plant.

In vascular plants, there are two types of vascular tissue.

- Xylem transports water and inorganic nutrients (mineral ions) absorbed from the soil up the plant.
- Phloem transports dissolved sugars, which are produced in the leaves by photosynthesis, throughout the plant. Other organic substances, such as amino acids are also transported in the phloem.

Xylem and phloem contain continuous, closed tubular pathways through roots, stems and leaves (Figure 5.4.8). Fluids flow through these tubules to all parts of the plant. All cells are close to vascular tissue.

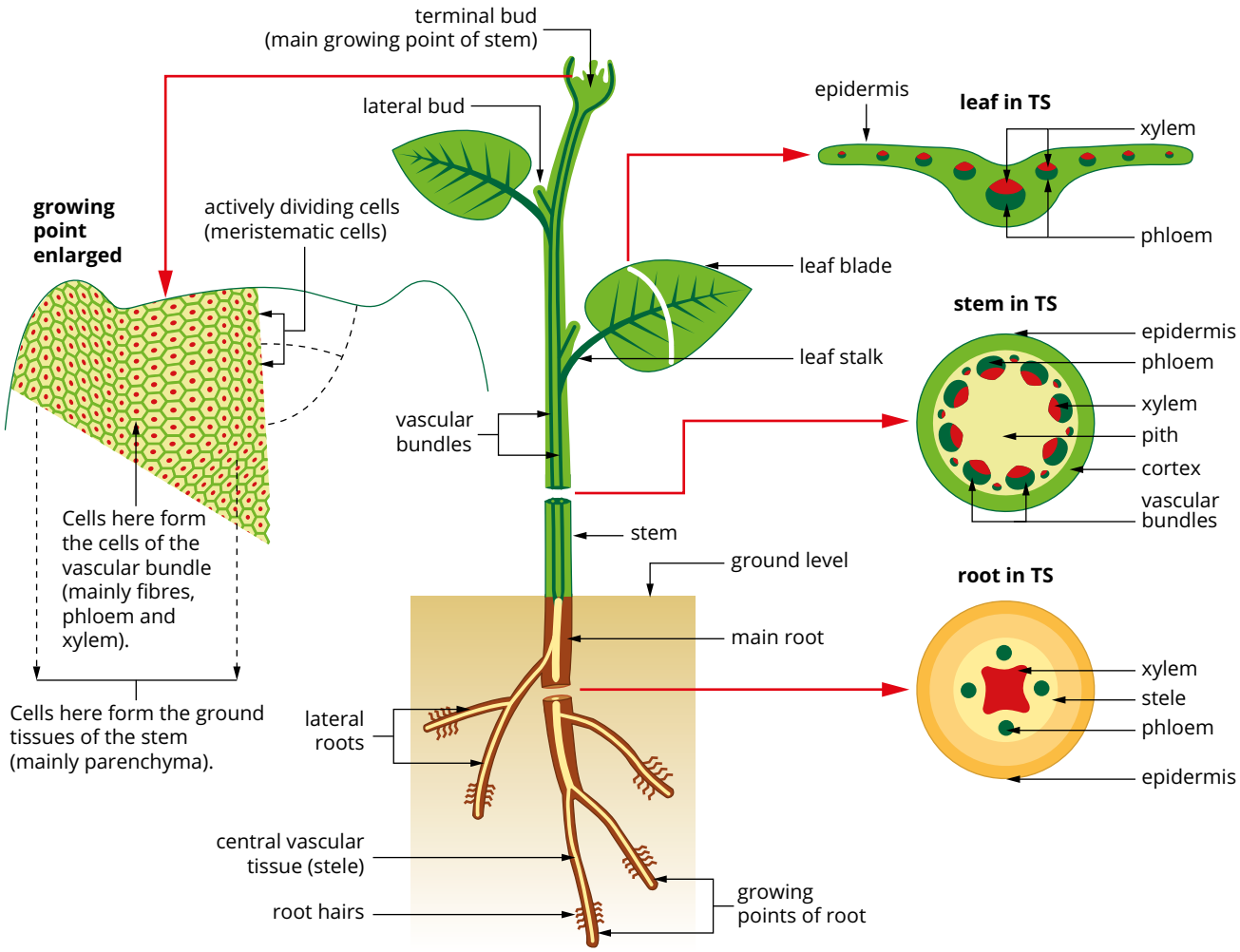


FIGURE 5.4.8 The main function of the transport system in plants is to transport water and organic solutes from the roots to the leaves and to transport food manufactured in the leaves (sucrose and amino acids) to the other plant tissues. The transport system tissues, the xylem and phloem, are continuous, tubular pathways through the roots, stems and leaves. (TS means transverse section.)

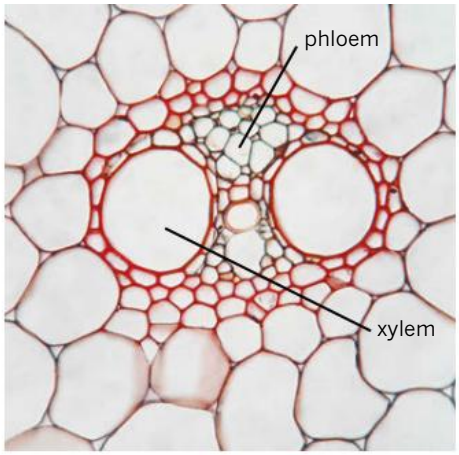


FIGURE 5.4.9 A cross-section through a stem, showing a vascular bundle containing xylem and phloem

The arrangement of xylem and phloem tissues in roots, stems and leaves is distinctive. Roots have a central core of xylem in a star or cross shape, with phloem between the arms of the xylem. In stems and leaves the xylem and phloem are grouped into vascular bundles, as shown in Figure 5.4.9. These vascular bundles extend into the leaves.

Xylem

Xylem is the vascular tissue that transports water and mineral ions obtained from the soil throughout the plant. It is composed of mainly of **xylem vessels** and **tracheids**.

A mature xylem vessel is a long, water-filled tube consisting of elongated cells joined end to end (Figure 5.4.10). As these cells mature, the cell wall is strengthened with lignin, becoming stronger and more rigid, and the cytoplasm and nucleus disintegrate. Mature xylem vessels have:

- cylindrical skeletons of dead cells joined end to end to form continuous tubes
- perforated or complete openings at each end, like a straw, so that fluid can flow directly through them
- pits (non-thickened areas) and perforations in the sidewalls that allow sideways movement of substances between neighbouring vessels in the vascular bundle
- no nucleus or cytoplasm.

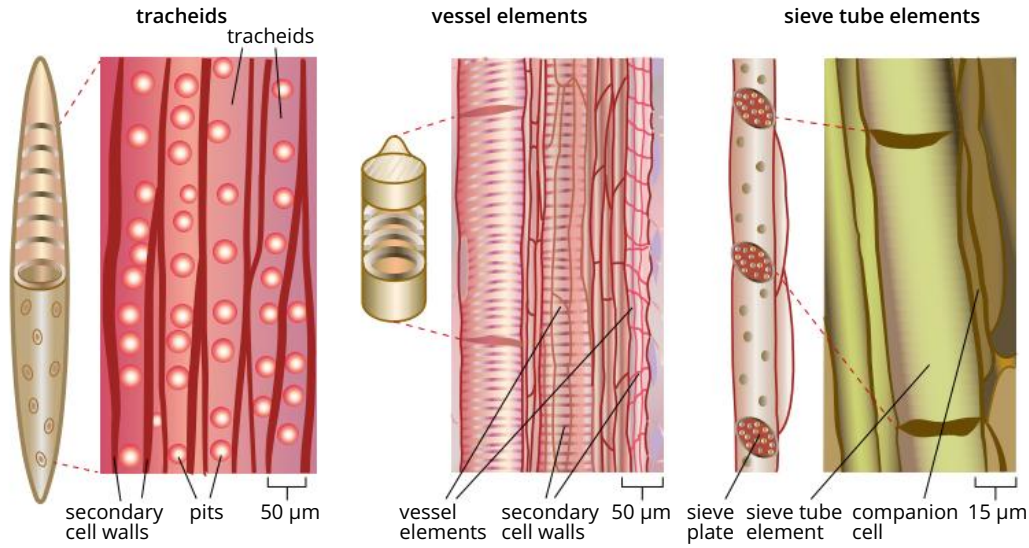


FIGURE 5.4.10 Water and mineral ions travel through tracheids and vessels in the xylem tissue. This figure shows the different forms of individual xylem elements. Tracheids exist singly and are connected through pits along their cell walls, while xylem vessels are joined end to end to form a long tube. Sieve tubes form part of the phloem.

Tracheids

Tracheids are single large, tapering water-filled cells that form part of the xylem tissue in all vascular plants (Figure 5.4.10). When mature, tracheids lose their nucleus and cytoplasm. This leads to cell death but creates an open structure for water to flow through. Mature tracheids have:

- cylindrical skeletons of dead cells joined to form continuous tubes, like xylem vessels
- pits and perforations in their lignified cell walls
- no nucleus or cytoplasm.

Unlike xylem vessels, tracheids are not connected end to end. Instead their ends overlap and water is transferred horizontally through the adjoining pits.

Phloem

Phloem transports organic solutes, especially sugars such as sucrose, from the site of synthesis (leaves) to the site of use or storage (stems and roots). It is composed of sieve tubes, companion cells, parenchyma cells and sclerenchyma cells (Figure 5.4.11).

Unlike xylem vessels, mature phloem sieve tubes are living cells with no nucleus and no lignin in the cell walls. Sieve tubes form linear rows of elongated cells. Their cell walls are perforated at each end by a number of holes or pores, forming sieve plates. Strands of cytoplasm (**plasmodesmata**) pass through these perforations, connecting one cell with the next.

Sieve tube cells are usually closely associated with one or more companion cells, connected by plasmodesmata. Both sieve tube cells and companion cells have thin cell walls. But unlike sieve tube cells the companion cells retain their nucleus, which probably enables the sieve tube cells to continue functioning.

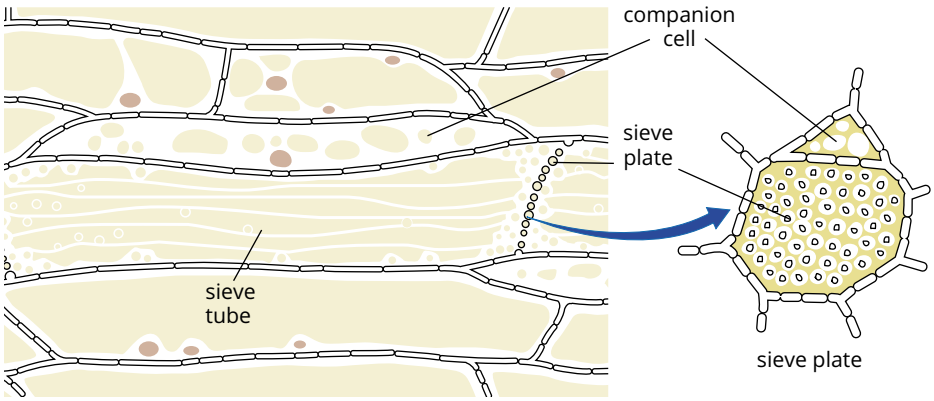


FIGURE 5.4.11 The cytoplasm of sieve tubes in phloem is continuous from cell to cell through the sieve plates. Adjacent companion cells probably enable sieve tube cells to continue functioning, since sieve tube cells do not have a nucleus.

Leaves

In vascular plants a leaf is an organ composed of three distinct layers of specialised cells, or tissues (see Figure 5.4.12):

- upper epidermis
- mesophyll
- lower epidermis.

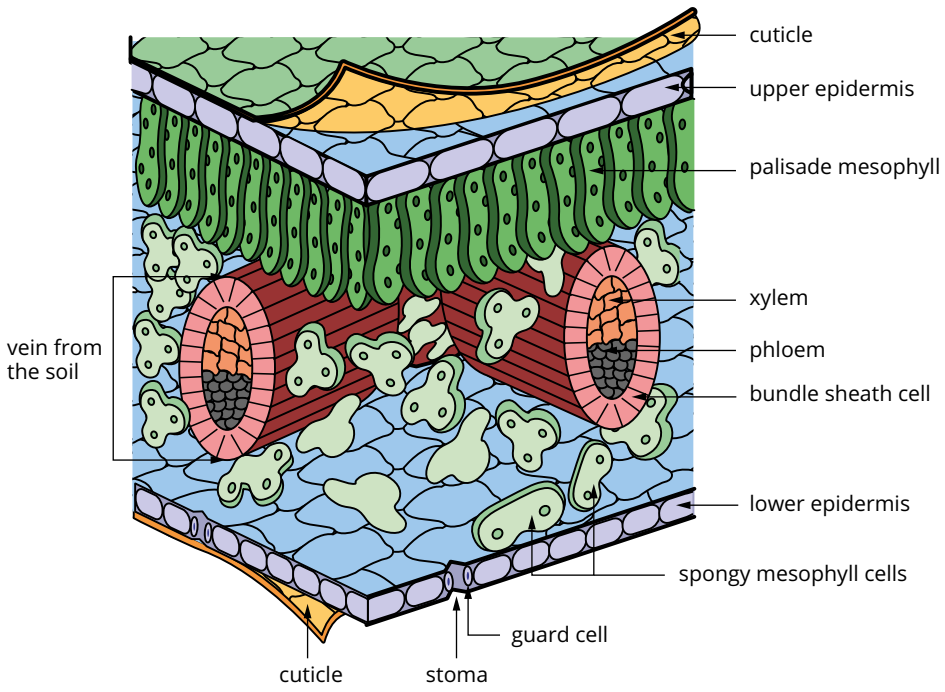


FIGURE 5.4.12 The three distinct layers of cells in leaves are the upper epidermis, the mesophyll and the lower epidermis.

The epidermis is a layer of cells covering the entire leaf. It secretes a waterproof waxy layer called the cuticle. Together the epidermis and cuticle provide a barrier that protects the cells and tissues inside the leaf and prevents excessive water loss. The epidermal cells lack chloroplasts but are transparent, allowing sunlight to reach the photosynthetic cells below.

Within the lower epidermis are stomata (singular stoma). Each stoma consists of two highly specialised epidermal cells called guard cells. The guard cells surround a pore, creating an opening through the epidermis and cuticle. They regulate gas exchange and water loss by changing shape, which causes the pore to open or close.

Between the epidermal layers are the mesophyll cells where photosynthesis takes place. The cells closest to the upper epidermis are the palisade mesophyll cells. These cells contain many chloroplasts and are tightly packed together. The spongy mesophyll cells below the palisade mesophyll cells are loosely packed together, with air spaces between them to allow gas exchange. These cells contain fewer chloroplasts.

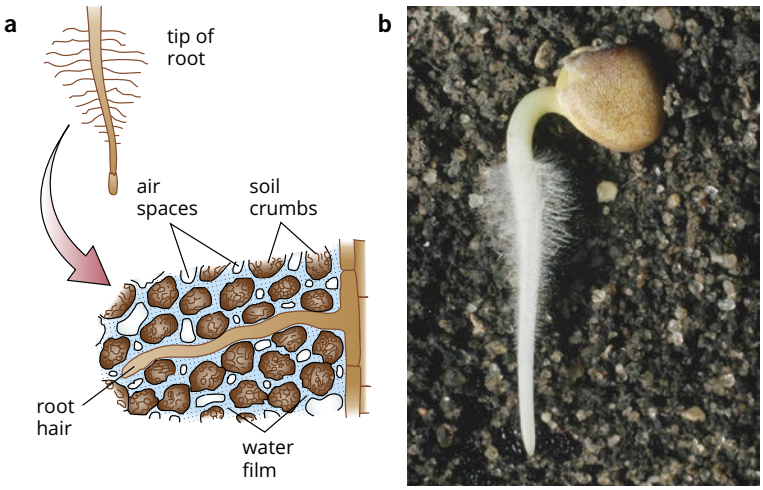
The vascular tissue (xylem and phloem) is also located between the two layers of epidermal cells. Vascular tissue is often visible in leaves as veins.

Table 5.4.1 summarises the structure and function of the parts of leaves.

TABLE 5.4.1 The structure and function of the specialised cells and tissues of leaves

Leaf tissue	Structure	Function
cuticle	thin, waxy waterproof layer	protects the inner cells, prevents water loss and allows sunlight to penetrate
epidermis (upper and lower)	transparent and usually thin	protects the inner cells, prevents water loss and allows sunlight to penetrate for photosynthesis
epidermis and cuticle	contains guard cells surrounding stomata	regulate gas exchange and water loss by opening and closing stomata
mesophyll	palisade mesophyll; tightly packed column-shaped cells with many chloroplasts, close to upper epidermis	photosynthesis
	spongy mesophyll; loosely packed, with air spaces around the cells	allows gas exchange, including the diffusion of carbon dioxide throughout the leaf
xylem and phloem	tubular vessels	transport fluids

WS 1.2.9 PA 1.2.4



MOVEMENT OF WATER AND SOLUTES

Root absorption

Roots have a branched structure that increases the surface area of the roots and their capacity to absorb water and mineral ions (Figure 5.4.13).

FIGURE 5.4.13 (a) Water and inorganic nutrients are absorbed by roots from soil water through many fine root hairs. (b) Root hairs on a radish seedling. The branched structure of the fine root hairs provides a greater surface area for the radish seedling to absorb water.

Water pathways

There are two possible pathways for movement of water and mineral ions absorbed from the soil through the roots. These are the extracellular pathway and the cytoplasmic pathway.

In the extracellular pathway, most water and some mineral ions pass in or between cell walls (Figure 5.4.14).

In the cytoplasmic pathway, most mineral ions and some water pass through the cytoplasm of living root cells (Figure 5.4.14).

The cytoplasmic pathway involves substances entering a root hair cell by crossing the cell's plasma membrane, and then passing from cell to cell through plasmodesmata. The three types of transport that move substances across plasma membranes along the cytoplasmic pathway are as follows.

- Active transport. Most dissolved mineral ions are selectively taken into roots by active transport. Proteins in the plasma membrane of root cells, specific for each ion, are used for this purpose. As a result, the concentration of ions in the vascular tissue of roots can be more than 100 times their concentration in the water of the surrounding soil.
- Osmosis. The high concentration of ions in the vascular tissues of terrestrial plants creates a very large osmotic concentration gradient. Large amounts of water move into root cells along this concentration gradient.
- Diffusion. Some mineral ions such as potassium and phosphate enter the roots by diffusion. The uptake of these nutrients therefore depends on the rate of water uptake.

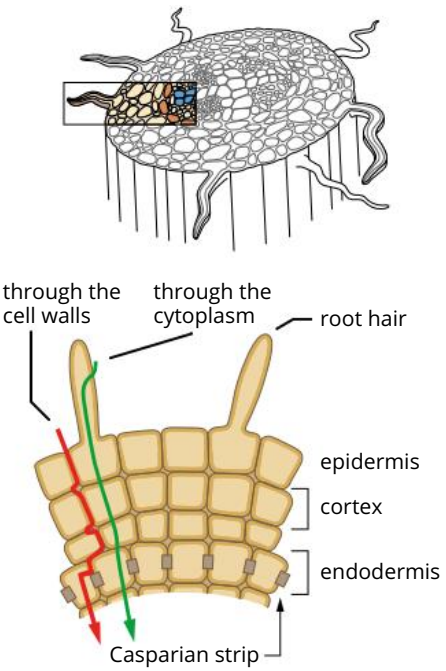


FIGURE 5.4.14 Water and mineral ions move through the roots via the extracellular pathway (red arrow) and the cytoplasmic pathway (green arrow). From the Casparian strip, water can no longer travel along the extracellular pathway and is forced into the cytoplasm before moving into the xylem.

Entering the xylem

From either of the two pathways through the roots, water and mineral ions must then reach the xylem tissue. Between the roots and the xylem is a waterproof layer of cells that form a barrier known as the **Casparian strip**. At this barrier, water travelling through the extracellular pathway is forced into the cytoplasm. In this way the Casparian strip ensures the regulation of the substances entering the xylem.

Root pressure

In some plants the osmotic gradient draws in so much water from the roots that it can travel up to 10 metres up the stem. This is known as **root pressure** (Figure 5.4.15). Root pressure causes the rising of sap (water and mineral ions) in spring in deciduous plants such as birch trees, but does not occur in all plants.

Transpiration

Transpiration is the passive movement of water through a plant from the roots, including its evaporation through the stomatal pores in leaves. The plant uses a small amount of water for metabolic processes, but 99% of the water absorbed by the roots is lost via transpiration.

Transpiration is a passive process: it does not require energy expenditure by the plant. It is driven by the heat energy in sunlight, which breaks the **cohesive bonds** between water molecules, allowing evaporation through the stomata.

Water molecules are very cohesive; that is, they have a strong tendency to stick together. When water evaporates from the cell walls of the leaf, cohesion between the water molecules remaining in the leaf draws water from nearby xylem vessels to replace the lost water.

In this way thousands of leaf cells, each drawing water from xylem, create a differential pressure that pulls water up xylem vessels from the roots. This continuous one-way flow of water from roots to leaves is called the **transpiration stream**. The pull of transpiration can be strong enough to draw water to the top of the tallest tree, more than 100 metres high.

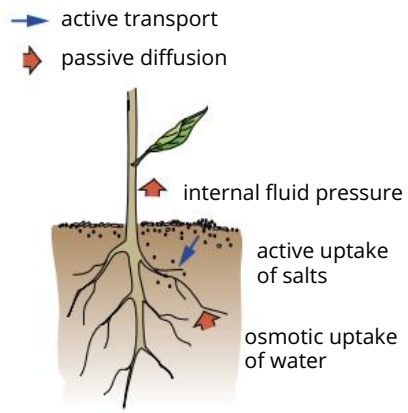


FIGURE 5.4.15 Internal fluid pressure (root pressure) in the roots of some plants causes fluid to rise through the xylem vessels.

The flow of the transpiration stream does not require an intact root system. It continues when cut flowers and leafy shoots are placed in a vase of water. It also continues in the roots after the stem dies.

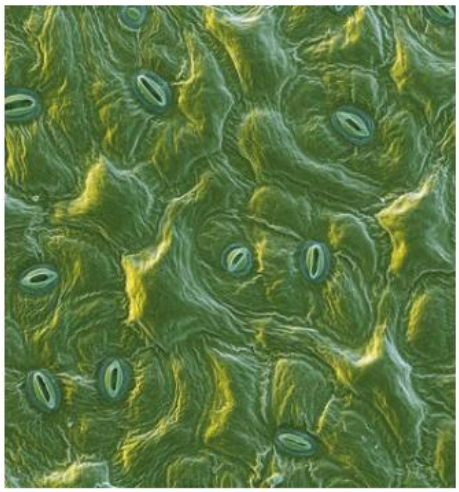


FIGURE 5.4.16 Stomata on the surface of a cabbage leaf, viewed at high magnification. Stomata regulate the exchange of gas and water between the plant and the atmosphere. The opening and closing of the stomata is controlled by two guard cells on either side of the pore. Stomata open during the day to exchange gases during photosynthesis and close at night to minimise water loss.

Although transpiration is the cause of 99% of a plant's water loss, it is vital because it enables plants to:

- absorb the water necessary for the process of photosynthesis
- transport mineral salts to leaf cells and fruits
- cool down and not become overheated.

Factors that affect transpiration rates

Water vapour is lost from leaves mainly by transpiration through open stomata. The total surface area across which transpiration takes place is related to the degree of opening of all stomata. This is by far the most important factor affecting the rate of transpiration. The greater the number of stomata and more open they are, the more surface area there is from which water can be lost (Figure 5.4.16).

Other factors that affect the rate of transpiration (Figure 5.4.17) include:

- humidity—transpiration rates decrease when there is a lot of water vapour in the air (i.e. a high level of humidity), because this reduces the water concentration gradient between leaf spaces and air, so fewer water molecules evaporate into the air.
- temperature—transpiration rates increase as temperature increases because heat energy increases the rate of evaporation of water.
- wind—air currents increase the rate of transpiration by moving water vapour away from the leaf and therefore increasing the rate of evaporation of water.

Environmental factors such as sunlight and humidity affect the rate of transpiration and therefore the rate of water uptake by the roots of the plant.

The rate of transpiration is low at night because it is cooler and more humid, and because stomata are usually closed.

The leaves of some plants that live in exposed conditions have developed structural features that reduce the rate of transpiration. For example, some plants have hairs on the leaf surface, which create a layer of relatively undisturbed, humid air.

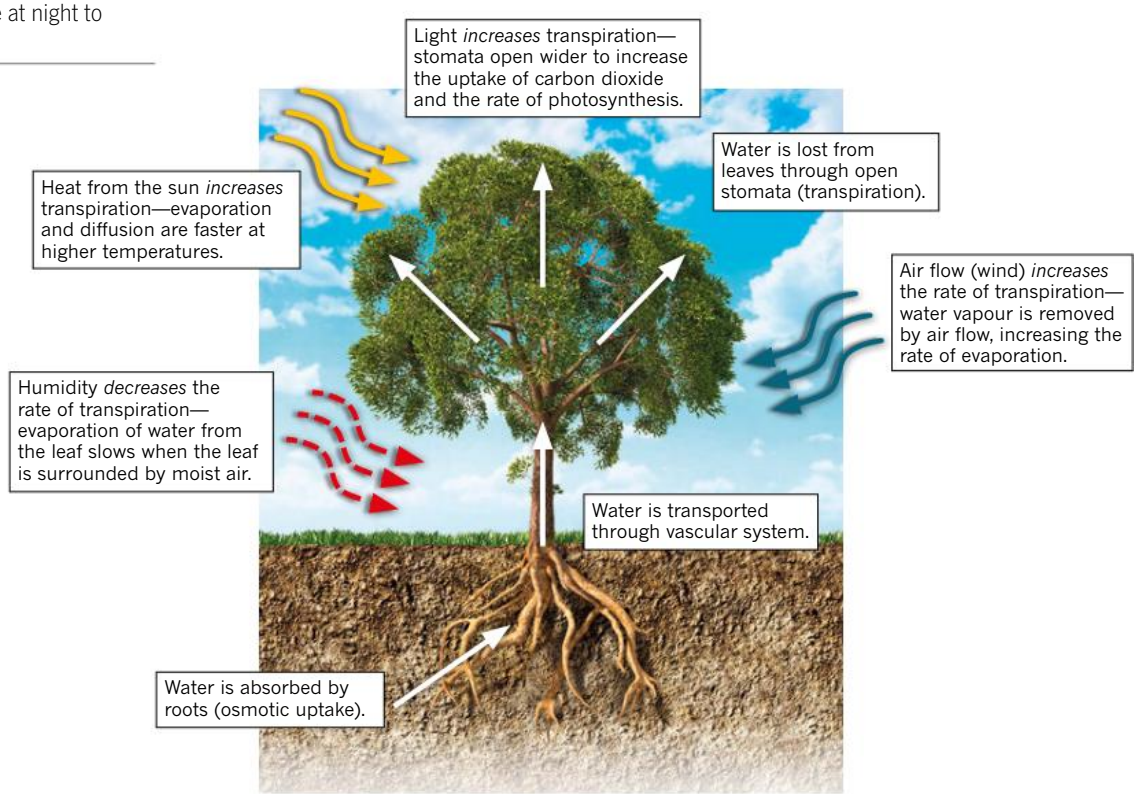


FIGURE 5.4.17 The movement of water through the xylem vessels of vascular plants and into the atmosphere through leaf stomata, in the form of water vapour, is the process known as transpiration.

Translocation: sources and sinks

The transport of organic solutes from the leaves to other tissues in the plant is known as **translocation**. Leaves produce carbohydrates in the form of sugars during photosynthesis. The non-photosynthetic tissues of the plant also need these carbohydrates and other organic compounds, such as amino acids, hormones and proteins, so these nutrients are transported from the **sources** (the leaves) to the **sinks** (regions where the nutrients are needed, such as roots, stems, flowers and fruits).

The tissue through which these organic solutes move is the phloem, and the material that flows through it is known as phloem sap. This sap is composed of around 90% sucrose. Sucrose is a disaccharide that dissolves easily in water, making it a good transport material. It is produced in the chloroplasts of the chlorenchyma (parenchyma cells with chloroplasts) and pumped into the companion cells. From the companion cells the sucrose flows into the sieve tube cells (Figure 5.4.18). Transport in individual sieve tube cells is in one direction only, but bundles of sieve tube cells are able to transport sap in both directions: upwards to leaves and fruit, or downwards to the roots.

Translocation is an active process. It involves the flow of cytoplasm in sieve tubes driven by a pressure gradient, and requires the expenditure of energy by the plant. This pressure gradient begins in the leaves, where sucrose is actively pumped into phloem sieve tube cells. This creates an osmotic gradient that draws water passively into the sieve cells. As water enters, it increases the fluid pressure (turgor) in sieve cells, which pushes fluid from these cells into adjacent sieve cells.

While this is happening in the leaves, sucrose is being actively removed from sieve cells in roots, growing shoots and developing fruit. This causes an osmotic gradient that draws water out of sieve cells and lowers their turgor pressure.

Fluid pressure is therefore high in sieve tube cells in leaves and low in sieve tube cells in roots and growing shoots. A bulk flow of the contents of sieve tubes occurs along this fluid pressure gradient, from sources to sinks. Translocation stops if the cells in the stem die.

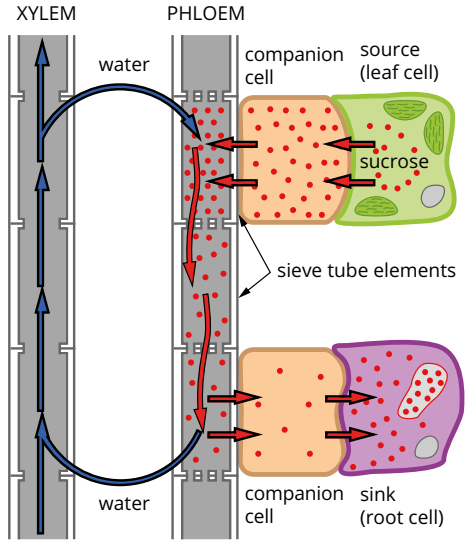


FIGURE 5.4.18 The movement of fluid through the phloem is the result of active pumping of sugars, with water flowing along an osmotic gradient. Sugars and water enter the phloem sieve tubes in leaves in this way and are translocated throughout the plant. Sugars are actively unloaded from sieve tubes where they are required.

Water transport adaptations in desert plants

Plants that live in deserts need specialised strategies to survive the hot, dry conditions. In an environment where water is scarce, plants have developed special structures that enable extremely efficient uptake and storage of this precious resource.

Cactus plants are specialised to hold large volumes of water in their fleshy leaves, stems and roots (Figure 5.4.19). When water does come along, they need to be able to absorb as much as possible, as fast as possible. Their roots are shallow and cover a large area, enabling them to harvest as much water from the soil as possible.

Once cacti have water, they need to hold on to it. Most cacti are spiny, bitter tasting or toxic, which deters thirsty animals. A thick, waxy cuticle also protects the leaves from damage and reduces water evaporation. While most plants open their stomata during the day, in a hot, dry environment this would lead to massive water loss through transpiration. To overcome this problem, cacti open their stomata at night and use crassulacean acid metabolism (CAM) photosynthesis (see Module 3.3). At night when stomata are open, carbon dioxide is taken in and converted to malic acid, which is stored in the vacuoles of mesophyll cells. In daylight, when the stomata stay closed to reduce water loss, the stored malic acid is broken down, releasing carbon dioxide, which diffuses into chloroplasts for conversion into glucose and carbohydrates, completing the photosynthetic process. CAM photosynthesis is excellent for conserving water, but the rate of photosynthesis is slow. This is why many cacti grow very slowly.

FIGURE 5.4.19 Cacti have many special adaptations to overcome the problem of water uptake and storage in harsh, dry environments.

5.4 Review

SUMMARY

- Plants do not have organs specialised for gas exchange, but they have large surface areas. Their tissues exchange gases directly with their environment.
- Stomata are found in the epidermis of leaves and some stems. They are the main route through which gas exchange occurs in plants.
- Conditions favouring opening of stomata are abundant water, bright light and low internal carbon dioxide concentrations.
- Roots exchange gases with air in soil spaces. The crumb structure of the soil and the activities of earthworms are important in maintaining well-aerated soil.
- Most terrestrial plants, including ferns, conifers and flowering plants, have vascular tissues (xylem and phloem) that are specialised for transporting fluid.
- The vascular tissues are:
  - xylem, which carries water and mineral ions from roots to leaves
  - phloem, which carries sugars and other organic molecules from leaves to roots.
- Xylem vessels:
  - are the skeletons of dead elongated cells
  - have perforations at each end
  - are joined end to end to form continuous tubes and allow the flow of fluid
  - have pits (thinner areas) in the side walls that enable the movement of substances into and out of the adjacent companion cells.
- Xylem tracheids:
  - like xylem vessels are dead and have pits in their lignified cell walls and have no nucleus or cytoplasm
  - unlike xylem vessels, are not connected end to end; their ends overlap and water is transferred horizontally through the adjoining pits.
- Water and inorganic nutrients (mineral ions) are absorbed by the root hairs from the soil by one of two pathways:
  - extracellular pathway
  - cytoplasmic pathway.
- Water and mineral ions are transported through xylem vessels as sap. This transportation occurs in one direction only: from roots to leaves.
- Transpiration is the evaporation of water from stomata in leaves. It is a passive process (driven by energy from sunlight) that also draws water up from the roots, through the xylem, following what is known as the transpiration stream.
- The rate of transpiration is affected by:
  - the number of stomata and their degree of opening
  - temperature
  - humidity
  - wind.
- Translocation is the transport of organic materials from the leaves to the roots, stem, flowers and fruits of the plant, through the sieve tube cells and companion cells of the phloem tissue.
- Translocation is an active process and requires an expenditure of energy by the plant.
- Translocation is driven by a pressure gradient that begins in leaves (sources), where sucrose is actively pumped into phloem sieve cells while being actively removed from sieve cells in roots, growing shoots and developing fruit (sinks).

KEY QUESTIONS

Retrieval

1 Recall the structure through which gas exchange primarily occurs in plants.

2 State the two types of vascular tissue in plants and their functions.

3 Recall two possible pathways for the movement of water and mineral ions, absorbed from the soil, through the roots.

Comprehension

4 Explain how it is possible for the tallest trees to transport water from their roots to their uppermost branches, sometimes more than 100 metres high.

5 Explain why most plants do not need specialised gas exchange organs.

6 Use labelled diagrams to show how stomata open and close.

7 Explain why transpiration is vital to plants.

8 Determine whether each of the following environmental factors increases or decreases transpiration rates in plants.

a high temperature

b high humidity

c darkness

d strong wind

Analysis

9 Predict what will happen to gas exchange in a pot plant if you over water it.

10 The following photograph shows an example of ring-barking, the removal of deep strips of bark from the trunk of a tree. It results in the death of the roots from depleted sugar, and eventually the tree dies. Deduce the cause of death in relation to transportation.

11 Guttation is the appearance of small water droplets along the margins of leaves, caused by water being forced out of the leaf. Identify the source of the water droplets.

12 Construct a table to compare the structure and function of phloem and xylem vessels. Consider the:

- structure of cells
- properties of cells
- substances that are transported
- direction in which substances are transported
- source of energy for transport.

Effect of temperature on enzyme function

Research and planning

Aim

To determine how temperature affects the action of the enzyme bromelain on gelatine.

Rationale (scientific background to the experiment)

Pineapple contains a group of proteases called bromelain. Most chefs know not to include fresh pineapple juice in gelatine desserts because the enzyme digests the protein gelatine and the gelatine will not set (or gel). Bromelain is used in meat tenderisers, in manufacturing precooked cereals, in some cosmetics and in the treatment of inflammation. Bromelain is measured in GDU (gelatine digesting units).

The protein gelatine is obtained by boiling the skin, tendons and ligaments of animals. As a result, it contains various amino acids and collagen. Collagen is a quaternary protein that is involved in maintaining the structure of a cell. It forms molecular cables to strengthen tendons and wide sheets to protect the skin and internal organs of our body. Unlike gelatine, collagen is not soluble in water. When a gelatine solution cools, it forms a matrix that traps water molecules. When the gelatine is digested by the enzyme bromelain, the trapped water molecules are released.

Like all enzymes, bromelain is a protein. The shape of the active site on the enzyme is specific to the substrate it binds. Any variation to this shape affects the efficiency of the enzyme. High temperatures cause enzymes to change their shape (denature), affecting the ability of the substrate to bind to the active site.

The optimum pH range for bromelain is 4.5–7.5 and its optimum temperature is 35–45°C. The maximum operating temperature for industrial applications (reaction time ≤4 h) is 50°C. Bromelain is stable at pH 3–6 and at temperatures up to 60°C.

Timing

45 minutes plus 15 minutes next day for recording data

Material

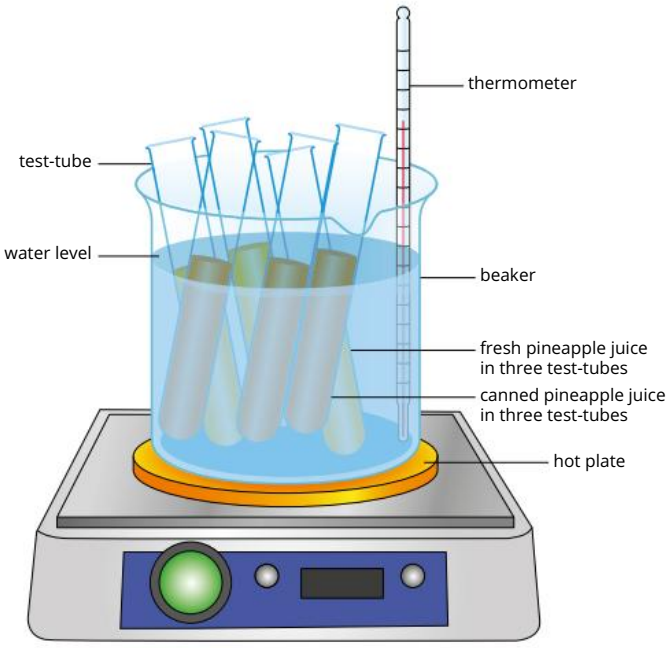
- 9 mL fresh pineapple juice (blended and strained pineapple)
- 9 mL canned pineapple juice (blended and strained canned pineapple)
- gelatine jelly packet (120 mL per group)
- 3 disposable 3 mL pipettes
- 12 test-tubes
- 2 test-tube racks
- test-tube holder
- 3 large beakers (to hold test-tubes)
- ice
- thermometer
- hot plate
- safety mat
- permanent marker

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. Make up the gelatine jelly according to the packet instructions. Put the jelly aside until step 11.
2. Number the test-tubes 1–12.
3. Use a disposable pipette to transfer:
   - 3 mL of fresh pineapple juice to test-tubes 1–5
   - 3 mL of canned pineapple juice to test-tubes 6–10
   - 3 mL of distilled water to test-tubes 11 and 12.
4. Place test-tubes 1, 6 and 11 in a beaker of ice and water. Record the temperature.
5. Place test-tubes 2, 7 and 12 in the test-tube rack at room temperature. Record the temperature.



6 Place the remaining test-tubes in the beaker of water with a thermometer.

7 Heat the beaker containing test-tubes slowly on the hot plate.

8 At 40°C, remove test-tubes 3 and 8 from the beaker using the test-tube holder, and allow them to cool in the test-tube rack.

9 At 60°C, remove test-tubes 4 and 9 from the beaker using the test-tube holder, and allow them to cool in the test-tube rack.

10 At 80°C, remove test-tubes 5 and 10 from the beaker using the test-tube holder, and allow them to cool in the test-tube rack.

11 Add 10 mL of gelatine mixture to all 12 test-tubes containing the treated pineapple solutions and the distilled water at room temperature.

12 Cover the test-tubes with plastic wrap and allow them to cool in the fridge overnight.

13 Record the level of solidification or liquidity of the contents. Note whether or not gelatine is present and measure the amount of any liquid present in the test-tubes.

Variables

i Independent: temperature, type of pineapple juice

ii Dependent: solidification of gelatine

iii Controlled: amount of pineapple juice, amount of gelatine, time for gelatine to set

Analysing

Raw data

1 Complete the table to record the effect of temperature on bromelain function.

Temperature (°C)	Gelatine present			Volume of liquid present (mL)		
	Fresh pineapple	Canned pineapple	Distilled water	Fresh pineapple	Canned pineapple	Distilled water
0						
20						
40						
60						
80						

Processed data

2 Create a graph showing the effect of temperature on bromelain function for both fresh and canned pineapple juice.

➤ 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

3 Explain why water was used in test-tubes 11 and 12.

4 Explain why a test-tube of water was not heated to 40°C, 60°C and 80°C.

5 Explain why a Bunsen burner was not used to heat the test-tubes directly.

6 Review the results for the canned pineapple juice. Explain why gelatine did, or did not, form.

7 State at what temperature bromelain denatures. Provide evidence from your results to support your answer.

8 Draw a labelled picture that shows what happens at a molecular level when the enzyme bromelain is heated.

9 Compare your results with those from three other groups.

a Explain why the results should be similar for each group.

b If a group did not obtain similar results, suggest a reason for this.

10 Identify a potential error encountered in the procedure. Suggest how it could be minimised if the procedure were modified.

➤ 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 Describe how temperature affected the action of bromelain on gelatine.

Evaluation

2 Explain whether the potential errors you identified above had a significant effect on your conclusions. In other words, do you consider the level of uncertainty caused by the potential errors reasonable?

Improvements

3 If you were to repeat this experiment, identify the steps that you would do differently.
Consider how you could:

a change the methodology
b improve your technique
c reduce error and uncertainty.

Extension

4 Investigate two other enzymes that are used in cooking. Find out the optimal pH and temperature ranges at which they operate, and explain how this information is used in cooking.

5 Doctors become very concerned if a patient has a prolonged and very high fever. Use your understanding of proteins and their role in the body to explain why.

➤ 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

WS 1.2.10 WS 1.2.11

05

KEY TERMS

aerobic
air sac
alveoli
ammonia
amylase
aorta
arteriole
artery
atrium
basal metabolic rate
bile
bladder
Bowman's capsule
bronchus
caecum
capillary
carnivore
Casparian strip
cellulose
chemical digestion
cilia
closed circulatory system
cohesive bond
connective tissue
coronary circulation
counter-current exchange
digestion
digestive enzyme
egestion
epiglottis
epithelium
excretion
exhalation
extracellular digestion
filtration
gill
glomerulus
glycogen
guard cell
haemoglobin
herbivore
hydrolysis
inhalation
interstitial space
intracellular digestion
lacteal
lamella
larynx
lenticel
lignin
lipase
liver
loop of Henle
lumen
lymph
maltose
metabolic rate
metabolism
myoglobin
nephron
nitrogenous waste
omnivore
open circulatory system
oxygen-carrying capacity
oxyhaemoglobin
partial pressure
peristalsis
pharynx
phloem
plasmodesmata
protease
pulmonary vein
reabsorption
root hair
root pressure
rumen
secretion
sink
source
starch
stoma
tidal volume
trachea
tracheole
tracheid
translocation
transpiration
transpiration stream
turgor
urea
ureter
urethra
uric acid
valve
vascular bundle
vascular plant
vascular tissue
vein
ventilation
ventricle
venule
vital capacity
xylem
xylem vessel

KEY QUESTIONS

Retrieval

1 Oxygen and carbon dioxide move freely through the respiratory surface of animals by:
- **A** active transport.
- **B** diffusion.
- **C** osmosis.
- **D** facilitated diffusion.

2 The mammalian respiratory surface:
- **A** has a low surface area to volume ratio.
- **B** has the ability to ventilate itself.
- **C** has a rich blood supply.
- **D** does not need to be moist.

3 Open circulatory systems:
- **A** are characteristic of mammals.
- **B** do not have a muscular pump.
- **C** have low pressure.
- **D** have specialised transporting fluid.

4 All arteries:
- **A** have valves to prevent the back flow of blood.
- **B** carry oxygenated blood.
- **C** have thick muscular walls.
- **D** are connected to ventricles.

Comprehension

5 There would be a net movement of oxygen into a plant:
- **A** all the time.
- **B** during the day.
- **C** when the rate of gas produced in cellular respiration is greater than the rate of gas used in photosynthesis.
- **D** when the rate of gas used in cellular respiration is less than the rate of gas produced in photosynthesis.

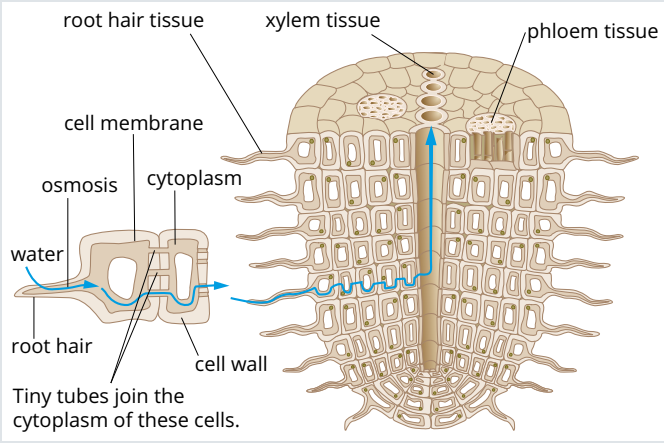
6 Plasma is an example of:
- **A** intracellular fluid.
- **B** extracellular fluid.
- **C** lymph.
- **D** interstitial fluid.

7 In autumn, the leaves of deciduous trees change colour and eventually fall. The change in colour is due to the movement of nutrients out of the leaves for storage. This involves:
- **A** xylem and phloem.
- **B** only the xylem.
- **C** only the phloem.
- **D** diffusion.

8 Identify which of the following statements relating to fermentation in herbivores is true.
- **A** In foregut fermenters, cellulose is digested in the caecum.
- **B** Fermentation in the gut requires oxygen.
- **C** The rumen is located between the oesophagus and the stomach.
- **D** All native Australian mammals are hindgut fermenters.

9 Celery curls are an attractive way of serving celery. They are made by taking sections of celery stalk, making several lengthwise cuts in one end and submerging them in cold water. If the cuts are made too close together, long strings of celery will peel away. Explain what causes the celery ends to curl.

10 Describe the pathway of water absorption in the diagram of plant root tissue below.



11 Global warming of oceanic waters poses a serious risk to aquatic life. Discuss this concern in relation to enzyme function.

12 Consider some of the features that plants living in harsh environments, such as deserts, have developed to achieve water transport.

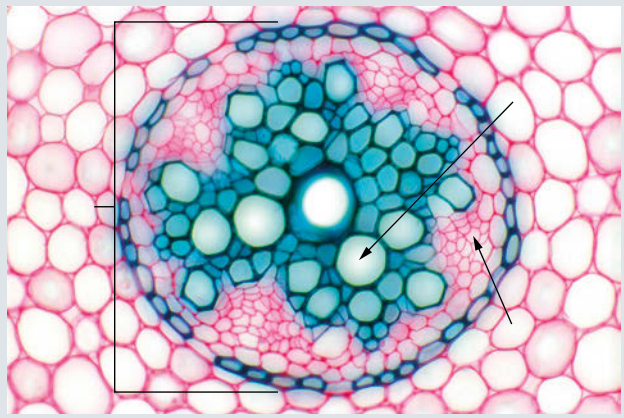
13 **a** Identify which side of the heart has thicker muscular tissue.
b Explain why.

Analysis

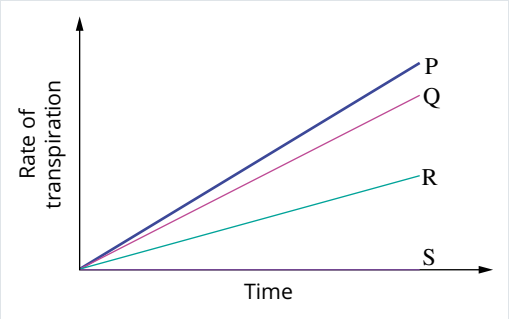
14 Coeliac disease causes the destruction of the villi cells. Identify which one of the following is most likely to happen to people with coeliac disease.
- **A** damage in the oesophagus caused by increase in acid reflux
- **B** incomplete digestion of proteins
- **C** increased levels of glucose in blood
- **D** poor absorption of calcium

15 Identify which process and location in the kidney each of these scenarios will affect. Justify your response.
- **a** You drink a large amount of water.
- **b** You play vigorous sport on a hot day.
- **c** Your blood pressure becomes very low.

16 The following image is a cross-section of the root of a buttercup plant viewed under a light microscope. Identify the parts of the root by labelling.



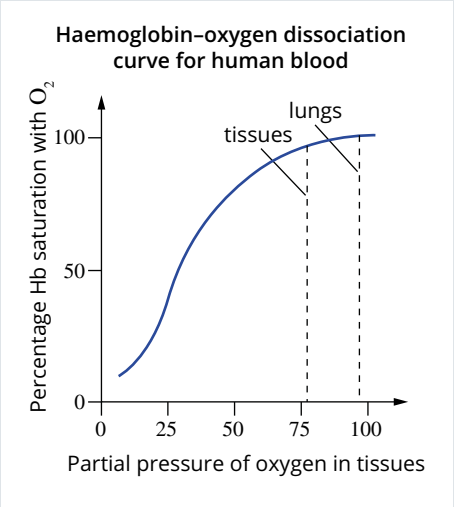
17 An experiment was conducted to determine the effects of applying a sticky gel onto a leaf on the rate of transpiration. The graph below shows the results of the experiment.



Differentiate each line labelled on the graph by matching to the correct experimental condition from the list below.

a no gel applied
b gel applied to the lower side of the leaves
c gel applied to the upper side of the leaves
d gel applied to the lower side and the upper side of the leaves

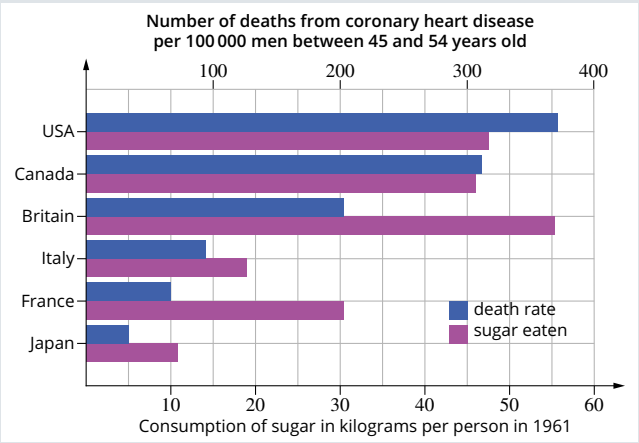
18 Using the information in the following graph, explore the relationship between oxygen, haemoglobin and the circulatory system.



19 A common problem for passengers on a long plane trip is that, upon arrival, their feet have become so swollen that they do not fit into their shoes. Airlines recommend exercises to help reduce this problem.

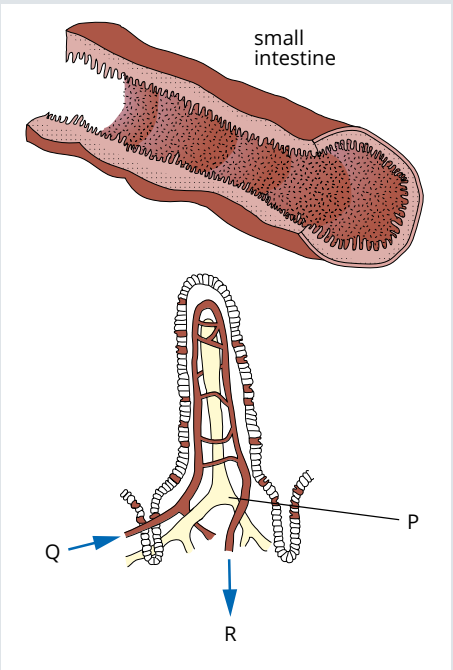
a Identify what causes feet to swell during air travel.
b Infer how exercise can help reduce swelling during air travel.

20 The following graph represents the results of a study on the relationship between sugar consumption and death rate due to heart disease.



a State what type of organic compound sugar is.
b Explain what nutritional value sugar has.
c Identify the relationship between sugar consumption and coronary heart disease.
d Judge and argue if it is likely that sugar consumption is linked directly to heart disease.

21 The following diagrams show a cross-section through the small intestine and a longitudinal section through a villus.



a Determine three ways in which the structure of the small intestine is related to its function of absorbing products of digestion.
b Identify structure P and state its function.

c The arrows in the second diagram indicate the direction of blood flow. State how the composition of blood entering from Q would be different from blood leaving R.

22 The following table shows the relative concentrations of urea, glucose, amino acids, salts and proteins in the primary filtrate and urine of mammals as a percentage of the concentration in blood plasma.

Substance	Primary filtrate (%)	Urine (%)
urea	100	700
glucose	100	0
amino acids	100	0
salts	100	200
proteins	0	0

a Identify the location and process in the kidney that results in the urine relative concentrations (%) for each constituent of blood.

b i In the situation where the blood flow and time in the nephron is typical of healthy people, deduce which values would be different and why for people with diabetes.

ii In the situation where the blood flow and time in the nephron is typical of healthy people, deduce which values possibly would be different and why for someone who receives a heavy blow to the kidneys.

23 The table shows the partial pressures of gases at a site of gas exchange in the human body.

Location A	P_{O_2} = 102 mmHg P_{CO_2} = 40 mmHg
Location B	P_{O_2} = 40 mmHg P_{CO_2} = 45 mmHg

Derive in which direction the gases move between locations A and B.

24 A gas mixture contains 15% oxygen, 40% nitrogen and 45% helium. If the total pressure of the gas mixture is 800 mmHg, determine the partial pressures of the three gas components.

Knowledge utilisation

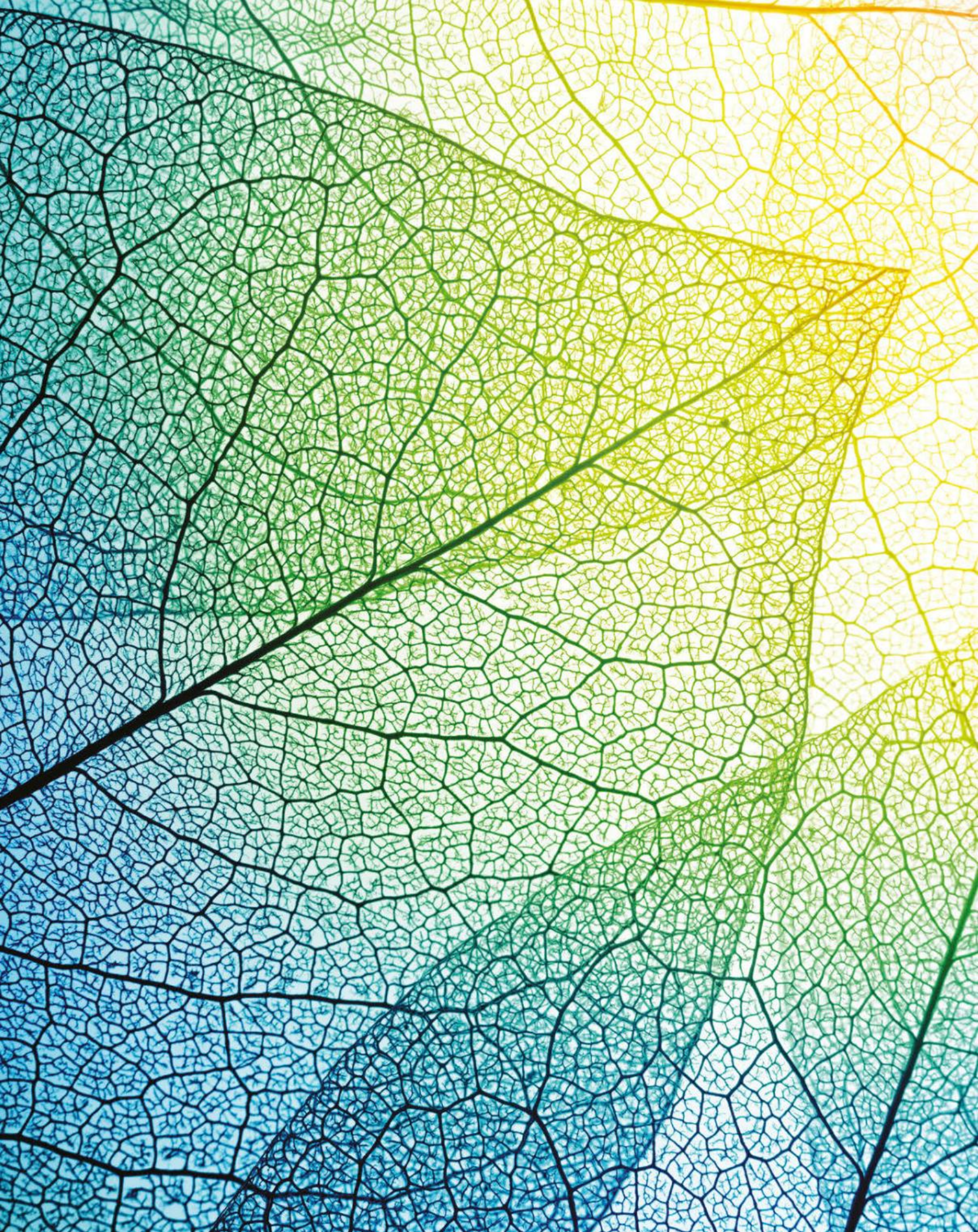
25 Sickle-cell anaemia is a red blood cell disorder. People with the disease have abnormal haemoglobin in their red blood cells. As a consequence, the red blood cells become sickle shaped and inflexible.

Based on your understanding of the functions of red blood cells, infer the effects of having sickle-shaped red blood cells on the functioning of the circulatory system.

26 Research three specialised cells in the respiratory system and state their functions in relation to gas exchange.

27 Devise an experiment you could carry out to determine if caffeine is a diuretic.

28 A recent weight loss proposal as an alternative to gastric band surgery (where the capacity of the stomach is reduced) involves removal of part of the small intestine. Consider whether this strategy might work, justify your suggestion, and recommend whether or not it would be an advisable treatment.



REVIEW QUESTIONS

TR 1.1 TR 1.2

Topic 1 Cells as the basis of life

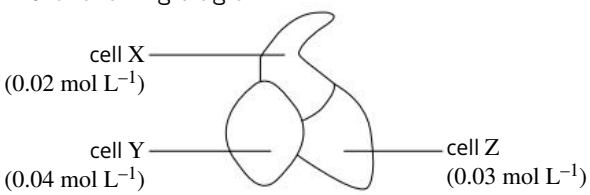
Multiple-choice questions

1 A student observes and draws an amoeba. The length of the drawing is 100 mm. The actual length of the amoeba is 100 µm.
Determine the magnification of the drawing.
A 0.001
B 1
C 100
D 1000

2 Select which of the following would not be visible under a light microscope.
A nucleus
B chloroplast
C vacuole
D ribosome

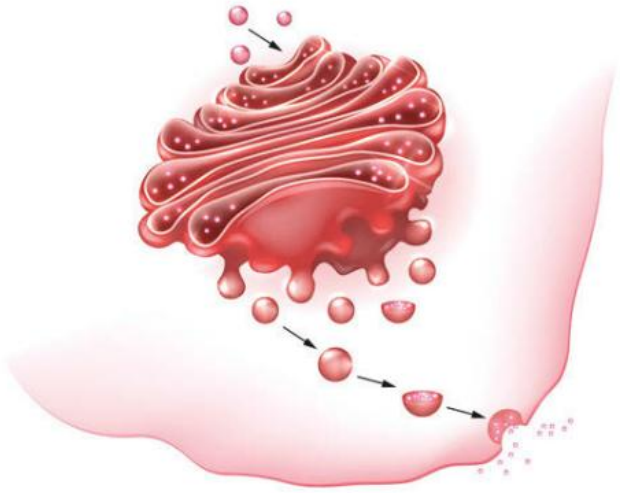
3 Identify which of the following features is/are present in mitochondria but not in chloroplasts.
I circular DNA
II ribosomes
III outer and inner membranes
IV cristae
A I, II and III only
B II, III and IV only
C I only
D IV only

4 Three cells X, Y and Z containing different solute concentrations were placed next to each other, as shown in the following diagram.



Predict the direction in which osmosis will occur.
A from X to Y only
B from X to Y, X to Z and Z to Y
C from Y to Z only
D from Y to Z and Z to X

5 In the following diagram, macromolecules are being transported to the exterior of a cell.

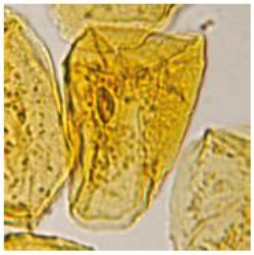


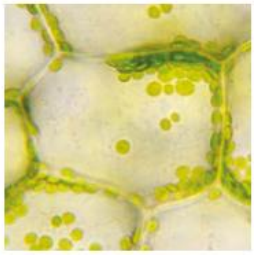
Select the name of this process.
A exocytosis
B pinocytosis
C endocytosis
D phagocytosis

6 Identify the major factor that determines whether entry to the cell by a substance will be by endocytosis.
A size of the molecules being moved across the membrane
B polarity of the substance
C water solubility of the substance
D concentration gradient of the substance between the inside and outside of the cell

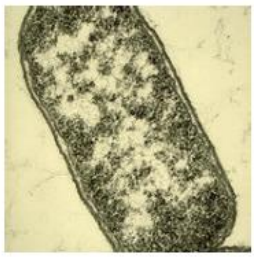
7 Classify each cell below as eukaryotic or prokaryotic and then select the alternative that only includes eukaryotes.

A cell 1, cell 2, cell 3 and cell 4
B cell 1, cell 2, cell 3 and cell 5
C cell 2, cell 3, cell 4 and cell 5
D cell 1, cell 2, cell 4 and cell 5


cell 1


cell 2


cell 3


cell 4

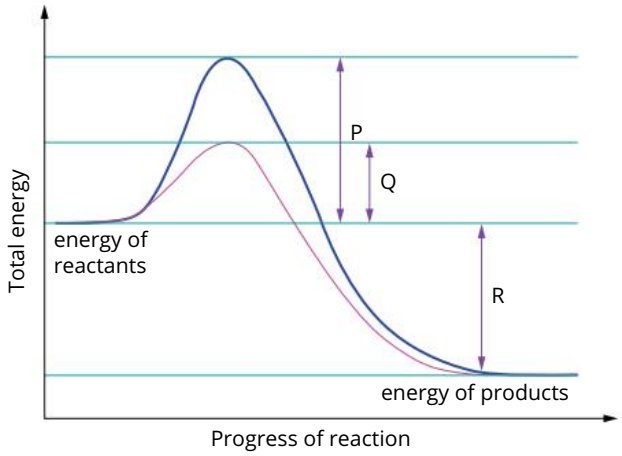

cell 5

8 Recall which of the following increases the surface area of membranes of cells without changing cell volume.

I increasing the cell size
II cell compartmentalisation
III a flattened shape
IV plasma membrane extension

A I and II only
B II and III only
C I, II and III only
D II, III and IV only

Use the following graph to answer questions 9 and 10. The graph shows the energy levels of a reaction in the presence and absence of an enzyme.



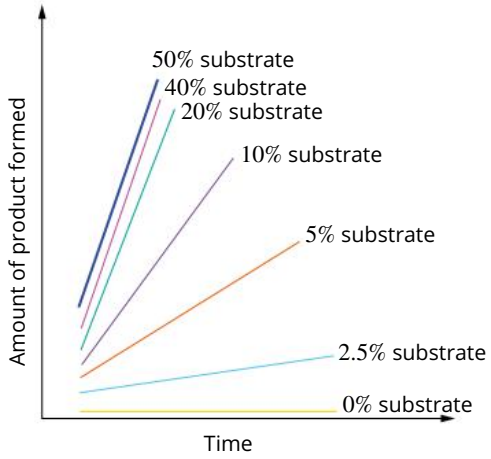
9 Conclude the best explanation for the different energy amounts labelled P, Q and R.

	P	Q	R
A	absence of an enzyme	presence of an enzyme	endergonic reaction
B	presence of an enzyme	absence of an enzyme	exergonic reaction
C	absence of an enzyme	presence of an enzyme	exergonic reaction
D	presence of an enzyme	absence of an enzyme	endergonic reaction

10 Infer which of the following represents the activation energy of the enzyme-catalysed reaction.

A P
B Q
C P + R
D Q + R

11 The following graph shows the effect of changing substrate concentration on the amount of product formed.



Identify the conclusion that can be drawn.

A The rate of reaction increases exponentially with an increase in substrate concentration.

B The rate of reaction decreases exponentially with an increase in substrate concentration.

C The rate of reaction increases greatly up to a point as the substrate concentration increases, and then the rate of increase starts to decrease.

D The rate of reaction is not affected by any change in the substrate concentration.

12 Identify which of the following is *not* a product of the Krebs cycle.

A CO_2

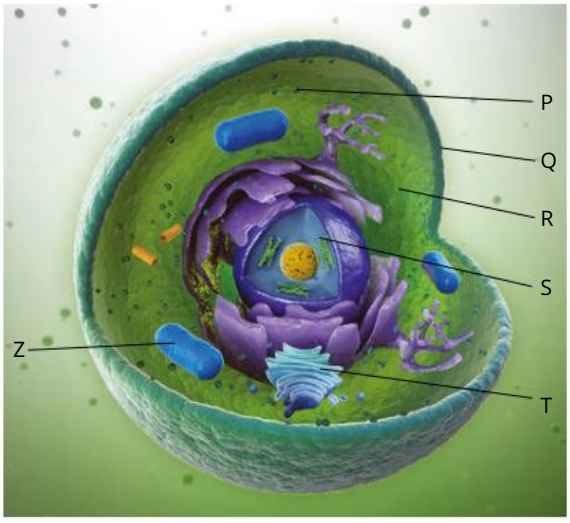
B $NADH + H^+$

C $NADPH + H^+$

D ATP

Short-answer questions

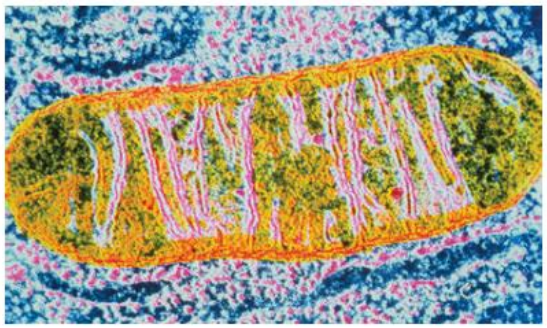
13 The following is a three-dimensional image of an animal cell.



a Identify structures P, Q, R, S and T.

b Describe a key feature of structure Q. Explain how this feature relates to its function.

A transmission electron micrograph of structure Z is shown in the following figure.

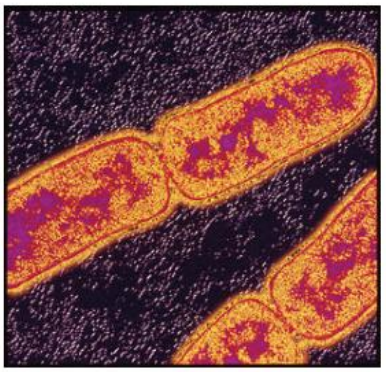


c Identify structure Z.

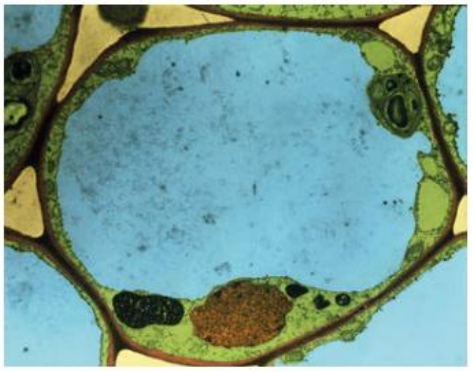
d State the overall chemical equation for the reaction that involves this structure, providing total inputs and outputs.

e Explain how oxygen from the blood eventually enters structure Z.

14 The following images show the transmission electron micrographs of two cells, P and Q.



cell P



cell Q

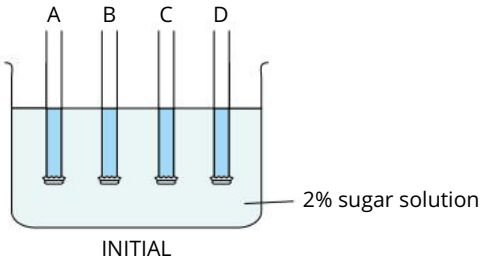
a Select the image that shows a prokaryote. Justify your answer.

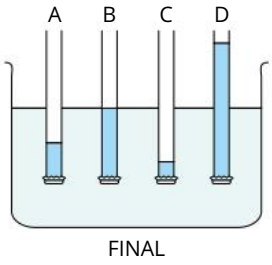
b Draw an arrow and label the structures where DNA can be found in each picture.

c Name two features in cell Q that are not visible in cell P.

15 Four tubes contain solutions with different sugar concentrations. One end of each tube is covered by a semipermeable membrane. The tubes are placed in a tank containing a 2% sugar solution and are left until the fluid levels are stable, as shown in the diagram.

Conclude the original concentrations of solutions A, B, C and D. Justify your conclusions.



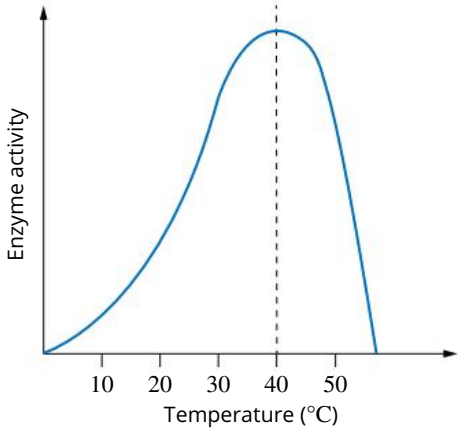


16 **a** Describe a similarity and a difference between simple diffusion and facilitated diffusion.

b A student describing to their parent what they had been studying in class stated that they had been learning about transport across cell membranes. However, they were quite confused and explained that the process of endocytosis was a kind of facilitated diffusion.

Compare endocytosis and facilitated diffusion to explain why the student was incorrect.

17 Study the following graph of enzyme activity.



a Outline what happens to enzyme activity as the temperature increases from 0°C to 40°C.

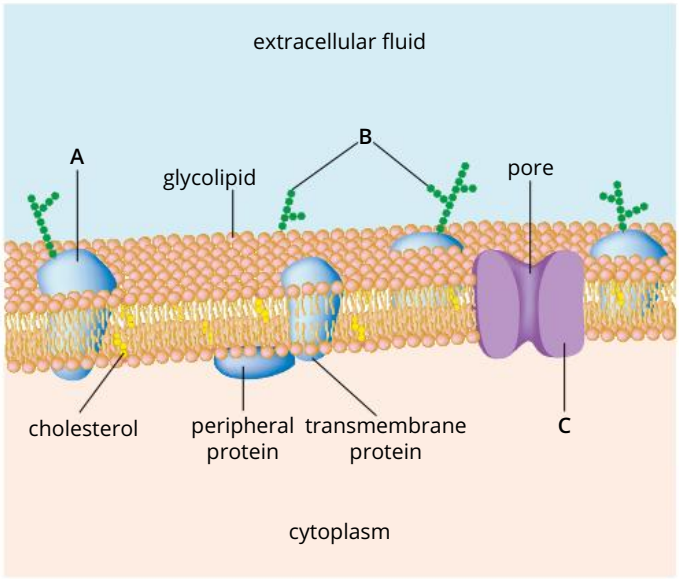
b Identify the optimum temperature for the enzyme.

c Explain what happens to the enzyme above 40°C.

d Name the other factors that affect enzyme activity other than temperature.

18 Compare anaerobic and aerobic cellular respiration.

19 The following diagram illustrates the structure of a cell membrane.



a Identify molecules A and B.

b **i** Name structure C.

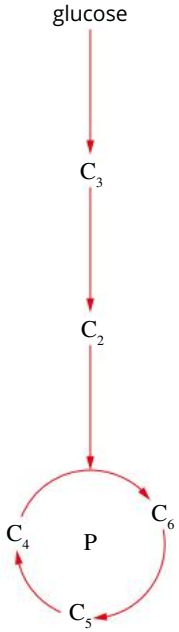
ii Describe the function of structure C.

c Explain the function of cholesterol in the cell membrane.

20 Many of the ribosomes found in a cell are attached to the endoplasmic reticulum, forming rough endoplasmic reticulum.

Hypothesise how this arrangement benefits the functioning of a cell.

21 The following diagram shows part of the cellular respiration pathway. The number of carbon atoms in each molecule is indicated.



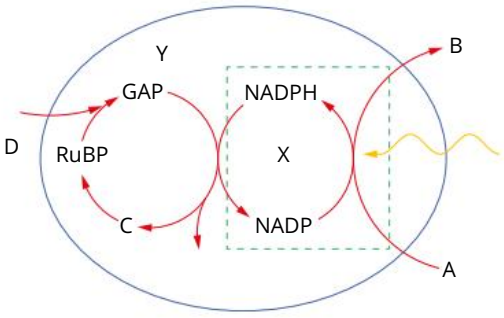
a Label pyruvate and acetyl CoA on the diagram.

b Interpret the diagram and then circle the part of this cellular respiration pathway that occurs in the matrix of the mitochondria.

c Identify process P.

22 The following diagram represents an outline of a chloroplast, with the letters A–D representing chemicals involved in photosynthesis.

Different compartments of the chloroplast are represented by X (within the dotted line) and Y.



a Identify substances A to D from the following list: CO_2, O_2, H_2O, glucose (G3P)

b i Identify compartments X and Y.

ii Name the group of reactions that takes place in each of the compartments.

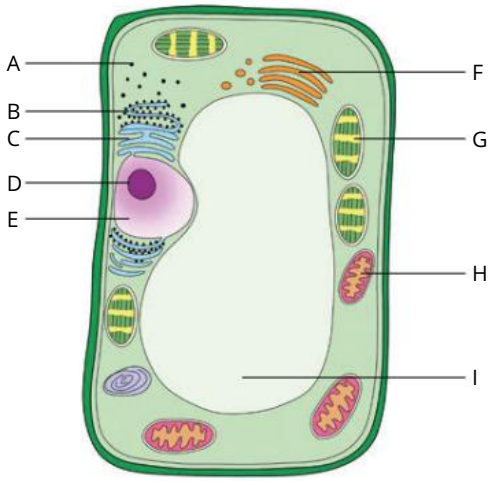
c Propose which of these substances would be in short supply on an overcast day. Justify your proposition.

d Propose how the production of glucose would be affected.

23 a Identify the three main components of an ATP molecule.

b Explain the process in which ATP releases energy for chemical reactions.

24 a The following diagram shows a eukaryotic cell.



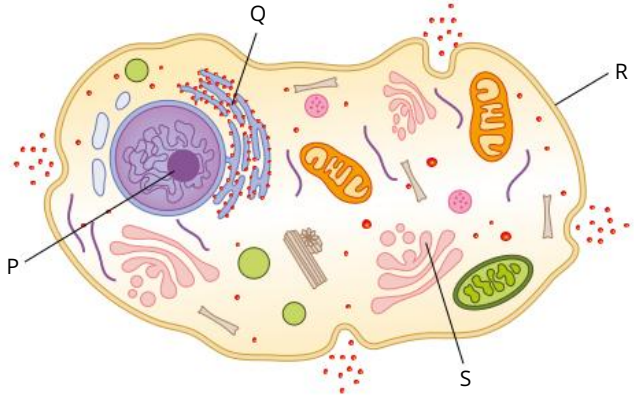
i Identify structures A–I.

ii Identify whether this is a plant cell or an animal cell. Justify your answer.

iii The table shows a list of functions of organelles. Label the organelles (selected from A–I) with their function.

Organelle	Function
	Site of photosynthesis
	Stores water in plant cells
	Site of lipid production
	Contains genetic information and controls the cell's chemical activities
	Site of ATP production

b Another generalised cell is shown.

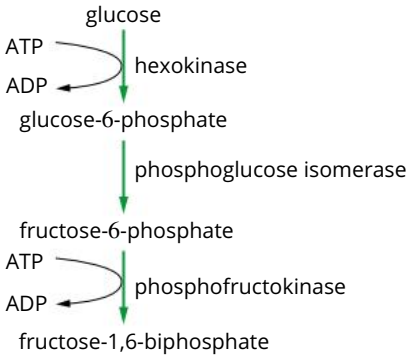


i Identify whether this is a prokaryotic or eukaryotic cell. Justify your answer.

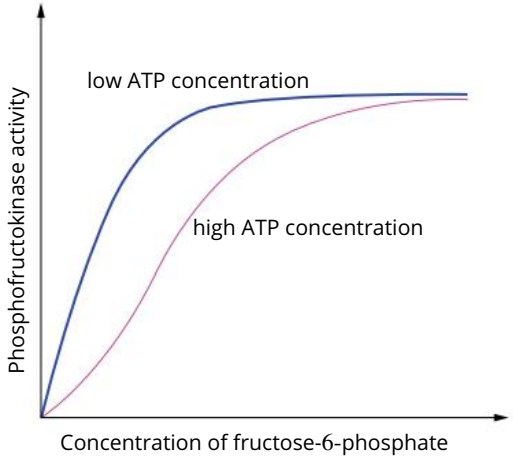
ii Identify organelles P–S.

iii Outline how organelles Q–S are involved in the secretion of a protein.

25 A section of the glycolysis pathway showing various substrates, products and enzymes is illustrated here.



Scientists measured the effect of different concentrations of fructose-6-phosphate on phosphofructokinase activity. Phosphofructokinase activity was also measured with low and high concentrations of ATP in the reaction mixture. The graph below shows the results.



a Outline the effect of increasing fructose-6-phosphate.

b Explain how increasing the concentration of fructose-6-phosphate affects the activity of phosphofructokinase.

c Outline the effect of increasing ATP concentration on the activity of phosphofructokinase.

d Given that one of the functions of glycolysis is to produce ATP, explain how the effect of ATP on phosphofructokinase is advantageous.

26 a An experiment was performed in which muscle cells were incubated in an oxygen-free environment at 20°C. The cumulative uptake of glucose was measured in grams. The results for the first 10 minutes are shown in the following table.

Glucose use in the absence of oxygen

Time (min)	Glucose uptake (g)
2	5
4	10
6	15
8	20
10	25

After 10 minutes, oxygen was infused into the culture and measurement of the uptake of glucose continued. The results for the next 10 minutes are tabulated below. Temperature was maintained at 20°C.

Glucose use in the presence of oxygen

Time (min)	Glucose uptake (g)
12	26
14	27
16	28
18	29
20	30

i Depict on a graph the uptake of glucose versus time for the 20 minutes of the experiment. Clearly mark the point at which oxygen was introduced into the culture.

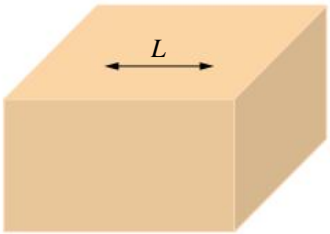
ii Explain why glucose use declined so significantly after oxygen was added to the culture.

iii Name the independent variable in the experiment.

iv Explain why was it necessary to ensure that the temperature remained at 20°C throughout the experiment.

b Some mitochondrial diseases are caused by mutations in the genes needed for respiration. Mitochondrial diseases caused by these mutations are relatively common in comparison to diseases caused by nuclear chromosomal mutation.
An experimenter investigating mitochondrial mutations performed the experiment from part **a** using cells with mitochondria possessing mutations. The scientist noted that when oxygen was added after 10 minutes to these cells no change in glucose use was observed. Draw a conclusion from these results about the effect of the mutation on mitochrondrial function.

27 To investigate the effect of surface area to volume ratio on the rate of diffusion, a student prepared different sizes of agar cubes containing phenolphthalein. The agar cubes were then suspended in a 4% sodium hydroxide solution for 10 minutes. When sodium hydroxide diffused into the agar, the agar turned pink. After 10 minutes, the agar cubes were cut in half and the length of the colourless area (L) was measured. The illustration shows a cross-section of the agar cube.



The following table shows the results of the experiment.

Surface area of cube = 6 × length of cube × length of cube

Volume of cube = length of cube × length of cube × length of cube

$$\text{Percentage diffusion} = \frac{\text{volume of cube} - (\text{volume of colourless area})}{\text{volume of cube}} \times 100$$

a Calculate the volume, surface area, surface area to volume ratio, and percentage diffusion of each cube, and complete the table below.

b Create a graph of percentage diffusion against surface area to volume ratio. Deduce and include a curve of best fit on the graph.

c Describe the relationship between surface area to volume ratio and diffusion in an agar cube. Use the graph you plotted in part **b** to assist you.

d Identify the size of the cube which was the most effective for maximising diffusion.

e Justify your answer to part **d**.

f A large surface area is essential for quicker diffusion into the cell. Explain why there is a limit to the size individual cells can grow. Justify your answer using the results of the experiment.

g Propose how the reliability and validity of this experiment can be improved.

Length of cube side (cm)	Surface area of cube (cm^2)	Volume of cube (cm^3)	Surface area to volume ratio of cube	Length of colourless area, L (cm)	Volume of colourless area ($L \times L \times L$) (cm^3)	Percentage diffusion (%)
1.0				0.0		
1.5				0.4		
2.0				0.8		
2.5				1.8		

28 Blood and tissue fluid in a human are generally maintained in a narrow pH range, between 7.35 and 7.45. This means blood is slightly basic.

A family of enzymes called carbonic anhydrases are responsible for the conversion of CO_2 to HCO_3^- in the tissues, and HCO_3^- back to CO_2 in the lungs. Carbonic anhydrase II is responsible for the conversion of CO_2 to HCO_3^-.

Under normal circumstances, carbonic anhydrase can catalyse the change of CO_2 to HCO_3^- at a rate of one million molecules per second. Imidazole is a chemical that inhibits the action of carbonic anhydrase II. An experiment was run at 37°C, with and without imidazole, at varying CO_2 concentrations. The amount of imidazole added was kept constant throughout the experiment. The results are shown in the table.

CO_2 concentration ($mmol\ L^{-1}$)	Rate of conversion	
	Without imidazole ($mmol\ min^{-1}$)	With imidazole ($mmol\ min^{-1}$)
0.1	3.2	1.6
0.2	4.5	2.7
0.3	6.7	4.1
0.5	7.1	6.3
1.0	8.8	7.8
2.0	10.3	10.1

a i Name the independent variable(s) in this experiment.

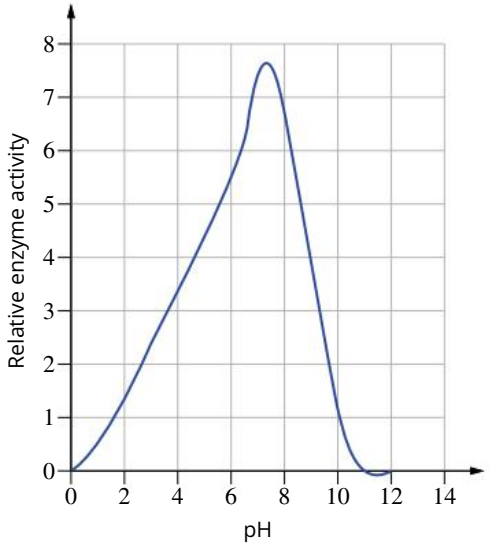
ii Imidazole is a competitive inhibitor of carbon dioxide conversion. Explain how imidazole slows the rate of reaction. Ensure you describe the structures involved in your answer.

iii Explain the difference in the rate of inhibition as the concentration of carbon dioxide changes.

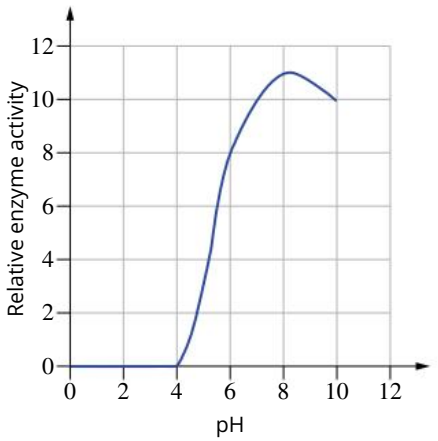
b In a further experiment on the activity of carbonic anhydrase II, its activity during changes to pH was investigated. The results were graphed. Four graphs are shown.

Propose which of the graphs is most likely to show the activity of this enzyme at various pH values? Justify your choice and explain what is occurring to the enzyme. State why the other graphs are not correct.

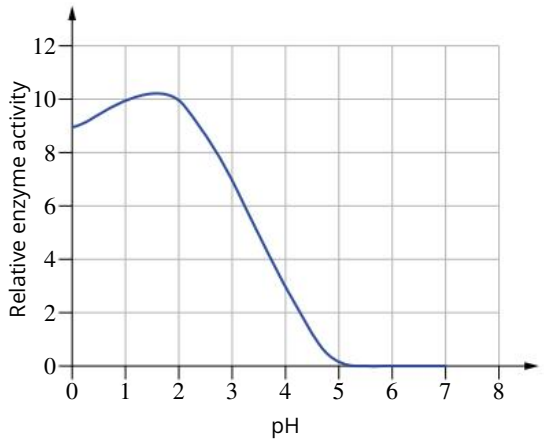
A



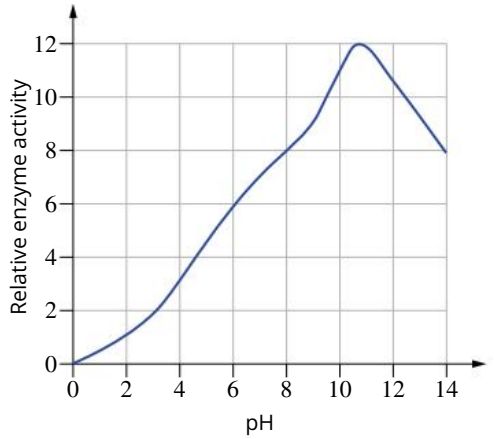
B



C



D



c Imidazole could be used as a poison. Explain how it would affect the metabolism of an organism.

Topic 2 Multicellular organisms

Multiple-choice questions

1 Select the alternative that best shows the levels of organisation in a complex organism.

A cell → organ → tissue → system
B cell → system → tissue → organ
C system → organ → cell → tissue
D cell → tissue → organ → system

2 Cells with the greatest potential to undergo different specialisation are those that are:

A unipotent
B plutipotent
C totipotent
D pluripotent

3 POU5F1 is a gene that codes for a protein called OCT4. The concentration of OCT4 has been shown to be reduced in cells that have undergone differentiation.

Consider the diagram of the development of a human embryo at the bottom of the page. Early developmental stages are shown in light grey, and development and differentiation progresses until complete at the end of the period in dark grey.

Analyse the diagram and determine when the highest levels of OCT4 would be expected.

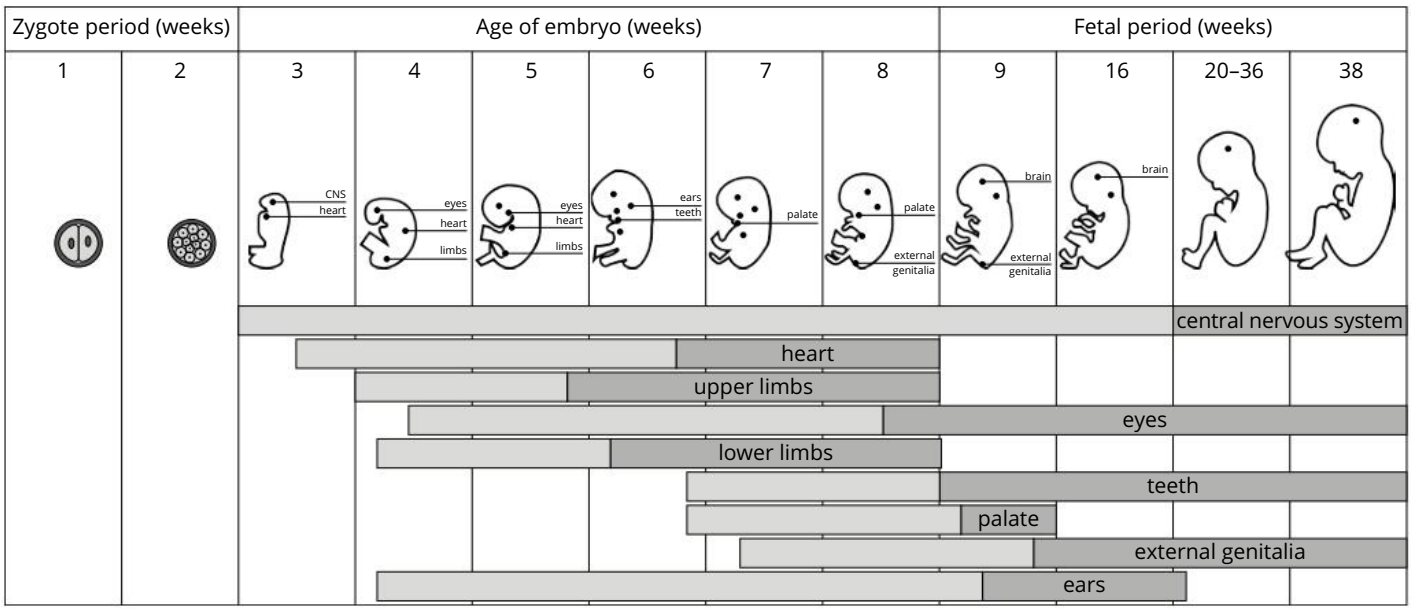
A upper limbs at six weeks
B heart at seven weeks
C ears at eight weeks
D teeth at nine weeks

4 Name the part of an organism that contains a large number of different types of cells working together to perform a particular function and that is often recognisable as a distinct structure.

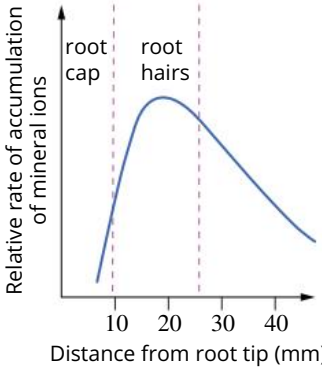
A tissue
B organ
C system
D organism

5 Select the example of an unspecialised cell.

A meristematic cell
B nerve cell
C red blood cell
D mesophyll cell



6 The following graph shows the relative rate of accumulation of minerals in the root of a plant at different distances from the growing root tip.



Identify the conclusion that can be drawn from the data.

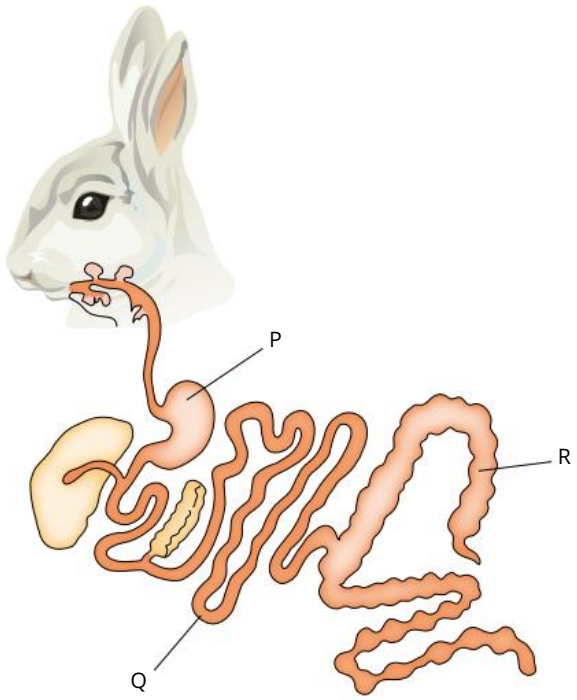
A Active transport causes ions to accumulate in the root.

B At larger distances from the tip all the minerals are lost from the root.

C A large surface area is necessary for mineral accumulation.

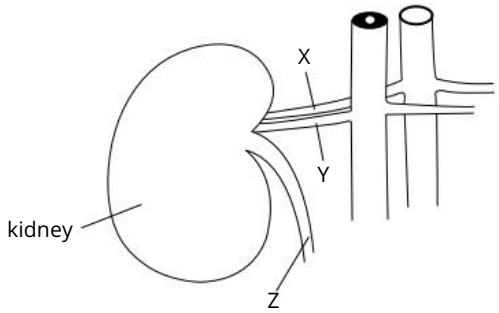
D Mineral accumulation is greatest in the part of the root with root hairs.

7 The following diagram shows the digestive system of a rabbit. Identify structures P–R.



	P	Q	R
A	liver	caecum	small intestine
B	stomach	small intestine	caecum
C	liver	small intestine	colon
D	stomach	caecum	large intestine

Questions **8** and **9** refer to the following diagram of a kidney.



8 Identify structures X–Z.

	X	Y	Z
A	artery	vein	ureter
B	artery	vein	urethra
C	vein	artery	urethra
D	vein	artery	ureter

9 Propose which structure in the diagram would contain a higher concentration of urea.

A X

B Y

C Z

10 Determine which of the following statements about the changes in the chemical composition of blood as it moves around the body is correct.

A The concentration of glucose increases as it passes through the muscle tissue.

B Fatty acid concentration increases in the blood as it flows through the small intestine.

C The oxygen concentration of the blood decreases as it flows through the brain.

D The bicarbonate ion concentration increases as blood flows through the alveoli.

11 Nitrogenous wastes are formed as a result of the break down of proteins. The most toxic of these wastes is a substance called creatinine. Name the second most toxic waste.

A urea

B ammonia

C uric acid

D nitric acid

12 Pytalin is a digestive enzyme. It assists in the break down of starch to maltose. Name the group of enzymes to which pytalin belongs.

A proteases
B lipases
C amylases
D nucleases

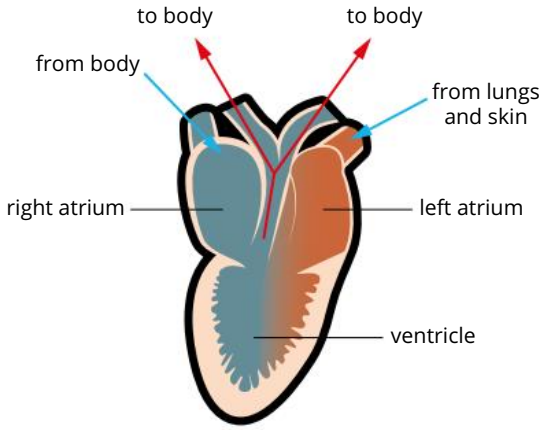
Short-answer questions

13 Many new parents have the blood from their newborn baby's umbilical cord frozen in liquid nitrogen. Discuss the advantage of umbilical cord blood over blood from an adult.

14 Name the three layers that are formed during gastrulation and describe the fate of each layer.

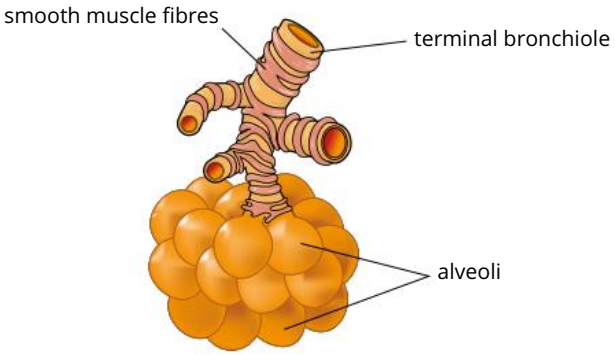
15 Research is being undertaken into induced pluripotent stem cells.
List advantages of these stem cells over other types of stem cells. Discuss both ethical and practical advantages.

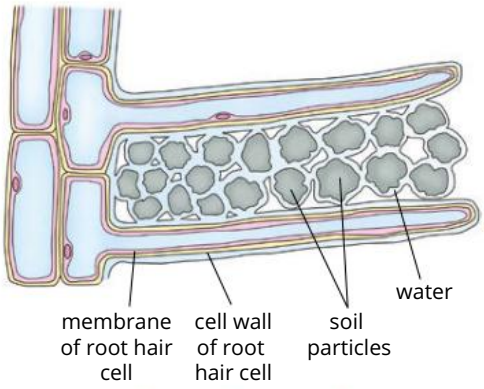
16 The following diagram shows the heart of an amphibian. Amphibians have a closed circulatory system.

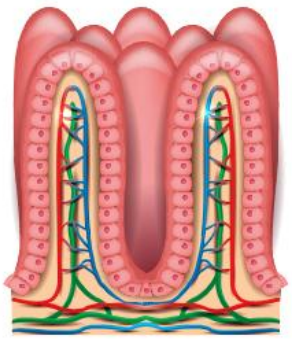


a i Explain what is meant by a closed circulatory system.
ii Identify and explain one advantage of a closed circulatory system.
b Explain how the amphibian heart differs from the mammalian heart.
c Explain why a heart structured like that of amphibians would not be suitable for a mammal or bird.

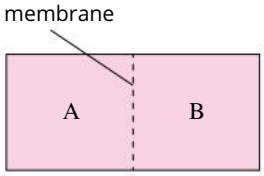
17 Explain what these three structures have in common and relate that commonality to their function.





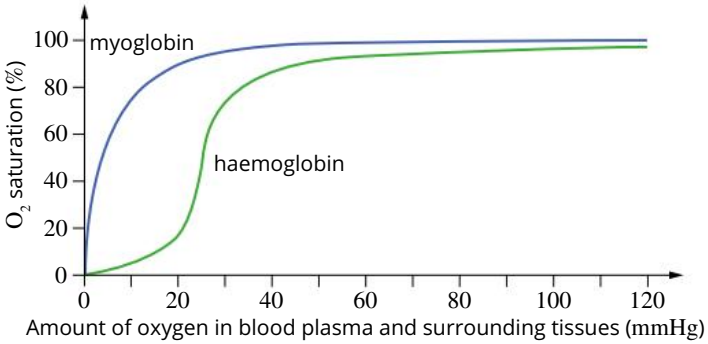


18 a A pressurised container has a total pressure of 980 mmHg. The container contains 25% oxygen, 40% nitrogen and 35% carbon dioxide. Calculate the partial pressure of each gas.
b A second container is joined to the first, as shown.



The two containers have a membrane between them that is permeable to all of the gases. The pressure in the second container is 600 mmHg. This container contains 60% oxygen and 40% nitrogen.
i Calculate the partial pressures of both gases in the container.
ii Conclude which way each of the gases will move.

19 Haemoglobin is the oxygen-carrying pigment in red blood cells that gives them their red colour. Myoglobin is an oxygen-carrying pigment found in muscle tissue. It is found in particularly high concentrations in the muscles of diving mammals such as dolphins and whales.



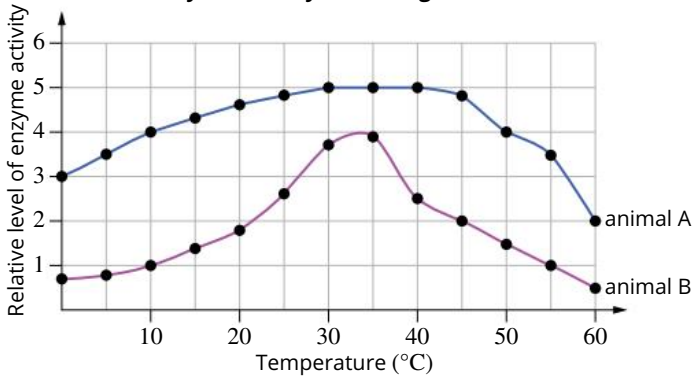
a Explain why haemoglobin is well suited to its role of collecting oxygen in the lungs and releasing it in the tissues. Refer to the data in your answer.

b Diving mammals have large amounts of myoglobin in their muscles. Propose how this helps them to stay underwater for long periods of time. Justify your answer using the data supplied.

20 The graph shows the activity of the enzyme catalase in two different animals. Catalase is an intracellular enzyme which breaks down hydrogen peroxide into water and oxygen, according to the equation:

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

Enzyme activity of two organisms



a Explain which of the organisms is most likely to be ectothermic.

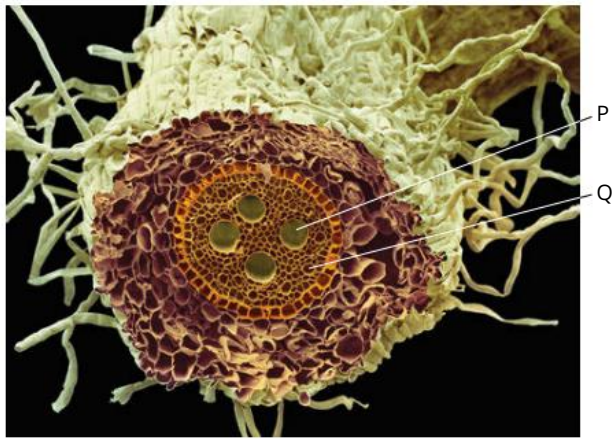
b Identify the optimum temperature for catalase activity for animal B.

c **i** Explain what is happening to the enzymes of animal B at 55°C.

ii Describe how the relative level of enzyme activity is different at 0°C. Explain why.

d The graph shows the relative level of enzyme activity. Propose how the experiment could be modified to provide a more exact measure of the activity of catalase.

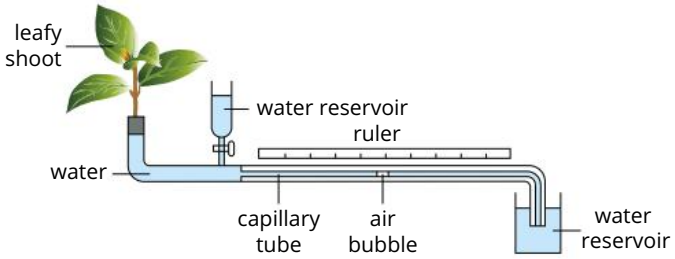
21 The following image shows a scanning electron micrograph of a root.



a Identify structures P and Q.

b Outline how structure P is involved in the transport and eventual loss of water.

22 The diagram shows an apparatus called a plant potometer. It is used to measure the rate of transpiration of a plant by timing the rate at which the bubble moves along the horizontal glass tube.



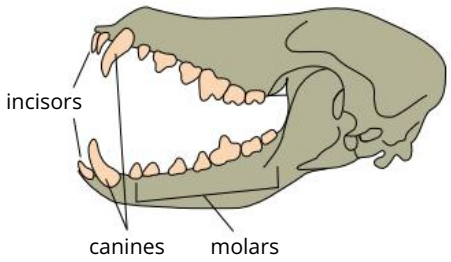
a Design a controlled experiment using a plant potometer to test the hypothesis that the leaves of Australian eucalypts do not lose water as fast as leaves of an English elm. In your answer mention the test and controlled variables.

b Propose the results you would expect if the hypothesis were to be supported.

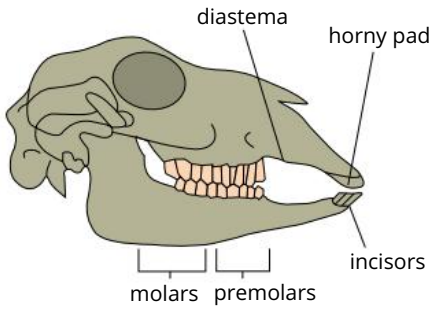
23 Compare xylem and phloem.

24 The following diagram is of the skulls of two mammals, organism A and organism B.

Organism A



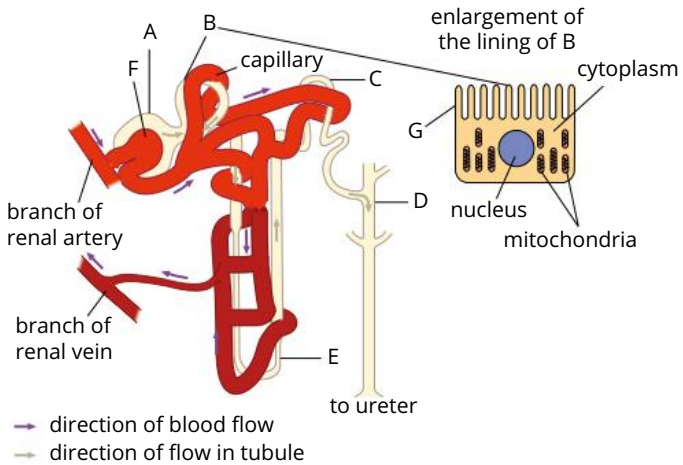
Organism B



a One role of teeth in mammals is to break food into smaller pieces. Explain the benefit of this.

b Describe the type of food that each organism would eat, justifying your opinion and explaining the consequences for the structure of their digestive tracts.

25 The kidneys are important in maintaining the osmotic balance of the body and in removing wastes such as the products of protein digestion and excess mineral ions. The functional unit of the kidney is illustrated here.



a Identify structures A–F.

b Explain how structure B assists the nephron to perform its function.

By filtration in the kidneys, 100 litres of fluid is removed from the blood in 24 hours. In this time, only 1.5 litres of urine is formed. The blood plasma contains on average 0.03% urea in solution, but urine contains 2% urea in solution.

c Calculate how many times (to the nearest whole number) urea is more concentrated in urine than it is in the blood?

d The table shows the ratio of nephron concentration to plasma concentration.

Chemical	A	Mid B	Start E	Mid E	End E	Mid C	D
glucose	0.8	0.08	0	0	0	0	0
amino acids	0.4	0.5	0	0	0	0	0
urea	1.0	1.2	1.6	7.0	15.0	20.0	50.0
Cl^-	1.0	1.0	1.0	2.0	0.35	0.4	0.8
Na^+	1.0	1.0	1.0	2.0	0.2	0.25	0.7
K^+	1.0	1.0	1.0	2.0	0.3	0.5	3.0
creatinine	1.0	2.0	5.0	6.5	16.0	20.1	50.0

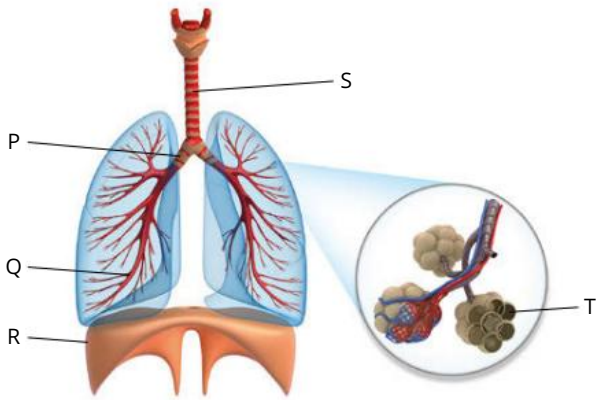
i Explain what a ratio of 1 for nephron/plasma concentration indicates.

ii Explain why less glucose and amino acids are found in the filtrate than ions such as Na^+ and K^+?

iii Discuss the function of the nephron and its surrounding capillaries. Justify your answer by making reference to the data in the table. In your answer identify how the molecules are being transported across the membrane.

iv Compare the glucose concentration between the renal artery and the renal vein. Justify your proposition.

26 a The following diagram shows the structure of the human respiratory system.



i Identify structures P–T.

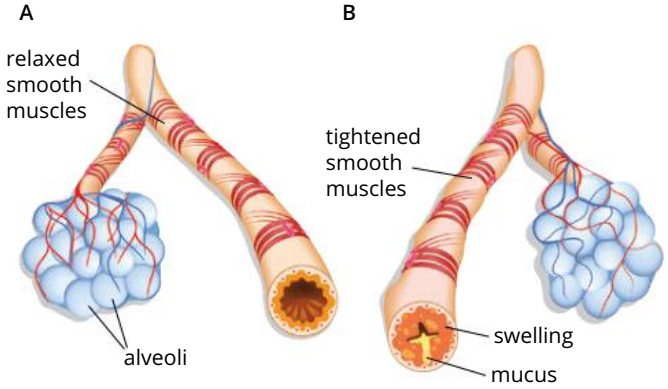
ii Describe how the movement of the rib cage and diaphragm results in air moving into T.

iii Describe the features of T that make it a suitable surface for the exchange of gases.

b i Draw a diagram showing how gas is exchanged between the capillary net surrounding the air sac and the interior of the air sac.

ii Compare the flow of gases at the body tissues, such as muscles, and gas flow in the lungs.

c This diagram shows structure P during normal breathing (A) and during an asthma attack (B).

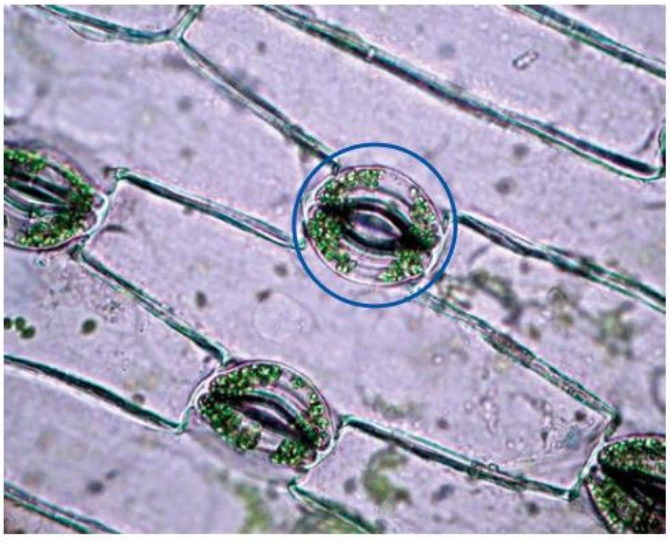


i List the conditions in a person's alveoli during an asthma attack.

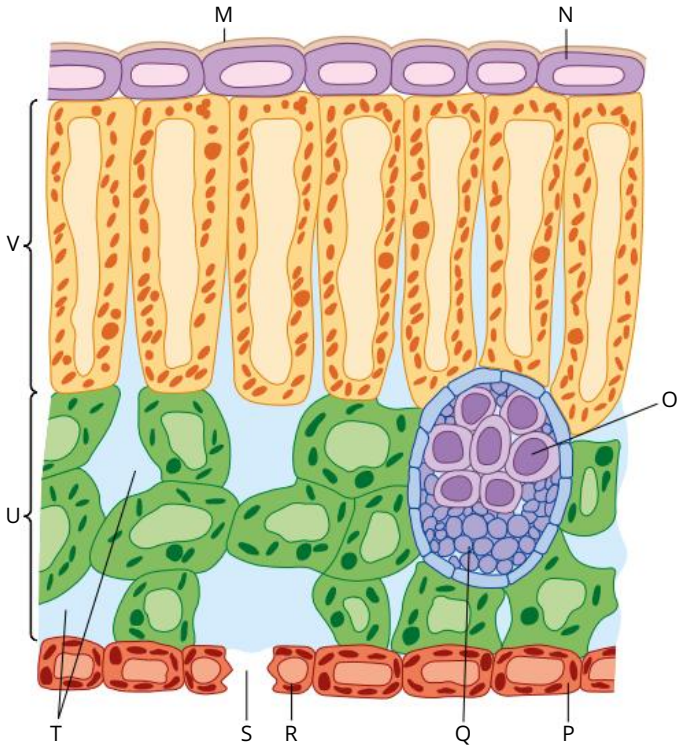
ii Explain the reason for the conditions listed in part **b(i)**.

iii Asthma interferes with one important component of the gas exchange process. Discuss.

27 a The image below is a micrograph of a leaf epidermis. Describe the function of the circled structure.

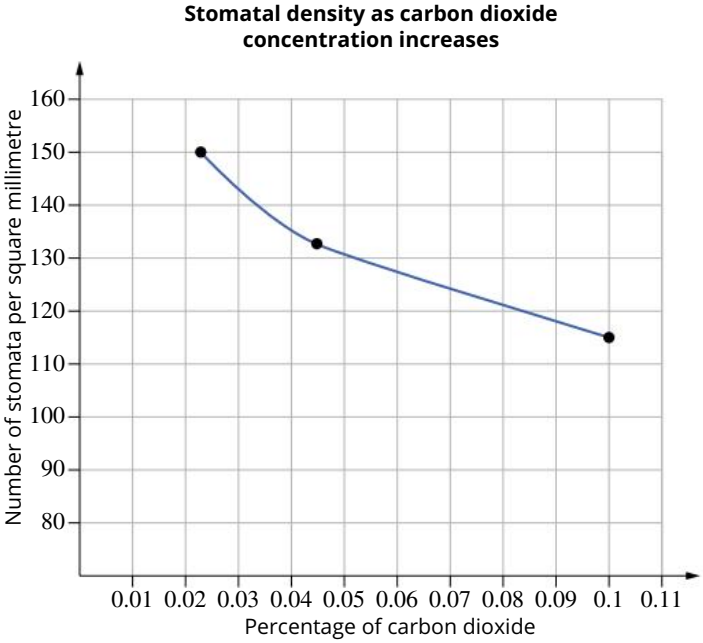


b Identify structures M–V.



c Explain the advantage to the plant of structure S.

d Analyse the graph.



i Describe the trend in number of stomata as carbon dioxide concentration increases.

ii Propose what advantage exists for the plant that results in this trend.

28 A group of students interested in plant transport systems performed two radioactive tracing experiments. Radioactive isotopes of elements act exactly the same as the non-radioactive forms but are able to be traced through the plant.

In the first experiment, the students grew the plants in a medium containing nitrates labelled with a radioactive isotope of nitrogen. In the second experiment, they grew the plants in an environment with an atmosphere containing carbon dioxide labelled with carbon-14, which is radioactive.

Experiment 1

All of the plants were grown in a full nutrient solution containing radioactively labelled nitrates. The nutrient medium of half of the plants contained a low concentration of arsenic. Arsenic is a poison that disrupts the electron transfer chain of cellular respiration. The reduction in concentration of nitrates in the nutrient medium was monitored and registered every 10 minutes.

a i Identify the control in this experiment.

ii Name the independent variable.

b The results of the experiment are shown in the table.

Time (min)	Nitrate concentration of nutrient medium for 'No arsenic' plants (mmol L^{-1})	Nitrate concentration of nutrient medium for arsenic-treated plants (mmol L^{-1})
0	1.1	1.1
10	1.0	1.05
20	0.85	1.0
30	0.8	0.98
40	0.75	0.97
50	0.6	0.97
60	0.5	0.97

i Draw a graph of the results.

ii Explain where would you first expect to see radioactive nitrogen in the plants.

iii Draw conclusions about nitrate absorption into plants from this experiment.

iv After 48 hours, the plants without arsenic were examined to discover the distribution of radioactive nitrogen in their tissues. Describe where in the plant would you expect to see evidence of radioactivity. Justify your suggestion.

Experiment 2

Mangrove plants use structures called pneumatophores to allow roots to undergo gas exchange. The canopy of a small mangrove plant was covered in a tent that had a constant supply of air. The carbon dioxide in the air contained radioactive ^{14}C rather than the normal ^{12}C. The pneumatophores were covered separately so as to collect any gases that were released by them.

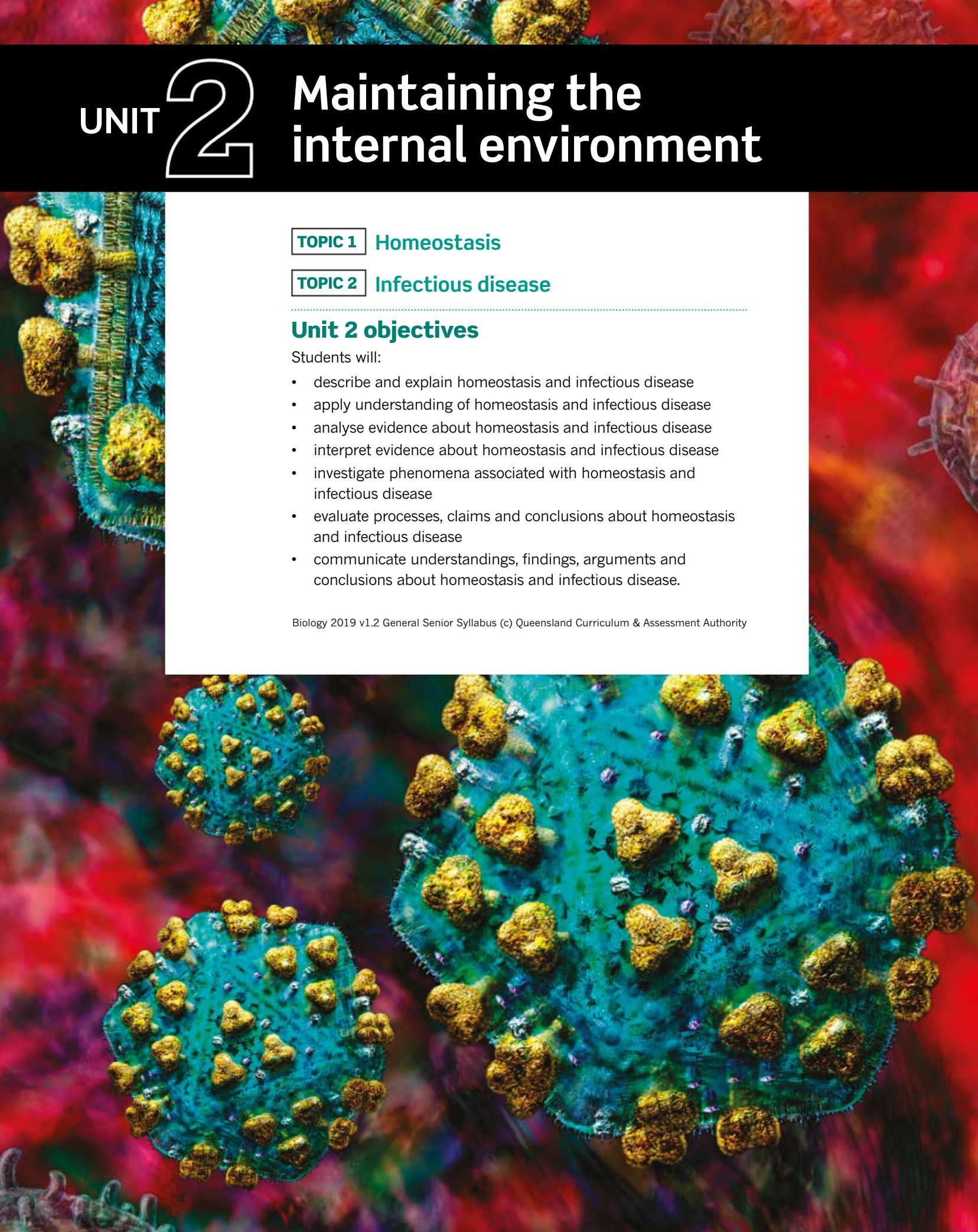
d Explain why the tents over the pneumatophores were filled with oxygen.

e Several hours after the start of the experiment the tents over the pneumatophores showed evidence of radioactivity.

i Name the compound that contained the radioactive material.

ii Explain in detail the pathway taken by the ^{14}C to get to the tent over the pneumatophores.

UNIT 2 Maintaining the internal environment



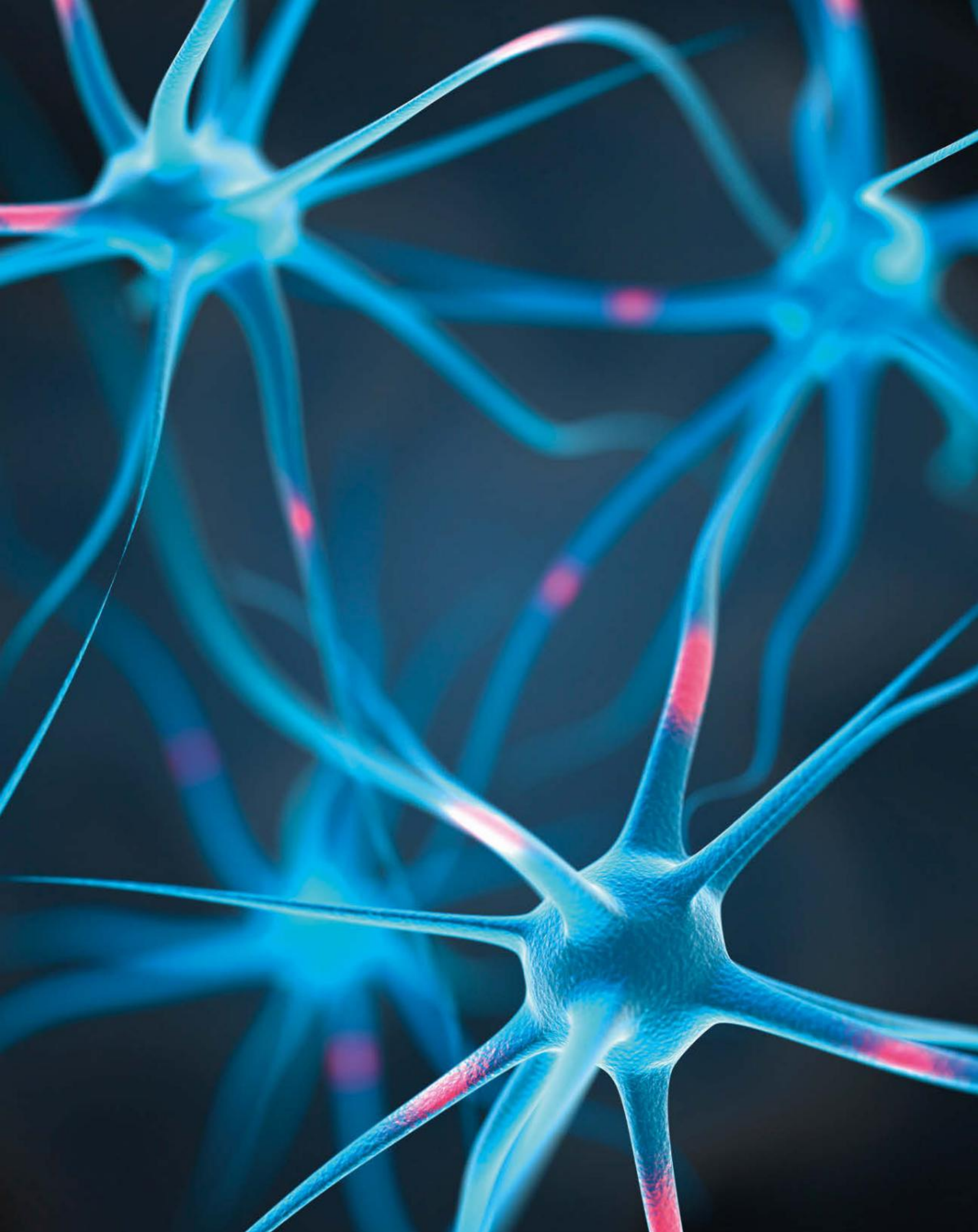
TOPIC 1 Homeostasis

TOPIC 2 Infectious disease

Unit 2 objectives

Students will:

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



CHAPTER

06 Homeostasis

Organisms and cells are constantly experiencing changes in their environment. These changes to the internal and external conditions can adversely affect the survival, growth and function of the organism. The internal environment of an organism must always remain within tolerable limits, even when conditions in the external environment fluctuate widely. When a change occurs in the external environment, an adjustment must be made to the internal environment.

Living organisms rely on their external environments to provide adequate levels of nutrients, water and oxygen, and suitable physical conditions, such as light and temperature. Organisms have a range of mechanisms that allow them to adapt to changing conditions while maintaining a stable internal environment when external conditions fluctuate. If an organism is not able to adapt to its external environment, it will suffer cellular damage and possibly death when conditions change.

Syllabus subject matter

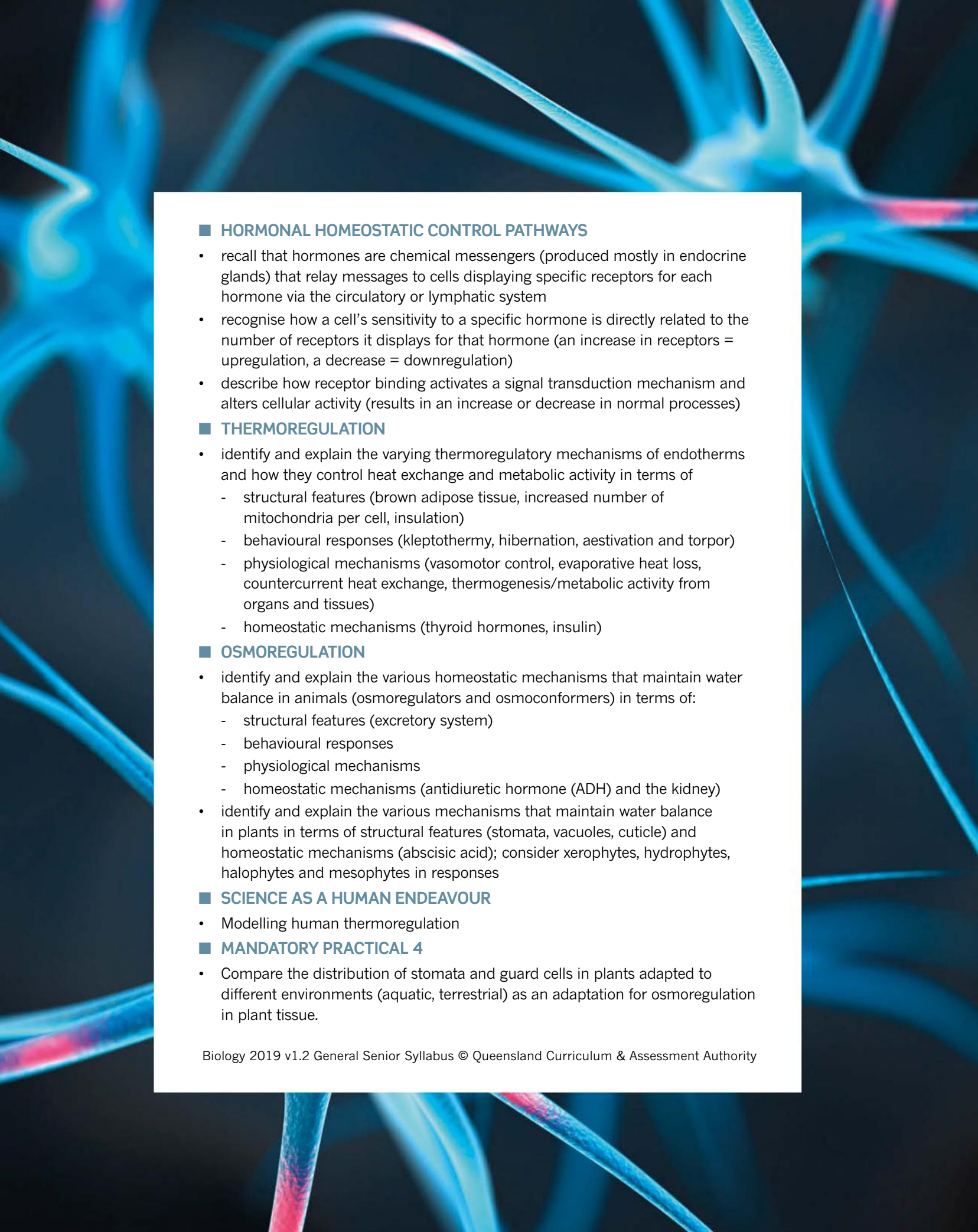
Topic 1 • Homeostasis

HOMEOSTASIS

- recall that homeostasis involves a stimulus–response model in which change in the condition of the external or internal environment is detected and appropriate responses occur via negative feedback
- recognise that sensory receptors (chemo, thermos, mechano, photo, noci) detect stimuli and can be classified by the type of stimulus
- recall that effectors are either muscles (which contract in response to neural stimuli) or glands (which produce secretions)
- interpret feedback control diagrams for either nervous or hormonal systems (i.e. recognise stimulus, receptors, control centre, effector and communication pathways)
- understand that metabolism describes all of the chemical reactions involved in sustaining life and is either catabolic or anabolic
- explain why changes in metabolic activity alter the optimum conditions for catalytic activity of enzymes (with reference to tolerance limits)

NEURAL HOMEOSTATIC CONTROL PATHWAYS

- identify cells that transport nerve impulses from sensory receptors to neurons to effectors
- discriminate between a sensory neuron and a motor neuron (consider dendrites, soma, body, axon, myelin sheath, nodes of Ranvier, axon terminal and synapse)
- explain the process of the passage of a nerve impulse in terms of transmission of an action potential (conduction within a neuron) and synaptic transmission (communication between neurons). Refer to neurotransmitters, receptors, synaptic cleft, vesicles, postsynaptic and presynaptic neurons and signal transduction



HORMONAL HOMEOSTATIC CONTROL PATHWAYS

- recall that hormones are chemical messengers (produced mostly in endocrine glands) that relay messages to cells displaying specific receptors for each hormone via the circulatory or lymphatic system
- recognise how a cell's sensitivity to a specific hormone is directly related to the number of receptors it displays for that hormone (an increase in receptors = upregulation, a decrease = downregulation)
- describe how receptor binding activates a signal transduction mechanism and alters cellular activity (results in an increase or decrease in normal processes)

THERMOREGULATION

- identify and explain the varying thermoregulatory mechanisms of endotherms and how they control heat exchange and metabolic activity in terms of
  - structural features (brown adipose tissue, increased number of mitochondria per cell, insulation)
  - behavioural responses (kleptothermy, hibernation, aestivation and torpor)
  - physiological mechanisms (vasomotor control, evaporative heat loss, countercurrent heat exchange, thermogenesis/metabolic activity from organs and tissues)
  - homeostatic mechanisms (thyroid hormones, insulin)

OSMOREGULATION

- identify and explain the various homeostatic mechanisms that maintain water balance in animals (osmoregulators and osmoconformers) in terms of:
  - structural features (excretory system)
  - behavioural responses
  - physiological mechanisms
  - homeostatic mechanisms (antidiuretic hormone (ADH) and the kidney)
- identify and explain the various mechanisms that maintain water balance in plants in terms of structural features (stomata, vacuoles, cuticle) and homeostatic mechanisms (abscisic acid); consider xerophytes, hydrophytes, halophytes and mesophytes in responses

SCIENCE AS A HUMAN ENDEAVOUR

- Modelling human thermoregulation

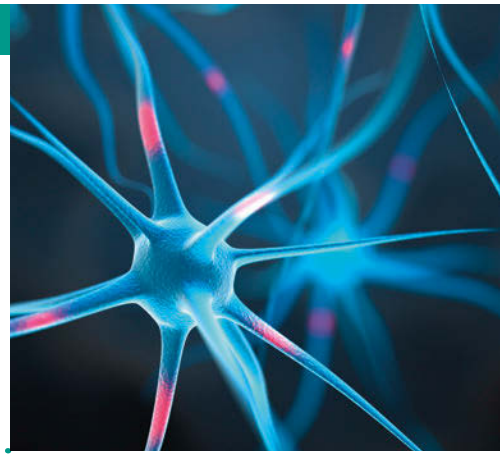
MANDATORY PRACTICAL 4

- Compare the distribution of stomata and guard cells in plants adapted to different environments (aquatic, terrestrial) as an adaptation for osmoregulation in plant tissue.

6.1 Homeostasis

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

- recall that homeostasis involves a stimulus–response model in which change in the condition of the external or internal environment is detected and appropriate responses occur via negative feedback
- recognise that sensory receptors (chemo, thermos, mechano, photo, noci) detect stimuli and can be classified by the type of stimulus
- recall that effectors are either muscles (which contract in response to neural stimuli) or glands (which produce secretions)
- interpret feedback control diagrams for either nervous or hormonal systems (i.e. recognise stimulus, receptors, control centre, effector and communication pathways).



Homeostasis is when variables in a system are maintained within certain limits. When an organism is healthy and functioning well, its systems are in homeostasis. Homeostasis is achieved by a variety of mechanisms that work to keep **internal environments** constant. This maintains conditions at an optimum level when the internal or **external environment** changes.

The ability to maintain these optimum levels is dictated by the organism's metabolism—the complex integrated network of biochemical reactions that sustain life but are regulated by enzymes. As you will recall from Chapter 3, enzymes work within optimal conditions. Homeostasis includes the maintenance of these conditions for both catabolic and anabolic reactions.

SENSORY RECEPTORS

All organisms have sensory receptors to detect aspects of either their internal or external environments that may affect their ability to survive and reproduce or to maintain a state of homeostatic equilibrium.

Animal sensory receptors

The types of sensory receptors present, and their sensitivity, differ substantially among animals. The receptors are related to the way that the animals have adapted to their environments. For example, a wombat has less visual acuity for distinguishing small objects than an eagle does, dogs use chemical scents much more than do humans (Figure 6.1.1), and some moths have **chemoreceptors** that can detect a single molecule of pheromone. Some animals respond to different parts of the energy spectrum. Snakes can detect infrared radiation, bees see ultraviolet (UV) light, and platypuses can detect weak electrical currents.

In humans, the five senses (vision, hearing, taste, smell and touch) are perceived through sense organs (eyes, ears, tongue, nose and skin) that collect and process sensory information. Receptors that detect external stimuli are known as **exteroreceptors**. These are usually located close to the surface of the body and detect stimuli such as pain and pressure. Some receptors detect internal states, such as blood pressure and blood chemistry (e.g. oxygen and carbon dioxide levels), and these are known as **interoreceptors** or visceral receptors. From a functional point of view, the types of sensory receptors involved in these senses can be classified as **photoreceptors** (vision), chemoreceptors (taste, smell, communication), **mechanoreceptors** (hearing, balance, pressure, touch) and **thermoreceptors** (temperature). Table 6.1.1 and Figure 6.1.2 on page 228 show some of these receptor types.

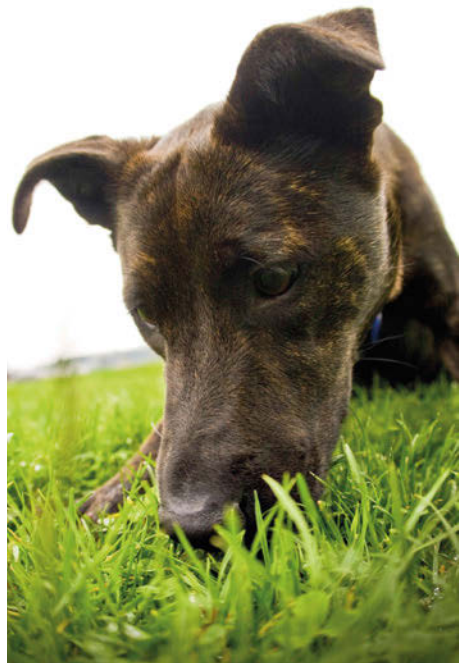


FIGURE 6.1.1 Dogs use their keen sense of smell to collect chemical scents.

TABLE 6.1.1 Receptor type, examples and stimulus received in complex animals

Receptor type	Examples	Received stimuli
Mechanoreceptors	Pressure (touch) receptors Blood vessels: • baroreceptors	stretching of blood vessel wall
	Skin: • Meissner corpuscle • Pacinian corpuscle	• light touch • heavy touch
	Proprioreceptors: • muscle spindles • Golgi cells • joint receptors	• movement, position of body • gravity • movement with ligaments
	Labyrinth in the vertebrate ear: • sacculus and utriculus • semicircular canals • ciliated cells in the cochlear duct	• gravity and linear acceleration • angular acceleration • sound waves
Chemoreceptors	Taste buds, olfactory epithelium	specific chemical compounds
Thermoreceptors	• thermoreceptors in blood-sucking insects and ticks • pit organs in pit vipers • nerve endings and receptors in the skin and tongue of many animals	heat
Electroreceptors	Organs in the skin of some fish	electric currents in water
Photoreceptors	• eyespots • ommatidia in arthropods • rods and cones in the retina of the vertebrate eye	light energy

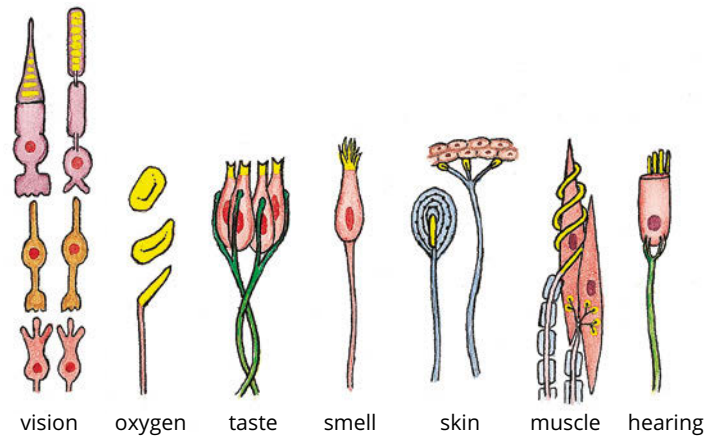


FIGURE 6.1.2 Different sensory receptors in the vertebrates. The yellow parts are the regions of the receptor that respond to the particular stimulus.

FIGURE 6.1.3 Planarians have simple light-sensitive receptors, called eye-spots, that help them detect and move away from light.

Photoreceptors (vision)

Photoreceptor cells that contain light-sensitive pigments appeared very early in animal evolution. Light interacts with the pigment and produces an electrical signal in a sensory nerve. This allows the animal to visually detect changes (stimulus) in its external environment and respond accordingly. The most primitive type of eye consists of a small patch of light-sensitive receptors that acts as a light-detecting organ and cannot form images (for example, the planarian eye-spot shown in Figure 6.1.3).

Optical systems that focus light to form an image arose much later in evolution and in fewer groups of animals. Because it has more photoreceptors, an eye can detect greater variation in light intensity and therefore form more complex images (Figure 6.1.4).

There are two types of eyes.

- Simple eyes are single-chambered eyes, as shown in Figure 6.1.5a. Vertebrate eyes, including the human eye, use a lens or a cornea, or both, to form an image on the photoreceptors of the retina. A camera is constructed on the same principle. Human eyes have approximately 200 000 light-sensitive cells per square millimetre in their retina. The cone cell pigments in human eyes can only detect red, blue and green light. The rod cells detect brightness, or intensity, of light.
- Compound eyes in insects consist of many ommatidia, which form very different images from what vertebrates see (Figure 6.1.5b, c). Their acuity (quality of vision) depends upon the number of ommatidia that they have. Dragonflies, being aerial hunters, have very good sight with around 30 000 lenses per eye. Insect eyes can usually detect blue and UV light, some insects having polarised vision as well. This gives them an advantage when finding food sources, or mates, because many flowers appear very differently to the insect eye than what a human eye can perceive.

All vertebrate eyes have an iris, a thin circular disc with a hole, or pupil, in the centre. The iris can contract or relax, and so restricts or enlarges the pupil. Light enters the eye through the pupil and a negative feedback mechanism maintains the intensity of light at an optimal level for the stimulation of the photoreceptors on the retina. If too much light enters the eye, then receptors in the retina will send an impulse to the brain (control centre). A neural impulse will be sent to the iris (effector muscles), causing it to contract and reduce the amount of light entering the eye.

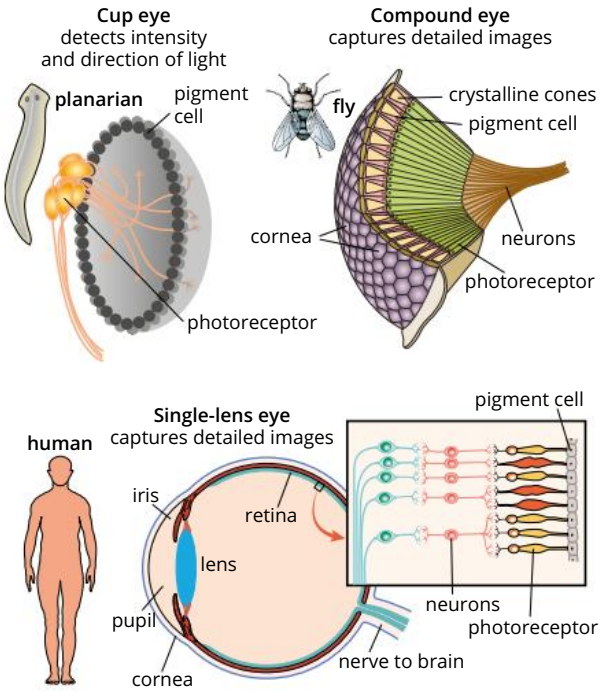


FIGURE 6.1.4 The simplest form of an eye is found in planarians and is capable of detecting the intensity and direction of light. Compound eyes and single-lens eyes are more complex, with a greater number of photoreceptors and connections to muscles and neurons. These structures allow the eye to detect greater variations in light intensity and capture detailed images

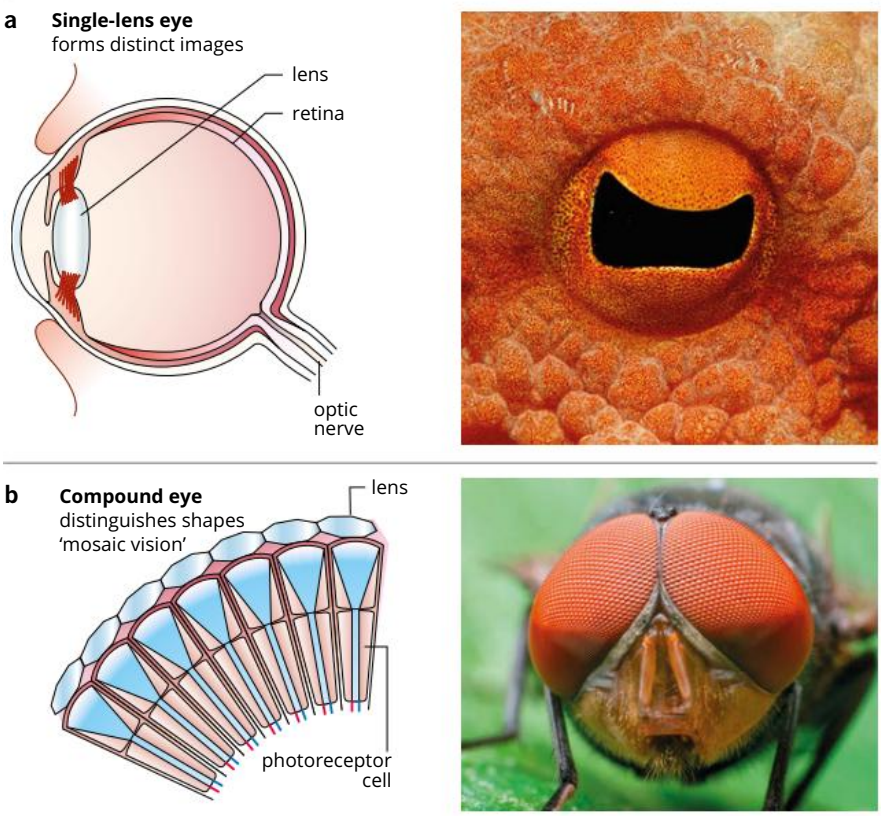


FIGURE 6.1.5 (a) A single-lens eye, in this case an octopus eye, has a focusing lens and a retina that gives better resolution than insect eyes. (b) The compound eye of an insect has thousands of individual detectors, each like a small eye. (c) An insect, such as a nocturnal moth with scotopic (night) vision, would perceive a passionfruit flower very differently (left) from the way a human does (right).

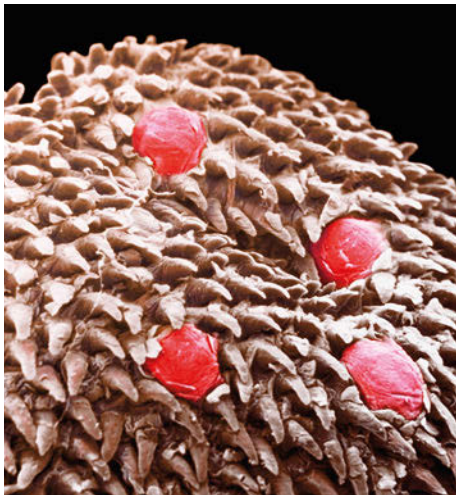


FIGURE 6.1.6 A coloured scanning electron micrograph of the surface of the human tongue. The scale-like projections are filiform papillae, which sense pressure. The red areas are fungiform papillae, which contain the taste buds.

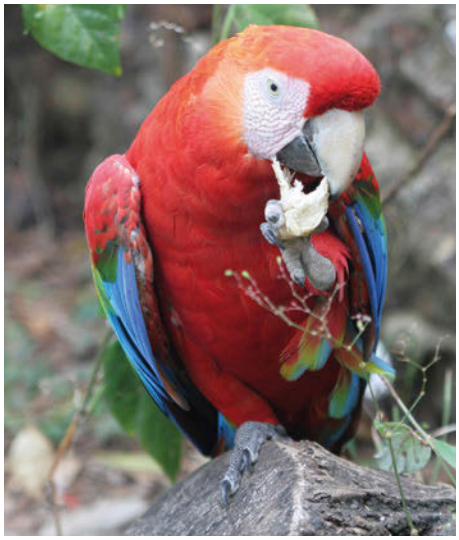


FIGURE 6.1.7 Birds in the western Amazon basin, such as this scarlet macaw (*Ara macao*), actively seek out clay bank salt licks to augment a sodium-poor diet. This is a behavioural response to a chemical homeostatic imbalance.

Chemoreceptors (taste and smell)

Chemoreceptors are cells sensitive to different chemicals. They may be grouped inside structures that maximise the probability of detection. Terrestrial animals have specialised organs for olfaction (smell) to detect airborne chemicals, and taste to detect chemicals in food and drink (such as the taste buds on the tongue shown in Figure 6.1.6).

Many animals also have receptors for specific chemicals emitted by prey or predators, or pheromone chemicals released by others of their species signalling sexual readiness. Animals will sometimes exhibit behavioural responses to a homeostatic chemical imbalance. An example of this is when animals that have a sodium-poor diet actively seek out salt licks to address this imbalance, such as the scarlet macaw shown in Figure 6.1.7.

Mechanoreceptors (hearing, touch and pain)

Sound travels as vibrations through air, water and solids. Animals detect sound using mechanoreceptors, which are sensory **neurons** that can detect minute vibrations. Vibration-sensitive neurons may be attached to larger vibrating structures that select and filter, and sometimes amplify the frequencies that are important to the animal. In human ears, vibrations are amplified by a system of bony levers (ossicles) and are then transmitted to a fluid-filled canal (cochlea) with sensory hair cells that have projections on the ends called stereocilia. You can see sensory hair cells in Figure 6.1.8. Vibrations entering the inner ear displace the fluid that surrounds the stereocilia, causing them to bend, generating nerve impulses that travel to the brain along the auditory nerve. The inner ear can transmit information about the volume and pitch of a sound. If sound wave pressure falls within an acceptable range, a state of equilibrium will be in place. However, if the sound pressure is too great, then a negative feedback response will be initiated where the animal will respond behaviourally by blocking out the sound stimulus, or by moving away from it.

Cutaneous mechanoreceptors detect external stimuli, including pressure and touch. Figure 6.1.9 shows some of these receptors in skin. A range of receptors detect internal mechanical stimuli, including joint position, muscle tension, and tension in the walls of organs such as the lungs and stomach. Examples of mechanoreceptors are stretch receptors, which aid in proprioception (the unconscious perception of body positioning and movement). When you stand on one foot, the slight movements you feel in your ankle are your body correcting its position because of the stimuli detected by these stretch receptors.

All animals with nervous systems avoid encounters with harmful external stimuli. It is not clear how complex a nervous system must be for an animal to experience something like the pain felt by humans. Some vertebrates can vocalise in response to certain stimuli that humans interpret as painful, and certainly behave as if their experience is similar. Although it is difficult to measure pain, most animals have the same mechanisms of pain detection and similar pain-processing areas in the brain, and show similar pain-response behaviours, indicating that their physiological experience of pain is likely to be similar to that of humans. The process of pain transmission is called **nociception**, and pain receptors (**nociceptors**) are found in most body tissues. The homeostatic response to a tissue injury, such as a cut on the finger, is very complex and involves the release of a range of chemicals that will initiate inflammation of the local tissue, increase blood flow, start the blood-clotting response and cause white blood cells to move to the injury site. It is a series of both positive and negative feedback loops that are activated and deactivated at various times during the initial response and healing process.

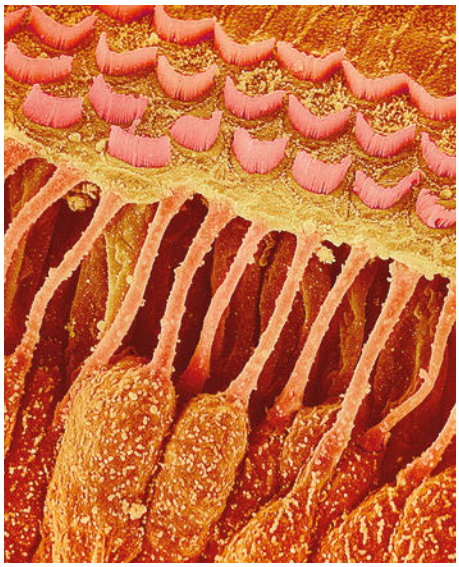


FIGURE 6.1.8 A coloured scanning electron micrograph of sensory hair cells in the cochlea. The inner ear converts sound waves into nerve impulses by stimulation of the stereocilia (the pink, crescent-shaped 'brushes') at the ends of the hair cells.

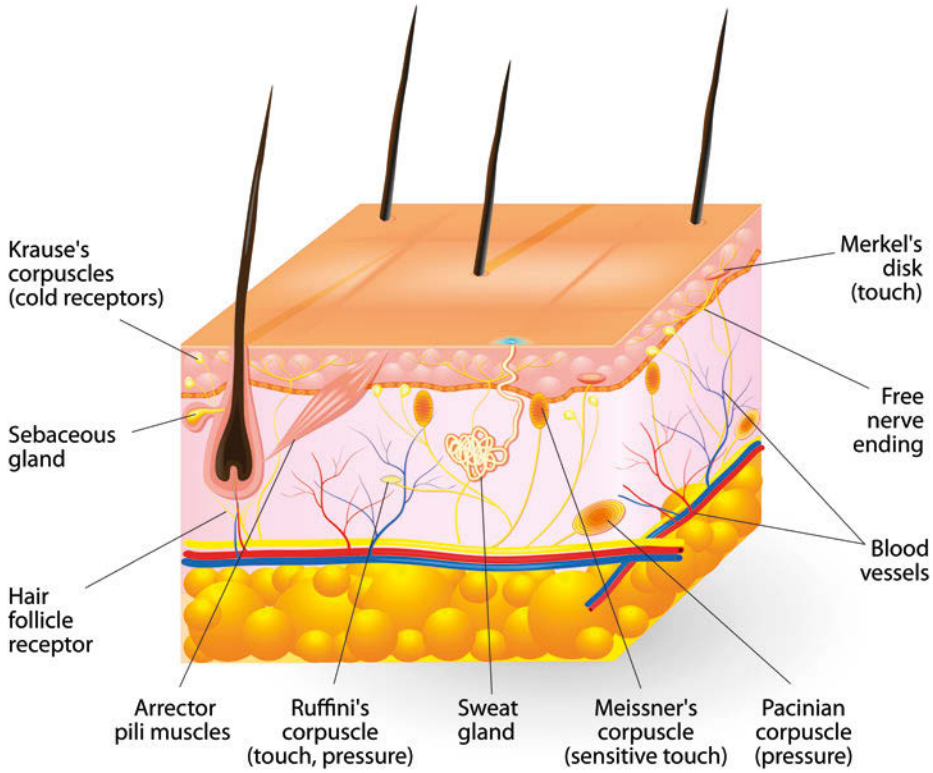


FIGURE 6.1.9 A cross-section of human skin showing the various receptors for touch, pressure and temperature

Thermoreceptors (temperature)

Thermoreceptors detect changes in heat energy. Thermoreception is complex and involves the detection of heat energy as well as changes in temperature. Different parts of the body have more receptors than others. For example, your hand, has more thermoreceptors than your leg, which means that it is more sensitive to temperature changes.

PLANT SENSORY RECEPTORS

Although much is known of animal receptors, there is still much to learn about plant sensory receptors. Plants respond to light, gravity, touch, temperature and water. The following are some of the receptors that we do understand.

Phytochromes are the plant's major sensors for light. These photosensitive pigments can be present in stems, leaves, root tips, flowers and even seed coats. When activated by specific wavelengths of light, they will initiate the secretion of hormones that, in turn, will cause a specific response in the plant. This may be to grow towards light or away from light, or to cause flower buds or stomata to open. For example, the phytochrome molecules in plant stem cells are stimulated by a certain wavelength of light. The phytochromes then initiate the secretion of auxins (a hormone that causes plant cell walls to become more plastic and stretchy) from the cell. The auxins migrate to the dark side of the stem, weaken the cell walls and the stem of the plant then leans towards the light. This initiates a second negative feedback response with an enzyme being released that will break down the auxins resulting in the hardening of the elongated cell walls.

Gravity and pressure are sensed by specialised plastids called **amyloplasts**. They contain one or two large starch granules, which will settle to the bottom of large plants cells in the roots or stems of the plants. Their position indicates the direction to be taken for root growth (positive **gravitropism**) and shoot growth (negative gravitropism) and acts as an indicator if the plant stem is being bent.

Thigmonasty, or a plant's rapid response to touch, is the initiation of an **action potential** across specific cell membranes in the xylem and parenchyma cells of the plant. It is very similar, but much slower than, the movement of an action potential along a human nerve cell.

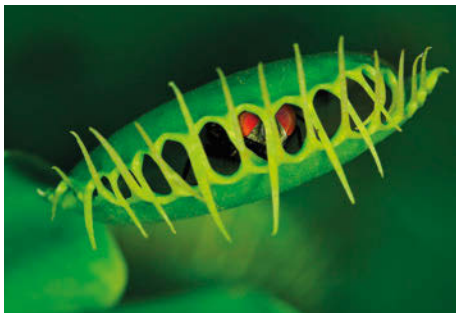


FIGURE 6.1.10 The Venus flytrap (*Dionaea muscipula*) uses mechanosensors (hairs) on the leaf surface to trigger cell pores to open in the lower side of the leaf. Water rushes into these cells, causing them to expand and forcing the trap to close.

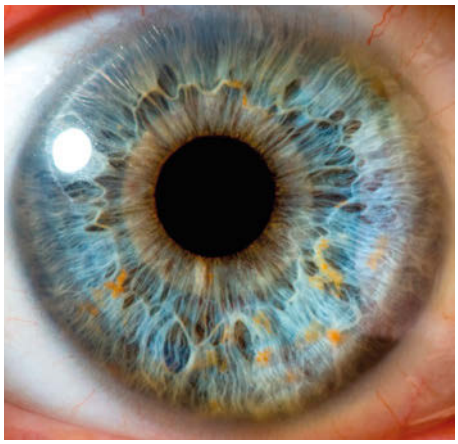


FIGURE 6.1.11 The iris is a pigmented muscle that responds to a light stimulus by dilating and constricting to regulate the amount of light entering the eye.

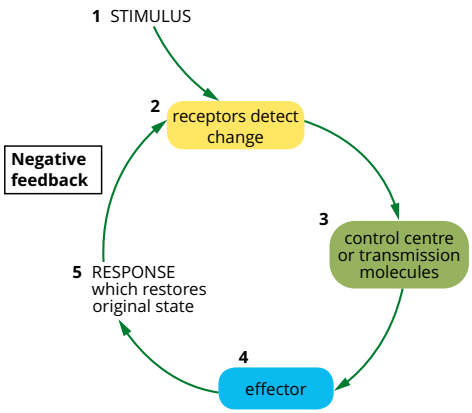


FIGURE 6.1.12 When the response reduces the initial stimulus or disturbance, it is operating as a negative feedback mechanism.

Thigmonastic movements include the rapid opening and closing of plant parts in response to touch, such as those observed in the Venus flytrap (*Dionaea muscipula*) as shown in Figure 6.1.10. The Venus flytrap is a carnivorous plant that is adapted to low levels of nitrogen in the soil. It obtains nitrogen by trapping prey such as flies, which it attracts by secreting a sweet sap. When a fly touches the tiny hairs (mechanosensors) on the leaves, an electrical signal is sent to the centre of the trap. This signal opens pores in the trap's lower layer of cells, allowing water to rush in from the cells in the upper layer of the trap. The rapid change in pressure (turgor) causes the cells on the lower side of the trap to expand, forcing the trap to snap shut trapping the fly inside. Enzymes released by the plant then digest the insect. About one-third of the ATP in the cells is used up in each movement. This is why after repeated touches, a leaf will not respond until its energy reserves have been replenished.

RESPONDING TO CHANGING ENVIRONMENTS

Homeostasis (from the Greek *homoios* and *stasis*, meaning 'staying in the same place') is achieved by negative feedback loops. In **negative feedback loops**, receptors detect a change in the internal environment, and **effectors** work to reverse the direction of the change to achieve equilibrium. (In positive feedback loops, the effectors work to maintain and enhance the direction of the stimulus; therefore, positive feedback is not usually involved in maintaining homeostasis.) Complex multicellular animals maintain the equilibrium of their internal environments by detecting and responding appropriately to the many changes in the external and internal environment.

Animals coordinate the activities of their cells, tissues and organ systems so that responses occur in an integrated and controlled manner. Detecting and responding to a stimulus requires an effective internal communication system. Communication in animals is achieved by hormonal and nervous system mechanisms, which transmit information between different parts of the organism, and also translate environmental disturbances into signals that can be interpreted and responded to. For example, the iris of the human eye detects light and responds by dilating or constricting to regulate the amount of light that enters the eye (Figure 6.1.11).

These regulatory systems are the most developed in mammals, which are able to maintain a relatively stable internal environment in the face of changing conditions.

Although in many ways hormonal systems and nervous systems appear distinctly different, they share one common feature: they both involve chemical communication. In both systems, signals are passed from one cell to the next by the release of specific molecules, known as hormones and neurotransmitters. Hormones are released from glands or other tissues, and neurotransmitters are released from nerve endings. These molecules exert their effects by highly specific interactions with a receptor on, or within, the responding or target cell.

Feedback loops

Feedback loops may involve the endocrine and nervous systems working together to regulate the internal environment.

Negative feedback loops promote stability in the internal environment and maintain homeostasis by responding to changes in the body and adjusting the variables to their original or optimal state. They are stimulus–response mechanisms in which the response produced reduces the effect of the original stimulus by reversing its direction. For example, if the concentration of a substance in the blood is too high, a negative feedback loop will work to lower the concentration. If the concentration is too low, a negative feedback loop will function to increase the concentration. Most feedback loops in biological systems are negative.

Negative feedback loops are called negative because the information produced by the feedback causes a reversal of the size or effect of the stimulus. Negative feedback loops maintain stability through the action of the nervous or hormonal systems, or both acting together.

A negative feedback loop is shown in Figure 6.1.12 and acts as follows.

- The system is in a stable state.
- A change (**stimulus**) occurs.
- The change is detected by an appropriate receptor.
- The receptor sends a signal to a control centre (hypothalamus or transmission molecules).
- The control centre sends a signal to an appropriate effector or a specific effector cell, tissue or organ.
- The effector responds to the signal.
- The original state is restored.

An example of a negative feedback loop is the regulation of blood sugar levels by **insulin** and glucagon. When blood sugar levels increase (stimulus), beta cells (receptors) within the pancreas detect the change and secrete insulin (effector). This lowers the blood sugar levels by stimulating glucose uptake into cells, and stimulates the liver into converting excess glucose into the storage molecule glycogen. Eventually, homeostasis is reached, at which point the pancreas stops releasing insulin. If blood sugar levels then drop too low (stimulus), this is detected by alpha cells (receptors) within the pancreas. Effectors then release glucagon to stimulate glycogen breakdown in the liver (Figure 6.1.13).

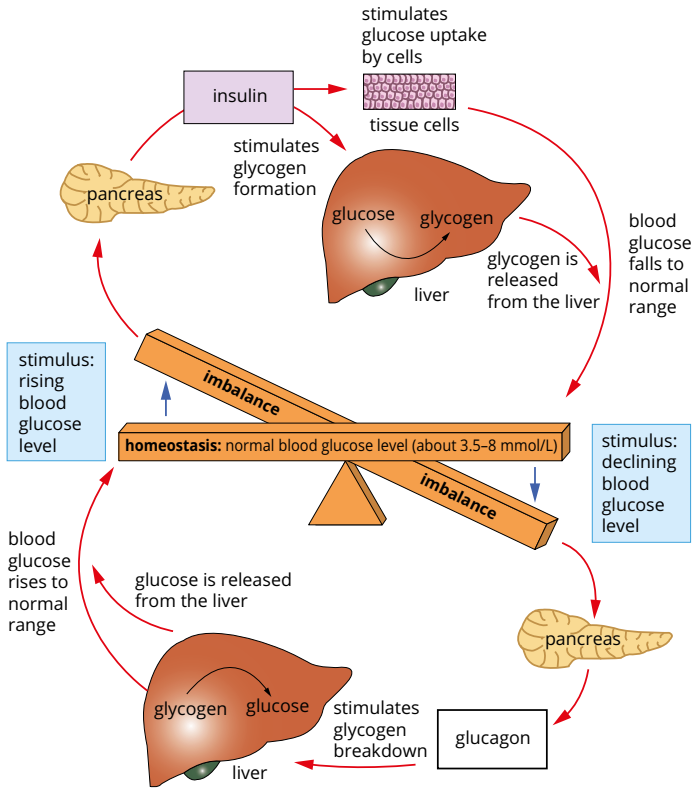


FIGURE 6.1.13 Insulin and glucagon from the pancreas regulate blood sugar (glucose) levels.

In the control centre, information from sensory receptors is received and compared with a set point (the optimal value for the functioning of that organism). This information is processed with other information about the state of the organism, and an appropriate response is initiated.

Therefore, regulation involves fluctuations around the set point. The size of the fluctuations depends on the:

- sensitivity of the receptor
- tolerance of the control centre to variation from the set point
- efficiency of the effector.

Some features of the internal environment, such as blood glucose levels, can vary considerably. Others, such as body temperature in mammals, are tightly controlled.

Effectors can be muscle groups that contract in response to a nerve stimulus, such as the human iris contracting in response to a bright light. Effectors may also be glands that either secrete additional hormones to target muscle groups or release products such as sweat, which has a cooling effect on the body.

In contrast to negative feedback loops, **positive feedback loops** force an organism out of homeostasis by maintaining the direction of the stimulus, and sometimes increasing the stimulus. An example of a positive feedback loop is uterine contractions during childbirth. The hormone **oxytocin** stimulates the uterus to contract.

Rather than the nervous system signalling the **endocrine system** to lower the oxytocin and reduce the contractions, more oxytocin is produced to stimulate stronger contractions. The contractions work to push the baby into the birth canal and continue until the baby is born and the pressure stimulus is removed.

The differences between positive and negative feedback loops are shown in Figure 6.1.14.

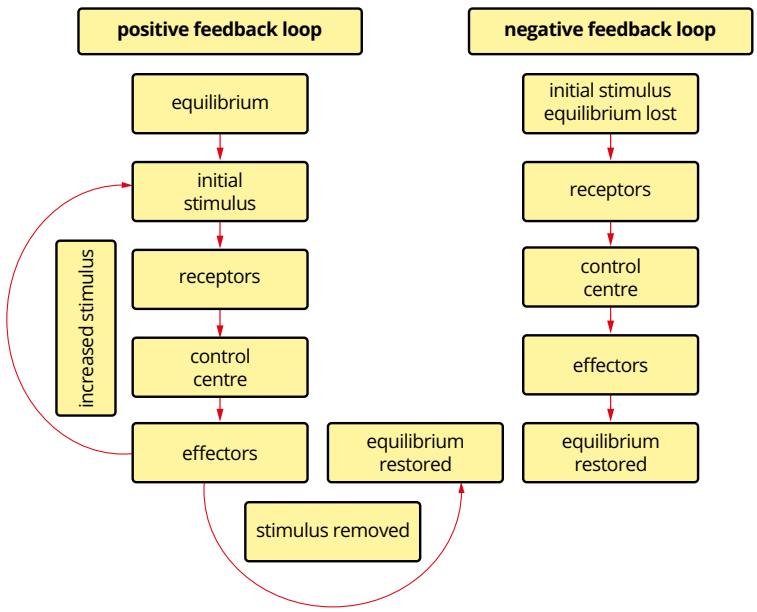


FIGURE 6.1.14 Pathway differences between positive and negative feedback loops

6.1 Review

SUMMARY

- Homeostasis is the maintenance of variables in a system within certain limits.
- Animals have a range of internal and external sensory receptors. These include mechanoreceptors (touch, hearing and pain), chemoreceptors (taste and smell), thermoreceptors (heat), electroreceptors (electrical currents in water—some fish and platypus) and photoreceptors (vision).
- Plants also have sensory receptors, which include photosensitive pigments (light intensity and wavelength detection), gravity and pressure sensors, and the ability to respond to touch by creating action potentials along cell membranes.
- Hormone and nervous systems have important roles in negative feedback mechanisms that promote homeostasis in animals.
- Negative feedback loops are stimulus–response mechanisms that respond to changes in the body by adjusting variables back to their original or optimal state, thus reversing the direction of the stimulus.
- Most feedback loops are negative.
- Positive feedback loops are the opposite of negative feedback loops. They promote a process rather than reversing the effect of the stimulus.

KEY QUESTIONS

Retrieval

1 Complete the table below by recalling and placing each of the following stimuli next to the receptor that it responds to: body position, temperature, internal stimulus, electrical current, touch and pressure, chemical stimulus, external stimulus, blood pressure.

Receptor	Stimulus
Baroreceptor	
Chemoreceptor	
Electroreceptor	
Exteroreceptor	
Interoreceptor	
Mechanoreceptor	
Proprioreceptor	
Thermoreceptor	

Comprehension

2 Define ‘homeostasis’ and explain why it is important.

3 Explain the difference between a muscle and a gland.

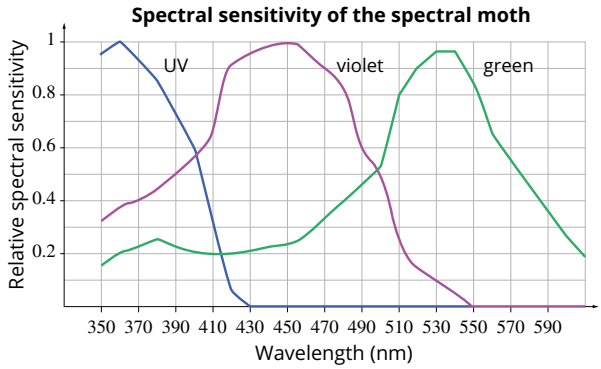
4 Explain, using an example, how negative feedback loops function.

Analysis

5 Use a table to compare single-lens human eyes and compound insect eyes.

6 Scotopic vision is the ability to see clearly in low light. The organism must have rod cells that are sensitive to wavelengths of light around 498 nm and are not sensitive to wavelengths longer than 640 nm. The spectral sensitivity graph below shows the wavelength sensitivity of the spectral moth (*Deilophila* sp.), displaying the wavelength sensitivity range of the visual pigments of the moths’ photoreceptors.

Based on the data displayed in the graph below, infer with justification whether or not the data supports scotopic vision.



6.2 Neural control pathways

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

- identify cells that transport nerve impulses from sensory receptors to neurons to effectors
- discriminate between a sensory neuron and a motor neuron (consider dendrites, soma, body, axon, myelin sheath, nodes of Ranvier, axon terminal and synapse)
- explain the process of the passage of a nerve impulse in terms of transmission of an action potential (conduction within neuron) and synaptic transmission (communication between neurons). Refer to neurotransmitters, receptors, synaptic cleft, vesicles, postsynaptic and presynaptic neurons and signal transduction.

Animals receive information about their environment and respond to external stimuli through the network of neural pathways that makes up the nervous system. The nervous system works closely with the endocrine system to respond to environmental changes and regulate the internal environment.

The rapid responses characteristic of most animals are brought about by the nervous system. Nervous systems typically involve a more direct pathway of communication between parts of the body than hormonal responses.

NEURONS

The **neuron** (or nerve cell) is the functional unit of nervous systems. Neurons are specialised cells with structures that enable rapid transmission of information between cells. As shown in Figure 6.2.1, there are three basic functional and structural classes of neurons.

- **Efferent (motor) neurons** transmit information from the central nervous system to the tissues and organs (effector cells).
- **Afferent (sensory) neurons** communicate information from tissues and organs to the central nervous system.
- **Interneurons** connect neurons within the nervous system.

The basic structure and function of neurons is very similar across all groups of the animal kingdom. Figure 6.2.2 shows the basic neuron structure.

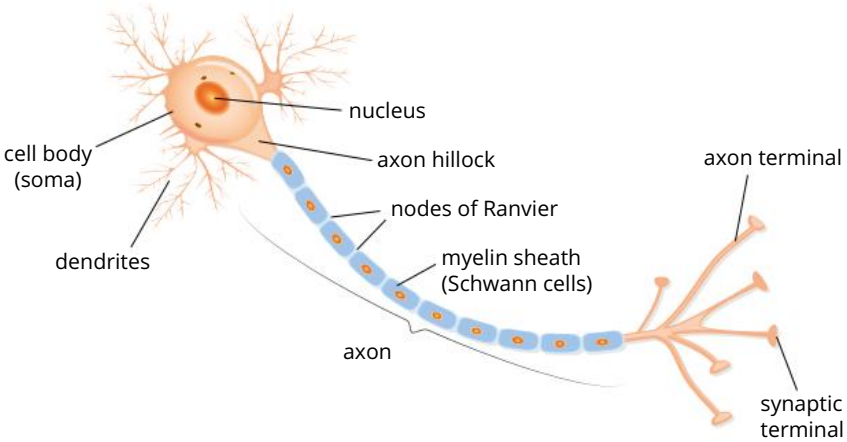
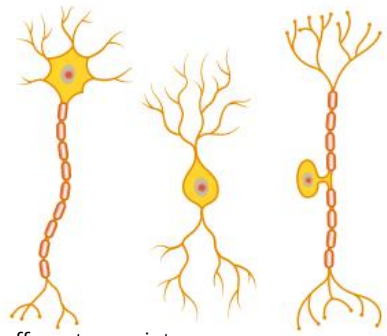


FIGURE 6.2.2 The key structures of a generalised neuron are very similar across all groups of the animal kingdom.

a Functional classes of neurons



b Structural classes of neurons

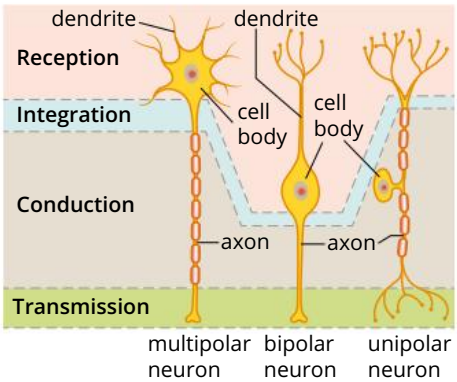


FIGURE 6.2.1 Different types of neurons vary in structure according to their function and can be divided into classes based on their (a) function or (b) structure.

Much of what we know of the function of mammalian nerves comes from studies comparing them to other animals; for example, frog neurons and giant neurons found in squids. Figure 6.2.3 shows the range of nervous systems found in animals.

These different types of neurons have different structures but are made up of the same basic components: one or more **dendrites**, a cell body (**soma**) and an **axon** (shown in Figure 6.2.2). Branching dendrites receive signals from other cells, and transmit these to the cell body. A single axon conducts a signal from the nerve cell body to nerve endings, which form synapses with other cells.

Longer axons may be covered with a **myelin sheath**. This is a series of Schwann cells wrapped tightly around the axon. The gaps between the Schwann cells are called the **nodes of Ranvier** (Figure 6.2.2). While the myelin sheath acts an electrical insulator for the axon, the nodes are rich in ion channels. This allows the nerve signal (action potential) to 'jump' from node to node, instead of having to move more slowly along the whole of the axon membrane. Generally, longer sensory neurons will be myelinated, and other neurons, which have no need for fast reflex action, will be non-myelinated.

Neurons are also grouped into classes based on their structure: multipolar neurons have two or more dendrites that are separate from the axon; bipolar neurons have a single dendrite; and unipolar neurons have just one extension from the cell body, made up of an axon and dendrite (Figure 6.2.1).

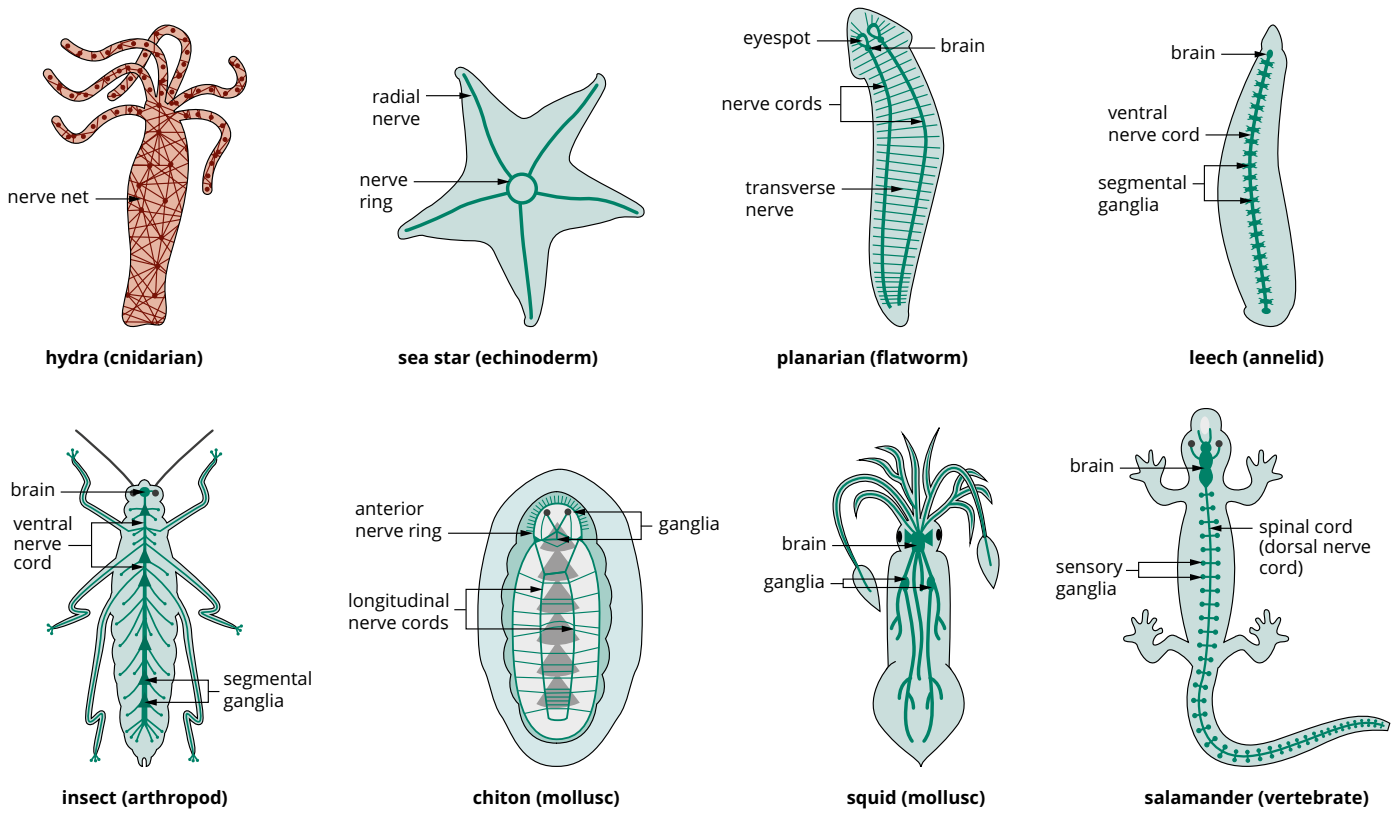


FIGURE 6.2.3 Nervous systems range from simple nerve nets in cnidarians (sea jellies and anemones) and sea stars, to complex networks of nerves connected to a brain in other invertebrates, and a brain and spinal cord in vertebrates.

In nervous systems, nerve cells connect to form pathways between receptor cells and responsive organs, sometimes via a central organ such as the brain or spinal cord. For example, when sensory cells detect an environmental disturbance, a signal is generated that passes as an electrical message along two or more neurons to reach particular effector cells, such as muscle or gland. Chemical transmitters communicate from sensory cell to nerve cell, between nerve cells, and from nerve cell to the effector cell that produces the response.

Although at times the passage of an impulse along a neuron has been likened to an electrical current flowing in a wire, there are great differences between the two processes. The nerve impulse travels along the surface of the membrane (which has a high impedance to charge), and uses chemical messengers to bridge the gap between neurons. The purely electrical charge travels at a much faster speed within the continuous section of wire, with any gaps effectively stopping the passage of the electrical current.

Neural response pathways are highly specific. Receptor cells are sensitive to specific environmental disturbances: the 'wiring' of neuronal pathways is direct, and to respond, effector cells must possess specific receptors. Because of the directness of the pathway, and the speed of conduction along nerve fibres, control by nerves is usually extremely rapid and short in duration, and the response is precisely directed.

PHYSIOLOGY OF A NERVE IMPULSE

Nervous responses require more energy than hormonal responses do. In nervous systems, the passage of signals (**signal transduction**) along nerve axons requires considerable energy to re-establish the balance of ions across the axon membrane after each signal, while hormones are carried to their target cells in the circulatory system (see Module 6.3).

Neurons establish steep concentration gradients of ions across their cell membranes to enable an electrical impulse or action potential to occur. Establishing these gradients uses active transport, which requires a large amount of energy. Therefore neurons need many mitochondria and a large supply of glucose.

Signal transduction in neurons

Transduction of a signal carried by the nervous system uses a combination of electrical and chemical signalling involving the opening of gated ion channels and the release of **neurotransmitters** through exocytosis.

Signal transduced into a neuron

When a neuron is stimulated, gated sodium and potassium ion channels on its membrane are opened. The sudden movement of the ions into and out of the neuron initiates the action potential, which travels the length of the axon of the neuron in a wave-like sequence, opening other ion channels along the membrane. An action potential is the reversal of the normal potential difference across a cell membrane, or between the inside and the outside of a nerve fibre.

Action potential

An action potential or nerve impulse is a wave of electrical change that passes rapidly along an axon membrane. When a neuron is not stimulated or is at rest, the membrane is **polarised**—the inside of the cell is more negative. You can see this in Figure 6.2.4.

A charge difference is maintained between the inside and outside of the cell largely by active transport using sodium–potassium pumps. The pumps actively transport sodium ions out of the cell and potassium ions into the cell.

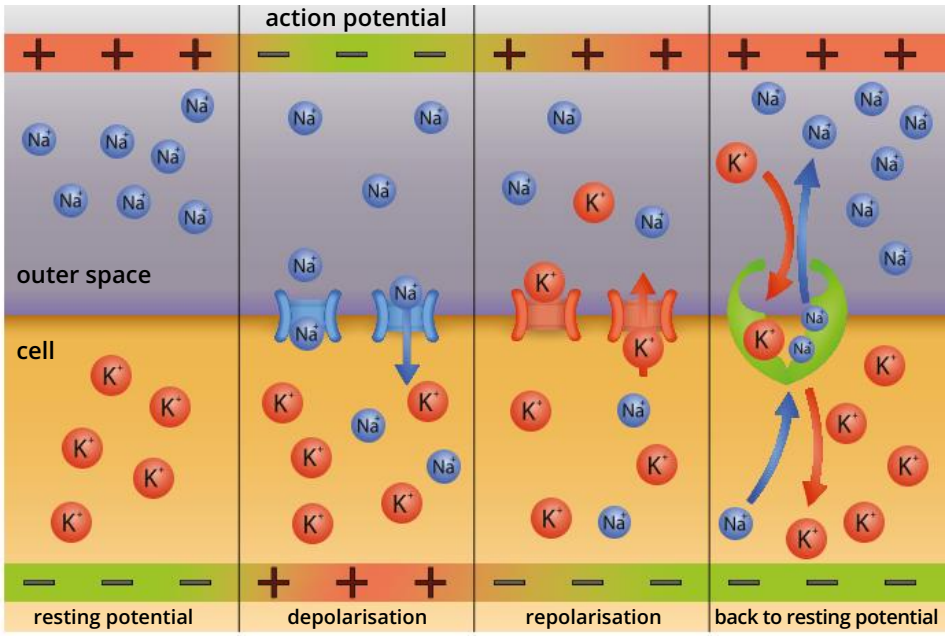


FIGURE 6.2.4 The inside of the neuron is negative with respect to the outside of the neuron, and there is an unequal distribution of sodium ions (Na^+) and potassium ions (K^+) across the cell membrane. Depolarisation occurs as the action potential moves along the membrane and Na^+ ions flood into the cell via Na^+ ion channels. Repolarising takes place as K^+ ions flood out of the cell through K^+ ion channels. The resting potential is again restored only by using ATP to actively pump Na^+ ions back out of the cell and K^+ ions into the cell. This requires large amounts of energy and so neurons will possess large numbers of mitochondria.

An action potential begins when a stimulus disturbs the cell membrane on a dendrite, causing sodium ion channels to open. Sodium ions (Na^+) are positively charged, so as they flow into the neuron, they cause the inside of the neuron to become slightly less negative. This causes the membrane to become depolarised. If the depolarisation is sufficient to reach the threshold potential for the cell, Na^+ channels in the membrane open and Na^+ floods into the cell along its concentration gradient, initiating an action potential (Figure 6.2.5). Because sodium ions are positive, the inside of the cell becomes briefly positive, which causes potassium ion (K^+) channels to open, and K^+ diffuses out of the cell along its concentration gradient. This process takes approximately 4 ms.

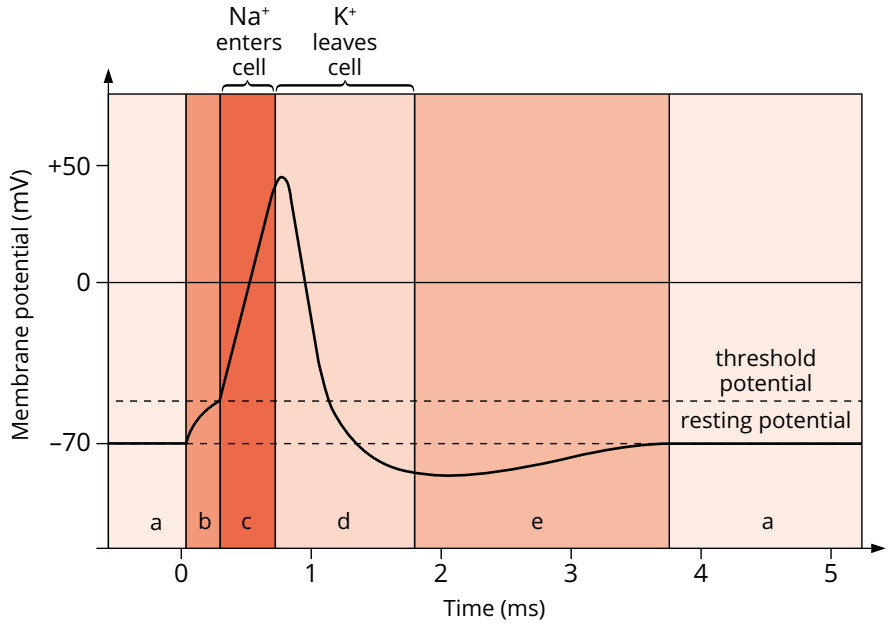


FIGURE 6.2.5 A simplified diagram of the internal membrane potential of a nerve cell during an action potential: (a) resting membrane potential; (b) depolarisation reaches the threshold potential of the axon; (c) the membrane depolarises and the inside of the cell becomes briefly positive as sodium ions (Na^+) diffuse into the cell; (d) the potential becomes negative again as potassium ions (K^+) diffuse out of the cell; (e) the resting membrane potential and the original distribution of ions are re-established by active transport of Na^+ and K^+ across the membrane.

As the positive potassium ions leave, the inside of the cell becomes negative again. Therefore, the inside of the cell first becomes briefly positive and then negative again. These electrical changes are the action potential. Following the action potential, the Na^+ and K^+ channels close and the membrane returns intracellular ion concentrations to their initial values. However, for the resting potential to be reinstated, Na^+ ions must be moved out of the cell and K^+ ions moved in—both against their concentration gradients. To achieve this, the membrane is studded with embedded Na^+–K^+ pumps, which use ATP energy to physically pump the ions against the concentration gradient. This is why neurons contain more mitochondria than other somatic cells in the body.

Once an action potential is generated, it sweeps along the neuron by conduction. During an action potential, when the sodium ions diffuse into the cell, some diffuse sideways inside the axon, depolarising the adjacent region of the axon membrane. As with the initial stimulus, this causes Na^+ channels in this part of the membrane to open and Na^+ floods into the cell, initiating an action potential in this region, as shown in Figure 6.2.6. This depolarises the next adjacent region of the axon membrane, and so the cycle continues, conducting the action potential along the length of the axon membrane.

As the action potential moves along the membrane, there can be some leakage of Na^+ ions from the axon, slowing down the rate at which the action potential passes along the axon membrane. The presence of a myelin sheath along the axon prevents such leakage and greatly increases the speed of the action potential along the axon. Na^+ channels reside mainly in the regular gaps (nodes of Ranvier) in the myelin sheaths.

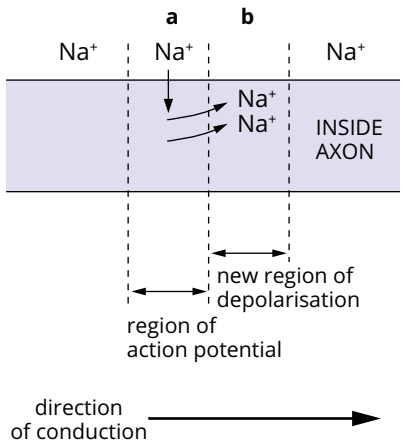


FIGURE 6.2.6 (a) As Na^+ enters the cell, some diffuses sideways, (b) depolarising the adjacent region of membrane and causing an action potential in this region. In this way, an action potential is conducted along the axon.

Cellular response of a neuron

Vesicles containing the neurotransmitters are located at the synaptic terminals. When the action potential eventually reaches the end of the axon, the **synaptic terminals**, it causes another ion, calcium (Ca^{2+}), to enter the cell. The increased concentration of Ca^{2+} causes these vesicles to fuse with the nearby membrane (known as the presynaptic membrane) and to release the neurotransmitters into the synaptic cleft via exocytosis.

The synaptic cleft is the space between the presynaptic cell and the postsynaptic cell. It is sometimes referred to as the synaptic gap.

The postsynaptic cell can be another neuron or another type of target cell such as a muscle or gland cell. The neurotransmitters released from the synaptic terminal diffuse across the synaptic cleft and bind to specific receptors on the postsynaptic cell. If the postsynaptic cell is another neuron, binding of neurotransmitters to the receptors on its dendrites triggers the ion channels of the postsynaptic membrane to open, leading to release of neurotransmitters from the synaptic terminals (Figure 6.2.7). In this case, the signal has been transformed, or transduced, from an electrical impulse into chemical signalling molecules and back again. If the postsynaptic cell is another type of cell, then it will respond to the action potential as an effector cell or tissue. For example, a bundle of muscle fibres will contract, or endocrine tissue will secrete hormones. Excess neurotransmitters are either broken down by enzymes or drawn back into the presynaptic cell by receptor channels or carrier molecules. An example of this is serotonin (5-hydroxytryptamine, 5-HT), which binds with a 5-HT carrier molecule. Similar to the active site on an enzyme, the 5-HT carrier will only bind with the specific shape of the serotonin molecule. Also like enzymes, the uptake of serotonin can be inhibited by a similar shaped molecule binding to the 5-HT receptor instead, resulting in the excess serotonin remaining in the synapse to constantly stimulate receptors to open sodium channels that initiate action potentials on the postsynaptic neuron.

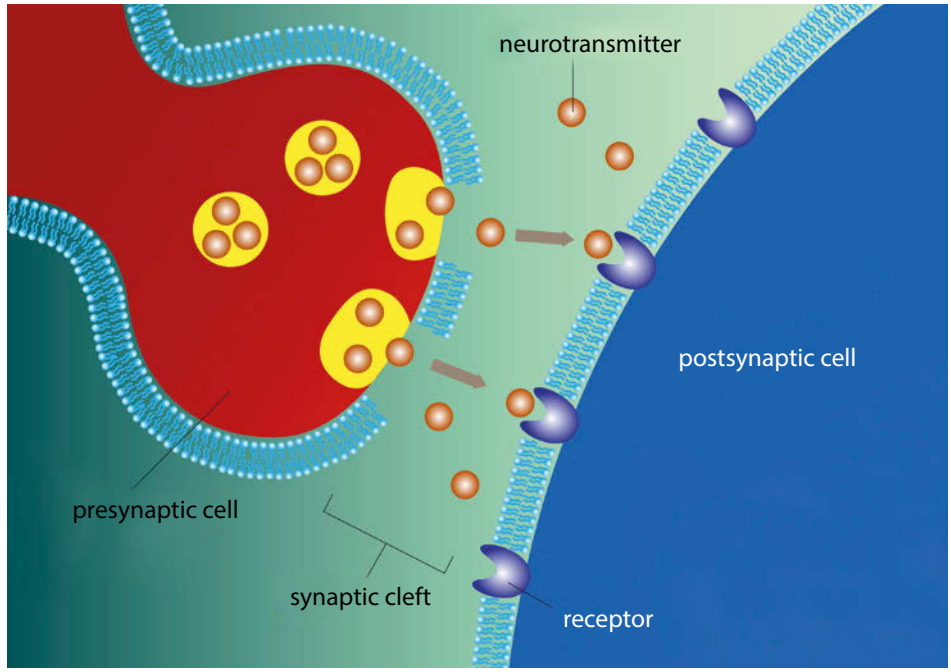


FIGURE 6.2.7 Secretory vesicles containing neurotransmitters fuse onto the presynaptic membrane, releasing the neurotransmitters into the synaptic cleft. Neurotransmitters will diffuse across the cleft and bind to receptors found on the postsynaptic cell.

Reflex responses

The ability to detect and quickly respond to changes in the internal and external environments is fundamental to the survival of all animals. Some responses to stimuli happen very quickly. If you put your hand on a hot stove or tread on a pin, your body will react in a rapid and coordinated way to move away from the painful stimulus. Stimulation of various receptors in the skin (thermoreceptors for temperature and nociceptors for pain) sends a message along nerves to the spinal cord, where the message is passed on to nerves that stimulate the muscles involved in withdrawing your hand (Figure 6.2.8) or pulling away your foot. At the same time, other nerves in the spinal cord carry the message up to your brain and you become aware of the pain. But, before you are aware of the pain, you have pulled your foot or hand away. This is an example of a rapid, unconscious response called a **reflex**. This kind of reflex protects the body from further injury. The contraction and dilation of the iris in response to light is also a reflex response.

A reflex is the simplest type of nervous response in an animal, and it may involve just two or three cells. A sensory receptor detects a change and when it has received enough stimulation, it sends a signal via a sensory (or afferent) neuron to the spinal column (part of the **central nervous system (CNS)**). Here it will interact with a motor (effector) neuron to send an impulse to cause muscle fibres to contract—the reflex response. The response is unconscious and automatic; it is not modified because of information received from other parts of the body. The nerve net of a sea jelly produces only reflex responses. Reflex responses are also important in highly complex animals, such as vertebrates, because they occur rapidly and unconsciously—for example, defensive reactions and changes in posture.

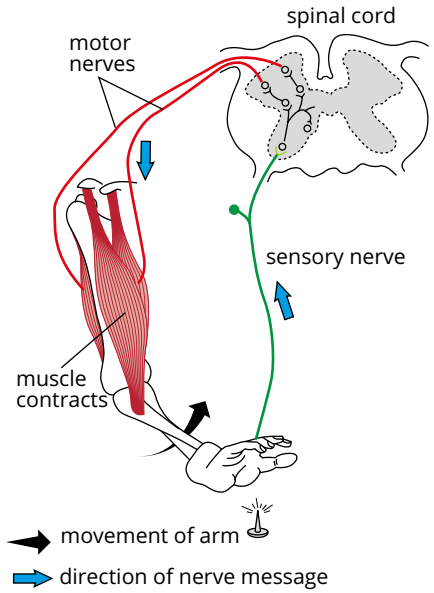


FIGURE 6.2.8 The pathway involved in the reflex withdrawal of the hand in response to a painful stimulus

The knee-jerk (stretch) reflex is an example of the simplest form of reflex in mammals, and involves only two neurons. It is known as a monosynaptic reflex. Most reflexes are polysynaptic and involve one or more additional neurons called interneurons (Figure 6.2.9) in the CNS, between the sensory and motor nerves, as in the withdrawal reflex.

Reflexes are also involved in homeostatic regulation of systems such as the circulatory system. For example, the baroreceptor–heart rate reflex helps maintain blood pressure in mammals. An increase in blood pressure increases the stretch on baroreceptors in major arteries, causing an increase in impulse activity from these sensory neurons. This leads to a reflex decrease in heart rate and a consequent decrease in blood pressure.

WS 2.1.4

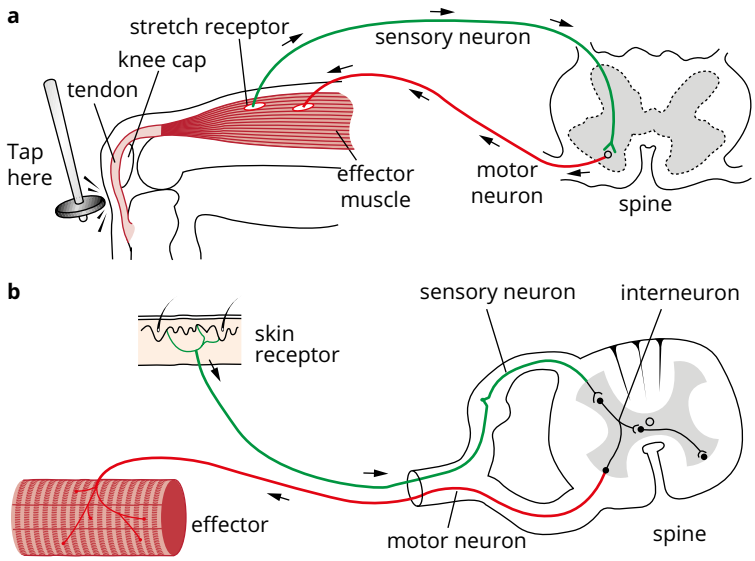


FIGURE 6.2.9 (a) The knee-jerk response is an example of a monosynaptic reflex. It is used most frequently by doctors to detect potential damage to motor areas of the central nervous system. (b) The withdrawal reflex is triggered by pain receptors in the skin and involves interneurons.

If you concentrate, you can increase or decrease your knee-jerk response. You can also repress the reflex that would cause you to remove your hand from a painful or uncomfortable stimulus. This indicates that there is a connection from the brain that can consciously override the automatic response. You can consciously send signals down the spinal cord to prevent the reflex stimulation of muscles by the sensory nerves. For example, most people do not pull away when being given an injection.

Interneurons and integration

An interneuron is a neuron that transmits information from one neuron to another. When interneurons are part of a pathway, the opportunity for coordination and integration increases. For example, the movements of joints operate by the action of opposing sets of muscles: one set causes flexion (bending), the other causes extension (straightening). Your elbow is flexed by the action of the biceps muscle, and extended by the triceps muscle, as shown in Figure 6.2.10. When a muscle is stimulated to contract, such as in a reflex response, interneurons in the spinal cord also carry a message inhibiting the contraction of the opposing muscle. For example, this prevents both the biceps and triceps from contracting at the same time, which would put the elbow under severe strain.

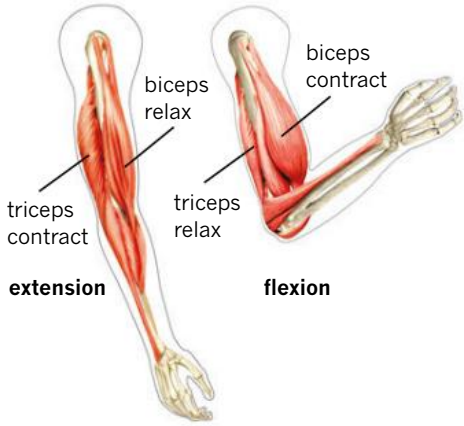


FIGURE 6.2.10 Extension (straightening) of the arm involves the biceps muscle relaxing and the triceps muscle contracting. The opposite action of flexion (bending) of the arm at the elbow joint involves the biceps muscle contracting, while the triceps muscle relaxes.

Many reflexes are integrated with other parts of the body. For example, there is a withdrawal reflex of the leg similar to the withdrawal reflex of the hand in response to pain (Figure 6.2.8). However, if you tread on a nail, you cannot simply withdraw your foot; if you did, you would fall over. You must first shift your weight onto the other foot. In this situation, interneurons also carry instructions to the muscles of the opposite leg, making it brace to take your weight as you lift the painful foot. At a more complex level, increased numbers of interneurons in the nervous system (primarily in the brain of the CNS) provide more opportunity for synapses between neurons, thus allowing increased integration of information received from all parts of the body.

Processing stimuli

After a stimulus has been detected by a receptor, a message is sent along the axon of the receptor cell to the processing centre of the nervous system. In complex animals, this processing centre is made up of the brain and spinal cord of the CNS, as shown in Figure 6.2.11.

Different regions of the brain are associated with particular functions.

- The cerebral cortex (cerebrum) has areas associated with motor activity, sensory input, speech, sight and hearing.
- The hypothalamus receives information relating to the wellbeing of the body, and functions in maintaining homeostasis.
- The cerebellum is involved in the coordination of muscular activity, including posture, balance and movement.
- The brainstem has centres associated with the control of the heart, blood vessels and lung ventilation.

As well as coordinating information from all parts of the body to produce appropriate responses, the brain stores information so that responses can take into account past experiences and learned information (memories).

In addition to the CNS, complex animals have a peripheral nervous system (Figure 6.2.12). The **peripheral nervous system (PNS)** includes sensory nerves, which carry information towards the CNS, and motor nerves, which carry signals to effector organs such as muscles and glands. The motor component of the PNS can also be subdivided into somatic (voluntary) and autonomic (involuntary) systems. The voluntary nervous system involves functions over which you have voluntary control, such as movement of the body by skeletal muscles.

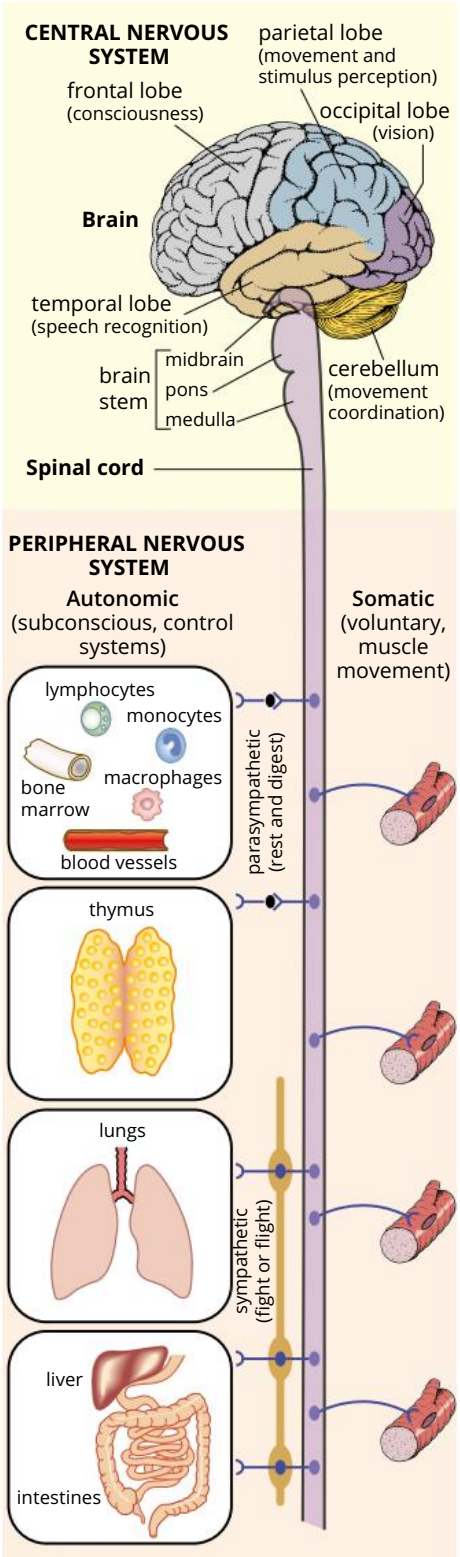


FIGURE 6.2.11 The nervous system of vertebrates consists of a brain and a spinal cord. The central nervous system (CNS) is made up of the brain and spinal cord. The peripheral nervous system is a network of nerves that branch throughout the body and send signals to and from the CNS, and comprises the autonomic and somatic nervous systems.

The **autonomic nervous system**, shown in Figure 6.2.12, includes nerves involved in unconscious responses, such as constriction of pupils, secretion from glands and heart rate changes. It conveys signals to smooth muscle (internal organs), heart muscle and glandular tissues, and regulates the activities of the digestive, cardiovascular, excretory, respiratory and endocrine systems. Table 6.2.1 outlines the roles of the autonomic nervous system.

The autonomic nervous system consists of two major subdivisions (sympathetic and parasympathetic) that work in similar but often opposite ways, as well as the **enteric nervous system**. In general, the **sympathetic division** increases energy use and prepares the body for action in emergency situations by increasing the heart and metabolic rate (the so-called 'fight or flight' response). The **parasympathetic division** enhances activities that conserve energy, such as digestion and slowing the heart rate. The enteric nervous system is the third part of the autonomic nervous system. It is an extensive network of nerve cells (and reflexes) within the wall of the gut that coordinates the functions of the gut.

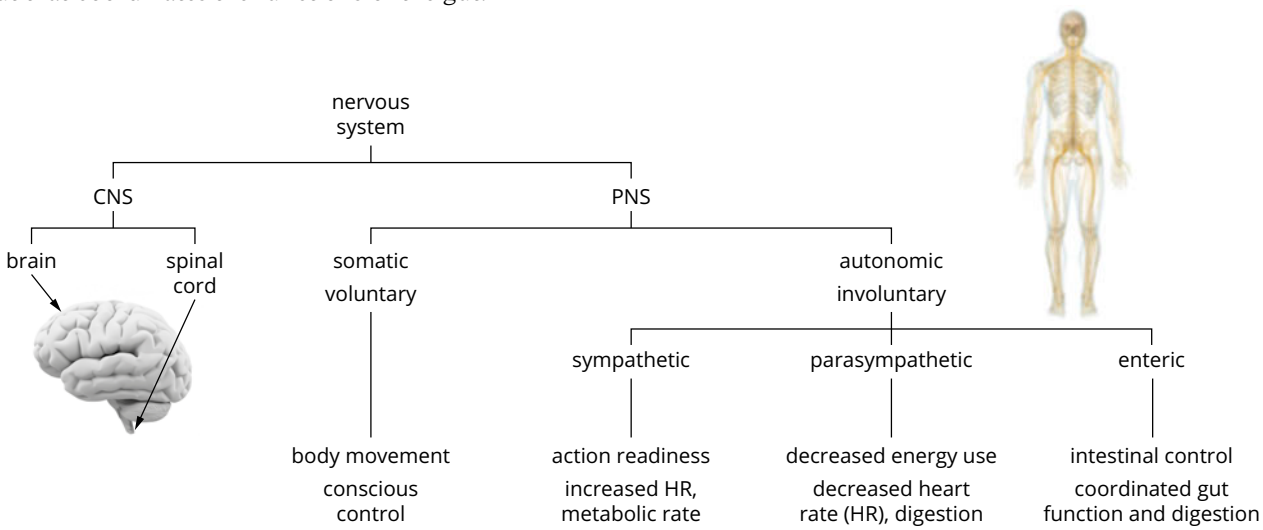


FIGURE 6.2.12 Components of the central nervous system and peripheral nervous system

The correct balance of activity in different divisions of the nervous system, along with their interactions with the endocrine system, is central to maintaining homeostasis.

TABLE 6.2.1 Roles of the autonomic nervous system

System/role	Function/description
cardiovascular system	Controls the rate and strength of the heartbeat and the distribution of blood to different organs by changing the diameters of arteries
digestive system	Controls mixing and movement of food through the gut and secretion of digestive enzymes in various regions of the gut
respiratory system	Controls the diameter of major airways of lungs and the secretion of mucus over respiratory surfaces
excretory system	Promotes emptying of the bladder and controls rate of production of urine by the kidneys
reproductive system	Controls contraction of various parts of the reproductive tract in males and females, and thus the passage of eggs, sperm and embryos
metabolic regulation	Controls the formation and release of hormones affecting overall metabolism
temperature regulation	Controls cutaneous blood flow and sweating
eye function	Controls the diameter of the pupil to regulate incoming light, secretion of tears and focusing of the lens

6.2 Review

SUMMARY

- The nervous system involves a more direct pathway of communication than hormonal responses. Control by nerves is generally rapid, short in duration, and precisely located.
- The neuron is the functional unit of the nervous system and its basic structure and function are very similar across all groups of animals.
- Neurons are excitable cells. The three basic steps involved in their function are:
  - generation of an action potential
  - conduction of the action potential along axons
  - chemical transmission to another cell across a synapse.
- Nervous responses require more energy than hormonal responses.
- Neuron signal transduction involves the conversion of the electrical impulse of the action potential into chemical signalling molecules, called neurotransmitters, and back again at the synapse between cells.
- Highly organised nervous systems have a central coordinating group of neurons (CNS—brain and spinal cord), and peripheral pathways of sensory and motor nerve fibres (PNS).
- A rapid unconscious nervous response is called a reflex.
- The simplest type of nervous response in a mammal, a monosynaptic reflex, involves just two cells.
- More complex circuits that include interneurons enable more control.
- The brain has four main regions which all have specific functions: cerebral cortex, hypothalamus, cerebellum and brain stem.
- The peripheral nervous system is composed of the somatic system and the autonomic (sympathetic, parasympathetic and enteric divisions) systems.
- Sensory receptors, often grouped into sense organs, monitor a wide range of conditions in an animal's internal and external environment and provide information that enhances the animal's ability to survive and reproduce.

KEY QUESTIONS

Retrieval

1 Describe how the conduction of a nerve impulse along an axon is different from the conduction of electricity along a wire.

2 Identify the main processes involved in the autonomic nervous system.

Comprehension

3 Explain the role of interneurons in a neural circuit entering a body joint.

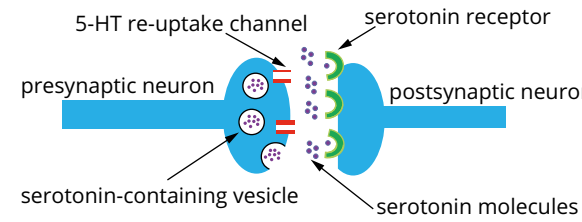
4 Represent, by drawing a flow chart, a reflex response for pulling your hand away from a hot frying pan. Label the neurons involved.

Analysis

5 Serotonin is an important neurotransmitter in the brain, which influences mood. Depression has been linked to serotonin imbalances in the brain. It has been postulated that depression is caused by low levels of serotonin in the synapse.

In the brain, serotonin is released from the presynaptic membrane. It diffuses across the synapse and attaches to receptors on the membrane of the next neuron. This stimulation results in an improved mood.

Unlike some neurotransmitters, which are broken down by enzymes in the synapse, serotonin is recycled back into the presynaptic neuron through special receptors called 5-HT re-uptake channels (or receptors) as shown below.



A group of drugs called selective serotonin re-uptake inhibitors (SSRIs) are one of the major treatments for clinical depression. The drugs work by increasing the amount of serotonin available in the synapse.

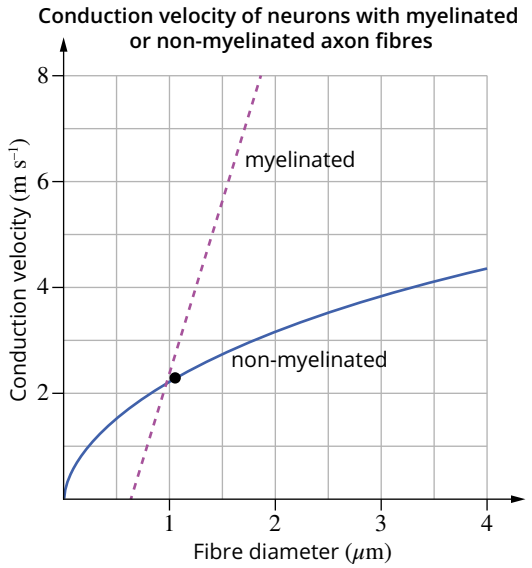
a Deduce what intended effect selective serotonin re-uptake inhibitors will have on action potentials in the postsynaptic neuron.

b Deduce how selective serotonin re-uptake inhibitors might decrease the re-uptake of serotonin.

6 Not all axons have myelinated sheaths. The conduction velocity of a neural impulse depends on both the diameter of the axon fibre and whether or not it is myelinated or non-myelinated. The graph shows data on the conduction velocity ($m s^{-1}$) of neurons that have either myelinated or non-myelinated axon fibres, as collated and graphed by Rushton (1951) from data also published by Hursh (1939). The small circle on the non-myelinated curve marks the fastest recorded velocity (2.3 $m s^{-1}$) for an impulse travelling on the largest (1.1 μm) non-myelinated fibres of the sympathetic nervous system.

a Determine at what diameter of axon fibre the myelinated sheathed axon fibre begins to conduct an action potential at a greater rate than a non-myelinated fibre.

b The optic nerve in humans has a diameter of 3 μm and a conduction velocity of approximately 16 $m s^{-1}$. According to Rushton's findings, deduce whether the optic nerve has myelinated or non-myelinated fibres.



6.3 Hormonal control pathways

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

- recall that hormones are chemical messengers (produced mostly in endocrine glands) that relay messages to cells displaying specific receptors for each hormone via the circulatory or lymphatic system
- recognise how a cell's sensitivity to a specific hormone is directly related to the number of receptors it displays for that hormone (an increase in receptors = upregulation, a decrease = downregulation)
- describe how receptor binding activates a signal transduction mechanism and alters cellular activity (which results in an increase or decrease in normal processes).

Hormones help to control many of the functions within a living organism. Most hormones are used in negative feedback loops in conjunction with the nervous system, and so maintain a state of homeostatic equilibrium.

The production of hormones from the brain is initially stimulated by the nervous system. Hormones, in turn, can greatly affect the central nervous system of the organism, resulting in changed behaviour and development of the organism.

CHEMICAL MESSENGERS

A **hormone** is a signalling molecule produced in tiny amounts that can have relatively long-lasting effects on target cells. Hormones help regulate the growth and activity of cells in most animals and plants. A given hormone can only act on those target cells that have the hormone's specific receptor proteins. Non-target cells lack the specific receptor proteins and so remain unaffected.

A hormone produces its effect by altering the activity of the target cell or tissue. It can change cell membrane permeability or membrane potential by opening or closing ion channels. It may stimulate the production of enzymes or other proteins within a cell, or can even activate or deactivate particular enzymes. Hormones can induce secretory activity, or stimulate mitosis of a cell.

A minute amount of hormone can have a cascade effect, or a step-by-step amplification effect on the production of a large amount of a secreted product, final product or physiological response within the organism.

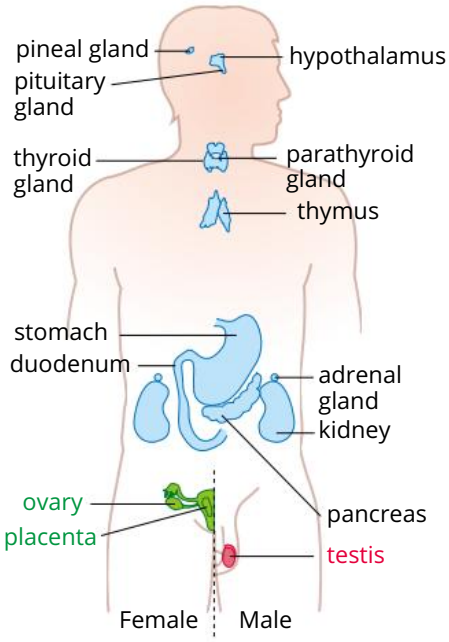


FIGURE 6.3.1 The organs and glands of the human endocrine system produce and secrete hormones into the bloodstream.

Animal hormones

In vertebrates, the endocrine system is responsible for coordinating many body functions, including growth, metabolism and reproduction. The endocrine system is made up of many glands and organs within the body that, along with some specialised tissues, synthesise and secrete hormones into the bloodstream (or in some cases the lymphatic system). The circulatory system transports the hormones from their site of production to the target cells and tissues. The main glands and organs of the human endocrine system are shown in Figure 6.3.1.

The production of hormones from the brain is initially stimulated by the nervous system. Hormones, in turn, can greatly affect the central nervous system of the organism resulting in changed behaviour and development of the organism.

Hormones can be broadly grouped into three main classes.

- Lipid hormones are a class of hydrophobic signalling molecules derived from fatty acids (**eicosanoids**) or cholesterol (**steroids**). Eicosanoids include prostaglandins, which are involved in cell growth, fever and inflammation. Steroid hormones help to regulate metabolism, salt and water balance, inflammation and sexual function. Examples of steroid hormones are testosterone, progesterone, oestrogen and **cortisol**.

- Peptide and protein hormones are a class of hydrophilic signalling molecules. An example of a peptide hormone is insulin and an example of a protein hormone is growth hormone.
- Amino-acid-derived hormones are a class of small signalling molecules derived from the amino acids tyrosine and tryptophan. They can be further divided into **catecholamines** and **thyroid hormones**. Thyroid hormones such as thyroxine are hydrophobic. Catecholamines are hydrophilic; examples are adrenaline and **dopamine**. (Dopamine acts as both a neurotransmitter and a hormone.)

A single hormone can trigger different responses in multiple target cells at the same time. For example, **adrenaline**, a hormone that is released from the adrenal glands, targets cardiac muscle cells, vascular smooth muscle cells and the various glands and organs of the digestive system. An increase of adrenaline in the bloodstream will result in an increase in heart rate and blood pressure and will simultaneously decrease digestive functions, preparing for a 'fight or flight' response.

Some common mammalian hormones, their sources, target tissues and functions are listed in Table 6.3.1.

TABLE 6.3.1 Common mammalian hormones, their sources, target tissues and functions

Gland (source)	Hormone(s)	Hormone class	Hydrophobic or hydrophilic	Target	Function
adrenal cortex	glucocorticoids	steroid	hydrophobic	many cell types	regulate glucose metabolism and stimulate fat breakdown
	mineralocorticoids	steroid	hydrophobic	kidney tubule cells	regulate reabsorption of salts
hypothalamus	dopamine	amino-acid-derived	hydrophilic	anterior pituitary	inhibits release of prolactin
	growth hormone releasing hormone (GHRH)	peptide	hydrophilic	somatotroph cells in the pituitary gland	stimulates release of growth hormone
anterior pituitary	adrenocorticotrophic hormone (ACTH)	peptide	hydrophilic	adrenal cortex	promotes release of adrenal cortex hormones
	growth hormone (GH)	protein	hydrophilic	• bone • muscle	promotes protein synthesis and growth
	follicle stimulating hormone (FSH)	protein	hydrophilic	ovaries	promotes development of follicle and secretion of oestrogen
	luteinising hormone (LH)	protein	hydrophilic	ovaries	promotes ovulation, development of corpus luteum and secretion of progesterone
	prolactin	protein	hydrophilic	mammary glands	stimulates milk synthesis and secretion
	thyroid stimulating hormone (TSH)	protein	hydrophilic	thyroid	promotes production and release of thyroxine
pancreas	insulin	peptide	hydrophilic	most cells	regulates blood glucose levels
thyroid	thyroxine	amino-acid derived	hydrophobic	most cells	regulates cellular metabolic rate

Pituitary gland

The pituitary gland is located at the base of the brain, just above the roof of the mouth. In humans, it is about 1 cm in diameter and weighs about 0.5 g. Despite its relatively small size, the pituitary gland is often called the 'master gland' of the endocrine system because it produces many of the body's hormones, a number of which help regulate the production of other hormones around the body. Hormones secreted by the pituitary gland are also involved in a range of cellular processes including growth, reproduction, lactation, kidney function, skin pigmentation and regulation of the activity of the thyroid and the adrenal glands. Research has shown that the pituitary gland consists of two distinct parts, called the anterior and posterior pituitary gland.

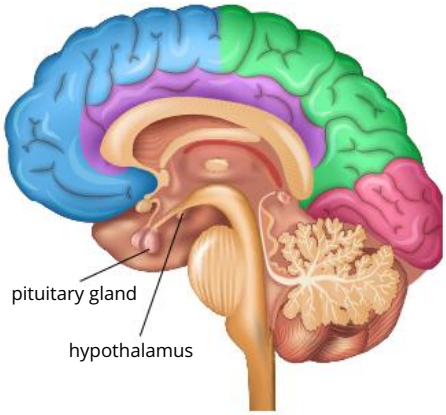


FIGURE 6.3.2 A cross-section of the human brain showing the location of the hypothalamus and pituitary gland

Another endocrine gland, the hypothalamus, is located above the pituitary gland, and connects directly to the pituitary gland (Figure 6.3.2). The hypothalamus is responsible for detecting internal stimuli from all over the body and determining whether or not optimal conditions are being maintained. These internal stimuli trigger the production of releasing hormones from the hypothalamus. Releasing hormones are those that control and regulate specific hormone production in the pituitary gland. The combined functions of the hypothalamus and pituitary gland are vital for homeostasis.

Plant hormones

Plant hormones, like all signalling molecules, are produced in low concentrations but have a significant effect on plant development and growth. In contrast to animal hormones, which are produced by specific glands and organs, each plant cell can produce many different types of hormones. Plant hormones also have a variety of modes of transmission.

There are five main types of plant hormones: **abscisic acid**, **auxin**, **cytokinins**, **ethylene** and **gibberellins**. These are sometimes called **phytohormones** (from the Greek *phyton*, meaning 'plant'). A summary of the biological roles of these hormones is provided in Table 6.3.2.

TABLE 6.3.2 The biological roles of the five main types of plant hormones

Type of plant hormone	Source	Effector site	Mode of transmission	Visible effect	
abscisic acid	leaves (chloroplasts), roots	seeds, buds, guard cells, leaves and fruit	transported in the xylem from roots and phloem from leaves	seed and bud dormancy, drought tolerance and apical dominance	
auxin	shoot tip (meristem), seeds	growing region of shoots and roots, developing fruit	transported from cell to cell, often with directional transport, usually moving from shoots towards roots	shoot tip bends towards the light (phototropism), roots grow downwards (gravitropism), apical dominance	
cytokinins	roots and developing fruits	branch and leaf buds	transported in xylem	growth of lateral branches	
ethylene	ripening fruits and other parts of the plant	most cells	diffusion (ethylene is a gas)	increases sugar content of fruit, fruit and leaf drop	
gibberellins	root and shoot apical meristems, growing leaves and seeds	meristems, leaves, seeds and flowers	typically used in the cell that made it, otherwise transported cell-to-cell in xylem and phloem	elongation of stems, leaf expansion, seed germination, fruit and flower maturation	

CELL SENSITIVITY AND RESPONSE

The sensitivity of a cell to a specific hormone depends directly upon the number of receptors that that cell has in its membrane for that particular hormone. The greater the number of receptors for a particular hormone that a cell has, the greater degree of sensitivity that cell has to the hormone. If a cell, or structure, increases the number of receptors for a hormone, it is said to be upregulating. A subsequent decrease in the number of receptors is called downregulation and the sensitivity of that target cell to the hormone will be decreased.

Signal transduction

The process of converting the original stimulus signal into a response is called **signal transduction** (Figure 6.3.3). Signal transduction involves changing the form of the signal in some way. This may involve a change in the type of signalling molecule used, passing the signal into or out of a cell, or converting the type of signal from one form to another (for example, from a chemical to an electrical signal). The specific processes involved in the transduction of a particular signal depend on the signalling molecules involved.

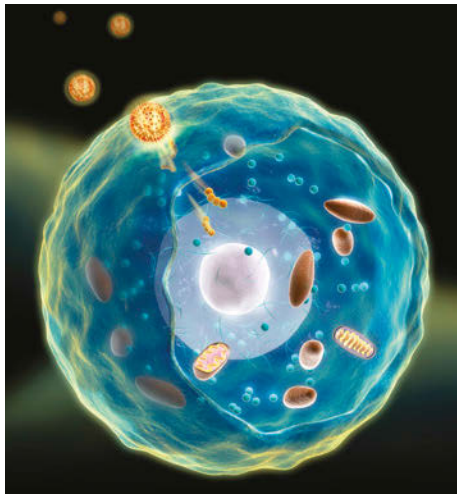


FIGURE 6.3.3 Signal transduction occurs when a signalling molecule from outside the cell (orange), activates a specific receptor located on the cell surface or inside the cell.

Stimulus–response model

The ability of a multicellular organism to detect and respond to stimuli relies on cells communicating with each other. As you learnt, cells communicate with each other through signalling molecules (Figure 6.3.4).

The processes involved in a cell detecting and responding to a signalling molecule are together known as signal transduction. The general characteristics of signal transduction depend on whether the signalling molecule is hydrophobic or hydrophilic.

Signal transduction can be considered in terms of a stimulus–response model (Figure 6.3.5).

The stimulus–response model is a three-step process.

1 Reception—the detection of the signalling molecule by a receptor
2 Transduction—the relay of the signal into the cell
3 Cellular response—the activation of a cellular activity or process

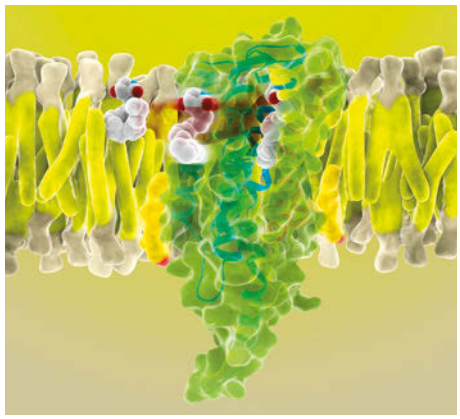


FIGURE 6.3.4 A digital illustration of a signalling molecule (mostly white) binding to a receptor (green)

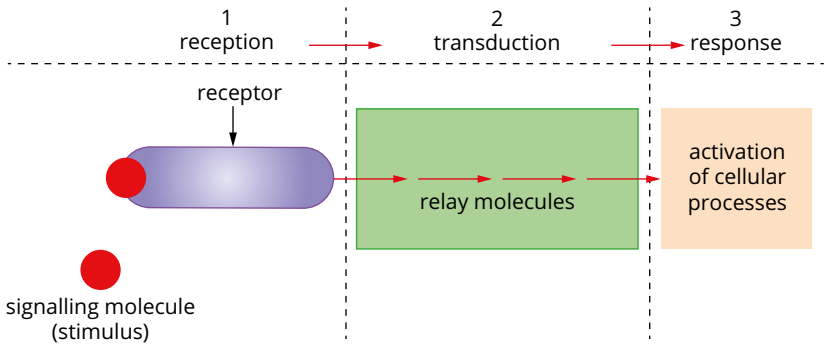


FIGURE 6.3.5 The stimulus–response model applied to the cell in terms of signal transduction

Reception

Reception involves the detection of a signalling molecule by a cell. The receptor that detects a signalling molecule can be located on the surface of the cell membrane or in the cytosol or nucleus of the cell. The position of the receptor depends on whether the signalling molecule is hydrophobic or hydrophilic. Receptors are specific and will only bind to particular signalling molecules (Figure 6.3.6).

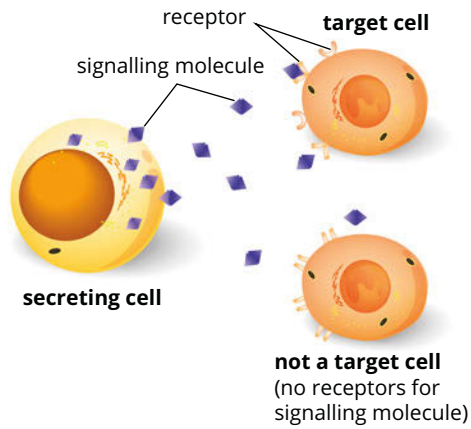


FIGURE 6.3.6 Each type of signalling molecule is designated for certain cells (target cells). Receptors are specific and will only bind to a particular signalling molecule.

Not all cells are responsive to all signalling molecules. If a cell does not express the gene for a specific receptor, it will not have the receptors and hence that cell cannot respond to the complementary signalling molecule. For example, in the brain, neurons in certain neural pathways may express a defined set of receptors to be responsive only to the specific neurotransmitters used in that pathway.

Transduction

Transduction involves converting the signal into a form that can be relayed to reach its final destination within the cell and bring about a cellular response. Transduction may involve a one-step process in which a signalling molecule binds to one receptor and this complex produces a response. Alternatively, it may involve a multi-step process in which a signalling molecule binds to its receptor, leading to the sequential activation of different molecules in a chain of events. These multi-step transduction pathways are commonly called cascades.

Cellular response

Following transduction, a response is initiated. Cellular responses include any cellular activity such as gene transcription, the activation of enzymes or the secretion of signalling molecules by the cell. Responses can occur in the:

- nucleus
- cytosol
- cell membrane.

Signal transduction of hydrophobic signalling molecules

Hydrophobic signalling molecules are usually lipid-based molecules involved in gene regulation. Lipid-based molecules are lipid soluble so can easily diffuse through the cell membrane. Inside the target cell, they bind to an intracellular receptor, either in the cytosol or in the nucleus.

Reception

Steroid hormones are examples of lipid-based hydrophobic signalling molecules that bind to receptors in the cytosol. Figure 6.3.7 shows some examples of steroid hormones. Once bound, the signalling molecule–receptor complex moves from the cytosol through nuclear pores to its final destination in the nucleus (Figure 6.3.8).

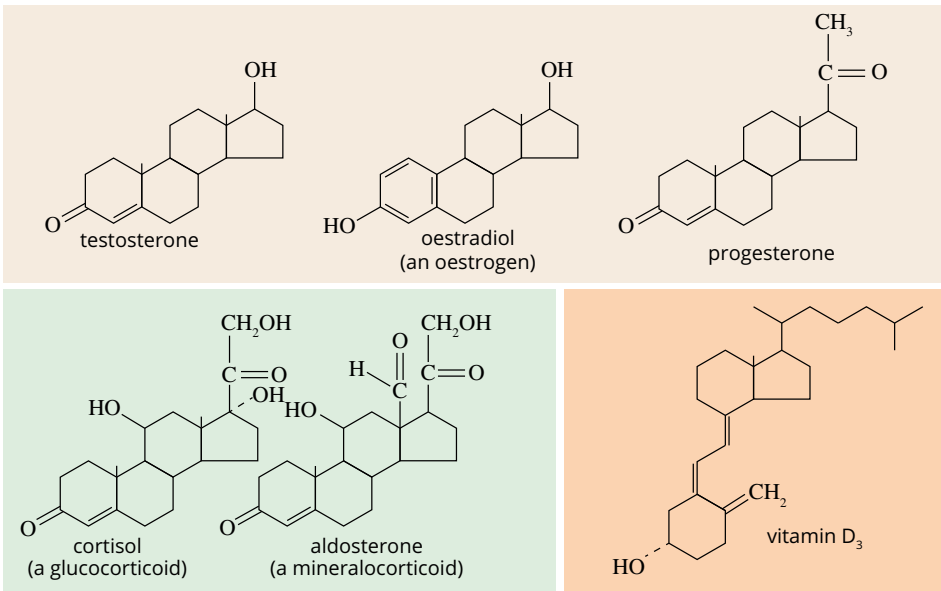


FIGURE 6.3.7 Examples of steroid hormones

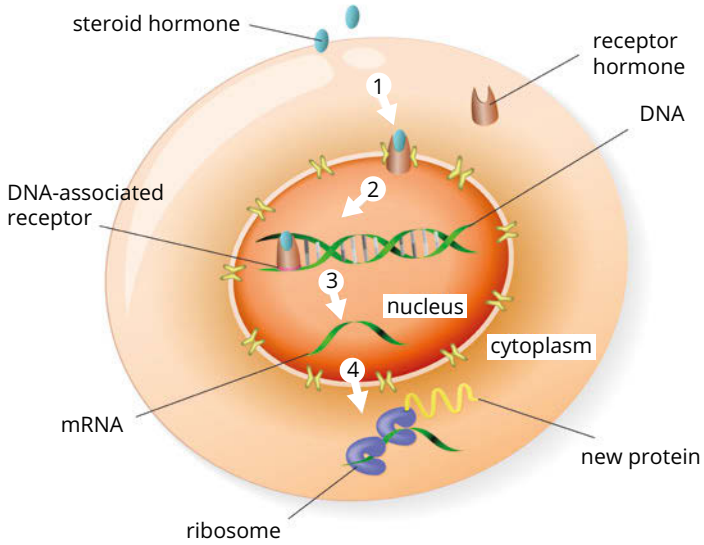


FIGURE 6.3.8 Once steroids are in the cytoplasm (1), they bind to receptors in the cytosol, then travel to the nucleus and move through pores in the nuclear membrane (2), which activates gene transcription (3) and causes proteins to be manufactured on the ribosome (4).

Transduction

In the nucleus, the signalling molecule–receptor complex acts as a transcription factor. Transcription factors are a group of proteins that help to initiate or regulate gene expression by either inducing or repressing gene transcription (e.g. copying a strand of mRNA from DNA). Figure 6.3.9 shows a molecular model of an androgen–receptor complex (signalling molecule–receptor complex) acting as a transcription factor and binding to DNA. The androgen receptor binds to hydrophobic signalling molecules called androgens, which are steroid hormones, such as testosterone. The binding of the androgen–receptor complex switches on the genes involved in development of reproductive organs and secondary sexual characteristics.

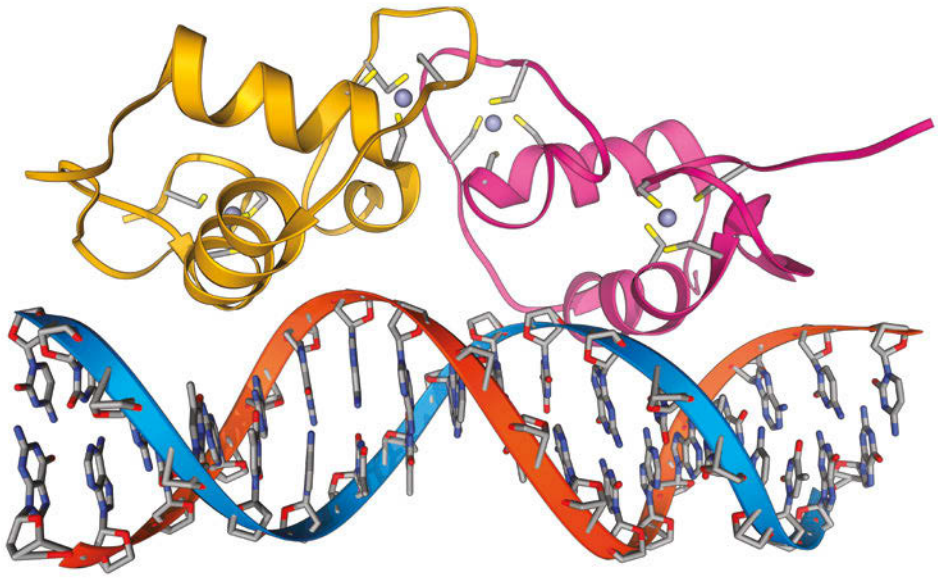


FIGURE 6.3.9 A molecular model of the DNA (red and blue) binding region of the androgen receptor (yellow and pink)

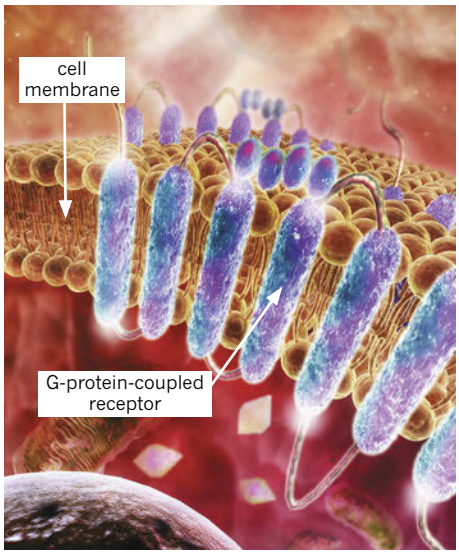


FIGURE 6.3.10 A digital illustration of a transmembrane protein, the G-protein-coupled receptor (purple), in a cell membrane

For example, testosterone is secreted by the cells of the testes in males. Testosterone travels in the bloodstream and enters all cells in the body. Only cells that contain androgen receptor molecules in the cytosol respond. In these cells, testosterone binds to the androgen receptor and activates it. The active form of the receptor then enters the nucleus and turns on specific genes that control male sex characteristics by binding onto a specific sequences of DNA known as hormone response elements.

Although traditionally thought of as male hormones, androgens are sex hormones produced in the testes and adrenal glands in men and ovaries and adrenal glands in women.

Signal transduction of hydrophilic signalling molecules

Hydrophilic signalling molecules include a wide range of hydrophilic peptide hormones, neurotransmitters and cytokines. They are water-soluble and so are unable to diffuse through cell membranes.

Reception

The first step for all hydrophilic signalling molecules is to interact with receptors on the external surface of the cell membrane. The receptors for these signalling molecules are transmembrane proteins, which are made up of one or more protein molecules and span both layers of the plasma membrane. An example of a transmembrane protein is the G-protein-coupled receptor. The G-protein-coupled receptor consists of seven membrane-spanning domains connected by extracellular loops. The receptor is activated by the binding of molecules on the surface of the cell to induce cellular responses inside the cell (Figure 6.3.10).

Transduction

Transmembrane receptors have an extracellular domain that acts as a binding site for the signalling molecule and an intracellular domain that transfers the signal into the cell (Figure 6.3.11). When the signalling molecule binds to the extracellular part, the intracellular part of the receptor typically changes shape. This conformational change (a change in shape of a macromolecule) of the receptor results in the activation of molecules inside the cell (cellular responses).

The receptor may initiate a cellular response either directly or indirectly by the activation of other molecules such as second messengers, G proteins or both.

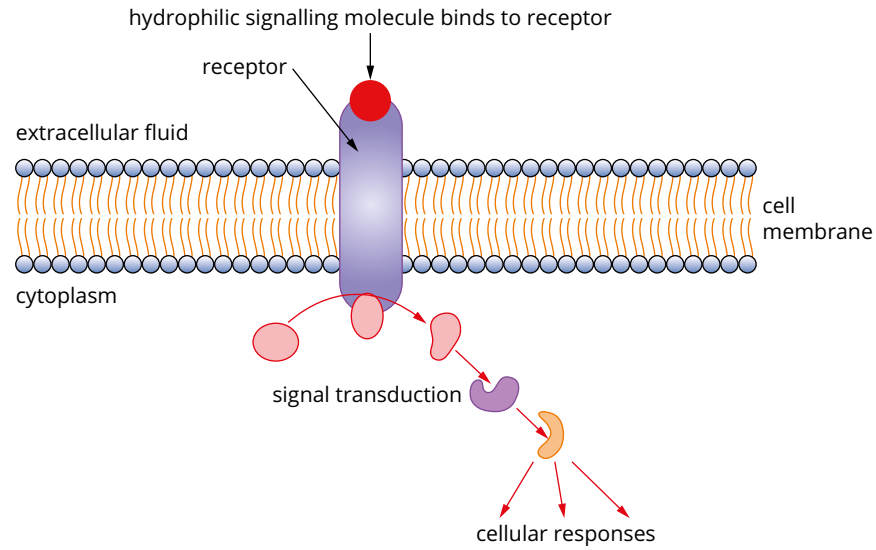


FIGURE 6.3.11 Hydrophilic signalling molecules interact with a specific membrane-bound receptor, causing the intracellular domain to change shape.

Signal transduction of hydrophilic signalling molecules typically uses intermediate proteins and other small non-protein molecules to relay the signal to its final destination. The small non-protein molecules are referred to as second messengers, and are usually water-soluble molecules. The size and solubility of second messengers enables them to diffuse quickly through the cytosol and to then trigger and amplify a response from multiple parts of the cell at once.

Whichever type of molecule that is activated by the conformational change of the receptor after binding to a hydrophilic signalling molecule, the result is the trigger of a transduction cascade inside the cell that eventually initiates the response.

Transduction cascade

Transduction cascades involve a series of events in which a change in one molecule causes a change in another, which in turn causes a change in yet another, and so on. The molecules may be enzymes, channel proteins or cell structure proteins. For example, when hydrophilic signalling molecules, such as peptide hormones, activate metabolic pathways, a second messenger might be produced that activates a series of enzymes in a set order, so that the activation of one enzyme causes the activation of the next in a sequence or cascade (Figure 6.3.12).

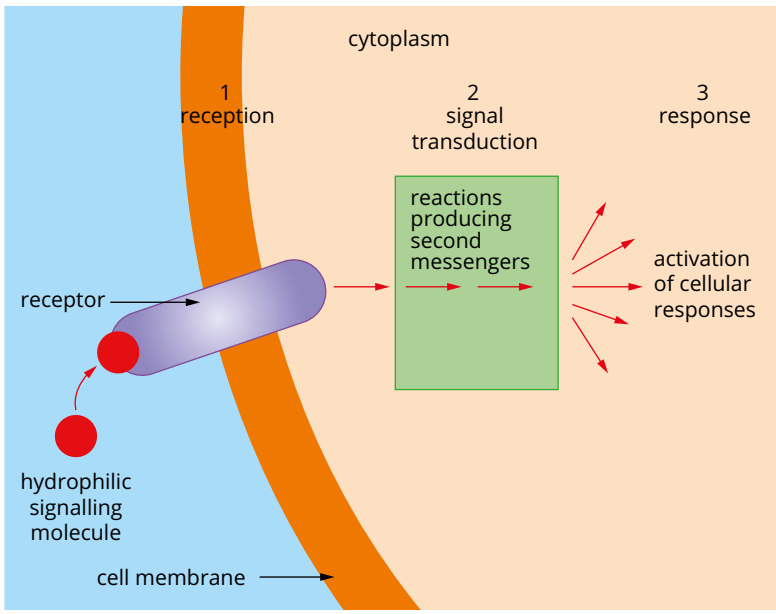


FIGURE 6.3.12 A hydrophilic signalling molecule binds to the receptor on the cell membrane, leading to a series of reactions that produce second messengers that, in turn, activate a cascade of enzymes or other molecules in the cell, leading to a range of possible cellular responses.

At the end of the cascade, molecules are activated that bring about a cellular response. A signalling molecule can initiate different responses in different cell types.

- Different receptors for the same signalling molecule exist in different cells, which may activate different transduction cascades.
- Proteins can be specific to particular cells and will lead to a particular response only in the cells in which they are present.

Even though signalling molecules are usually found in low concentrations, a cascade in a transduction pathway allows the amplification of the original signal that leads to enough response molecules to have an effect on the cell.

Cellular response

Gene regulation is vital for a cell to adapt and respond to incoming stimuli. The cell's need for enzymes and products such as signalling molecules fluctuates. By regulating gene expression to synthesise proteins as required, cells can optimise their functionality. For example, a hormone will only be produced when needed, in order to conserve energy and also to limit the amount of space required to store excess hormone.

You have already learnt that hydrophobic hormones are able to cross the cell membrane. Once within the cytosol or nucleus, they form a complex with their receptor and in the nucleus this complex acts as a transcription factor.

Some hydrophilic hormones elicit a similar response but through a different transduction process. Peptide and protein hormones can activate protein receptors in the cell membrane that, in turn, activate a signal transduction cascade. The cascade ends with a functional transcription factor, leading to gene regulation (Figure 6.3.13). One example of a peptide-based hormone that regulates gene expression is oxytocin. This hormone is produced in the pituitary gland and is involved in lactation, uterine contractions to expel the placenta after the birth of a baby and social bonding.

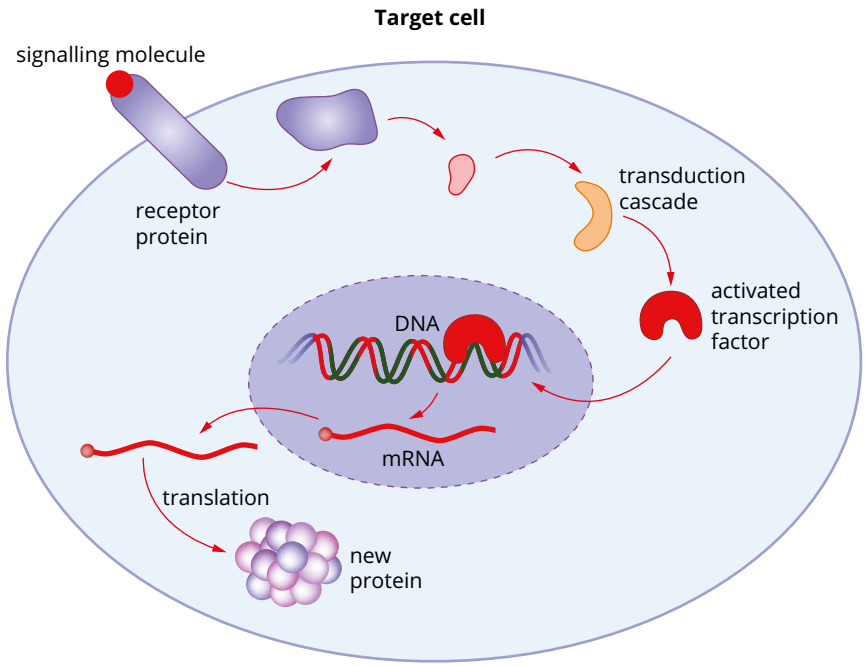


FIGURE 6.3.13 A hydrophilic signalling molecule interacts with its membrane-bound receptor, causing transduction of the signal into the cell with the resultant gene expression.

Signal transduction can result in the inhibition or activation of enzymes in the cytosol of the target cell. Enzymes regulate cellular processes by catalysing chemical reactions, so inhibiting or activating enzymes will decrease or increase cellular functions respectively.

One example is the response of the liver cells to insulin. When glucose levels in the blood are high, insulin is released from the pancreas. Insulin binds to insulin receptors on the liver cell surface, which allows the receptor to activate second messenger molecules and initiate multiple transduction cascades. In liver cells, the pathway initiated by insulin leads to the activation of enzymes for glycogen synthesis, fatty acid synthesis, increased glycolysis and an increase in glucose transporters in the cell membrane for the uptake of glucose into the cytoplasm.

The cell membrane of a cell controls all the substances that move into or out of the cell. Not all substances can cross the membrane passively. Some cellular responses involve changes to the cell membrane that allow certain substances to enter or exit the cell.

An ion channel is a type of transmembrane protein that allows specific ions to cross the cell membrane. Some ion channels can be opened or closed in response to signalling molecules (Figure 6.3.14).

Ion channels are important in converting chemical signals to electrical signals. Skeletal muscle cells are an example of cells that respond to signalling molecules by opening ion channels. When acetylcholine, a neurotransmitter released by neurons, binds to the receptors on the cell membrane of a skeletal muscle cell, ion channels open that allow Na^+ to move into the cell. Sodium ions flowing into the muscle cell leads to the cellular response, which in this case is contraction of the muscle.

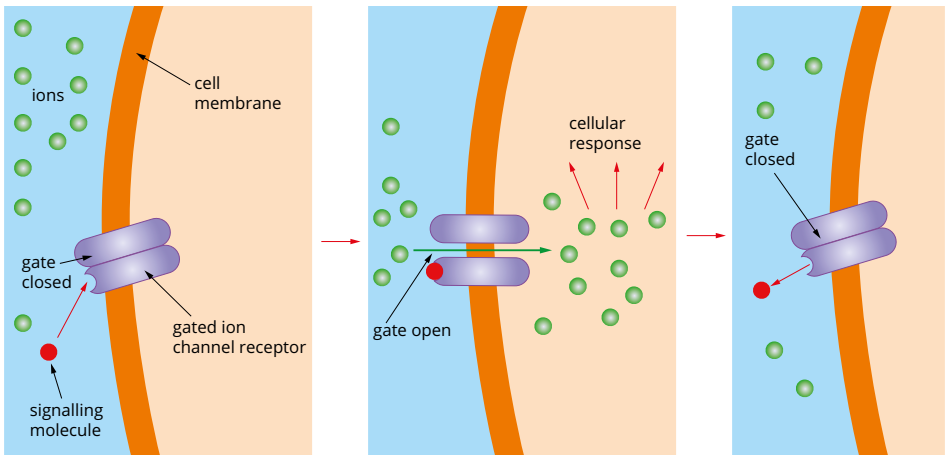


FIGURE 6.3.14 A gated ion channel receptor is both a receptor and an ion channel. It opens when a signalling molecule binds to the extracellular part of the channel, allowing ions to move through the channel from the extracellular fluid into the cytoplasm.

WS 2.1.5

6.3 Review

SUMMARY

- Multicellular organisms produce signalling molecules as a form of intercellular communication.
- Signalling molecules transmit information about an internal or external stimulus to other cells, including, ultimately, the effector cells, which enact the response.
- Signalling molecules can be classified according to their chemical structure, their source and their mode of transmission.
- Animal hormones:
  - are produced by organs and glands in animals
  - can be hydrophilic or hydrophobic.
- Plant hormones:
  - are produced in a variety of cells in plants
  - can be hydrophilic or hydrophobic
  - are transported cell-to-cell or via the xylem and/or phloem.
- The stimulus–response model outlines the three main steps involved in signal transduction in cells:
  - reception—the detection of a signalling molecule (the stimulus) by its specific receptor (including the physical binding of the signalling molecule to the receptor)
  - transduction—the transformation of the signal in terms of form, type of signalling molecule and the passage into and out of a cell
  - response—the change in cellular activity as a result of the initial stimulus.
- Cellular responses depend on the stimulus and the type of cell, the signalling molecules and response molecules involved.

KEY QUESTIONS

Retrieval

1 Describe the feature of a target cell that makes it receptive to a particular signalling molecule.

2 Identify the source of dopamine.

3 Identify the source of cytokinins.

Comprehension

4 Hormones and neurotransmitters are both signalling molecules. Explain the difference between the two.

5 **a** Define 'signal transduction'.

b Summarise the steps of the stimulus–response model in signal transduction.

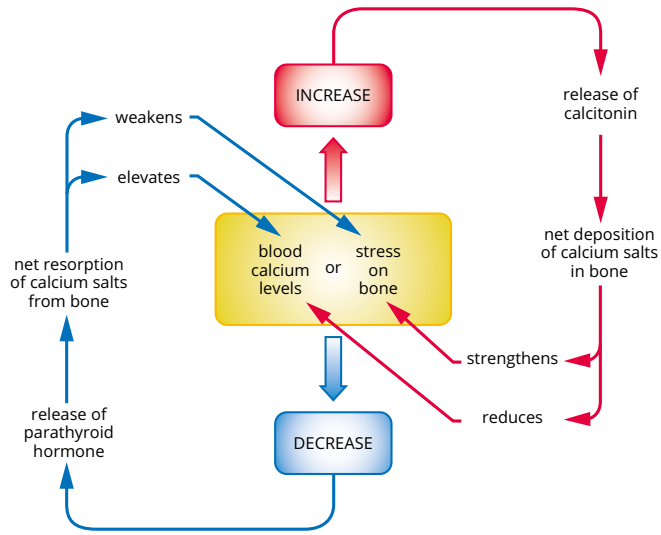
Analysis

6 Evaluate (using one paragraph) the affirmative statement that 'The pituitary gland is the master gland of the body'.

7 Many people in Victoria become vitamin D deficient through the winter months because of lack of sun exposure. In the absence of vitamin D dietary calcium is not absorbed efficiently from the digestive tract.

a Use the diagram below to infer the likely effect that this will have on the relative concentrations of parathyroid hormone in the blood.

b Low levels of calcium can lead to problems at neuromuscular junctions, resulting in poor muscle control. Determine why this observation is valid.

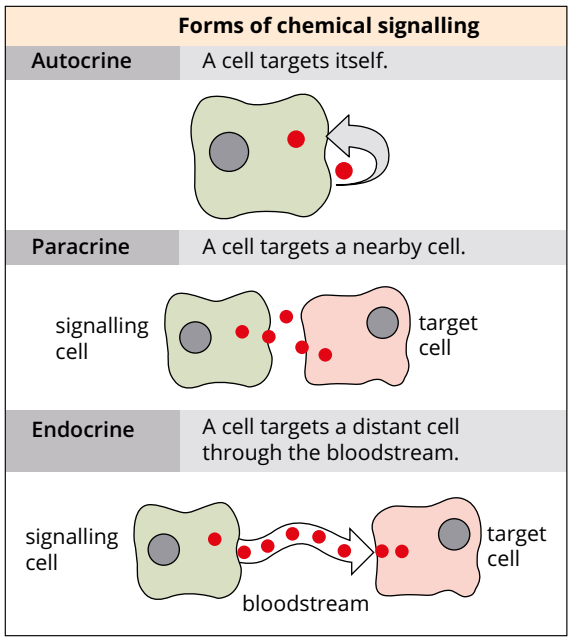


8 Guard cells, found in the leaf epidermis, are the entry point for carbon dioxide. Abscisic acid is a plant hormone that has been shown to be a significant contributor to guard cell opening and closing. When plants are under water stress guard cells lose turgor and close.

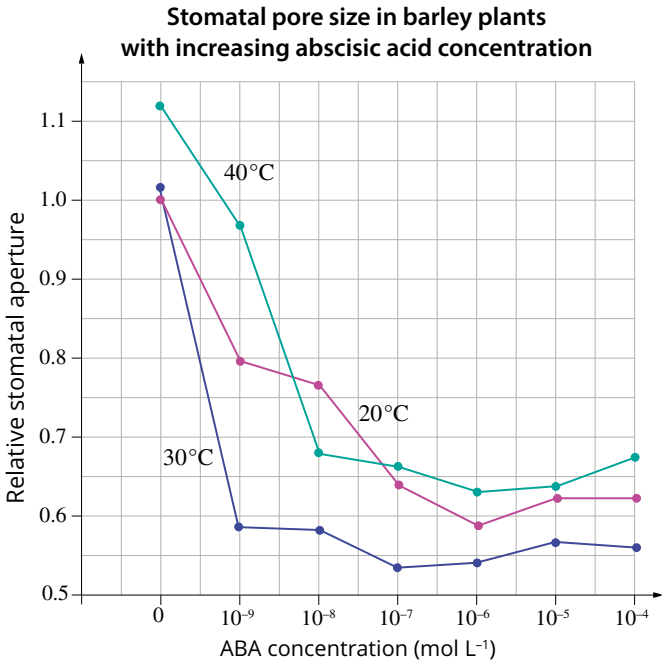
As soils dry out, cells in the roots lose turgor. This stimulates these cells to produce abscisic acid.

a Explain how the abscisic acid produced in the roots is transported to the guard cells in the leaves.

b The following diagram shows three types of cell signalling in humans. Explain which type of signalling is most like the action of abscisic acid.



c The graph shows the size of the stomatal pore (relative stomatal aperture) of barley plants as the concentration of abscisic acid is increased. The experiment was undertaken at three different temperatures.



Interpret the information displayed on the graph to answer the following questions.

i Deduce at which temperature was stomatal aperture size most affected by an increase in abscisic acid.

ii Describe the trends in stomatal aperture size as abscisic acid concentration increases at 40°C.

6.4 Regulation

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

- identify and explain the varying thermoregulatory mechanisms of endotherms and how they control heat exchange and metabolic activity in terms of:
  - structural features (brown adipose tissue, increased number of mitochondria per cell, insulation)
  - behavioural responses (kleptothermy, hibernation, aestivation and torpor)
  - physiological mechanisms (vasomotor control, evaporative heat loss, countercurrent heat exchange, thermogenesis/metabolic activity from organs and tissues)
  - homeostatic mechanisms (thyroid hormones)
- identify and explain the various homeostatic mechanisms that maintain water balance in animals (osmoregulators and osmoconformers) in terms of:
  - structural features (excretory system)
  - behavioural responses
  - physiological mechanisms
  - homeostatic mechanisms (antidiuretic hormone (ADH) and the kidney)
- identify and explain the various mechanisms that maintain water balance in plants in terms of structural features (stomata, vacuoles, cuticle) and homeostatic mechanisms (abscisic acid); consider xerophytes, hydrophytes, halophytes and mesophytes in responses
- understand that metabolism describes all of the chemical reactions involved in sustaining life and is either catabolic or anabolic
- explain why changes in metabolic activity alter the optimum conditions for catalytic activity of enzymes (with reference to tolerance limits).

Organisms and cells are constantly experiencing changes in their environment. These changes to the internal and external conditions can adversely affect the survival, growth and function of the organism. The internal environment of an organism must always remain within tolerable limits, even when conditions in the external environment fluctuate widely. When a change occurs in the external environment, an adjustment must be made to the internal environment.

Living organisms rely on their external environments to provide adequate levels of nutrients, water and oxygen and suitable physical conditions, such as light and temperature. Organisms have a range of mechanisms that allow them to adapt to changing conditions while maintaining a stable internal environment when external conditions fluctuate, as shown in Figure 6.4.1. If an organism is not able to adapt to its external environment, it will suffer cellular damage and possibly death when conditions change.

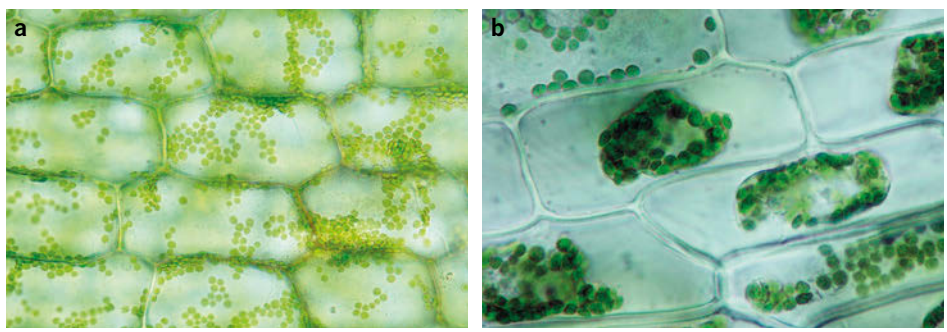


FIGURE 6.4.1 The internal cellular environment of the freshwater Canadian pondweed (*Elodea* sp.) responds to changes in the external environment using osmosis. (a) In fresh water, chloroplasts move freely through the cytoplasm, as solute concentration is equal in both the internal and external environments. (b) When the cells are exposed to a salty environment, water leaves the cell by osmosis and the cell membrane contracts, clumping the chloroplasts in the middle of the cell. Because *Elodea* is a freshwater plant, it does not have the regulatory mechanisms needed to survive in a saltwater environment.

There is no one simple mechanism that enables organisms to respond to changing environmental conditions. In this module, you will learn that organisms have structural features and behavioural responses, in addition to physiological and homeostatic mechanisms, that regulate their internal environment in a constantly changing world.

THERMOREGULATION

Thermoregulation is when an organism regulates its body temperature either by increasing its metabolic activity or through behavioural responses. As you will recall from Chapter 3, all our biochemical mechanisms are driven by enzymes. Enzyme efficiency in catalysing chemical reactions depends on the organism maintaining an optimal internal temperature. Should thermoregulation fail because of an inability to cope with extremes of external temperatures, enzyme function decreases to a level unable to sustain life. But as you will learn in this module, some animals have adapted very well to living in extreme climatic conditions.

Homeostatic mechanisms

Regulation of body temperature in humans and other **endotherms** involves a complex negative feedback pathway with several sensory inputs and many effector responses that act together to maintain a stable body temperature. The control centre for measuring the body temperature set point in humans (37.2 ± 0.6°C) is in the hypothalamus. A change in the temperature of the hypothalamus initiates regulatory responses that can either reduce heat loss, or initiate heat production or heat exchange.

Endotherms (from the Greek *endon*, meaning 'within', and *thermos*, meaning 'heat') are warm-blooded animals that can generate heat to maintain their own body temperature.

Detecting temperature change

Regulation of temperature in humans is an example of the way different sensory receptors work together to produce an integrated response. Arterial blood has the most constant temperature. The relatively constant temperature of many other parts of the body indicates that they are well supplied with arterial blood.

In endotherms, a group of temperature-sensitive cells in the hypothalamus act as misalignment detectors, triggering homeostatic responses if blood temperature deviates from the optimal temperature range, or set point. Lowering or raising the temperature of the hypothalamus initiates regulatory changes in heat production or heat exchange.

Temperature receptors are also found in the skin. If these receptors detect a decrease in environmental temperature, they initiate regulatory responses, such as decreased blood flow to the skin to reduce heat loss, and behavioural changes, such as moving into a warmer or more sheltered environment. These responses take place long before there has been any change in the internal temperature of the body. Skin temperature receptors act as disturbance detectors, detecting changes in the external environment and triggering responses before there is a change in core body temperature.

As the environmental temperature falls, disturbance detectors stimulate responses that reduce heat loss and increase heat production. The reverse occurs as environmental temperature increases. If the arterial temperature falls despite the regulatory responses that have been initiated, or if it rises because the responses made have been too effective, these changes will be detected by the misalignment receptors in the brain, which will fine-tune the temperature-regulating mechanisms.

The function of the disturbance detectors in the skin is to reduce fluctuations in arterial blood temperature, providing a more precise control around the set point level than there would be if misalignment detectors (the brain's temperature receptors) alone were involved.

Heat loss

Organisms are constantly exchanging heat with their environment. This heat exchange occurs through four mechanisms (Figure 6.4.2).

- Conduction occurs when the temperature of the organism and the environment are different. Heat exchange is a result of direct contact (e.g. a lizard basking on a warm rock).
- Convection is transmission of heat from a warmer region to a colder region, resulting from the movement of liquid or gas (e.g. heat moves from the inside of living organisms to the body surface by convection).
- Radiation occurs all the time, without direct contact, regardless of temperature differences between the organism and their environment (e.g. heat radiating from dark coloured surfaces).
- Evaporation of water causes heat loss. This occurs most rapidly when the air is hot and dry (e.g. sweating).

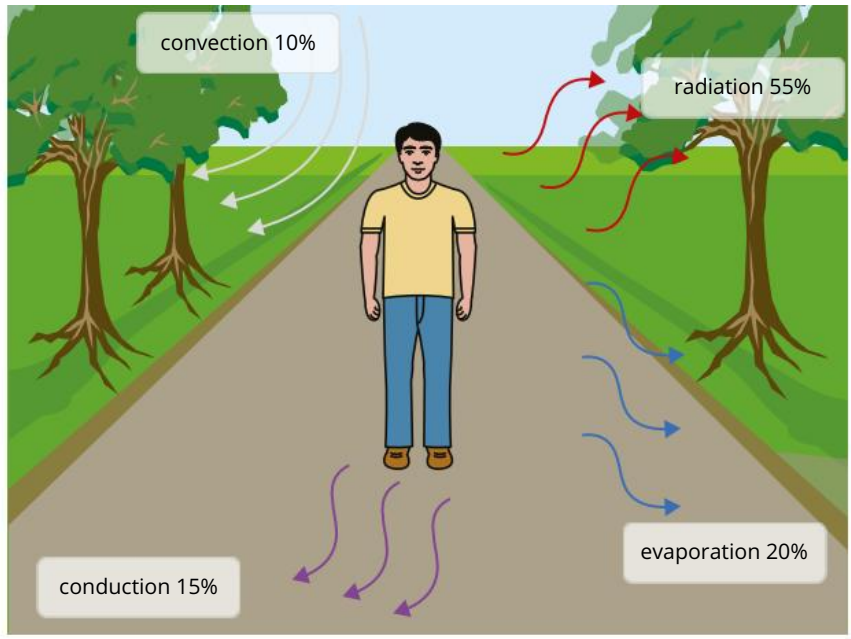


FIGURE 6.4.2 Methods of heat exchange with the environment and the average amount lost via each route in a human at rest

FIGURE 6.4.3 The emperor penguin (*Aptenodytes forsteri*) has mastered living in extremely cold environments. The thick layer of feathers and blubber are two of many important features that make this lifestyle possible.

Structural features

All endotherms have structures that help them to conserve or to release heat. Examples are:

- special body coverings and blubber to insulate against cold
- vascular body parts such as ear size to reduce (small ears), or to increase (large ears), heat exchange with the environment
- brown adipose (fat) tissue
- increased numbers of mitochondria for heat generation.

Body coverings and insulation

The emperor penguin (*Aptenodytes forsteri*) has many structural features to cope with life in the harsh Antarctic climate. Penguins have four layers of thick, scale-like feathers, creating a windproof coat (Figure 6.4.3). They also have thick blubber to keep them warm while swimming in the icy ocean. Juvenile penguins have soft down for insulation, which is a more effective insulator on land than the adult feathers but of little use in the sea. Juveniles must moult before they can swim. Penguins and other animals in cold climates tend to have bodies with a small surface area to volume ratio to assist them in conserving body heat.

Marine and seagoing mammals also have a thick layer of blubber beneath their skin. Polar bears and fur seals have a dense layer of fur that aids in insulation on land but need a layer of blubber for insulation while swimming. Depending on their size, whales have a very thick layer of blubber to conserve their body heat (Figure 6.4.4).

Vascular body parts

Features of animals living in hot, dry climates include large ears, long tails or a long body. When the extremities are highly vascular, it enables the animals to release heat efficiently and keep their bodies cool. The greater bilby (*Macrotis lagotis*) of the Australian inland, shown in Figure 6.4.5, is an example of a desert dweller with highly **vascularised tissue** (ears). Highly vascularised tissues contain many blood vessels.

This works in reverse with animals such as the Arctic fox (*Alopex lagopus*). Figure 6.4.6 shows their very small ears, which limit vascular heat loss.

Brown fat

Many small animals with high metabolic rates undergo either **hibernation** or **torpor** during winter (see *Torpor* below). Their metabolic rate and body temperature drops down quite low during this time. Brown adipose tissue, or brown fat, is a structure that aids in the transition from hibernation to a full metabolic functioning, awakened state.

Brown fat cells are packed with large mitochondria (which contribute to its colour). This tissue has a rich blood supply and many sympathetic nerve endings. Unlike typical mitochondria that synthesise ATP, these mitochondria have been uncoupled from that mechanism, and focus on the oxidation of fat. The heat given off is picked up by the vascular system and distributed to the vital organs of the animal. The heat production is switched on by either noradrenaline, or by nervous stimulation. Figure 6.4.7 on page 262 shows a mountain pygmy possum (*Burramys parvus*), which has reserves of brown fat. It is the only marsupial known to hibernate for extended periods of time and is fully adapted to living solely in alpine regions of Australia.

Increased mitochondria in cells

ATP is produced primarily within the electron transfer chain of the mitochondria. Animals with high metabolic rates generally have a larger number of mitochondria per cell. This allows them to generate heat, although their higher rate requires them to eat more food than ectothermic animals (such as snakes and lizards).

Behavioural responses

In addition to physiological homeostatic mechanisms, animals use behavioural responses to protect themselves from, or to adjust to, their environment.

Kleptothermy

If you have ever huddled together with your friends on a cold and windy day, you have practised **kleptothermy**. Kleptothermy is the thermoregulatory behavioural response of sharing another organism's body heat.

Huddling is the prime example of this. Many animals use huddling to cope with cold temperatures. Figure 6.4.8 on page 262 shows emperor penguin chicks, thousands of which can huddle together for warmth in the spring, when they begin to develop their adult plumage. By huddling, penguins decrease the surface area of the group exposed to the harsh environment. They continually change which birds are on the outside of the group, so that each takes a turn in the freezing cold winds.

Torpor

Torpor is a physiological state in which the metabolic rate is lowered to save energy. This enables an organism to cope with environmental stresses such as extreme cold or heat or decreased food or nutrient availability, and torpor can occur over short or long periods.

FIGURE 6.4.4 These scientists are dissecting a dead male sperm whale (*Physeter macrocephalus*) found on Henne Strand, Jutland, Denmark. The whale was 14 metres long and weighed about 30 tonnes. Cutting tools and a backhoe loader were used to remove large portions of the whale's tissue. The thick layer of blubber is visible beneath the skin. The tissue samples and skeleton are used for further study by the scientists.

FIGURE 6.4.5 The greater bilby (*Macrotis lagotis*) has highly vascularised ears that allow it to release heat rapidly, lowering the body temperature in the extreme desert heat.

FIGURE 6.4.6 The Arctic fox (*Alopex lagopus*) has very small ears that allow it to limit heat loss in freezing Arctic conditions

FIGURE 6.4.7 The endangered mountain pygmy possum (*Burramys parvus*) lives in Australia's alpine region. It is the only marsupial known to store food and hibernate for extended periods.

FIGURE 6.4.8 Emperor penguin chicks (*Aptenodytes forsteri*) huddle together for warmth.

FIGURE 6.4.9 Although a very good thermoregulatory, the echidna (*Tachyglossus aculeatus*) readily enters torpor when food is scarce and temperatures are low.

FIGURE 6.4.10 The green-striped burrowing frog (*Cyclorana alboguttata*) aestivates for up to nine months of the year underground.

A long period of torpor is often called dormancy. Hibernation, **brumation** and **aestivation** are different forms of prolonged torpor.

Hibernation is prolonged torpor that occurs in winter. Over summer and autumn, the animal builds up a thick layer of brown body fat that will provide them with energy during the hibernation period in winter. During hibernation, the animal can decrease its metabolic rate so that its body temperature falls to almost that of its surroundings. Accordingly, its heart rate and oxygen consumption also become very low and very little energy is required to maintain life. When external temperatures fall below freezing, the animal will either die, or follow one of two options. Its metabolic rate will increase and the animal will awaken out of torpor. Alternatively, the animal's thermoregulatory system will increase its metabolic rate just enough to keep the animal's internal temperature at about 5°C. With such a low metabolic state, heat exchange with the external environment ceases to become an issue because the internal temperature of the animal is close to the external temperature (when above freezing).

An example of this is the echidna (*Tachyglossus aculeatus*) (Figure 6.4.9), which can maintain its normal body temperature even at freezing temperatures. However, if low temperatures are combined with a lack of food, the echidna readily becomes torpid. It regulates its body temperature at around 5.5°C, its heart rate decreases from an average of 70 beats per minute (bpm) to just 7 bpm, and its oxygen consumption becomes about one-tenth of its normal rate.

When in torpor, animals show little response to either noise or touch. Without the metabolic requirement of maintaining a high body temperature, an animal can live off its fat reserves for extended periods of time under unfavourable conditions. And while virtual suspended animation saves energy, arousal, or coming out of torpor, is an active process where the animal's metabolic rate increases to a maximum level, as does their oxygen consumption, until the animal is fully revived. In the case of small animals undergoing torpor for 10-hour periods, 75% of the energy consumption over that period is used in the arousal stage at the end.

Hibernation occurs mostly in mammals, but some species of birds also hibernate. Bears, bats and squirrels are examples of animals that hibernate.

Reptiles such as snakes and lizards undergo brumation. Brumation is similar to hibernation but involves different metabolic processes. Brumation is triggered by decreases in air temperature and daylight hours. It begins just before winter and can last 1–8 months, depending on the air temperature and the size and age of the animal. Once brumation begins, the reptile eats less or not at all, but wakes regularly to drink.

Aestivation is prolonged torpor under hot and dry conditions. Examples of aestivating animals are snails, frogs, crocodiles, tortoises, lungfish and some birds.

Green-striped burrowing frogs (*Cyclorana alboguttata*) (Figure 6.4.10) inhabit semi-arid to arid regions of eastern Queensland and northern New South Wales. These frogs spend up to 9 months of the year in aestivation. During this time, they live underground in small burrows and do not eat. Research has shown that during this time they can reduce their metabolic rate by up to 80%. This allows them to survive these underground periods just on their store of body fat. By burrowing, they have insulated themselves from the hot arid conditions outside and so do not experience heat stresses.

Torpor is an example of both a behavioural response (retiring to a cave or seeking shelter and going to sleep) and a physiological mechanism (the slowing of the heart, breathing and metabolic rates associated with periods of torpor).

Other animal behaviours

Other animal behaviours that are considered **adaptations** in animals and which help them to survive extreme environmental conditions include seeking or leaving shade or shelter, and evaporative cooling to lower temperature. Adaptations are responses that aid homeostatic mechanisms and maintain health and survival.

Many desert animals have behavioural adaptations that are very important in regulating the rate of heat exchange with their environment. An example is the central netted dragon (*Ctenophorus nuchalis*), shown in Figure 6.4.11. To raise its body temperature, this lizard emerges from under a rock and basks in the sunshine, spreading itself out at right angles to the Sun's rays. To lower its body temperature or reduce the rate of increase in body temperature, the lizard orientates its body parallel to the Sun's rays, minimising the exposed surface area, or simply retreats beneath a rock or into a burrow.

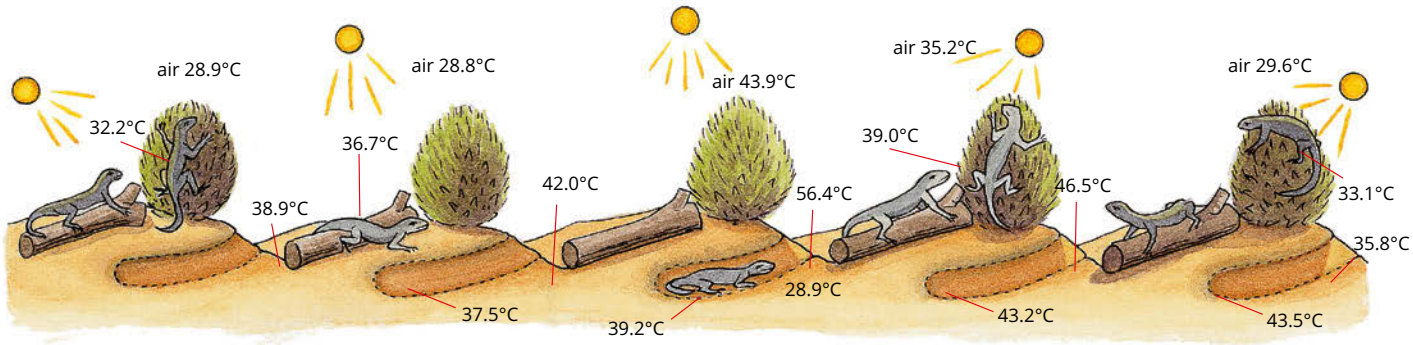


FIGURE 6.4.11 The central netted dragon (*Ctenophorus nuchalis*) has adapted its behaviour to desert conditions, regulating its temperature throughout the day by seeking shade or basking in sunlight.

Some animals such as desert snakes and tortoises adopt nocturnal behaviour during summer to prevent overheating. They move only in the cooler evening, avoiding the extreme heat of the day. Animals may also seek shelter to increase their body temperature when it is cold or windy.

Many land animals use evaporative cooling to lower their body temperature by releasing heat into the environment. Although it is a physiological mechanism it is achieved by behavioural responses, such as:

- panting or licking limbs
- spraying water on the body
- wallowing in mud or water
- mouth gaping
- gular fluttering (flapping membranes in the throat by birds to increase evaporation)
- urohydrosis.

Panting or licking limbs enable animals to release heat effectively using evaporative cooling. For example, kangaroos lick their paws, and animals such as dogs, gazelles and foxes pant. The fennec fox (*Fenecus zerda*) has been observed panting at a rate of 690 times per minute after chasing prey. The rate of panting is proportional to the amount of air flowing over the tongue. If animals can flatten their tongue, increasing surface area, while increasing their panting rate, then the cooling effect is greater. Sometimes even penguins have to pant. In warmer weather, they also hold their flippers out of the water so that both surfaces are exposed and can release heat via evaporative cooling.

Spraying water on the body is commonly seen in elephants (Figure 6.4.12) but is also a behaviour used by many other animals.

Wallowing in mud or water is a very common behaviour. Animals such as pigs, elephants, rhinoceroses and deer wallow in mud; the wet mud acts like sweat to cool the skin. Animals such as hippopotamuses, tapirs, bison, horses and cattle wallow in water to cool down.

FIGURE 6.4.12 A female African elephant (*Loxodonta africana*) splashes water over her body. She is using evaporative cooling to control her body temperature. Mud remaining on the elephant's skin provides protection against solar radiation.

Physiological mechanisms

Animals display an astounding complexity in the **heat exchange** system that they use. Heat exchange systems are physiological systems that allow the organism to rid themselves of heat, conserve heat, or selectively by-pass insulation layers. They do this through the use of **countercurrent blood flows**, vascular switches and evaporative cooling.

Heat exchange for cooling

Heat exchange systems work in different ways in different animals. An example is the gemsbok oryx (*Oryx gazella*), which is a desert ungulate (hooved animal, Figure 6.4.13). It needs homeostatic mechanisms to counteract the heat in deserts, dehydration and the potential to die from overheating vital organs. Counteracting the heat is achieved through a network of small arteries that intertwine with a network of veins (the **carotid rete system**) to cool the blood before it enters the brain, as shown in Figure 6.4.13b.

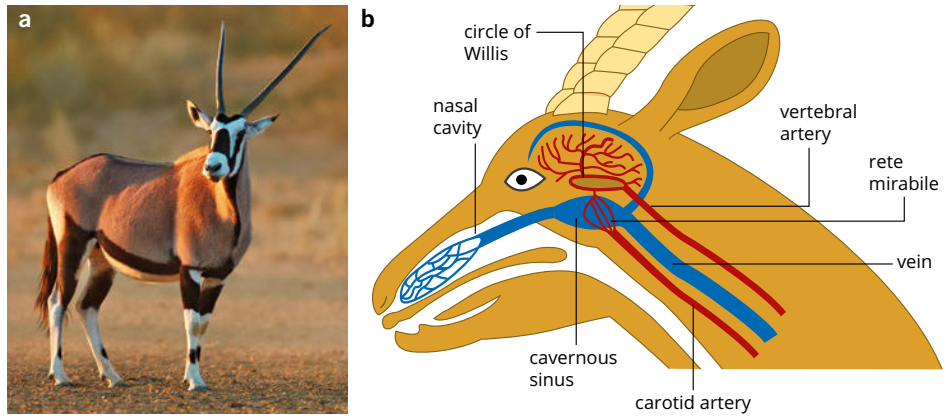


FIGURE 6.4.13 (a) A gemsbok oryx (*Oryx gazella*) in the Kalahari desert, South Africa. (b) The oryx's carotid rete system cools the hot arterial blood from the body before it enters the brain.

The blood in the veins is cooler because it has experienced evaporative cooling in the nostrils. It passes in the opposite direction to the warmer blood from the body in the arteries and the heat flows from the hotter to the cooler blood. This process is known as countercurrent heat exchange, and cools the blood entering the brain by several degrees.

Heat exchange for heating

Countercurrent heat exchange also occurs in animals living in extremely cold climates to reduce heat loss and maintain body temperature.

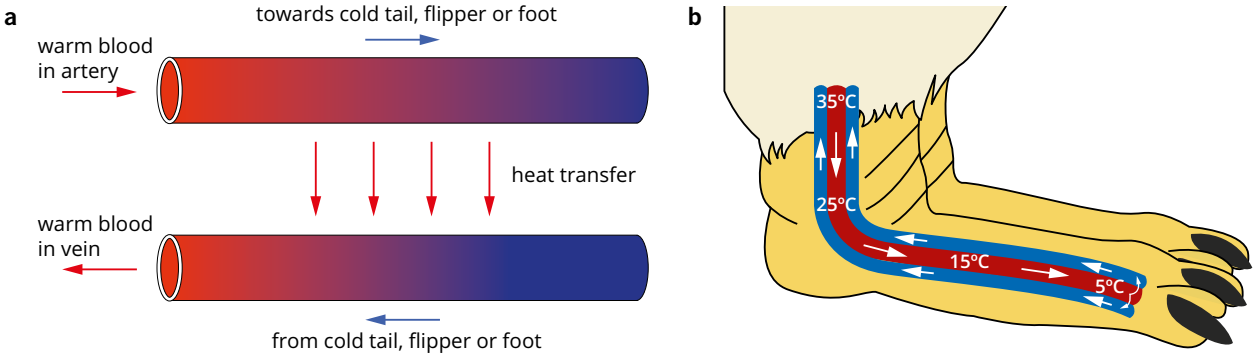


FIGURE 6.4.14 The heat exchange mechanism in the circulatory system of penguins ensures that heat loss at the extremities is minimised, while the core body temperature is maintained.

Penguins have heat exchangers in their flippers, feet and tails. These extremities have a relatively large surface area and are exposed to the cold, so they lose heat quickly. Blood from the feet flows back to the heart through veins close to the arteries. The warm blood in the arteries transfers heat to the veins so that blood moving back towards the heart is warmed, maintaining the penguin's body temperature (Figure 6.4.14). The blood travelling to the feet is cooled, so heat loss is minimised.

The diameter of the arteries flowing through the feet is also reduced to decrease the flow of blood to the extremities and further reduce heat loss. In this way, the cells in the feet receive oxygen and nutrients and remain warm enough to function, but less heat is lost to the environment.

Human responses to temperature change

Humans have an array of physiological mechanisms to cope with extreme temperatures (Figure 6.4.15), as do all endotherms. This section examines the human response to heat and cold.

Response to heat

Humans are one of the few animals that produce sweat to cool down. Evaporative cooling is a very effective way of losing heat energy from the body. A change of state from liquid to gas is an endothermic process; that is, it requires an input of energy. In evaporative cooling of the skin, this energy comes from your body, in the form of heat energy (Figure 6.4.16).

FIGURE 6.4.16 Sweating results in evaporative cooling and is one of the human body's homeostatic mechanisms to regulate body temperature.

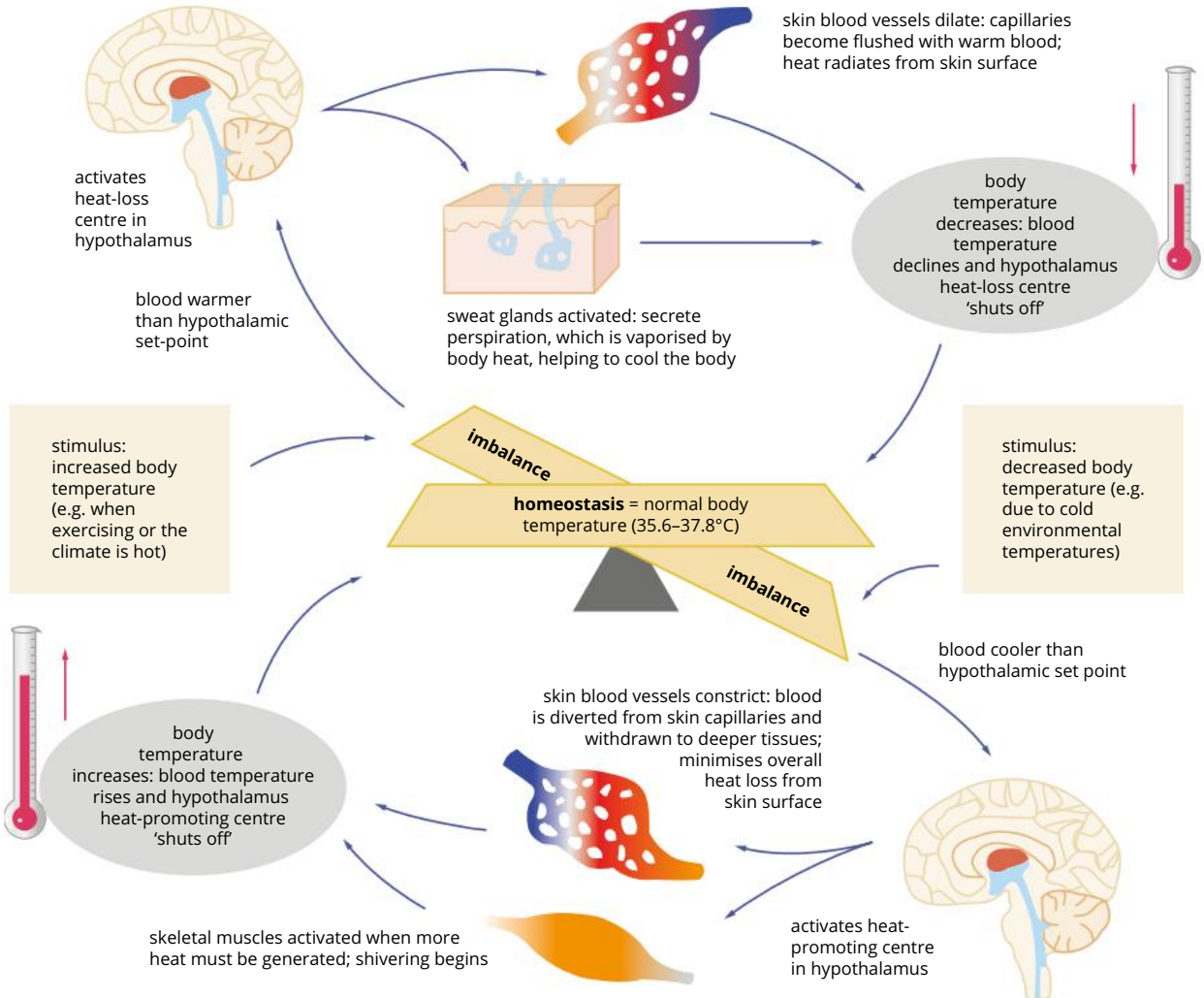


FIGURE 6.4.15 Thermoregulation in humans involves a range of regulatory mechanisms that function to maintain thermal homeostasis (normal body temperature) for optimal functioning of the organism.

Humans have two types of sweat glands: apocrine glands and eccrine glands. The function of apocrine glands is thought to be mainly scent or pheromone production, while the eccrine sweat glands function to control body temperature. These glands are distributed over much of the body and release sweat onto the skin surface through pores when your body temperature rises. These glands extend just below the surface of the dermis and secrete odourless sweat that is high in electrolytes and sodium. The rate of sweat secretion increases from almost zero in cold conditions to about 1.5 litres per hour in a hot environment. After about six weeks' acclimatisation to heat, this can increase to 4 litres per hour, which means a much greater evaporative cooling capacity is possible.

Some other voluntary and involuntary ways that your body responds to heat are:

- slowing the rate of cellular respiration in internal organs, which decreases heat generation, thus decreasing body temperature
- covering your body with water or spraying water on your skin to produce the same evaporative cooling effect as sweating
- swimming or bathing in cool water, which causes heat loss through conduction across the skin. Evaporative cooling also occurs when you are out of the water and your skin is still wet
- **vasodilation** (dilation of the blood vessels in the skin). Dilation means more blood is sent to the extremities. Heat is lost to the environment by radiation and convection (especially if it is windy)
- changing your body shape to increase its surface area; for example, by standing with your arms and legs outstretched
- removing clothing, which reduces the insulating effect of clothing layers and allows heat to escape from the skin
- moving out of sunlight into shade
- decreasing activity.

FIGURE 6.4.17 A close-up of a human forearm with goose bumps. The contraction of blood vessels and small muscles (arrectores pilorum) that are attached to the base of each hair follicle pull the hair into an upright position. In this position, the skin resembles plucked goose skin.

Response to cold

In humans, a number of nervous and endocrine responses occur rapidly to reduce heat loss from the body and to increase heat production when the body becomes too cold.

The following voluntary and involuntary responses reduce heat loss from the human body.

- **Vasoconstriction** (constriction of the blood vessels in the skin) reduces heat loss from the skin, as the amount of blood moving close to the exposed surface is reduced.
- **Piloerection** is the constriction of the piloerector muscles around hair follicles ('goose bumps'), which increases the insulating effect of the hairs (Figure 6.4.17). This response has a minimal effect in humans but in animals with thick fur, the layer of trapped air increases significantly and reduces heat loss from the body.
- Seeking shelter with less exposure to harsh winds and cold temperatures will maintain body heat for longer.
- Changing body shape or decreasing surface area (e.g. curling up to make yourself small) reduces the area exposed to the cold and reduces the rate at which heat is lost from the skin.
- Clothes trap a layer of air (which is the best insulator), so putting on more clothes will help keep you warm. Some fabrics are better than others at trapping air and increasing insulation.

The following responses increase heat production in the human body.

- Voluntary movement—during physical effort, the amount of heat produced by the muscles is increased.
- **Shivering thermogenesis**—the production of metabolic heat is increased through shivering. This involuntary movement of the muscles generates especially large amounts of heat. Shivering thermogenesis is stimulated by adrenaline.

- **Non-shivering thermogenesis** in brown fat—increased cellular activity in brown adipose tissue, which is a tissue specialised for heat production, causes the tissues to warm up. The heat produced is carried to other parts of the body in the blood.
- Increasing metabolism (the rate of cellular respiration)—metabolic processes in the internal organs are the main source of heat when the organism is at rest. In humans, around 60% of the energy released during cellular respiration is transformed into thermal energy. In humans, the overall metabolic rate, and therefore the rate of heat production, is controlled by hormones.
- **TRH (thyrotropin releasing hormone)** secretion by the hypothalamus—TRH acts on the anterior pituitary to secrete TSH (thyroid stimulating hormone). As the name suggests, TSH acts on the thyroid gland to release thyroid hormones, tri-iodothyronine (T3) and thyroxine (T4) (Figure 6.4.18). T3 and T4 hormones regulate metabolic processes, increasing heat production and body temperature.

The amount of T3 and T4 in the bloodstream is regulated by the pituitary gland by a negative feedback loop; if there is too much or too little T3 or T4, the pituitary gland reduces or increases the amount of TSH it secretes. This mechanism allows a very delicate regulation of the level of thyroid hormones in the blood.

The hormone insulin is also involved in thermoregulation. Insulin acts on temperature-sensitive neurons in the brain, which stimulate brown adipose tissue to produce heat. The release of heat from brown adipose tissue increases core body temperature.

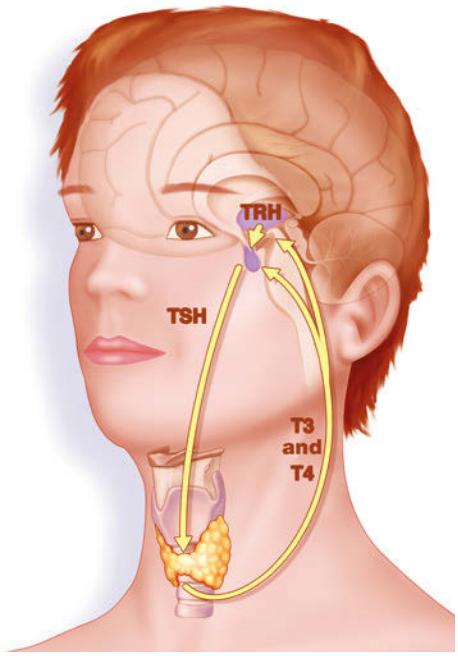


FIGURE 6.4.18 The thyroid is a gland that produces hormones that stimulate cellular respiration. The hypothalamus releases TRH, which stimulates the secretion of TSH by the pituitary gland, which in turn stimulates production of T3 and T4 hormones by the thyroid. The increase in cellular respiration creates thermal energy.

OSMOREGULATION IN COMPLEX ANIMALS

Some animals maintain water balance simply by living in environments where fresh water is freely available. Others can regulate the composition of their internal environment, allowing them to live in drier or saltier environments. **Osmoregulators** are animals that maintain the internal osmotic concentration of their body fluids regardless of external concentration changes. Animals that change the internal osmotic concentration of their body fluids to maintain the same osmotic concentration of the external environment (they remain in an isotonic state with their surroundings) are called **osmoconformers**. Most marine invertebrates are in this group.

PA 2.1.1

Maintaining water balance is necessary to control salt concentrations. Salts form ions in solution, and cells require the concentrations of ions to be held within narrow limits for biochemical processes to occur efficiently. Moreover, if internal salt concentrations are too high, water will move by osmosis out of cells into extracellular fluid (Figure 6.4.19). Some ions (such as the hydrogencarbonate ion) are also important for regulating the pH of body fluids, which must be at a suitable pH for enzymes and other molecules to function efficiently. Maintaining the correct concentrations of ions is achieved by regulating both water and salt balance.

Water balance involves regulating the intake and loss of both water and salts. In organisms, net movement of water into and out of cells occurs as a result of osmosis, which is regulated by solute concentrations. Water moves across a semipermeable membrane from regions of lower solute concentration (higher concentration of free water molecules) to regions of higher solute concentration (lower concentration of free water molecules).

The amount of water lost or gained throughout the day differs between individuals and depends on the amount of exercise, temperature, humidity, food and fluid intake. Urination rather than water intake is a better indicator of whether an individual has good water balance. A healthy person with adequate hydration usually urinates 4–8 times per day, and the urine is pale yellow.

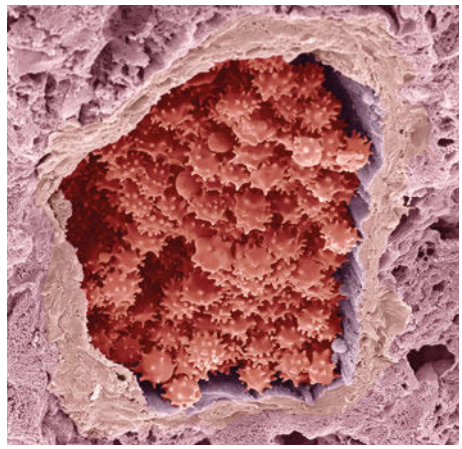


FIGURE 6.4.19 The maintenance of constant osmotic pressure in the blood is important because it prevents red cells from dehydrating or bursting. This scanning electron micrograph of a section through an arteriole shows crenated (wrinkled) red blood cells caused by dehydration, which distorts the red blood cell.

Water gain and loss

The total volume of fluid taken into the body depends on diet and activity levels, and typically varies from about 2 to 16 litres per day. The minimum water requirement for fluid replacement in a 70 kg person in a cool climate is about 3000 mL per day. Of this, about 400–600 mL is obtained by eating, and about 400 mL is produced by aerobic respiration. (This is called metabolic water because it is produced in cellular respiration.) The remainder of about 2000–2200 mL must be obtained by drinking.

For a 70 kg person, water will be lost mainly in urine (500–1500 mL per day), evaporation from the respiratory system (400–800 mL per day), sweat (100–800 mL per day), and faeces (100–200 mL per day).

Salt gain and loss

Salt intake varies greatly depending on diet. The three major salt groups in the human diet are sodium salts, potassium salts and calcium salts.

Daily sodium salt intake (mostly as sodium chloride) ranges from about 1 to 10 grams, mainly in bread, meat and processed cereal products. Highly processed foods usually contain more sodium salts than unprocessed foods. The recommended daily intake of sodium salts for Australians is 1.6 grams.

Daily potassium salt intake (mainly potassium chloride and potassium citrate) ranges from about 2.0 to 4.0 grams. The recommended daily intake of potassium salts for Australians is 4.7 grams. Highly processed foods usually have a much lower potassium salt content than unprocessed foods.

Daily calcium salt intake (mainly in dairy foods and green vegetables) is up to about 2.4 grams. The recommended daily intake of calcium salts for Australians is 1.0–1.3 grams, depending on age.

Salts are lost mainly in urine but also in sweat and faeces. The kidney filters excess salts from the blood and excretes them into the urinary system. However, most salts are reabsorbed into the blood plasma for recirculation to tissues.

Hormonal control of water balance

Water and solute concentration are monitored by **osmoreceptors** in the hypothalamus and **baroreceptors** in the atria of the heart. Osmoreceptors are sensitive to blood solute concentrations, while baroreceptors detect changes in blood pressure, which is an indication of the volume of blood. Collectively, these receptors detect the solute concentration in blood and extracellular fluid. The unit of measurement used for these blood solute concentrations is osmolality, because they contribute to osmotic effects on cells.

Osmolality is a measure of the concentration of particles (such as sodium ions and chloride ions) that affect osmosis.

Because cell membranes are permeable to water, the **osmolality** in the extracellular fluid is approximately the same as it is in the intracellular fluid (cytosol). Changes in the osmolality of the extracellular fluid will therefore affect cytosol concentrations, which can cause problems with cellular metabolic reactions. Compared to extracellular fluid, the cytosol of cells is high in potassium and magnesium and low in sodium and chloride ions.

Antidiuretic hormone (ADH), also called vasopressin, regulates water reabsorption. It is synthesised in the hypothalamus and transported to the posterior pituitary gland, where it is stored (Figure 6.4.20). When osmoreceptors in the hypothalamus detect an increase in the osmolality of the blood, a signal is sent to the posterior pituitary gland, and ADH is released.

ADH acts on the kidneys to increase the permeability to water of the distal tubules and collecting ducts. The collecting ducts run through the medulla of the kidney, which has high salt levels (and therefore a higher osmotic potential). This causes the absorption of water from the tubules back into the blood by osmosis, decreasing urine output; the urine becomes more concentrated and has a darker yellow colour. As the blood returns to a normal concentration, negative feedback stops the production of ADH.

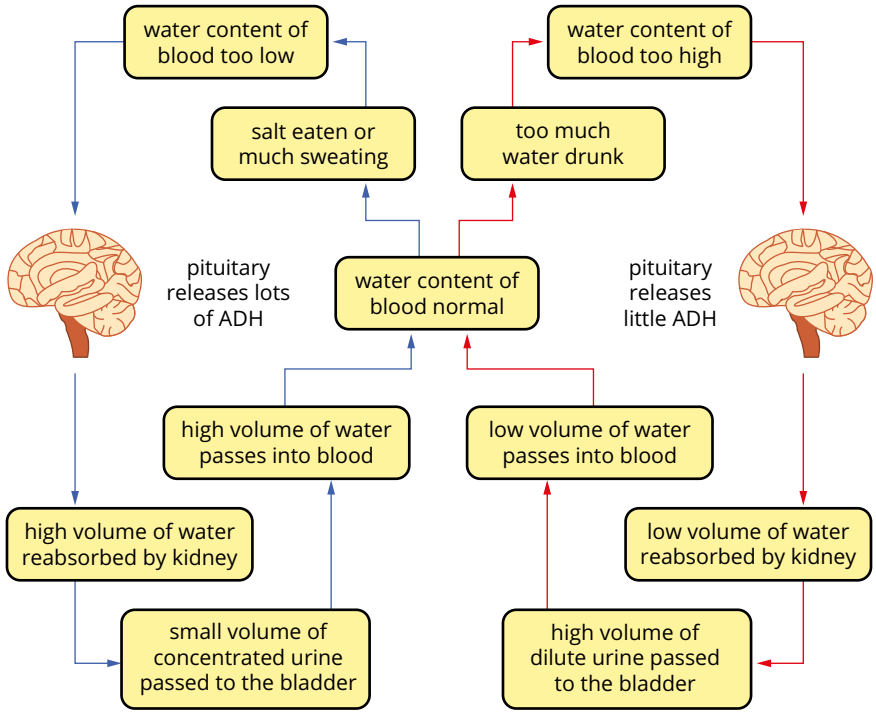


FIGURE 6.4.20 Hormonal control of water balance by antidiuretic hormone (ADH).

Conversely, if the osmoreceptors detect a decrease in osmolality (e.g. if too much water has been taken into the body), ADH release will be decreased. This reduces the reabsorption of water and consequently increases urine volume; the urine becomes more dilute and has a paler yellow colour (Figure 6.4.20).

A number of substances such as nicotine, alcohol and narcotics can interrupt the feedback control of water balance in the body. This can also occur because of pain, stress or hypothermia (lowered body temperature).

Changes in blood osmolality or blood pressure also stimulate counteracting response. Initially an enzyme called **renin** is secreted from the kidneys in response to these changes (Figure 6.4.21). Renin then triggers a series of reactions involving other hormones that results in the release of **aldosterone** from the adrenal glands situated above the kidney. Aldosterone simultaneously regulates sodium and potassium levels by increasing potassium excretion into the urine and causing sodium reabsorption into the blood. This causes more water to be drawn into the blood by osmosis, thus increasing blood volume and pressure.

A lack of aldosterone can result in low sodium levels, high potassium levels and high acid levels in the blood. These are potentially dangerous conditions. People with an aldosterone deficiency suffer from Addison's disease and must take a synthetic hormone called fludrocortisone acetate to manage this condition.

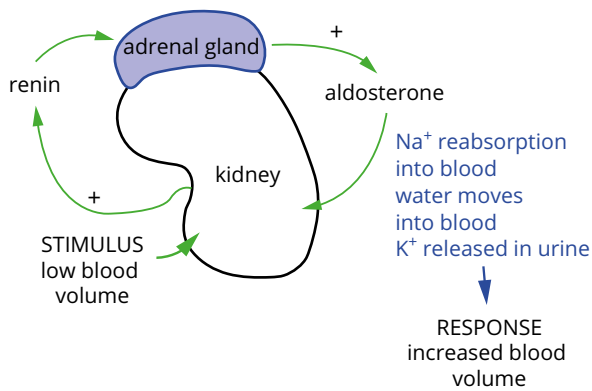


FIGURE 6.4.21 Hormonal control of blood volume. The stimulus for this negative feedback loop is low blood volume.

WS 2.1.3 PA 2.1.2

OSMOREGULATION IN PLANTS

Structural features of plants

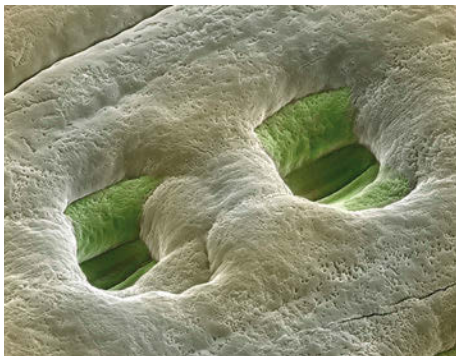


FIGURE 6.4.22 A scanning electron micrograph of the sunken stomata of a needle leaf of the coastal sitka spruce (*Picea sitchensis*).

Water is essential for photosynthesis. Therefore, a large number of structural features that we observe in plants reduce water loss caused by salinity, heat and wind in the environment. These features include:

- leaf surface area
- few stomata
- stomatal hairs that create a humid microclimate
- sunken or protected stomata
- thick, waxy cuticle
- extensive root systems
- rolled leaves
- leaves orientated away from the sun.

Plants that grow in dry, hot environments are known as **xerophytes** (from Greek *xeros*, meaning 'dry', and *phyton*, meaning 'a plant'). Some of their adaptations are discussed in more detail below.

Cacti are well-known xerophytes. Xerophytes have structural features that conserve moisture and prevent the leaf temperature from rising too much. They also have an increased tolerance to desiccation (drying). Some of the adaptations of xerophytes are shown in Figures 6.4.22 and 6.4.23.

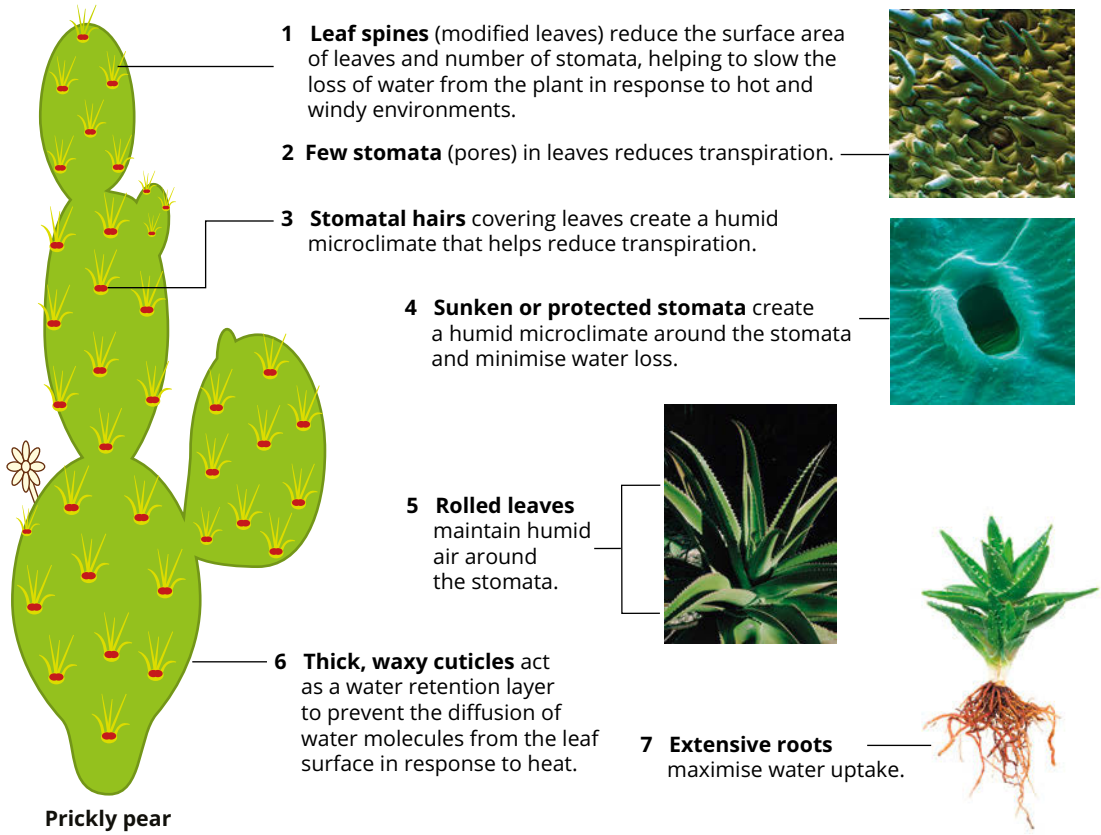


FIGURE 6.4.23 Plants that live in harsh, dry environments such as deserts, have evolved features that enable them to conserve water.

Marram grasses (*Ammophila* species) are xerophytes that grow well in the salty, sandy soils of coastlines (Figure 6.4.24a). When conditions are hot and dry, thin-walled bulliform (bubble-shaped) cells partially collapse, causing the leaves to roll inwards, reducing water loss. Hairs on the inside of the rolled-up leaf trap moisture, creating a humid microclimate (Figure 6.4.24b). This humidity reduces the concentration gradient between the outside and inside of the leaf, which reduces transpiration. Because of this and other adaptations, these grasses can survive in and then stabilise sand dunes that are prone to erosion.

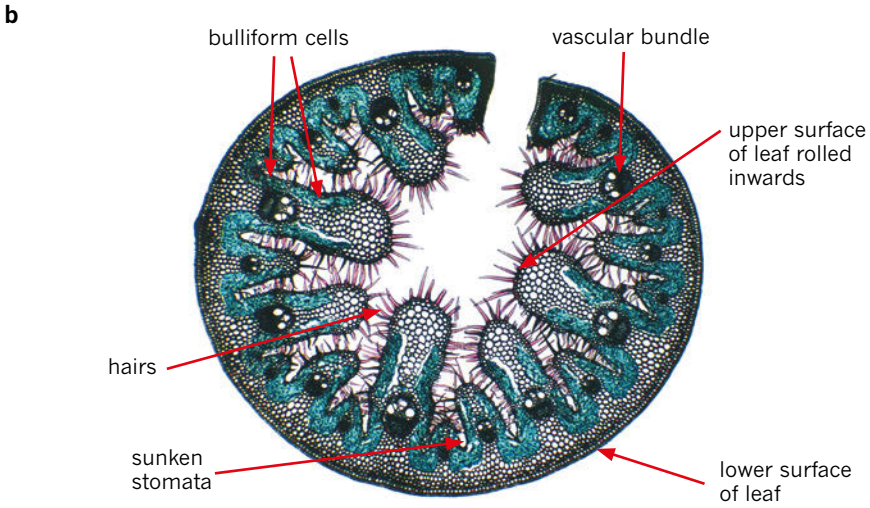


FIGURE 6.4.24 (a) Marram grasses (*Ammophila* species) grow well in the salty, sandy soils of coastlines. They have features and mechanisms that allow them to survive in this dry, salty environment. (b) One of these mechanisms is leaf rolling. This enables the plant to trap moisture and reduce water loss.

Eucalypt trees also have structural features that enable them to survive in hot, dry environments. They have hard leaves with waxy cuticles on both sides to reduce water loss. In many species the leaves also hang vertically, which reduces the amount of direct sunlight they receive (Figure 6.4.25) and so reduces transpiration and water loss.

FIGURE 6.4.25 The leaves of this adult eucalypt tree are hanging downwards, reducing their exposure to sunlight. This structural feature reduces transpiration in hot, dry climates.

Physiological mechanisms in plants

Plants inhabit an incredible range of environments, from the hottest deserts to high mountain peaks, fast-flowing rivers and even the coastal intertidal zone. So they need an equally impressive range of physiological mechanisms to cope in what are often stressful conditions. These mechanisms play an important role in enabling plants to meet environmental challenges.

Crassulacean acid metabolism, also known as CAM photosynthesis (see Module 3.3), is an example of a physiological adaptation that enables improved efficiency in water storage and use in plants. It is most commonly found in plants living in dry environments, such as succulent plants in deserts. Some xerophytes and some plants adapted to saline conditions can minimise water loss during the heat of the day by using the CAM metabolic pathway.

In CAM plants, the stomata open only at night to collect carbon dioxide. Rather than using the carbon dioxide immediately, as non-CAM photosynthesising plants do, it is stored as malic acid in cell vacuoles. During the day the malic acid is transported to the chloroplasts, where it is used to produce the carbon dioxide needed for photosynthesis (Figure 6.4.26). By storing the carbon dioxide required for photosynthesis at night, the plant is able to close its stomata during the heat of the day to reduce water loss. This physiological mechanism allows plants to survive in environments of extreme heat and aridity.

The range of environmental conditions in which an organism can survive is called its **tolerance range**.

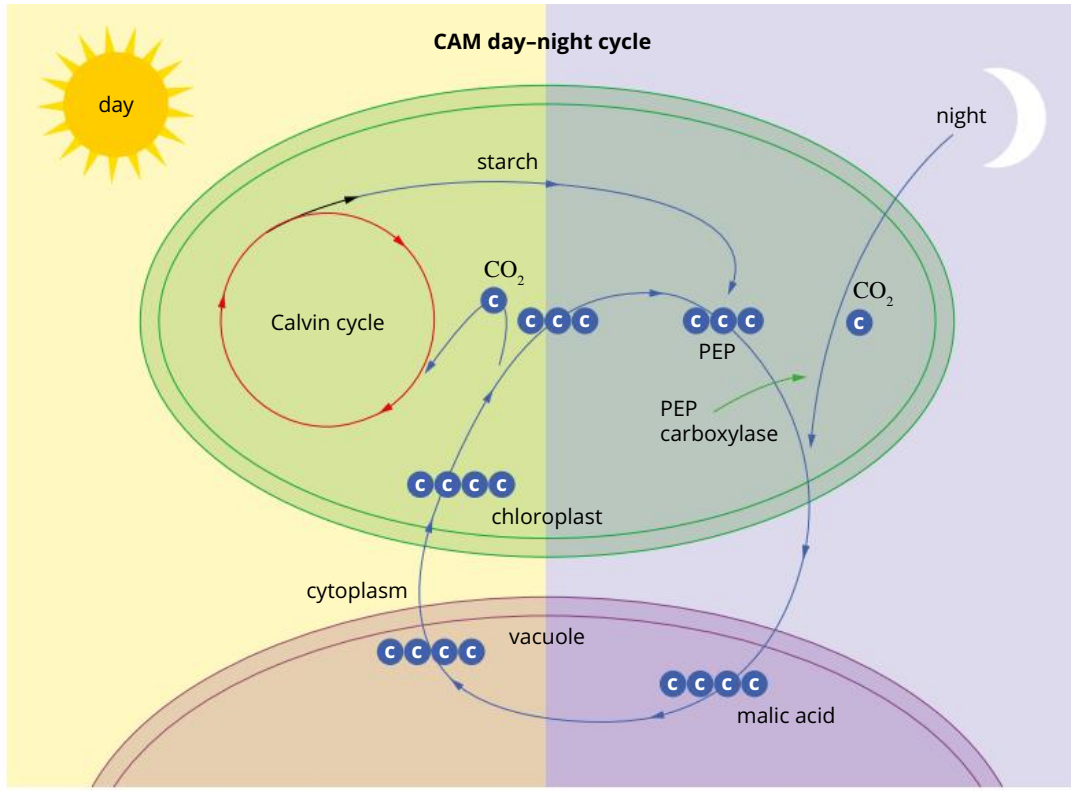


FIGURE 6.4.26 A summary of the complex CAM metabolic pathway of some plants in hot and dry or saline environments. This metabolic pathway enables the plants to absorb and store carbon dioxide at night to avoid losing precious water during the day. 'C' denotes the number of carbon atoms in each molecule.

Salinity is a major problem for many agricultural crops. In many areas, over-irrigation of agricultural land has resulted in highly saline soils, which most food crops cannot tolerate. Saline soils disrupt water and nutrient uptake by the roots, suppressing plant growth. When salt enters the plant's cells, it causes ion imbalance, inhibiting metabolic processes, and eventually leads to cell death. Plants living in saline environments such as coastal dunes, salt marshes or salt lakes have evolved physiological mechanisms to cope with the salinity. Plant species that can survive high salinity are known as halophytes (from Greek *halos*, meaning 'salt' and *phyton*, meaning 'plant') (Figure 6.4.27). These plants use a variety of mechanisms to exclude or regulate the concentration of salt in their tissues.

Some of the many physiological mechanisms that plants have evolved to cope with salinity include:

- compartmentalisation of ions within the cells and tissues of the plant by transporting excess salt to vacuoles or old tissue. This avoids the toxic accumulation of salt in the cytoplasm
- excluding salt at the roots and leaves by:
  - shedding leaves that are overloaded with salt
  - excreting salt from salt glands
  - pumping salt out of the roots
  - controlling transpiration to avoid excess salt being delivered to the shoots from the soil
  - balancing the rate of growth with the uptake of soluble ions to maintain a constant salt concentration in tissues
  - increasing water uptake to dilute salt concentrations in tissues.

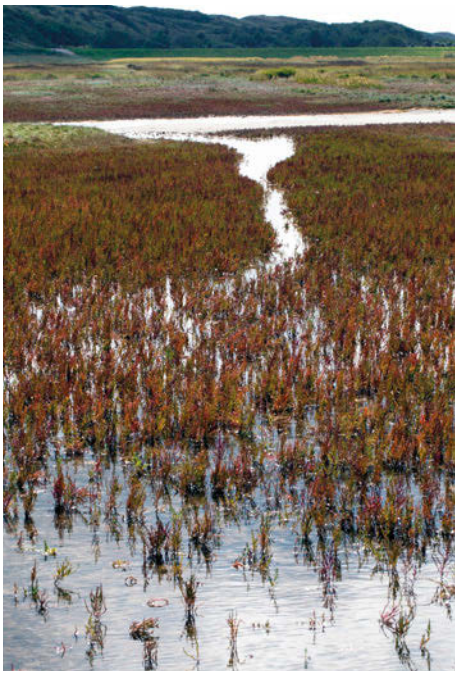


FIGURE 6.4.27 *Arthrocnemum indicum* is a coastal halophyte adapted to living in a highly salty environment. This species is able to control salt levels by increasing water uptake.

Homeostatic mechanisms in plants

As mentioned in Module 6.3 and listed in Table 6.3.2 (page 248), there are five major groups of plant hormones. Plant hormones are involved in the loss of plant organs, the process known as abscission. The three hormones involved in abscission are ethylene, auxin and abscisic acid. When production of these hormones is stimulated by a lack of water, saline soils, cold temperatures or frost, it signals to plant organs that they will be undergoing some sort of stress, and then stimulates responses that help the plant protect itself.

For example, in some plants, receptors in the roots respond to the drying out of the soil by releasing abscisic acid into the xylem tissue. The secreted abscisic acid then moves with the root-absorbed water to the leaf epidermis. Under continued drought conditions, abscisic acid can also cause the dropping off, or abscission, of flowers, immature fruits and leaves. It does so by causing the disintegration of a special layer of cells (abscission zone) that are located at the base of the plant structures. Shedding of leaves reduces the surface area exposed to dry air and slows the water loss in the plant (Figure 6.4.28).

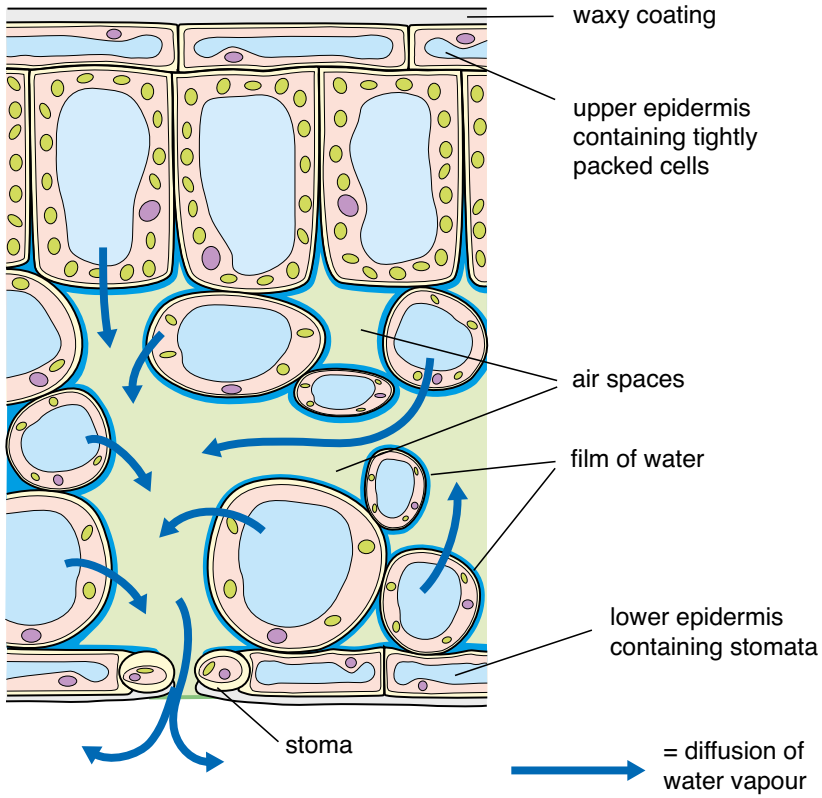


FIGURE 6.4.28 Under drought conditions, abscisic acid released from the plant's roots into the xylem makes its way up to the leaf epidermis and causes the closure of the leaf stoma. This prevents the loss of water vapour by simple diffusion.

Hydrophytes

So far, the emphasis has been on plants subjected to severe conditions involving a lack of water, high temperature or high salinity. Another group of plants, called **mesophytes**, have features that allow them to thrive in moist habitats and require well-aerated soils. These plants have fibrous roots and the ability to produce rhizomes, corms or bulbs for water and food storage.

But there are a group of specialised plants known as **hydrophytes** that only live in water, and their need is for CO_2 and light for photosynthesis. These plants, which include water hyacinths and *Elodea*, have generally got thin or reduced cuticles and a reduced root system. Stomata in land-based plants are mainly on the underside of the leaves, but in hydrophytes they are present only on the upper surface of the floating leaves. Submerged leaves generally do not have many stomata. These plants will also have air sacs and less vascular tissue. This assists their flotation to the surface, or as close to it as possible, in order to be exposed to as much sunlight as possible (Figure 6.4.29).

FIGURE 6.4.29 Hydrophytes are plants specially adapted to living in or under water.

WS 2.1.6

Cool clothing

As homoeothermic organisms, humans metabolise 70–110 watts of heat when resting. However, under physical stress or exertion, adults can generate >1000 W of heat energy. This becomes an issue when the person is fighting a fire, working near furnaces, in toxic waste disposal, or perhaps is on a spacewalk around the International Space Station attending to repairs. The excessive heat loads being generated cannot be dissipated by the normal means of human thermoregulation. Instead, the heat is retained by the wearer's protective clothing (Figure 6.4.30).

Research has been conducted since 1959 on the design and manufacture of protective clothing that has built-in cooling systems. It is generally agreed that a form of liquid cooling system (very much based on the efficiency of the human vascular system) be somehow utilised to carry body heat away from the skin surface of the wearer and dissipate it into the surrounding environment. Since then, the design of Microclimate Liquid Cooling Systems ($_{LQ}$MCSs) has been a priority for bioengineers and different versions of $_{LQ}$MCSs are commonly used today.

However, their efficiency, manoeuvrability and wearability vary greatly. A.D. Flouris and C.C. Cheung in *Design and Control Optimization of Microclimate Liquid Cooling Systems Underneath Protective Clothing* (2006) noted the following areas for future research and development of $_{LQ}$MCSs:

- Replace polyvinyl chloride as the transport tube because it is a natural heat insulator.
- Because of manufacturing difficulties, garments are all of a generic size; however, one size never fits all.
- Ensure that tubing is evenly spread throughout the whole garment.
- There is no integrated 'Command Control' centre. More research is required in order to achieve an optimum automatic control design for $_{LQ}$MCSs.

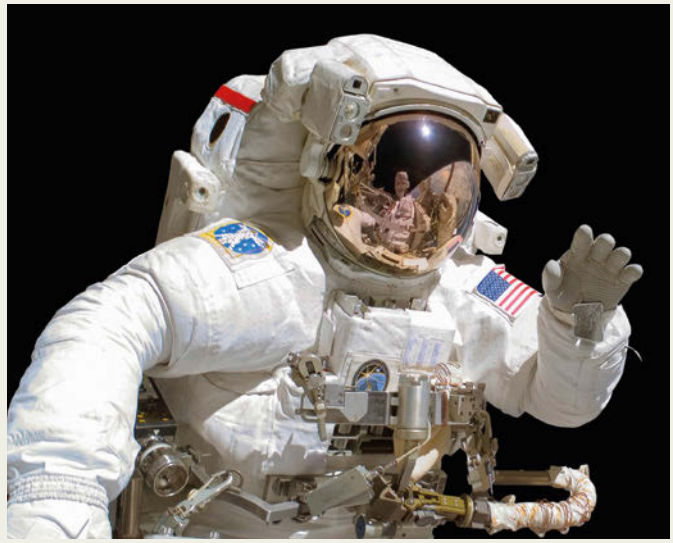


FIGURE 6.4.30 Current $_{LQ}$MCSs such as this spacesuit, are bulky and not as sophisticated as the human thermoregulatory system. Research is ongoing to make the suits more thermoregulatory and ergonomically efficient.

Review

1. Compare the similarities of the human thermoregulatory system with the first three recommendations for future research of $_{LQ}$MCSs, and contrast their differences.
2. Using your knowledge of human thermoregulation, determine what components need to be present when designing an 'integrated command centre' for an $_{LQ}$MCSs.

6.4 Review

SUMMARY

- A change in the temperature of the hypothalamus initiates regulatory responses that can involve heat production or heat exchange.
- Temperature receptors are found in the skin and hypothalamus.
- Heat is lost from the body by conduction, convection, radiation and evaporation.
- The responses to reduce heat loss are vasoconstriction and piloerection.
- The responses to generate heat are voluntary movement, shivering thermogenesis, non-shivering thermogenesis and increasing the rate of cellular metabolism.
- The responses to heat are sweating or perspiring, covering your body with water and vasodilation
- Structural adaptations of animals include thick fur and blubber (fat), which insulates against cold; large ears to increase heat loss and small ears to reduce heat loss.
- Behavioural adaptations of animals to lose heat include huddling for warmth, panting, licking skin, wallowing and gular fluttering, seeking shade or sunlight, nocturnal activity and burrowing.
- Physiological adaptations of animals include countercurrent heat exchange mechanisms, dormancy, hibernation, torpor and aestivation.
- Water enters body cells throughout the day from: drinking, eating and cellular respiration.
- Salt is gained from our diet.
- Water is lost from the body mainly as urine, in faeces, across the skin and from the lungs.
- Salt is lost through: the skin, kidneys and faeces.
- Osmoreceptors in the hypothalamus and baroreceptors in the atria of the heart detect the osmolality of the blood.
- An increase in osmolality causes a release of ADH from the pituitary, which acts on the kidney to increase water absorption back into the blood.
- As a result, osmolality of the blood decreases and the blood volume increases and urine concentration increases and urine volume decreases.
- A decrease in osmolality causes decrease in ADH levels and urine volume will increase.
- Low blood volume stimulates the secretion of aldosterone.
  - Renin is secreted from the kidneys
  - Renin causes release of aldosterone
  - Aldosterone causes absorption of sodium into the blood
  - Aldosterone causes potassium excretion into the urine
- As a result of this multiple hormone action blood volume and blood pressure increase.
- Structural adaptations of plants include:
  - reduced leaf surface area
  - fewer stomata
  - stomatal hairs to create a humid microclimate
  - sunken or protected stomata
  - thick, waxy cuticle
  - extensive root systems
  - leaf shape: rolled leaves; reduced surface area
  - leaves orientated away from sunlight.
- Physiological adaptations of plants include CAM, salinity tolerance (halophytes), drought tolerance (xerophytes) and water abundance (hydrophytes)
- Plants respond to dry soil conditions by their root cells secreting abscisic acid, which passes up the xylem tissue to the leaf epidermis and stimulates the closing of stomata.

KEY QUESTIONS

Retrieval

1 Recall three mechanisms humans use to produce heat.

2 **a** Describe what osmolality measures.
b Identify two receptors that detect changes in osmolality in the blood.

3 Define what ABA is and describe what it does.

4 Identify and list structural features of xerophytic plants.

5 Identify and explain at least one structural feature, one physiological mechanism and one behavioural response that the emperor penguin uses to survive in the Antarctic environment.

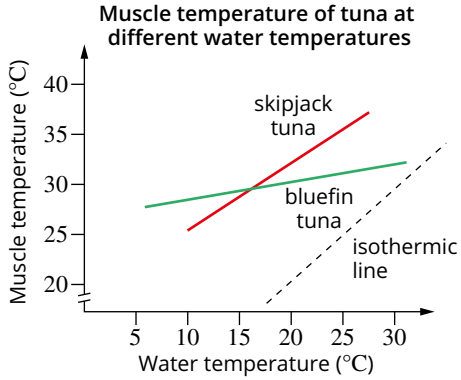
Comprehension

6 All organisms exchange heat with their environment. Using examples, summarise and explain each of the four methods of heat exchange.

7 Using a well-annotated diagram, represent the process of hormonal control of sodium and potassium levels by renin and aldosterone.

Analysis

8 Groups of two species of tuna (skipjack and bluefin) were kept in water at different temperatures. Maximum muscle temperature was measured in fish of each species taken from different water temperatures. The collected data is shown on the graph. The isothermic line represents tissue temperature equivalent to water temperature. If the muscle temperature of a fish is parallel to the isothermic line, it means that the muscle temperature is a constant value above the ambient water temperature.



a Identify, at a water temperature of 25°C, the muscle temperature for:
i skipjack tuna
ii bluefin tuna.

b i Explain the difference between an endotherm and an ectotherm.
ii Fish are ectotherms. Infer why there is such a difference between muscle temperature and water temperature for each species.

9 Occasionally an individual is born without sweat glands, and cannot lose heat or water through their skin. A person without sweat glands and a person with normal sweat glands were placed in cool, dry conditions and their skin and mouth temperatures were recorded. The two people were then placed in a moist, hot environment, and further recordings were made. The results of the experiment are recorded in the table. Deduce which person (A or B) was born without sweat glands. Explain your reasoning.

Response	Person A		Person B	
	Cool, dry	Hot, moist	Cool, dry	Hot, moist
skin temperature (°C)	33.8	40.5	32.7	37.4
oral temperature (°C)	36.9	38.6	36.8	37.2
water loss from skin and lungs (mL)	not recorded	20.0	not recorded	282.0
urine volume (mL)	not recorded	280.5	not recorded	12.6

MP 4

Comparing stomata and guard cell distribution in leaves

Research and planning

Aim

- To prepare mounts showing stomata and guard cells.
- To compare the distribution of stomata and guard cells in plants from different environments.

Rationale (scientific background to the experiment)

The leaf is the primary site of photosynthesis in plants. In order to carry out photosynthesis, gases and water vapour must be exchanged with the environment. The stomata and guard cells control the movement of these substances into and out of the plant.

Stomata and guard cells also play an important role in osmoregulation in plants. When stomata are open, water vapour exits the plant. The exiting water pulls water up the xylem vessels from the roots, ensuring continuous one-way flow of water from roots to leaves, known as transpiration.

Up to 90% of water loss in plants occurs through transpiration. This significant amount of water loss is a problem for plants living in environments with limited water. Consequently, plants have adapted several structural features that reduce the rate of transpiration, a number of which relate to stomata and guard cells.

You will examine the stomata and leaves from a range of plants adapted to live in various environments to identify structural adaptations in plants.

Timing

60 minutes

Materials

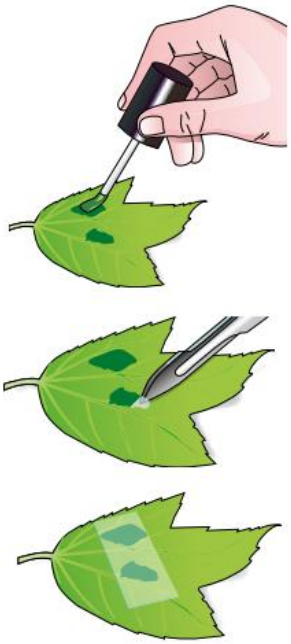
- light microscope
- microscope lamp
- leaves from various plants (e.g. *Eucalyptus*, *Bergenia*, lily)
- clear fingernail polish
- clear sticky tape
- microscope slides
- forceps
- scalpel
- scissors

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.

Part A Preparing slides



1. Paint three thick 1 cm^2 squares of nail polish on one side of the leaf being studied. Do not paint the polish over the leaf veins.
2. Allow the nail polish to dry.
3. Use the scalpel to carefully lift one corner or side of the dried nail polish. Continue carefully separating the polish from the leaf with the scalpel or forceps.
4. Tape a piece of sticky tape to the patch of nail polish.
5. Tape the peeled nail polish to a microscope slide. Use scissors to cut off any excess tape.
6. Label the slide, indicating the leaf type and location (e.g. *Eucalyptus*, top, or *Bergenia*, bottom).

7. Repeat the above steps to make mounts for the remaining nail polish patches, and for the top and bottom sides of each leaf.

Part B Viewing and drawing slides under the light microscope

1. Set your microscope up on the workbench.
2. Calculate the field of view diameter at ×400 magnification.
3. View each of the slides you have prepared at ×400 magnification. You may need to close the condenser aperture to better observe the stomata and guard cells.
4. Sketch what you observe under the microscope, labelling any stomata, guard cells and epidermal cells.
5. Count the number of stomata in your field of view, and record this in a table. Include stomata in your count only if you can see the entire opening.
6. Repeat for the other two patches you have prepared.

Analysing

Raw data

1 Complete the table.

Leaf species	Epidermal layer (top or bottom)	Number of stomata viewed			Average number of stomata
		Sample 1	Sample 2	Sample 3	

Processed data

2 Sketch the epidermal layer using the ×10 objective lens. For each diagram, include: slide title, magnification, scale, labelled organelles.

3 Use the two formulae below to calculate the area of the field of view (FOV) and the density of stomata for each leaf. Record these values in the table:

$$\text{FOV area} = \pi \times \left(\frac{1}{2}\,\text{FOV diameter}\right)^2$$

$$\text{stomata density} = \frac{\text{number of stomata}}{\text{FOV area}}$$

Leaf species	Epidermal layer (top or bottom)	FOV diameter (mm)	FOV area (mm^2)	Number of stomata	Stomata density (stomata/mm^2)

➤ 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

4 Explain why it is important that you did not touch the nail polish with your fingers.

5 Explain why you needed to use three samples for each side of each leaf.

6 List the species and leaf side for which you saw stomata and guard cells.

7 The distribution of stomata and guard cells in leaves is a structural adaptation to reduce excessive water loss while still allowing gas exchange to occur. Review the density of stomata and leaves, and account for the distribution patterns you observed based on the plant's known habitat.

8 Did any of the leaves you observed lack stomata entirely? Explain why.

➤ Reflect and check that your analysis demonstrates these characteristics

- ☐ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis
- ☐ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships
- ☐ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis

Interpreting and communicating

Conclusion

1 Summarise the relationship between stomata density, stomata location, and plant habitat.

Evaluation

2 Suggest why a higher magnification may not be beneficial for this experiment.

3 Explain whether the potential errors you identified above had a significant effect on your conclusions. In other words, do you consider the level of uncertainty caused by the potential errors reasonable?

Improvements

4 If you were to repeat this experiment, identify the steps that you would do differently. Consider how you:

- **a** might change the methodology
- **b** might improve your technique
- **c** could reduce error and uncertainty.

Extension

5 Search the internet for images of stomata for two of the plant species you observed. Ensure the images have a scale. Print out the micrographs and calculate or measure the size of the stomata.

6 Determine the average rainfall for the area where you live. Suggest which plant species you observed would be best suited to grow in your area.

7 Search the internet for images of stomata on plants that live in deserts. Print out the micrographs, calculate stomata density and explain stomata distribution.

➤ 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

WS 2.1.7 WS 2.1.8

06

KEY TERMS

abscisic acid
action potential
adaptation
adrenaline
aestivation
afferent (sensory) neurons
aldosterone
amyloplasts
antidiuretic hormone (ADH)
autonomic nervous system
auxin
axon
baroreceptor
brumation
carotid rete system
catecholamine
central nervous system (CNS)
chemoreceptor
cortisol
countercurrent blood flow
cytokinin
dendrite
dopamine
effectors
efferent (motor) neuron
eicosanoid
endocrine system
endotherm
enteric nervous system
ethylene
external environment
exteroreceptor
gibberellin
gravitropism
heat exchange
hibernation
homeostasis
hormone
hydrophyte
insulin
internal environment
interneuron
interoreceptor
kleptothermy
mechanoreceptor
mesophyte
myelin sheath
negative feedback loop
neuron
neurotransmitter
nociception
nociceptor
nodes of Ranvier
non-shivering thermogenesis
osmoconformer
osmolality
osmoreceptor
osmoregulator
oxytocin
parasympathetic division
peripheral nervous system (PNS)
photoreceptor
phytochrome
phytohormone
piloerection
polarised
positive feedback loop
receptor
reflex
renin
shivering thermogenesis
signal transduction
soma
steroid
stimulus
sympathetic division
synaptic terminal
thermoreceptor
thigmonasty
thyroid hormone
tolerance range
TRH (thyrotropin releasing hormone)
torpor
vascularised tissue
vasoconstriction
vasodilation
xerophyte

KEY QUESTIONS

Retrieval

1 Homeostasis in an organism is achieved by:
- **A** external conditions.
- **B** enzymic reactions.
- **C** negative feedback loops.
- **D** mostly positive feedback loops.

2 Identify which of the ions listed below does not assist in the generation of an action potential.
- **A** Na^+
- **B** Li^+
- **C** Ca^{2+}
- **D** K^+

3 Gibberellins, cytokinins and auxins are all recognised examples of:
- **A** phytohormones.
- **B** osmoregulation hormones.
- **C** thermoregulation hormones.
- **D** mammalian reproductive hormones.

4 Hibernation, brumation and aestivation are recognised as different forms of:
- **A** homeostasis.
- **B** torpor.
- **C** physiological mechanisms.
- **D** kleptothermy.

5 Recall which two systems are the most important in regulating the internal environment of animals.

6 Identify which type of nervous system response protects the body from further pain and injury.

Comprehension

7 Using your understanding of plant hormones, explain why placing a ripe banana next to an unripe avocado will cause the avocado to ripen.

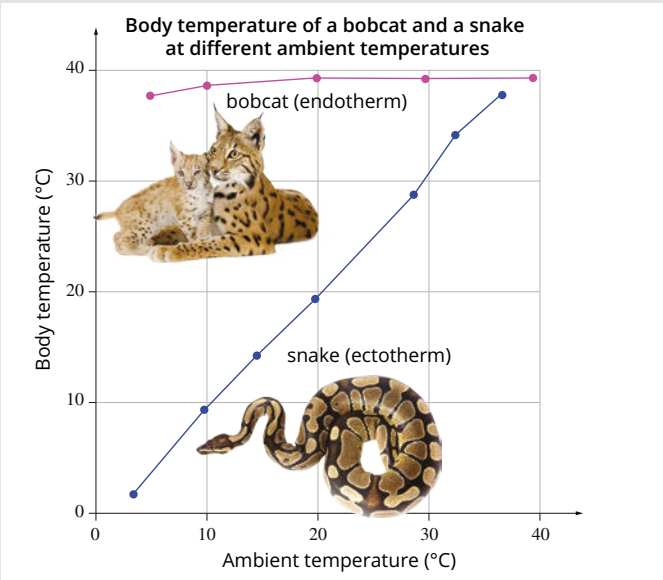
8 Describe how signal transduction occurs from one neuron to the next neuron.

9 Explain the role of ADH in homeostasis.

10 Jack rabbits, which are often found in deserts, have disproportionately large ears that have a rich network of blood vessels close to the skin. Kangaroos have a special network of capillaries that lie near the surface of the skin on the inside of the forearms. On very hot days, kangaroos can often be seen licking their forearms.
Identify the type of homeostatic mechanism employed and explain how this common feature might help each animal regulate its temperature.

11 **a** Explain the principle of negative feedback in maintaining homeostasis.
b Using a diagram, explain how a decrease in body temperature can be reversed. In your diagram, draw and label an arrow to show where negative feedback occurs.

12 Endothermic and exothermic animals regulate their body temperatures in different ways. Consider the following graph, which shows the body temperatures of a bobcat and a snake for different ambient environmental temperatures.
a When the ambient temperature is 30°C, state the body temperature of the snake.
b Explain why the body temperature of the snake continues to increase as the ambient temperature increases, but the body temperature of the bobcat does not.



Analysis

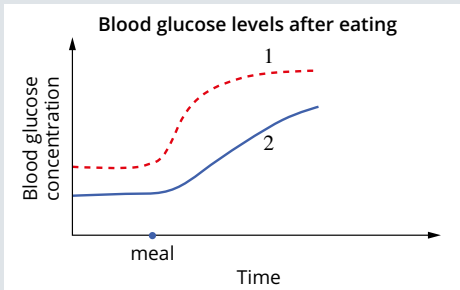
13 The pituitary gland was formerly called the 'master' gland, yet it is stimulated by two hormones released by the hypothalamus. Evaluate which gland truly does deserve the title of the 'master'.

14 *Clostridium botulinum* is a bacterium that grows in poorly preserved foods. It produces a toxin that binds to the membrane of vesicles containing acetylcholine. Acetylcholine is an important neurotransmitter. One of its functions is as a signalling molecule used at neuromuscular junctions with skeletal muscles.
a Describe a neuromuscular junction.
b Determine how the botulinum toxin could disrupt nerve transmission.
c Provide a justified prediction for the symptoms you would expect to see in a person with botullism (*Clostridium botulinum* toxin poisioning).

15 Cortisol is an important human hormone. It has a role in glucose regulation, immune system regulation and regulation of metabolic rate.
a Despite its role in many aspects of human physiology, not all cells respond to cortisol. Explain why some cells do not respond to cortisol.
b Insulin is the hormone that stimulates the uptake of glucose by cells. Fat and muscle cells are generally particularly sensitive to insulin but cortisol is known to limit their response to this hormone. Infer how cortisol could reduce the normal response by fat and muscle cells.

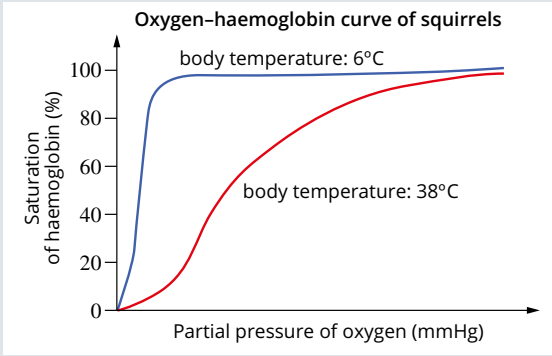
16 You will recall from Module 6.4 the physiological aspects of hibernation, which is a form of torpor. Mammals that hibernate are generally quite small (bats, rodents and pigmy possums) and yet bears (brown, black, grizzly or polar) are also said to be hibernators. A bear's body temperature may only drop a few degrees, compared to other hibernators whose temperatures can go down to as little as 5°C.
Based on what you know of torpor and hibernation, judge whether or not bears are true hibernators.

17 Blood glucose levels in individuals with and without diabetes, after eating similar meals are shown in the graph below.



a Determine which results (1 or 2) displayed on the graph represents the individual with diabetes. Explain your reasoning.
b Draw a diagram to represent the negative feedback model for the control of blood glucose levels in the body.

18 During hibernation, the oxygen–haemoglobin dissociation curve of squirrels shifts to the left as shown on the graph below. This means that oxygen binds more readily to haemoglobin in the blood. Determine how this might be an advantage to a hibernating animal.



19 The table below shows the rate and relative percentage of blood flow to the various organs and tissues of the body at rest and during strenuous exercise.

	Blood flow			
	Rest		Exercise	
	Amount ($mL\,min^{-1}$)	Proportion of total (%)	Amount ($mL\,min^{-1}$)	Proportion of total (%)
Brain	750	13	750	5
Heart	250	5	750	5
Muscle	1200	20	12 500	71
Skin	500	9	1900	11
Kidney	1100	19	600	3
Abdomen	1400	24	600	3
Other	600	10	400	2
Total	5800		17 500	

- **a** Assess by what factor the blood flow rate increases from rest to exercise.
- **b** Distinguish which organs/tissues experience a decrease in blood supply from those that have an increase.
- **c** Determine why these changes occur.
- **d** Interpret from the data which organs/tissues have the greatest overall increase or decrease in their blood supply.
- **e** Infer whether or not the data indicates that the demands of the brain are any different during exercise.

Knowledge utilisation

20 The following question is based on your having completed Mandatory practical 4. Ideally, you would have examined a range of plant leaves from open forest, grassland, aquatic systems and closed or rainforest plants to ascertain stomatal distribution. You would have carefully noted the distribution of the stomata for each type of plant and have devised an overall theory of stomatal distribution of Australian plants.

But you may not have encountered beaded samphire (*Sarcocornia quinqueflora*), which is a common succulent halophyte growing in salt marsh areas that are regularly inundated by tides along most of the Queensland coast.

- **a** Based on your experimental results, predict the stomatal and guard cell distribution of this plant.
- **b** Having made your prediction, list in order of preference (whether or not you have access to coastal regions), the steps you will take to validate your statement.

21 Experiments have shown that plants show positive phototropism as the result of the movement of auxin to the side of the shoot that receives less light. Devise experiments to demonstrate the following research statements and briefly list the procedures you would follow.

- **a** Gravity is an important factor in the movement of auxin.
- **b** The degree of bending of the shoot does not vary with the colour of light available.

CHAPTER

07 Infectious disease

In this chapter, you will learn about disease and its causes. You will also learn about cellular and non-cellular pathogens associated with infectious disease in plants and animals. You will also learn about how pathogens enter the body of the host and cause harmful alterations to the functioning of the host's body. You will examine data about the prevalence and cause of disease so as to learn to evaluate the accuracy, validity and reliability of scientific data.

Syllabus subject matter

WS 2.2.1

Topic 2 • Infectious disease

INFECTIOUS DISEASE

- identify the difference between infectious diseases (invasion by a pathogen and can be transmitted from one host to another) and non-infectious diseases (genetic and lifestyle diseases)
- identify the following pathogens: prions, viruses, bacteria, fungi, protists and parasites
- describe the following virulence factors that aid in pathogenesis: adherence factors, invasion factors, capsules, toxins and lifecycle changes

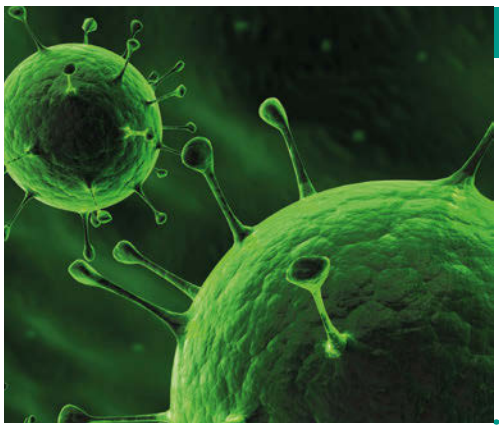
SCIENCE AS A HUMAN ENDEAVOUR

- Explore the historical development of our understanding of the nature of disease transmission (e.g. the work of Koch and Semmelweis).

MANDATORY PRACTICAL 5

- Investigate the effect of an antimicrobial on the growth of a microbiological organism (via the measurement of zones of inhibition)—laboratory or virtual.

7.1 Non-infectious disease



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

- understand that some diseases are caused by genetic mutations or chromosomal abnormalities
- understand that heterozygote advantage can maintain genetic diseases in populations
- recognise that many diseases have complex causes, including genetics and environment
- understand the role of nutrition in disease development
- recognise the role of statistical analyses such as regression analysis in determining the cause of disease.

A **disease** is any condition that impairs the normal functioning of an organism. The symptoms of disease can result from tissue destruction, blocked transport systems, starvation or malfunction due to an overuse of resources, the production of toxic substances or genetic mutations. Disease symptoms may also be due to an inappropriate immune response, such as an allergic reaction or an attack on the organism's own body cells, as occurs with auto-immune diseases. Immune rejection, which causes severe disease, is a current hurdle that medical innovation is trying to overcome by tissue transplant and cellular therapies. You will recall learning about stem cell therapies in Chapter 4.

Many diseases are caused by infectious agents, called **pathogens**, which are passed from one individual to another. Non-infectious diseases are those that are not caused by pathogens and in general are not passed between organisms. Non-infectious diseases fall into three broad categories.

- Inherited diseases are transmitted genetically during reproduction.
- Nutritional diseases are caused by insufficient or inadequate diets.
- Environmental diseases are the result of environmental factors, such as exposure to dangerous chemicals.

In some cases, diseases develop as a result of interactions between the above factors. For example, in some people, asthma is caused by exposure to pollens or spores in the environment but these people must already have a genetic tendency towards asthma.

Some diseases have multiple causes; for example, cancer. Cancer is characterised by the uncontrolled division of tissues. These tissues invade surrounding tissues, causing mechanical damage and blocking off blood supplies. Cancer is not really one disease. It is many different diseases with a range of different causes: genetics, environment and viruses have all been shown to contribute to the chances of developing cancer.

Mesothelioma (a type of lung cancer) has been linked to envrionmental exposure to asbestos. The chemicals in cigarette smoke greatly increase the risk of many cancers, including throat and lung cancer. Excess exposure to ultraviolet radiation causes skin cancers such as melanoma. Several strains of the human papilloma virus (HPV) can increase the risk of developing cervical cancer.

Genetics also plays a strong role in the development of cancer. Some people are highly resistant to cancer as a result of their genetic make-up. Other poeple have genetic predispositions that make cancer almost certain. For example, two genes that are active in breast tissues are BRCA1 and BRCA2. The normal versions of these genes are involved in regulating cell division in healthy breast tissue. Mutations in these genes have been linked to a loss of cell division regulation and thus an increased chance of developing breast cancer. Mutations in BRCA1 and BRCA2 have also been linked to an increase in the chance of developing ovarian cancer.

The risks of developing breast or ovarian cancer are listed in Table 7.1.1.

TABLE 7.1.1 Risk of developing breast or ovarian cancer for people with and without BRAC mutations who have not previously been diagnosed with either of these cancers

	Incidence in the general population (%)	Incidence in individuals with mutated BRCA1 or BRCA2 gene (%)
female breast cancer by age 70	7	56–87
ovarian cancer by age 70	<2	27–44
male breast cancer by age 70	0.05	6

GENETIC DISEASES

All cells contain DNA (deoxyribonucleic acid). This molecule contains the information needed to build all of the cells that make up the organism. The DNA that carries the information for making a protein, such as an enzyme, is called a gene. The DNA of organisms is arranged into 'packets' called **chromosomes**. Humans have 46 chromosomes in all of their body cells and 23 chromosomes in their gametes (sperm and ova).

When new cells are made, the chromosomes are copied so that each of the new cells has a complete copy of the DNA. On rare occasions, during the formation of gametes, the DNA is copied incorrectly or the gamete ends up with too many or too few chromosomes. This is called a **mutation**. Some mutations can be inherited by future generations but many are fatal to the individual. Some mutations allow the individual to survive but stop them reproducing.

Some mutations always result in disease; others don't directly cause disease but increase an individual's chances of developing a specific condition. Many types of cancer, type 2 diabetes and heart disease show this pattern.

Chromosomal diseases

Most chromosomal diseases occur when too many chromosomes end up in a gamete and thus in the individual. The cause of such diseases is identified by photographing the person's chromosomes and arranging them in pairs. The photograph of a person's chromosomal pairs is called a **karyotype**. Using the karyotype, it is possible to determine if a person has extra or missing chromosomes in their cells, or if there are extra or missing pieces of individual chromosomes. Disease in these cases is caused by having too much or not enough of the proteins coded for by the genes on that chromosome. One of the most common disorders caused by too many chromosomes is Down syndrome, which is the result of having an extra copy of the number 21 chromosome (Figure 7.1.1).

Single gene diseases

In sexually reproducing organisms, such as humans, half of all of the DNA of an offspring is inherited from each parent. Each parent provides half of the information needed for each trait. The interaction between these two pieces of information, called **alleles**, determines the trait of the offspring. Normally, inheritance of a mutated allele does not cause disease because the other allele inherited from the other parent provides sufficient information to make the necessary protein. People with two different alleles of a particular gene are described as being **heterozygous** for that gene. If the two alleles of an individual gene are the same, the person is **homozygous** for that gene.

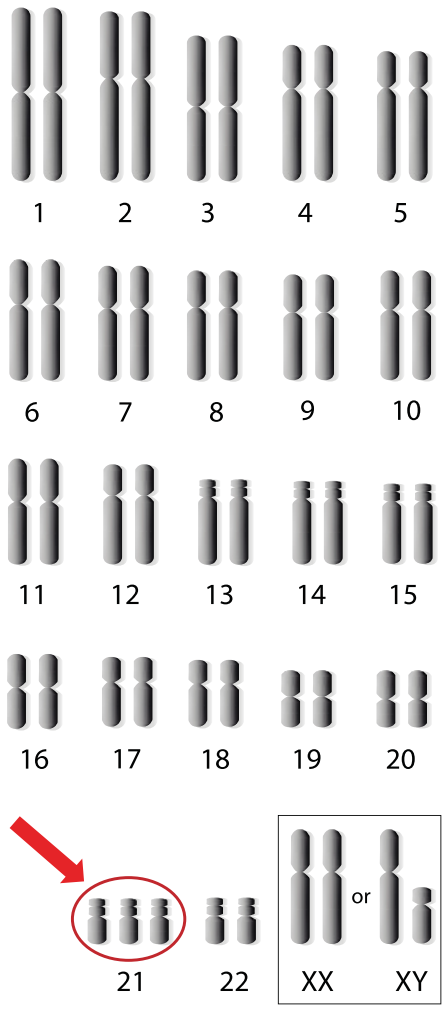


FIGURE 7.1.1 A karyotype of a person with Down syndrome. Instead of two members of the 21st pair, there are three. Both pairs of sex chromosomes are shown; the person would be either XX (female) or XY (male).

If a person inherits mutated alleles from both parents, then the required proteins are not made, or are made but do not work properly, and a disease usually results. The only possible cure for a genetic disease is genetic engineering, which is highly experimental and only being tried in a few very specific cases, but treatments are available for many genetic conditions.

There are many inherited diseases. These may have only minimal impact on the organism (e.g. red-green colour blindness) or they may have very serious consequences (e.g. sickle-cell anaemia and cystic fibrosis).

Sickle-cell anaemia

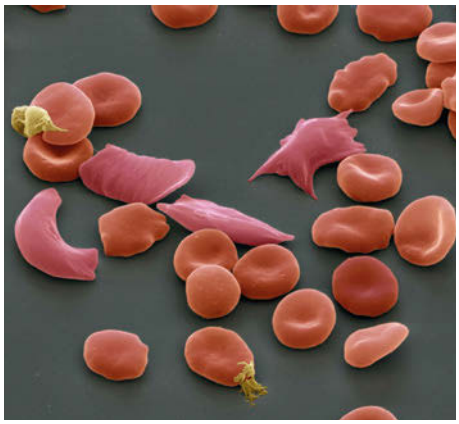


FIGURE 7.1.2 A scanning electron micrograph of red blood cells of a person with sickle-cell anaemia. The sickle-shaped red blood cells (pink) become stuck in small blood vessels, causing blockages that result in the symptoms of the disease.

Sickle-cell anaemia is a condition in which the red blood cells are malformed. Normal red blood cells are soft and flexible, enabling them to move easily through blood vessels. Sickle cells have an appearance similar to a crescent moon and are sticky and rigid (Figure 7.1.2). They easily become stuck in small blood vessels, blocking blood flow and causing the symptoms that are typical of the disease.

The function of red blood cells is to carry oxygen around the body. To do this, red blood cells contain two types of haemoglobin, alpha and beta, which are proteins (see Module 5.2). Beta haemoglobin is coded for by the Hb gene. People with sickle-cell anaemia have a different variant of this gene, called HbS. In order to have sickle-cell anaemia, a person must inherit HbS from both parents (Figure 7.1.3).

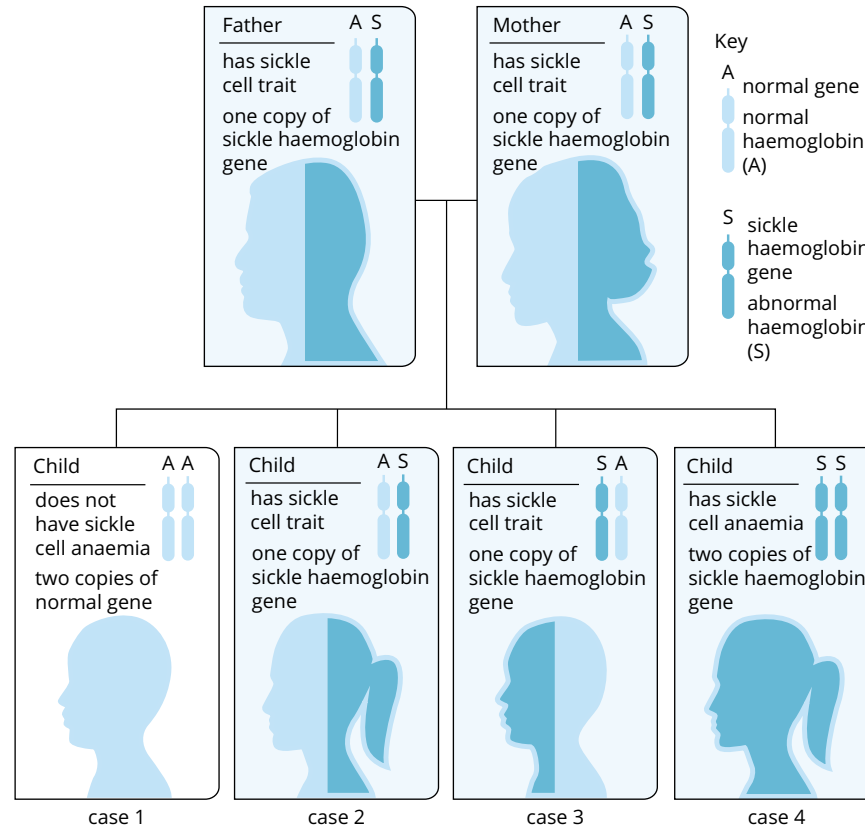


FIGURE 7.1.3 A couple who both have the sickle-cell trait have a quarter of a chance of having a child with sickle-cell anaemia.

People who are heterozygous for sickle-cell anaemia—that is, they inherit the trait from only one parent—have sickle-cell trait. These people generally live normal lives because under usual conditions their red blood cells are normal and they have no symptoms. However, the red blood cells of people who are heterozygous for sickle-cell anaemia may deform when their body is under extreme stress such as during severe dehydration or severe illness, as occurs when the malarial parasite tries to infect the person.

People who are homozygous for sickle-cell anaemia—that is, they inherit the trait from both parents—suffer continuous problems, including severe joint pain, swelling of hands and feet, vision problems due to damage of small blood vessels in the eyes, and frequent infections. They also have a significantly increased risk of stroke caused by blockages in the blood vessels in the brain. Their life expectancy is approximately 20 years less than the average person in developed countries, although the effect on life span in areas of Africa is unknown. Unlike normal red blood cells, which live for around 120 days, sickle cells survive for only around 20 days. The short life span of sickle-cell red blood cells means there is a severe shortage of red blood cells so sufferers have a shortage of oxygen to tissues and thus also experience extreme tiredness.

In studying the prevalence of the disease sickle-cell anaemia, epidemiologists noticed that the frequency of the disease seemed to align with the frequency of malaria caused by a protozoan, *Plasmodium falciparum*. Further research showed that the plasmodium's ability to enter red blood cells, where they spend a part of their life cycle, was severely reduced when the red blood cells were sickle shaped. This led to the hypothesis that having the sickle trait helped people to resist malarial infection but did not significantly reduce their life span. Their cells only became sickle shaped during infection. *Plasmodium falciparum* could not enter the cells to hide from the immune system and continue their life cycle and the people's red blood cells returned to normal once the attack by the pathogen was defeated. The protective value of having the sickling trait is thought to explain the high prevalence of the HbS allele in high malaria areas (Figure 7.1.4).

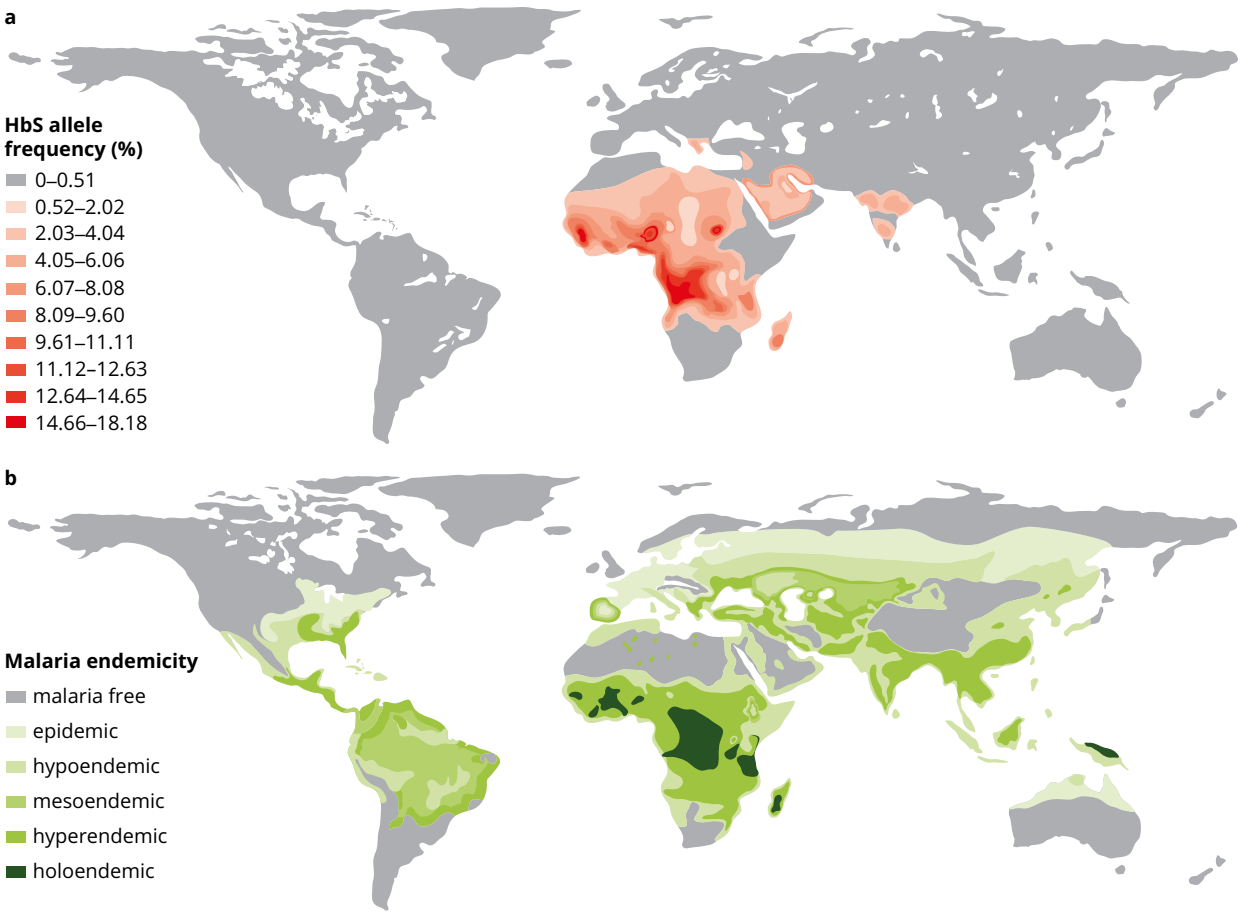


FIGURE 7.1.4 (a) Areas in Africa having high levels of malaria have a high frequency of the HbS allele. (b) The highest frequencies of the HbS allele, of 12.64% or more, occur in holoendemic areas. In holoendemic areas, virtually every individual is infected, childhood mortality is high but most adults are largely asymptomatic due to having a level of tolerance.

Although the sickle-cell trait protects against malaria, it is not common in Asia and the Americas, where malaria rates are also relatively high. This is thought to be due to other similar genetically determined blood diseases in these areas, such as β-thalassaemia, which occurs around the Mediterranean and in Asia. Also, in Asia and the Americas, the most common cause of malaria is *Plasmodium vivax*, not *Plasmodium falciparum,* which is associated with higher rates of mortality. Thus, the advantage provided by sickle-cell trait is higher in *P. falciparum* areas than in areas where *P. vivax* is the commonest malarial cause.

Heterozygote advantage

Some genetic diseases are very low in frequency while others are relatively common, particularly in specific populations. This has resulted in scientists hypothesising that certain genetic traits that can cause disease when inherited from both parents convey protection against pathogens: this is called **heterozygote advantage**. These genetic diseases include cystic fibrosis (typhoid, cholera, amoebic dysentery), thalassaemia (malaria and coronary heart disease) and connexin-26 deafness (bacterial ear infection). However, other scientists dispute that these mutations give increased resistance to disease.

For example, the heterozygote advantage conferred by cystic fibrosis (CF) was examined using a mouse model. CF is a disease in humans caused by defects in the proteins that move salt across cell membranes. It results in the formation of thick, sticky mucus in the lungs, digestive tract and reproductive tract.

Mice with a mutation that caused the same reduction in movement of salt and water across cell membranes as human CF were infected with cholera. The mice with the CF mutation suffered less dehydration than the mice without the mutation. This supported the hypothesis that CF gave resistance to the effects of cholera. This would be an advantage to heterozygotes, who would not suffer from CF but would gain some of the advantages of having the gene.

Many disease experiments are done using animals as the subjects. However, animals do not always respond as humans do and so any findings in animals must be treated with caution when extrapolating to humans. A human study was done using data collected during a cholera **epidemic**. The severity of symptoms and rates of mortality were noted at the time of the epidemic, tissue samples were taken and analysed after the epidemic to determine whether individuals were heterozygous for CF. Analysis of the data showed no difference in the severity of cholera between people heterozygous for CF and people who did not have the allele. This study did not support the hypothesis that CF provides a heterozygote advantage to cholera.

Genetics, environment and disease

In many cases, diseases are not caused by a single genetic mutation. Instead, individuals show a genetic predisposition for a disease and the environment provides the trigger, which results in the disease manifesting. A genetic predisposition means that a particular individual has an increased chance of developing a particular condition. This is the result of having certain genetic variations. These variations are often inherited but may also result from new mutations. Having a genetic predisposition does not mean an individual will develop a disease, only that they are more likely than a person without the predisposition.

It is often difficult to identify the size of the genetic contribution and the size of the environmental contribution to the disease. Despite having a genetic predisposition, diseases that have an environmental trigger only develop if the trigger is encountered by the individual. Diseases known to have a mixture of environmental and genetic causes are heart disease, many forms of cancer, asthma, obesity and type 2 diabetes.

Identifying the influence of genetics on disease—twin studies

With most forms of disease, genetics plays a role in determining either the chances of developing the disease or how severe the disease is if it occurs. One important method that scientists use to identify the role of genetics is twin studies.

There are two types of twins: identical and fraternal. Following fertilisation, the zygote starts dividing to grow into a new individual. Sometimes, for unknown reasons, the bundle of cells splits (usually between the morula and late blastocyst stage) so that two separate bundles of cells are formed from the original fertilised egg. Both of these bundles grow to form a baby, and because they both came from the same zygote, they are genetically identical. These are identical twins and so must both be the same sex.

Fraternal twins, or non-identical twins, arise when a female releases two eggs at the same time, both of which are fertilised by two different sperm. Both zygotes undergo division and become babies but like all brothers and sisters, they are from separate eggs and sperm from the same parents. They are no more genetically alike than any other brothers and sisters from the same parents. They can be the same sex or different sexes.

Many studies are done on twins because identical twins can be used to identify environmental effects. Because identical twins have no genetic differences, any difference in disease prevalence between the pair must be due to environment. Fraternal twins are also useful to study because there are many more of them. While fraternal twins have genetic differences, there are many fewer environmental differences for researchers to take into account because they are the same age and developmental factors relating to age can be discounted as the cause of any difference between them.

The results of one such twin study looking at the causes of asthma is shown in Table 7.1.2. The data for the study was collected through a survey sent to the participants who then self-reported whether or not they had ever had asthma. The results of surveys, especially those that involve self-reporting, can be less reliable because the researcher must rely on the participants to accurately assess and report on their own situation.

TABLE 7.1.2 Results of a study into asthma prevalence among adult twins

Type and sexes of twins	Total number of pairs who participated	Number of pairs with asthma (and percentage)			
		Both Yes	Yes No (elder twin Yes)	No Yes (elder twin No)	Both No
identical, both female	1232	67 (5.4%)	87 (7.1%)	98 (7.9%)	980 (79.5%)
identical, both male	567	39 (6.9%)	33 (5.8%)	31 (5.5%)	464 (81.8%)
fraternal, both female	751	19 (2.5%)	67 (8.9%)	69 (9.2%)	596 (79.4%)
fraternal, both male	352	12 (3.4%)	43 (12.2%)	39 (11.1%)	258 (73.3%)
fraternal, male and female	906	32 (3.5%)	105 (11.6%)	98 (10.8%)	671 (74.1%)

Because identical twins are genetically the same, differences in observed characteristics between the twins can be ascribed to different environmental effects. Of particular significance in the study on asthma were the identical twins where only one twin had asthma. For females, that was 185 out of 1232 or 14.94% of the twin pairs. A 14.94% difference between identical twins is significant because it shows that there must be a substantial environmental component to the disease.

Examining the differences between fraternal and identical twins can indicate the importance of genetics in susceptibility to disease. For example, significant differences in disease prevalence between male and female twins could indicate a hormonal cause for the disease. However, if there is a difference in disease prevalence between first born and second born twins, then it may be that factors during the birthing process are a cause of disease (e.g. inhalation of amniotic fluid or increased stress due to a longer time birthing).

NUTRITIONAL DISEASES

Nutritional diseases include conditions that are caused by either inadequate or excessive intake of nutrients and/or kilojoules. In developed countries, many nutritional diseases are caused by excessive kilojoule intake and may involve insufficient intake of required nutrients such as vitamins and/or minerals. In developing countries, many nutritional diseases are associated with inadequate intake of both kilojoules and nutrients.

Lack of a vital component in the diet results in a deficiency disease. For example, lack of vitamin C causes scurvy (Figure 7.1.5), lack of iron causes anaemia and lack of protein causes kwashiorkor (Figure 7.1.6). Starvation causes muscle and tissue wasting and a lowering of metabolic rate.

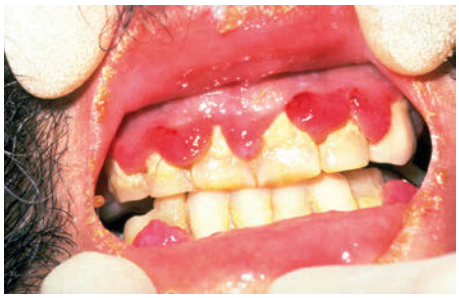


FIGURE 7.1.5 Mild cases of scurvy, such as that shown here, are easily treated with increased vitamin C intake. Severe scurvy used to occur on long sea voyages. Severe scurvy results in bleeding into the joints, causing severe pain, loss of teeth, increased bruising and poor wound healing, shortness of breath and finally death.

FIGURE 7.1.6 Kwashiorkor results in symptoms such as anaemia, tissue wastage, skin sores and fluid accumulation in the tissues (oedema), which results in a 'pot' belly.

Vitamin D deficiency

Nutritional deficiencies are uncommon in Australia, except in some Indigenous communities, with the exception of iron and vitamin D deficiency. While vitamin D can be obtained from the diet, most of our vitamin D is produced by skin cells when they are exposed to sunlight. Ironically, vitamin D deficiency has become more of an issue as Australians have become conscious of the dangers of developing skin cancer. Vitamin D deficiency is more of an issue in southern areas of Australia, especially in the winter months when there is less sunlight. But, even in Queensland, 15 out of every 100 people are at risk. Relative risks of vitamin D deficiency in Australia for summer and winter are shown in Figure 7.1.7.

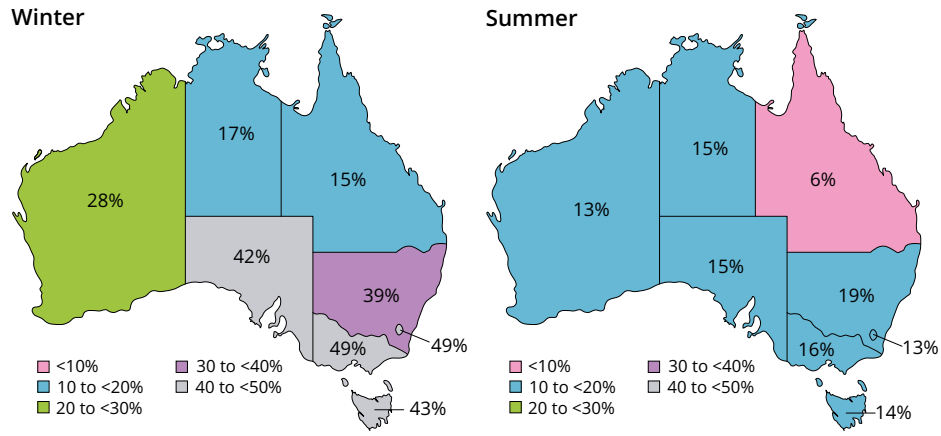


FIGURE 7.1.7 Maps of Australia showing the prevalence of vitamin D deficiency across the country in winter and summer. The map shows that there are significant levels of vitamin D deficiency throughout the year, even though Australia has high levels of ultraviolet radiation especially in summer.

Vitamin D is essential for building and maintaining healthy teeth and bones. Children who are vitamin D deficient are in danger of developing rickets. Rickets is a disease in which the bones become chalky and brittle. In adults, the most common consequence of vitamin D deficiency is osteoporosis or the less severe osteopenia, both of which are the result of low bone density. It is estimated that by 2022, there will be 6.2 million Australians over the age of 50 years with either osteoporosis or osteopenia. This will lead to more people requiring access to the health system for the treatment of broken bones.

Obesity

A more common nutritional disease in Australia is obesity. Obesity occurs when the intake of kilojoules exceeds the energy used for daily activity over a substantial period of time. In Australia, the 2014–15 National Health Survey, conducted by the Australian Bureau of Statistics, showed that 63.4% of adults and 27.4% of children aged between 5 and 17 years were overweight or obese. Being overweight has been linked to increased prevalence of several life-threatening conditions, including:

- type 2 diabetes
- high blood pressure (hypertension)
- heart disease
- stroke
- fatty liver disease
- kidney disease
- sleep apnea
- some cancers.

Links between some of these conditions and obesity have been identified through epidemiological studies that compare people with and without obesity, as shown in Figure 7.1.8.

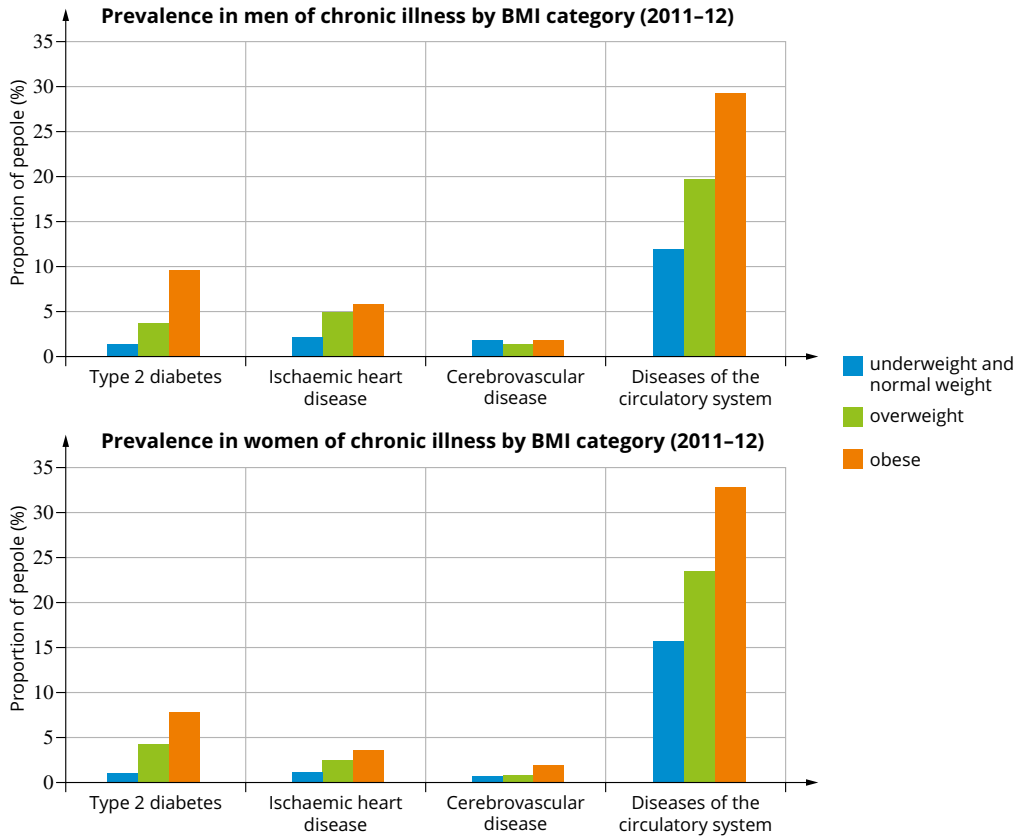


FIGURE 7.1.8 Prevalence of chronic illness by body mass index (BMI) category (2011–12) for men and women. The graphs indicate that higher weights lead to higher levels of disease. This study was undertaken by the self-reporting method.

The link between hypertension and obesity required long-term studies of people and the collection of large-scale statistics. Comparisons were then made between groups with and without obesity and prevalence was calculated. In the case of obesity and cardiovascular disease, there seemed to be a significant difference in prevalence of cardiovascular disease between people with and without obesity.

ENVIRONMENTAL DISEASES

Environmental diseases are caused by factors in the environment such as exposure to toxic chemicals, radiation, stress and pollutants. The study of cause and effect between disease and the environment is the realm of epidemiology.

Epidemiology is the study of diseases in populations. It includes the statistical analysis of data to try to identify cause-and-effect relationships of a disease. In the past, researchers such as Robert Koch and Ignaz Semmelweis used these studies to establish relationships between pathogens and disease, but today epidemiology is more frequently used to show relationships between non-infectious agents and human diseases. The relationship between smoking and lung cancer was established using epidemiological studies.

CASE STUDY 7.1.1

Using statistical evidence to establish causal links for lung cancer

Today around 1 billion people smoke cigarettes, about half of whom live in China, and worldwide over 6 million people die from smoking-related diseases. About 50% of those deaths are from lung cancer. In Australia, smoking-related lung cancer kills about 7500 people each year.

The now accepted link between smoking and lung cancer was not firmly established until around 1950, even though suspicions arose early in the 20th century. The first suggestion that smoking tobacco was a cause of lung cancer appeared in scientific literature in 1912. By the 1930s, scientists and doctors were becoming more concerned about the rising incidence of lung cancers and noted that the use of cigarettes was also increasing (Figure 7.1.9). During the 1940s and 1950s, the epidemiological studies and evidence from animal experiments provided further strong evidence of the link between smoking and lung cancer.

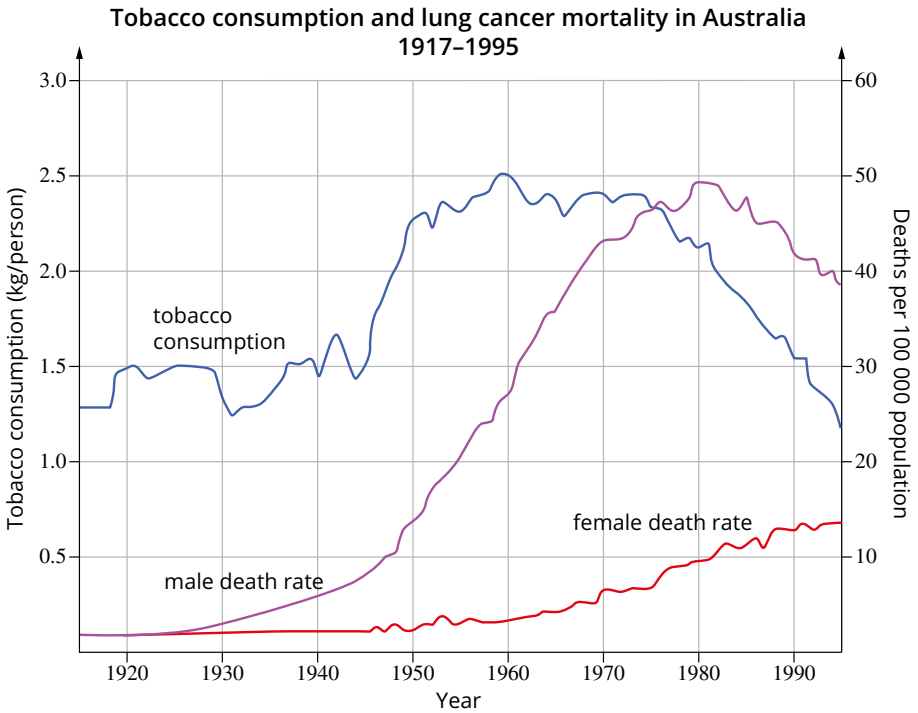


FIGURE 7.1.9 Tobacco consumption and lung cancer mortality in Australia between 1917 and 1995. Shortly after tobacco consumption declined, so did death rates.

Other epidemiological studies have established causal links between:

- leukaemia and exposure to benzene
- heart attacks and high cholesterol
- salt intake and hypertension
- lead and brain damage.

Epidemiological studies can also show that there are no causal links between environmental factors and disease. For example, a few years ago there was a media campaign by a group who oppose vaccinations. They suggested that the MMR (measles, mumps and rubella vaccine) caused autism. Large-scale studies were undertaken that showed that there is no evidence of a causal link between the MMR vaccine and autism.

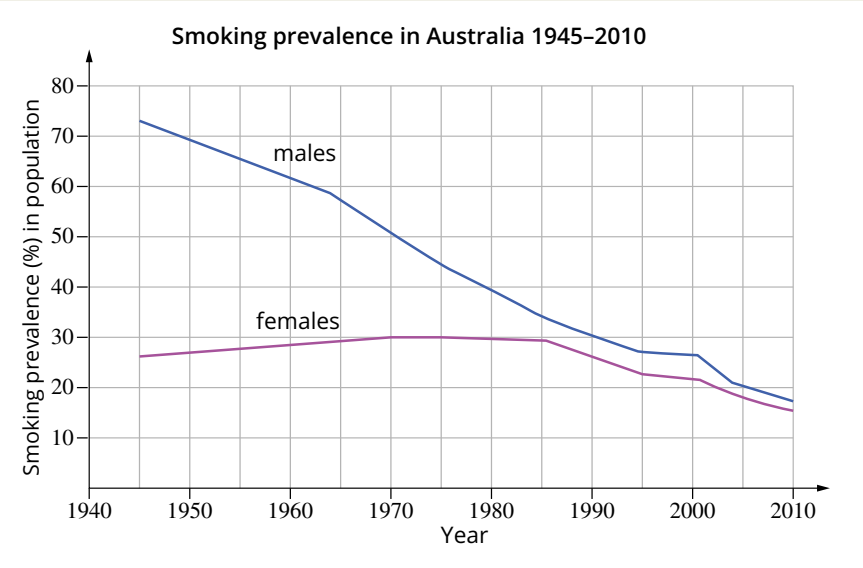


FIGURE 7.1.10 Smoking prevalence in Australia 1945–2010. Statistics for 2014–2015 show that smoking has declined even further to 16.9% of men and 12.1% of women, so Australia can expect a continuing decline in the rates of lung cancer.

The time lag between the reduction in smoking and reduction in cancers (Figure 7.1.9) is now attributed to the time needed for the carcinogenic properties of tobacco to build up to the point of causing disease. However, the time taken for tobacco to cause cancer meant that the link was hard for many people to accept. Acceptance of the link between smoking and cancer was made even more difficult by studies being done and published by tobacco companies, indicating that there was no causal link between smoking and lung cancer. Despite all of these factors, by the mid-1960s people in Western countries began to accept the relationship between smoking and lung cancer; as a consequence, cancer rates began to fall, especially among men.

The decline in women's lung cancer rates has been much slower than for men and this has been attributed to a sharp rise in women smoking during the 1970s, a much slower decrease in smoking rates (Figure 7.1.10) and the slow onset of disease.

Review

1. Identify the decade in which female smoking began to decline.
2. Discuss why epidemiological studies were needed to establish the link between smoking and lung cancer.
3. Compare the declining trend of tobacco consumption and male death rates.

CASE STUDY 7.1.2

Does early exposure to lead cause life-altering brain damage?

Investigation into some environmental diseases requires long-term studies to produce results. A number of long-term studies have been undertaken on the effects of lead exposure on children. It has long been known that lead is toxic; even writings as early as 250 BCE mention gastric problems and anaemia caused by lead. We now also know that lead damages the nervous system and especially the brains of children.

In the human population, the mean intelligence quotient (IQ) is 100, with a standard deviation of 15 and 95.44% of all scores falling within two standard deviations of the mean. For many years, arguments occurred about the possibility that exposure to lead caused brain damage, especially in children, and that this damage would affect IQ.

A large number of studies in various countries indicated that all levels of exposure to lead are harmful. One particular series of studies, involving cities in a number of countries (including Port Pirie, South Australia, and Mount Isa, Queensland) investigated the consequences of lead exposure in young children. The studies specifically looked at the effect of lead exposure on brain damage, using IQ deficit as a measure of the damage to the brain.

These studies indicated that any level of lead is harmful, but that severe damage begins at 5 μg dL^{-1} of blood, increases rapidly and then increases slowly from 10 μg dL^{-1}.

It was established that there is a step-like pattern to the damage associated with lead-caused brain damage. The critical points seemed to be 5 μg dL^{-1} and 10 μg dL^{-1}. Within each section, damage slowly increases from the lowest concentration to the highest but as the critical concentration is reached, the damage, and consequent loss of IQ points, increases significantly (Figure 7.1.11).

Within each graph, the trend line and measure of variance (R^2) shows that there is very little significance to any variations within each section. This shows that within these groups, there is not much change in IQ deficits. However, examining the means of each group shows a significant trend (Table 7.1.3 and Figure 7.1.12).

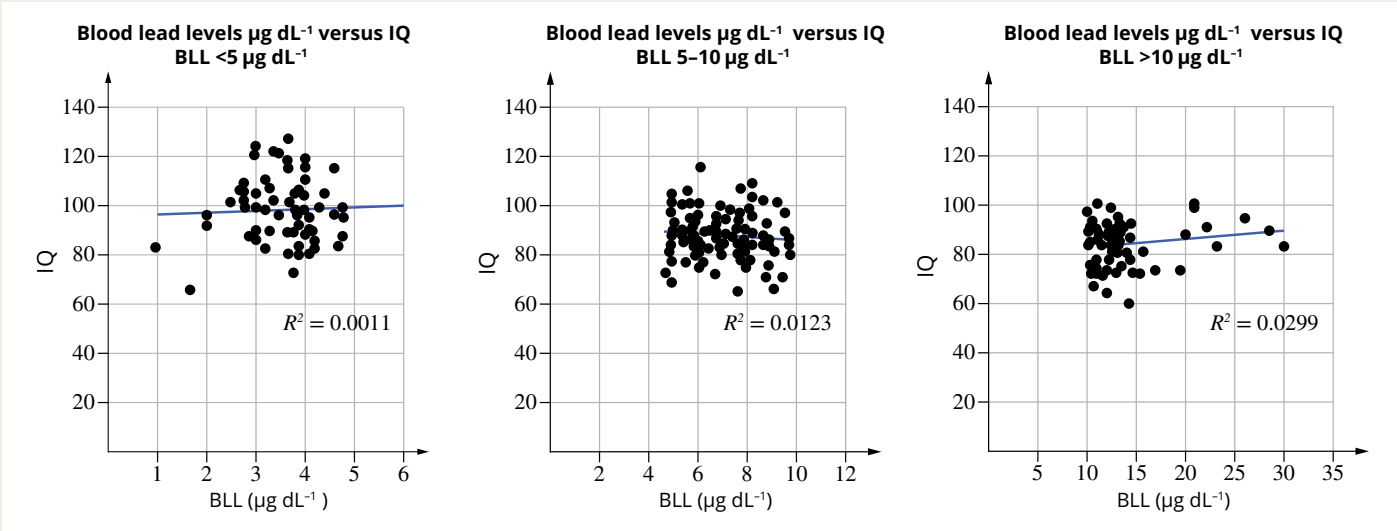


FIGURE 7.1.11 Blood lead levels (BLL) versus IQ. The data collected from one study is represented in the three scatterplots. Trend lines and R^2 values were calculated using Excel.

1 μg is one-millionth of a gram and 1 dL is one-tenth of a litre.

TABLE 7.1.3 Relationship between mean blood lead level and mean IQ

Blood lead level (μg dL^{-1})	Mean blood lead level (μg dL^{-1})	Mean IQ	Standard deviation for IQ	Number of subjects
<5	3.6583	98.49	12.64	71
5–10	7.076	89.111	9.2109	116
>10	13.668	84.103	9.054	67

The value of R^2 indicates that there is a strong correlation between the two variables without much additional influence from variables other than the independent variable.

Most studies showed similar results, which indicated that mean IQs of children exposed to lead had an average IQ deficit between 10 and 13 points even once other factors such as health, economic position and social status were taken into account. Most of the studies took place in mining towns where there was a perceived problem, but the results of some of the earlier investigations correlated with changes in society. Beginning in 1985, leaded petrol was phased out in Australia because of concerns about the effects of lead on brain development.

Some scientists are now looking at lead-caused brain damage and correlating it with crime statistics. In many countries, there seems to be a correlation between falling levels of childhood exposure to lead (due to the reduction in the use of leaded petrol) and falling levels of crime as those children reach adulthood. As the graph in Figure 7.1.12 shows, there seems to be a high level of correlation between the two factors. However, such correlations must be treated with caution. Correlation does not mean causation. The possibility of coincidence must be ruled out, as must the possibility that the two factors are related because they have the same cause. One factor that could cause both high blood lead in children and a high crime rate 23 years later is growing up in an economically depressed area. In such areas, schools are often of lower standard and children miss out on experiences that their parents cannot afford; so the children suffer educational and social disadvantage, resulting in angry adults who may be more inclined to commit crimes. Also, in those areas the housing stock tends to be older and more poorly maintained. Older houses often contain large amounts of lead paint, which was used in the past. If the houses are poorly maintained, such paint would be flaking from the walls, which would increase exposure. In carrying out the studies, the researchers had to ensure they were not just studying the effects of living in an underprivileged area.

Review

1. Explain the significance of an R^2 value of 0.0299, shown in Figure 7.1.11.
2. Compare the spread of data in Figure 7.1.11 for the different BLLs and the typical population IQ results of 100 with a standard deviation (σ) of 15 and 95.44% within 2σ.
3. The ancient Romans undertook many advanced engineering projects, among which was the piping of water into cities and even individual wealthy homes. Unfortunately, they used lead pipes for most of this movement of water and some historians think that this may have contributed to the fall of the Roman Empire. Discuss the plausibility of this hypothesis.

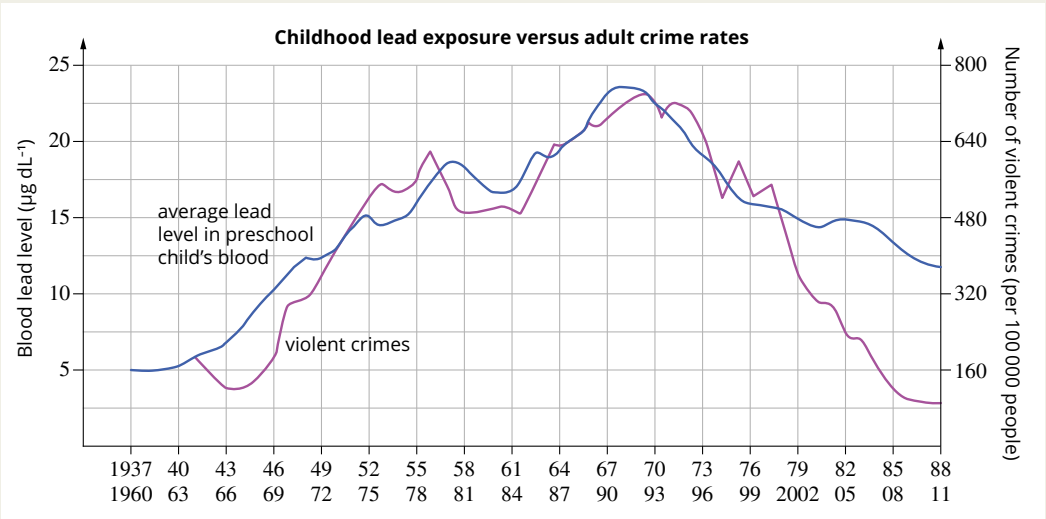


FIGURE 7.1.12 A comparison between childhood lead exposure (1937–1988) and adult crime rates (1960–2011) seems to show a strong correlation.

7.1 Review

SUMMARY

- Disease is any disruption to normal body functioning.
- Diseases can be caused by pathogens, environmental factors, nutritional factors, genetics or combinations of two or more of these factors.
- Genetic diseases are caused by mutations (changes) in genes or having too many or too few chromosomes.
- In the case of some single gene diseases, heterozygotes have an advantage in resisting certain pathogens; for example, sickle-cell anaemia and malaria.
- Nutritional diseases are caused by lack of vitamins, minerals or proteins or an excessive intake of kilojoules.
- Large-scale studies and twin studies assist in determining the relative contributions of genetics and environment to the development of disease.
- Individuals may have a greater or lesser chance of developing cancer depending on their genes and the environment to which they are exposed.
- Both cigarettes and childhood exposure to lead are significant environmental causes of disease.

KEY QUESTIONS

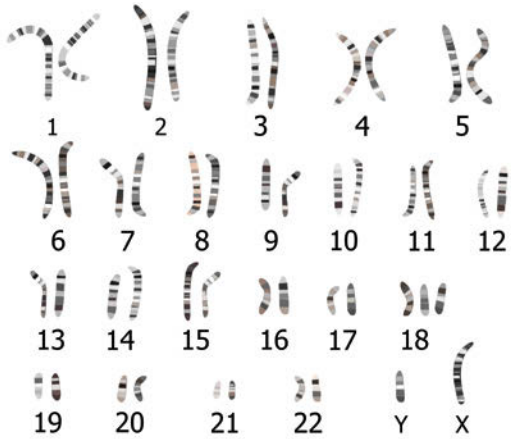
Retrieval

1 Identify the three broad categories of non-infectious disease and state the main cause of each of them.

2 Name two diseases caused by nutritional deficiencies. State the specific cause and describe the symptoms of each disease.

Comprehension

3 Examine the following picture.



a Name this type of picture.

b Identify the abnormality shown in the picture.

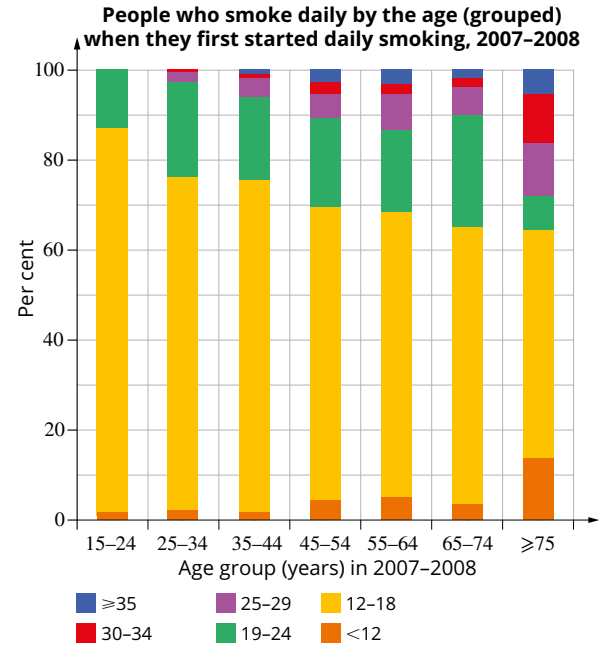
4 **a** Explain why establishing the cause of many non-infectious diseases involves the collection of very large amounts of data.

b Explain why twin studies are so useful in separating the genetic and environmental components of disease.

5 Identify the type of non-infectious disease that vitamin D deficiency is, and justify your choice.

Analysis

6 Smoking is a major contributor to the development of non-infectious diseases such as lung cancer and heart disease. For this reason, the Australian Health Survey collects data on the prevalence of smoking in the Australian population. The following graph shows the number of Australians in 2007–2008 who smoked daily in age groups and the age when they first started to smoke (colour coded).



a Identify the age group from the period 2007–2008 that contains the highest percentage of people who took up smoking before their teens.

b Determine the percentage of 35–44 year olds who took up smoking when they were between 19 and 24 years.

c **i** Calculate for each age group the approximate percentage of people who took up smoking before their 25th birthday.

ii In a population of smokers, determine the likelihood that you will meet someone who started to smoke after the age of 25 years.

d Conclude what the graph indicates about age of uptake of smoking for the age groups 18 years and younger over the last several decades. Specify the evidence you used for your conclusion.

e Propose a significant piece of data that cannot be determined from the graph.

7 In a number of countries, including Australia, there have been numerous studies of the effect of childhood exposure to lead and the incidence of violent criminal behaviour later in life. One such study examined people living in an Australian city. This was a longitudinal study—children's blood lead levels were measured and then 20 years later the incidence of violent crime in the area was recorded. The data collected in the 2007–2008 survey is summarised in the following table.

Year 1	Air lead levels ($\mu g\,m^{-3}$)	20 years later	Assault rate per 100 000 people
1991	0.39	2011	97.5
1989	0.73	2009	112
1988	0.84	2008	112
1990	0.78	2010	120
1987	0.78	2007	123
1986	0.92	2006	125
1985	0.99	2005	133
1983	1.10	2003	137.5
1984	1.22	2004	142.5
1981	1.30	2001	138
1980	1.30	2000	143
1982	1.39	2002	148

a Draw a graph in which you plot air lead levels against assault rate per 100 000 people.

b Draw a linear regression line and calculate R^2. Explain whether the value for R^2 suggests that there is a correlation between lead exposure and violent crime 20 years later.

c **i** Propose other factors that could account for a decrease in assault rates from 1982 to 1991.

ii Explain why other factors should be considered.

d Propose other information that would be valuable to increase confidence in the conclusion that exposure to lead in childhood results in higher levels of violence in adults.

8 Obesity has been established as a contributor to a large number of health problems. Study of the dietary behaviour of obese people and those with a healthy weight has significant problems because it is difficult to gain accurate information about what individual people eat. Generally, three sorts of studies are used:

- a food diary in which people write down what they eat each day at a time convenient to them
- a 24-hour retrospective report in which people are interviewed and report on what they ate the previous day
- a food frequency questionnaire in which the subject is given a long list of foods and they tick off what they ate over the period of the study, which could be a day, a week, a month or even a year.

The reliability of these studies has been questioned. Discuss the sources of error for each type of study. In your discussion, propose the effect of the errors on the accuracy of the evidence and identify which type of study is likely to be the most reliable.

9 The following table shows relationships between high blood pressure, deaths due to all cardiovascular diseases and obesity rates, by state and territory.

a Calculate regression analyses of obesity rates/high blood pressure by state/territory, obesity rates/% deaths due to all cardiovascular diseases and high blood pressure by state/territory/% deaths due to all cardiovascular diseases. Use the data in the table.

State or territory	% High blood pressure by state/territory	% Deaths due to all cardiovascular diseases	Obesity rates
Queensland	22.5	30.6	30.2
Tasmania	25.2	30.5	32.3
South Australia	22.6	30.2	30.0
Victoria	22.8	29.3	26.4
New South Wales	21.3	30.7	28.2
Western Australia	20.4	27.1	24.6
ACT	23.7	28.4	29.0
Northern Territory	21.5	22.5	23.9

Source: Australian Bureau of Statistics—2014/15 Australian Health Survey

b Explain what the R^2 values indicate about the relationships between the three factors.

7.2 Pathogenic organisms

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

- understand that pathogenic organisms are a major cause of disease
- recognise the different types of pathogens
- be able to identify possible methods of disease spread
- understand how the interaction between the pathogen and the host determines the severity of the disease
- have a better understanding of how evidence is used to support theories in regards to disease incidence and spread.

PATHOGENS AND PATHOGENESIS

Pathogens are agents that cause disease. Many diseases are **infectious**; that is, they are caused by pathogens that can be passed from one organism to another. These pathogens may be cellular or non-cellular.

Depending on their ability to cause disease, pathogens are divided into two groups.

- Primary pathogens cause disease any time they are present.
- Opportunistic pathogens only cause disease when the host's defences have been weakened; for example, by poor nutrition, stress or infection by other pathogens.

Most cellular pathogens are **parasites**. They complete part of their life cycle in or on another organism, known as the host. All parasites live at the expense of their host, but some cause no significant harm or disease in normally healthy hosts. Sometimes, the parasite infects two different hosts in sequence—the **primary host** is used for the adult stage of the parasite and the **intermediate host** is used for the larval stage. **Endoparasites** (e.g. tapeworms) live inside an organism; **ectoparasites** (e.g. lice) attach to the outside.

Some organisms, such as mosquitoes, are not true parasites but they have the ability to transmit pathogens between hosts, such as the plague (or Black Death), carried by fleas, and malaria and zika virus, carried by mosquitoes. Organisms that carry pathogens between organisms are called **vectors**.

Many pathogens spread directly from animals to humans. Diseases spread this way are called **zoonoses**. It has been estimated that 60% of current infectious diseases of humans are zoonotic and that 75% of emerging (new) diseases started out in animals. Infection by pathogens can occur through direct contact such as by touch; by contamination from faeces; by inhaling droplets of moisture released during breathing, coughing and sneezing; through exchange of body fluids; and through cuts and scratches (see Chapter 9 for more details).

When infection occurs through direct contact, the disease is said to be **contagious**. Highly contagious diseases such as influenza can spread rapidly through unprotected populations (see Chapter 9).

Infection can also occur by injection with a contaminated needle, or by bites from insects and other vectors. Another important source of infection is ingestion of contaminated food or water (see the case studies in Chapter 9).

The potential ability of a pathogen to cause disease in a host is called its pathogenicity. **Virulence** is the disease-producing power (i.e. the degree and severity) of a pathogen's pathogenicity. Traits of both the host and pathogen combine to determine the virulence of any particular pathogen. For example, some pathogens do not always infect the same tissues. Which tissues are infected has a significant influence on the severity of the disease, as in the case of *Bacillus anthracis*, which causes anthrax. *Bacillus anthracis* can infect the skin, where it causes lesions that, with antibiotics, usually heal, or it can infect the lungs. Infection of the lungs with anthrax is fatal in more than 80% of cases.

Characteristics of the host, such as its level of resistance to infection and the speed and strength of its immune response, will also affect the virulence of a pathogen.

After infection has occurred and the pathogen has become established, there is a period during which the pathogen reproduces and multiplies. During this period, the host may not show any signs of disease. Once the incubation period is completed, most hosts will show symptoms of disease. Sometimes, though, the host does not become ill but they remain infectious. This infectiousness can continue for a long period of time. An organism that remains infectious in this way is called a **carrier**. Carriers are an important method of spreading disease.

The period between infection and the onset of symptoms is called the **incubation period**. Figure 7.2.1 shows the progress of disease from infection to wellness.

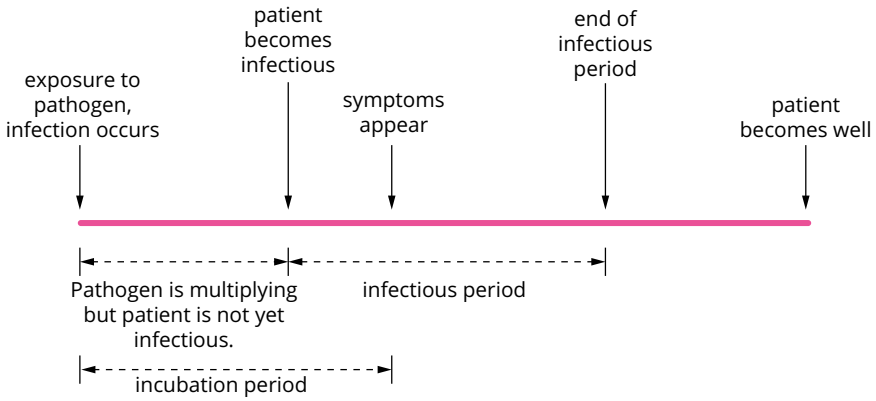


FIGURE 7.2.1 The progress of disease from exposure and infection to wellness includes several stages. The period when the pathogen is most likely to spread is between the start of infectiousness and the onset of symptoms.

The length of the incubation period can show considerable variation. This variation may be a result of the characteristics of the pathogen, such as the rate at which it reproduces, or because of traits possessed by the potential host. Also, some hosts resist infection more than others because of their genetics, general health or previous exposure to similar pathogens. Exposure to a similar pathogen may provide some level of protection. Finally, the number of particles of pathogenic material that enter the host also affects the incubation period; more particles result in a shorter incubation.

At some point during the incubation period, the host becomes infectious. A long period of pre-symptomatic infectiousness helps a pathogen to infect a larger number of hosts and spread further. During the pre-symptomatic infectious period, the host feels well and continues normal activities, which brings them into contact with other potential hosts, thus spreading the pathogen more widely.

The major groups of organisms that cause disease are bacteria, protozoa (animal-like protists), oomycetes (fungus-like protists), fungi (including yeasts), several types of worms and a few arthropods.

BACTERIA

Most bacteria are free-living and have important ecological roles such as decomposers and as nitrogen-fixing organisms in the nitrogen cycle. Many bacteria can form dormant, temporarily non-reproductive spores in response to unfavourable conditions. With thick outer walls, the spores are resistant to many agents that destroy vegetative bacteria and may remain viable for thousands of years. If the environment becomes favourable, they recommence activity. There are bacteria that thrive under extremes such as very high or low temperatures or pH values and high radiation or salinity, but many bacteria grow best in a moist environment with a pH close to neutral and a temperature between 20°C and 40°C.

Many bacteria are parasites of other living organisms. Some bacteria are major pathogens of humans, crops and animals. The symptoms of bacterial disease result from the destruction of cells and tissues by bacterial enzymes, irritation by bacterial waste products, reactions to bacterial toxins that interfere with normal cellular functions, and the exaggerated immune responses of the sufferer to the foreign cells. Bacterial toxins can remain dangerous long after all bacteria have died. Pathogenic bacteria in humans include those that cause typhoid fever, syphilis, chlamydia, botulism, tetanus, pneumonia, diphtheria and tuberculosis. People can become carriers by being infected and carrying microbes in their body without showing any symptoms of disease.

Characteristics of bacteria

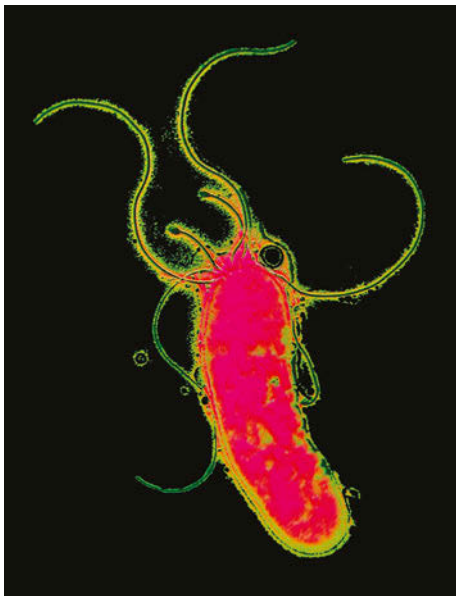


FIGURE 7.2.2 *Helicobacter pylori* is a flagellated spiral-shaped bacterium.

Different species of bacteria are identified by a number of physical and chemical properties such as:

- shape—cocci (spheres), bacilli (rods), spirochetes (spirals)
- organisation—single, clumps, pairs, chains
- the presence or absence of a capsule
- mobility—some have flagella or cilia to assist with movement
- requirement for oxygen—aerobic (need oxygen), obligate anaerobic (harmed by oxygen), facultative anaerobic (neither need nor are harmed by oxygen)
- nutritional requirements
- gram-staining characteristics—positive, negative.

Figures 7.2.2 and 7.2.3 illustrate some typical bacteria and their shapes and arrangements.

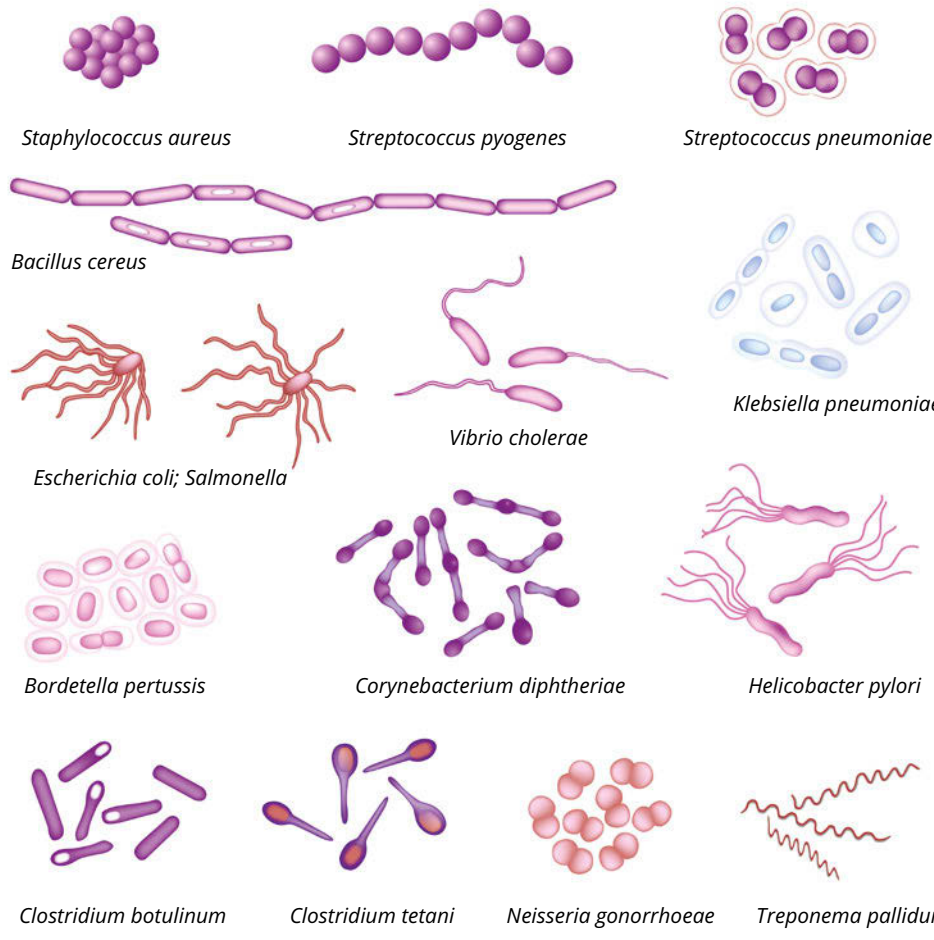


FIGURE 7.2.3 Common pathogenic bacteria, showing typical shapes and arrangements

Gram stain distinguishes between two large groups of bacteria on the basis of a fundamental difference in the chemistry and structure of their cell walls. It has been a key test in the initial identification of bacteria since the late 1880s and is the most widely used staining procedure. Gram-positive bacteria stain purple (Figure 7.2.4) and their cell wall is a relatively thick layer of peptidoglycans, macromolecules made of protein and carbohydrate, found only in bacteria. Gram-negative bacteria stain pink and have a much more complex, multi-layered cell wall that contains enclosed peptidoglycans and lipopolysaccharides. The outer membrane layer of gram-negative bacteria effectively excludes many substances, including certain antimicrobial medications. Gram-negative bacteria are generally less susceptible to penicillin than gram-positive bacteria.

Exotoxins are highly toxic chemicals released by bacteria into their environment. They are primarily produced by gram-positive bacteria, such as *Clostridium botulinum* shown in Figure 7.2.5a, but they are also produced by some gram-negative species. Gram-negative bacteria also produce **endotoxins**. Endotoxins are highly toxic chemicals produced inside a bacterial cell that are released when the bacterial cell ruptures. The lipopolysaccharides of the gram-negative cell wall are an example of endotoxins (Figure 7.2.5b).

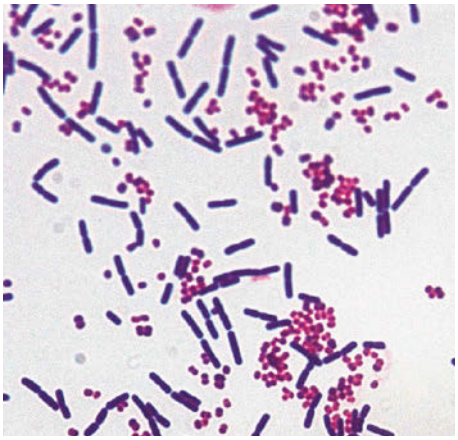


FIGURE 7.2.4 In this photo, two kinds of bacteria are visible–gram-positive bacilli (rods), which have stained dark blue–purple, and gram-negative cocci (spheres), which have stained pink.

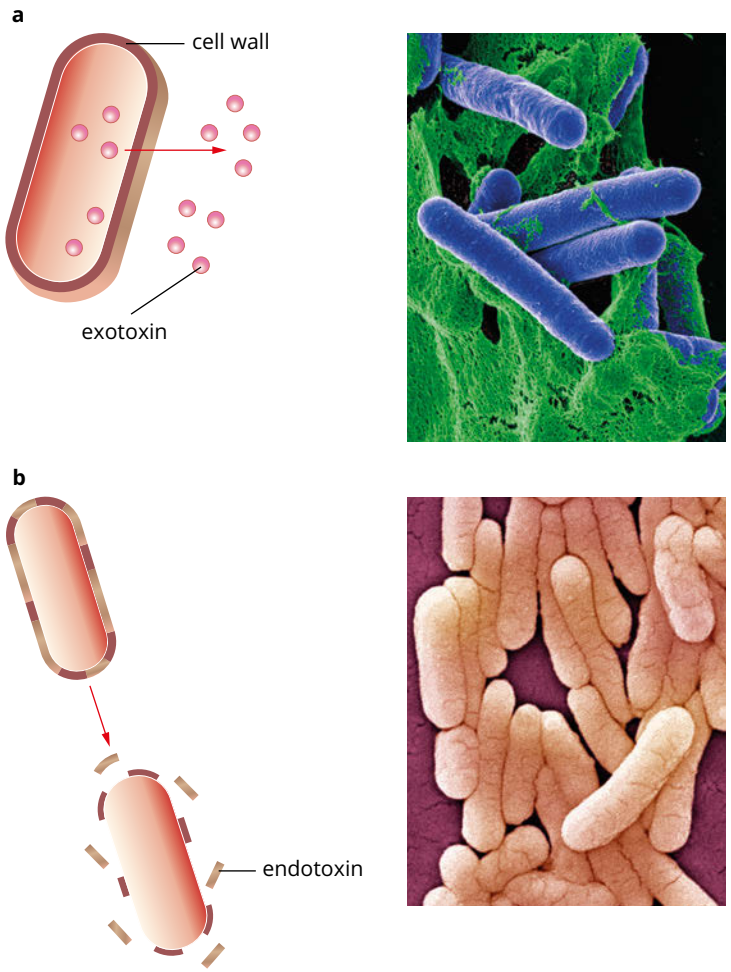
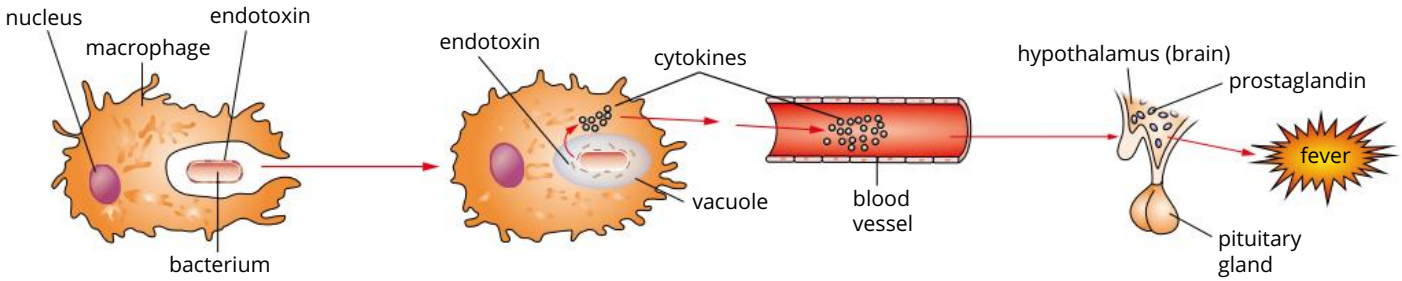


FIGURE 7.2.5 (a) Exotoxins are produced inside gram-positive bacteria as a normal part of their metabolism and are secreted into the surrounding tissues. *Clostridium botulinum* is a gram-positive bacterium that produces exotoxins. (b) Endotoxins are a part of the lipopolysaccharides of the outer membrane of gram-negative bacteria. The endotoxin is released when the bacteria die and the cell wall breaks apart. *Salmonella typhimurium* is a gram-negative bacterium that produces endotoxins.

Different toxins have different actions. Some toxins, such as the toxin produced by the bacterium *Clostridium tetani*, prevent the release of neurotransmitters, inhibiting muscle contraction, while others disrupt the membranes of the host's cells and cause the host cell to lyse.

The lipopolysaccharides in endotoxins can produce fever in the host, and increase the possibility of septic shock and circulatory collapse (extreme low blood pressure) in the patient. They do this through a pathway that leads to the release of **prostaglandins**. The pathway to fever is shown in Figure 7.2.6. During the process, white cells called **macrophages** release signalling molecules called cytokines. You will learn more about macrophages and cytokines in Chapter 8. The ability to produce a variety of different toxins, along with the resistance of some bacteria to certain antibiotics, greatly increases the virulence of the bacteria.



1 An endotoxin-containing gram-negative bacterium is engulfed by a macrophage and enclosed in a vesicle.The vesicle fuses with a lysosome.

2 The vesicle fuses with a lysosome and the bacterium is digested, allowing endotoxins from the bacterial cell wall to be released. The macrophage releases cytokines, which enter the circulation.

3 The cytokines, including prostaglandins, travel in the circulatory stream to the brain where they cause the hypothalamus to increase the set point for body temperature.

4 Fever results.

FIGURE 7.2.6 The pathway to fever involves the release of cytokines which signal the hypothalamus and cause the rise in body temperature.

Bacterial invasion of the host is assisted by **adhesins**. These are proteins or carbohydrates on the surface of the pathogen. Adhesins help to overcome the host's mechanisms designed to wash pathogens from the body, such as mucus or tears (see Chapter 8). Adhesins are structures that enable the bacterium to stick or adhere to host cells (Figures 7.2.7 and and 7.2.8) and are one of numerous adherence factors.

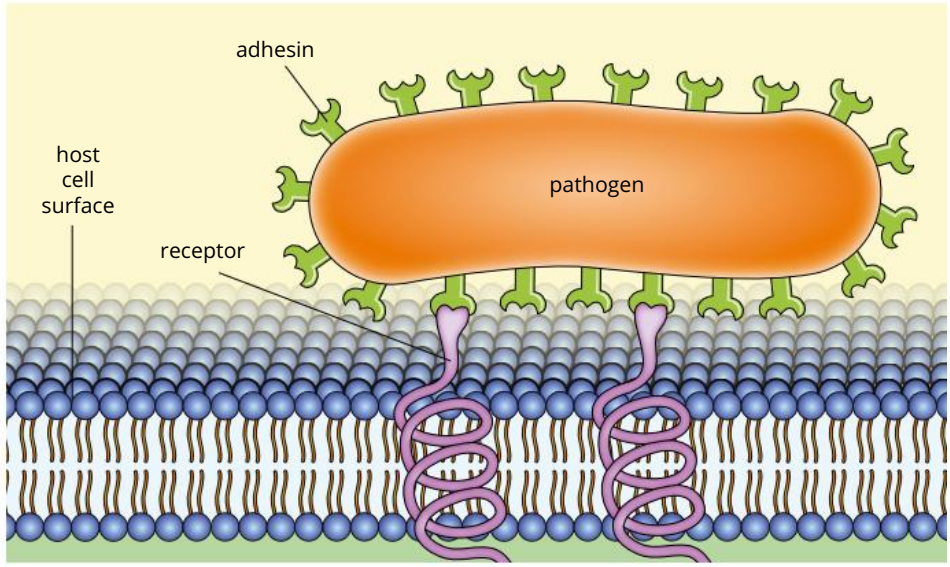


FIGURE 7.2.7 This receptor on the host cell has been used as a site for the adhesion of a pathogen.

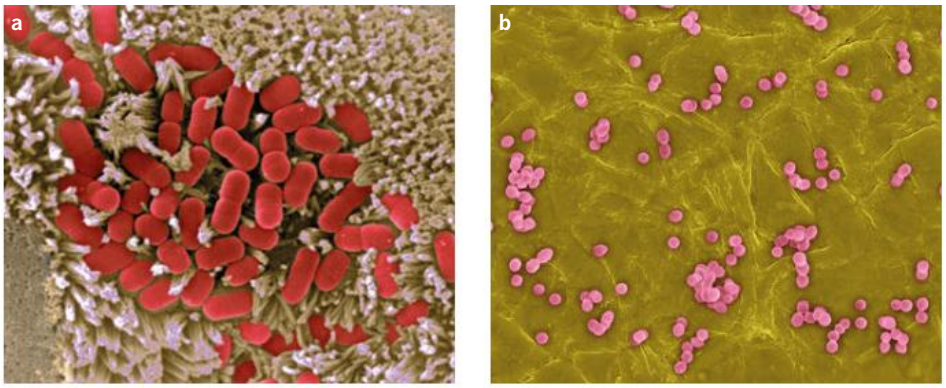


FIGURE 7.2.8 (a) *Escherichia coli* (a bacillus, red) bacteria adhering to the small intestine, and (b) cocci bacteria (pink) adhering to skin

Some adhesins are hair-like structures, called **pili** (singular: pilus), made of protein, while others are more compact structures made of carbohydrate. Gram-negative bacteria commonly rely on pili for adhesion. Gram-positive bacteria use both pili and carbohydrates. These adhesins often bind to proteins on the surface of the host cell. These host cell proteins perform a required function for the host cell, such as reception of signalling molecules like hormones or acting as protein channels. Their presence is exploited by the pathogen.

Many bacteria are also coated with a **capsule** that completely covers their entire surface. These capsules are made of polysaccharides. They help the bacteria evade the host's immune system. The capsules block the phagocytosis of bacteria by leukocytes. Figure 7.2.9 illustrates the structure of a bacterium. The pili and the bacteria's surrounding capsule can be seen.

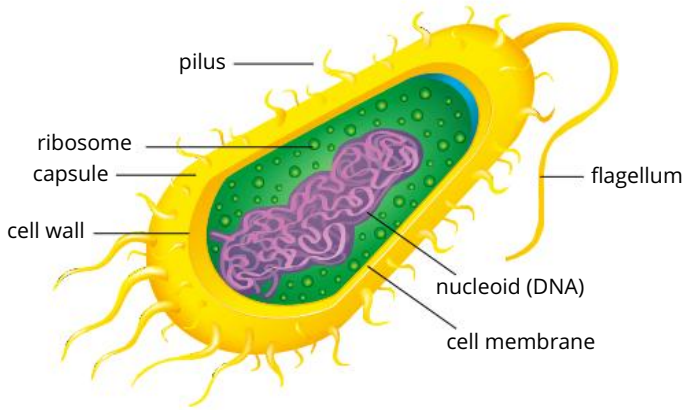


FIGURE 7.2.9 Many bacteria have pili, which assist in adhesion, and a capsule, which helps them evade the immune system of host organisms.

Antibiotic resistance is also becoming a critical problem as bacteria with antibiotic resistance are being selected through antibiotic-rich environments. In any population of bacteria, some individuals will have a natural resistance to antibiotics. In an antibiotic-rich environment, these individuals are the ones most likely to survive and reproduce. This creates highly resistant strains. The problem is exacerbated by the misuse and over-use of antibiotic medications because this allows the survival of a few highly resistant bacteria, which then increase in numbers. Further, the ability of bacteria to swap blocks of genes means that resistant strains can pass their resistance genes to previously non-resistant bacteria.

CASE STUDY 7.2.1

Legionnaire's disease—tracking the cause

Legionnaire's disease is caused by bacteria in the genus *Legionella*. As recently as 1976, this disease was completely unknown. The first recognised case of Legionnaire's disease occurred after a convention held in Philadelphia, USA, in 1976. After the convention, 221 people became ill and 34 of them died. They presented with a pneumonia-like illness that also included diarrhoea, nausea and confusion. As reports of deaths from an unknown pneumonia-type illness came into the Centers for Disease Control (CDC), research began to identify the cause. The first commonality identified between all of the affected people, even though they were now spread throughout the USA, was that they had all either attended the Philadelphia convention or had been working or visiting in the area. This allowed the scientists to narrow the outbreak down to the hotel in Philadelphia where the convention was held.

In order to further narrow down the cause, the disease detectives interviewed the surviving victims and their families, along with a number of people who had also been at the convention but who had no sign of illness.

Each method of disease spread was considered.

- Contaminated food—along with the food served in the hotel, there were many restaurants and cafes in the area, most of which had been visited by at least some of the patients and the healthy controls, but there was no pattern that pointed to a particular food source.
- Waterborne—both patients and controls were asked about drinking un-bottled water or consuming ice. There was no link to ice consumption but a higher rate of water consumption in the ill than in the healthy was observed. The difference was considered to be statistically significant, but drinking water could not be used to account for all of the cases.
- Direct person-to-person contact—this was ruled out because there was no clustering of cases among families or people who had shared rooms at the convention.
- Vectors—no evidence was found to suggest that any of the patients had come in contact with animals and none of them complained of suffering from insect bites.
- Airborne—having ruled out all other sources, in at least some cases, the scientists concluded that the most likely method of transmission was airborne with some contamination of drinking water from the air. They decided that the cause was most likely inhaled into the lungs, causing the pneumonia symptoms. This conclusion was further supported by the fact that cigarette smokers were over-represented in the group with the disease. Lung damage caused by smoking has been shown to increase susceptibility to lung infection by bacteria. The data in Table 7.2.1 shows that the mean increase in the probability of a smoker developing Legionnaire's disease, if exposed, is 3.6 compared to non-smokers.

Having decided that an airborne pathogen of unknown type was likely responsible for the outbreak, researchers continued to try to find the cause of disease. The researchers decided to test the recovering patient's blood for the presence of the same **antibody**. Antibodies are proteins made during the immune response to a particular pathogen. You will learn more about antibodies in Module 8.2.

Antibodies in the recovering patients were compared with antibody samples taken from the hotel employees. The presence of the same antibodies in the employees who had not been ill during the outbreak suggested that this disease had been prevalent in the area for some time before the convention and that exposure did not necessarily cause a severe illness.

It took several months to identify the cause of the disease as *Legionella* bacteria. By then, the source at the convention hotel could not be identified, but it was probably the air-conditioning towers. Individuals who stood near vents would have been exposed to more airborne bacteria than those who stood further away, and some individuals were also more susceptible because of other health issues, age or smoking.

After identifying the cause of the outbreak, scientists searched records and a number of other outbreaks of similar character were identified and are now ascribed to Legionnaire's disease. *Legionella* outbreaks continue to occur, usually through improperly decontaminated air-conditioning towers.

TABLE 7.2.1 Bacterial infections of the respiratory tract associated with smoking. Odds ratio is a measure of the association between an exposure and an outcome.

Infection	Odds ratio (95% confidence interval)
nasopharyngeal and respiratory pathogens (e.g. *Streptococcus pneumoniae*, *Haemophilus influenzae*, *Legionella pneumophila*)	2.5 (1.1–6.0)
Legionnaire's disease	3.6 (2.1–5.8)
pneumonia	2.6 (1.9–3.5)

Review

1 Describe the methods used to track down the cause of Legionnaire's disease.

2 Explain why poorly maintained air-conditioning towers can lead to outbreaks of bacterial diseases.

Plants and pathogenic bacteria

Infection by bacteria is not confined to humans or even animals. Plants can also be infected by pathogenic bacteria.

The bacterium *Agrobacterium tumefaciens* infects plant roots, where it causes cells to proliferate. Figure 7.2.10a illustrates the cycle of infection and disease in infected plants. Crown gall bacteria enter the plant through a fresh wound and multiply in intercellular spaces. They produce large amounts of auxin (a plant growth hormone), which causes nearby plant cells to multiply and produce nutrients that only the bacteria can use. These plant cells then transform into tumour cells, which continue to grow out of control (in a similar fashion to cancer cells), producing a lot of food for the pathogen but preventing normal growth of the plant. As the tumours develop, xylem and phloem (vascular tissue) become blocked. The plant's ability to move water and nutrients is compromised, resulting in reduced growth, death of parts of the plant or, in cases of major infection, the death of the whole plant. Figure 7.2.10b shows a typical example of a swelling called a **gall** caused by *Agrobacterium tumefaciens*.

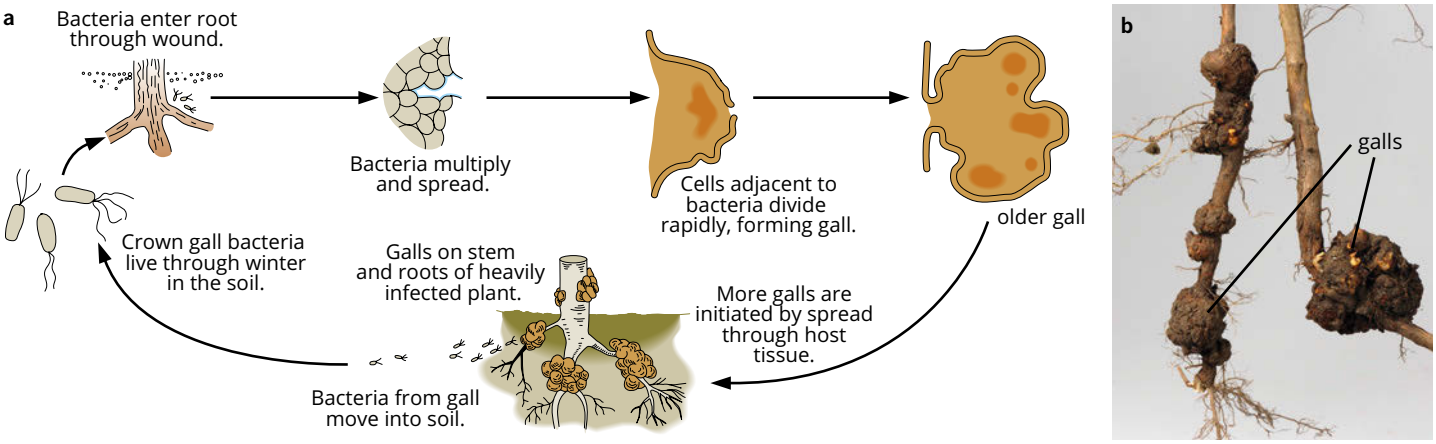


FIGURE 7.2.10 (a) The disease cycle of crown gall, which is caused by *Agrobacterium tumefaciens*. (b) Raspberry seedlings with crown gall disease.

PROTISTS

Protists are a very diverse group of organisms. They range from multicellular photosynthetic organisms, such as seaweed, to highly pathogenic, unicellular organisms, such as the **plasmodium** that causes malaria. Three groups of protists have members that are pathogenic to animals:

- zooflagellates (e.g. *Trypanosoma*, which causes sleeping sickness, *Giardia*, a common cause of diarrhoea, and *Leishmania* (Figure 7.2.11a), which causes leishmaniasis)
- sporozoans (e.g. *Plasmodium* (Figure 7.2.11b), which causes malaria)
- sarcodines (e.g. *Entamoeba histolytica* (Figure 7.2.11c), which causes amoebic dysentery).

Another group of protists—oomycetes—are primarily pathogenic to plants.

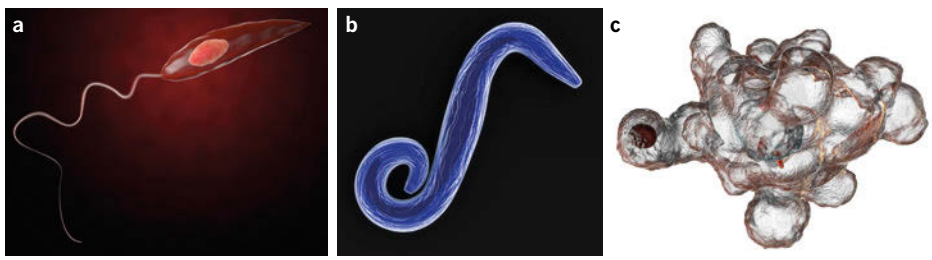


FIGURE 7.2.11 Examples of the three classes of pathogenic protozoans: (a) *Leishmania*, (b) *Plasmodium* and (c) *Entamoeba*

Pathogenic sporozoan: malaria

Malaria is a disease that occurs across large areas of the world. It causes up to 1.8 million deaths a year, with more than 50% being of children under five years. Figures from different sources vary significantly because many factors are involved, so deciding whether a death is due to malaria or another cause is often difficult. In many cases, malnutrition, other diseases and malaria combine to cause death.

There are several species of the plasmodium that cause malaria. The most common are *Plasmodium falciparum* and *P. vivax*. *P. falciparum* is linked to higher levels of mortality in people infected than *P. vivax*. Figure 7.2.12 shows the distribution of these two species.

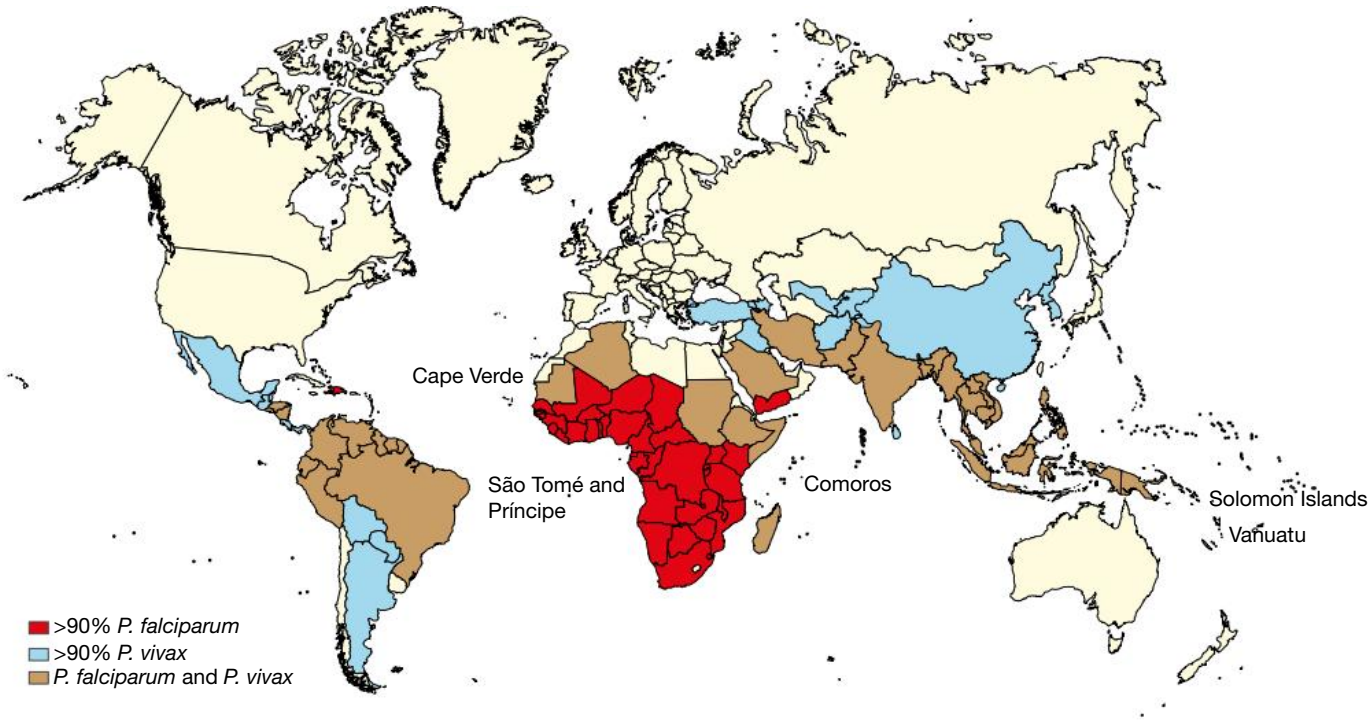


FIGURE 7.2.12 The distribution of *Plasmodium falciparum* and *P. vivax* across the world

There are two hosts in the life cycle of *Plasmodium* parasites, as can be observed in Figure 7.2.13, which illustrates the various stages of the malarial life cycle. The adult stage occurs in humans (the primary host). After a person is bitten by an infected female mosquito (only female mosquitoes feed on blood), *Plasmodium* larvae pass in the blood to the liver, where they feed and multiply asexually for two weeks. The larvae then leave the liver and pass into the bloodstream and infect red blood cells. Inside the red blood cell, the parasite grows and feeds, almost filling the cell, before the parasite splits into many tiny larvae. It is then that symptoms associated with malarial infection begin to appear. Symptoms include recurring bouts of fever every few days, with high temperature, sweating, shivering and delirium.

Malarial attacks are associated with the bursting of red blood cells that spill the parasites, which at this stage of their life cycle are called **merozoites**, into the circulatory system. The presence of one million merozoites in the blood is sufficient to produce symptoms of malaria. As the red blood cells rupture, the oxygen-carrying capacity of the blood is compromised, causing the symptoms of fatigue. Rupture of cells in any part of the body initiates the symptoms of inflammation, which include fever and chills. You will learn more about this process in Chapter 8.

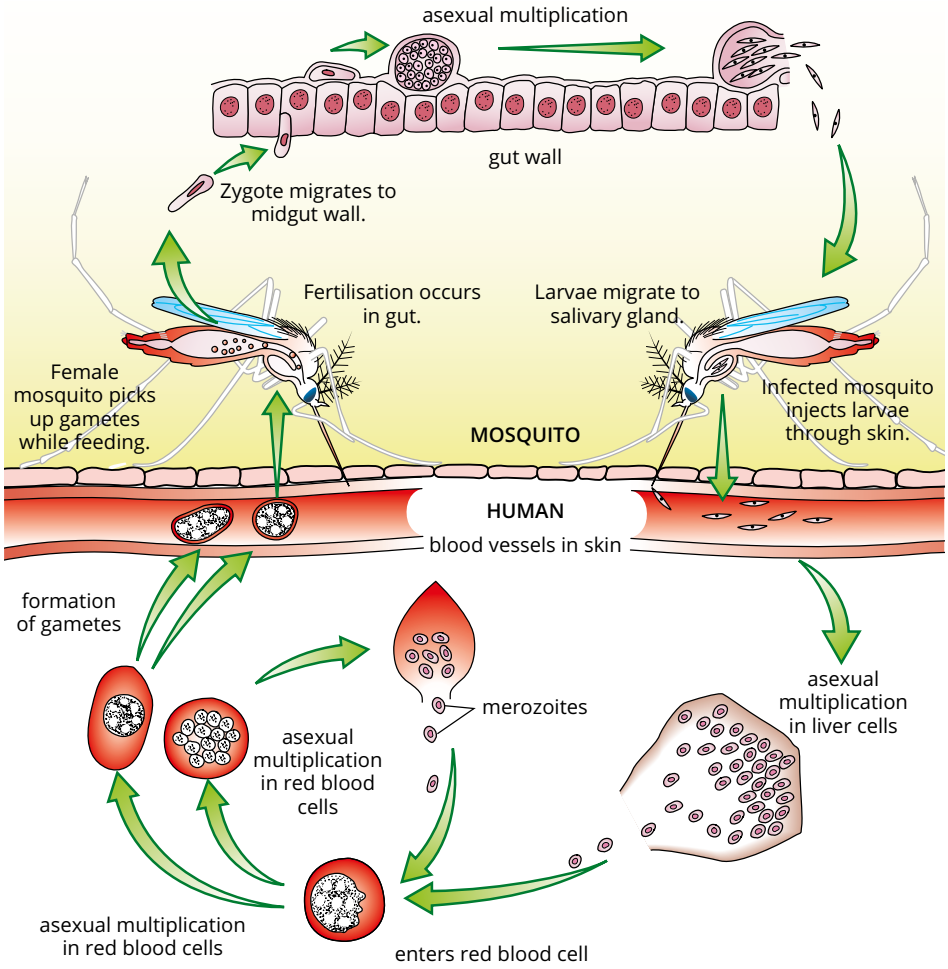


FIGURE 7.2.13 The life cycle of the malarial parasite (*Plasmodium* sp.) involves two hosts, with humans being the primary host.

Fevers occur in regular cycles because merozoites take a fixed period (1, 2 or 3 days, according to the species of parasite) to grow, mature and divide asexually inside red blood cells, which then all burst together. The newly released merozoites attach to and infect more red blood cells. They grow for the same period within the red blood cells, then burst out, and the cycle continues. While it has not been shown definitively, there is evidence that the malarial merozoite uses a protein found on the surface of red blood cells, called **Duffy**, to enable it to attach to the cells and push its way inside. The merozoite does this by a process that is similar to endocytosis. This enables the parasite inside the red blood cell to be enclosed in a vesicle. Unlike endocytosis, this process is not controlled by the red blood cell; rather, the merozoite is in charge.

During the process of merozoite invasion of red blood cells, some of the merozoites in the bloodstream develop into a gamete, producing forms that can be ingested by mosquitoes and transferred to a new host. The development of the gamete-producing stage tends to follow a circadian rhythm. They are found in the blood at times of the day when the intermediate host, the *Anopheles* mosquito, is feeding, which is usually in the early evening and night. When taken up with blood, gametes fertilise in the stomach of the female mosquito and develop into larvae, which migrate through the stomach wall and into the salivary glands of the mosquito, where the larvae then undergo asexual reproduction. In the salivary gland, a single larva can multiply asexually to produce 10 000 larvae, which are passed on to a primary host during feeding.

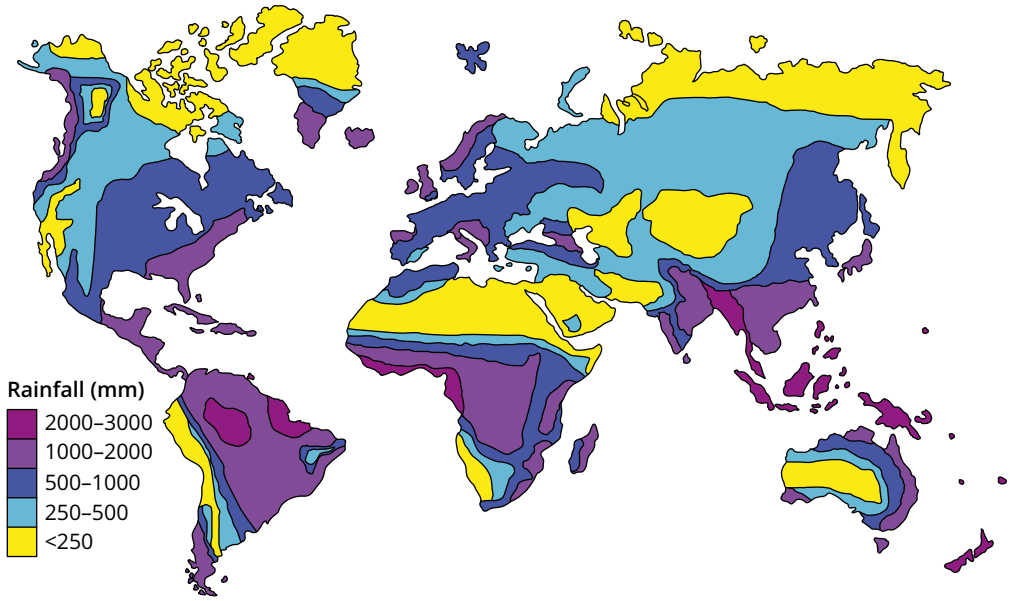


FIGURE 7.2.14 The mean annual precipitation across the world. Rainfall is important in the spread of malaria.

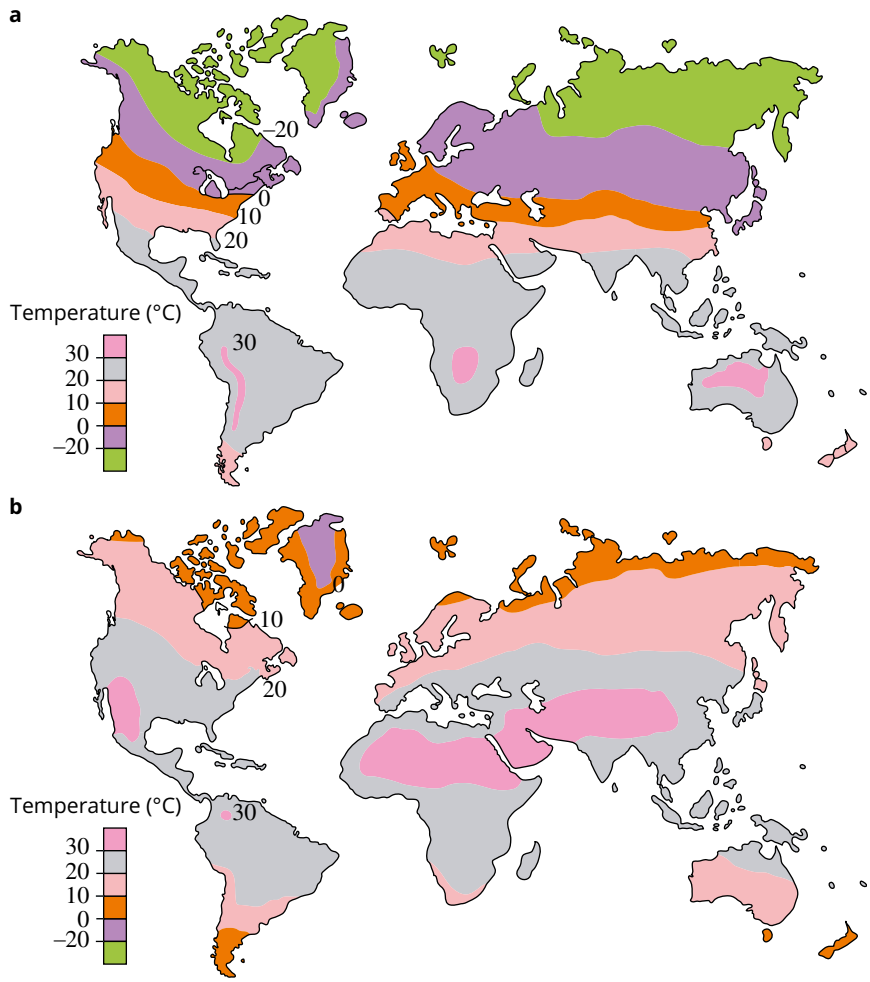


FIGURE 7.2.15 Mean annual temperatures worldwide in (a) January and (b) July. Temperature is important in the development and spread of malaria.

Malaria can only be transmitted in regions where the *Anopheles* mosquito lives. There are several species of *Anopheles*. Most of the species are able to transmit malaria but how likely they are to infect humans varies enormously. Some species prefer animal blood and others prefer human. Two species of *Anopheles* in Africa, *A. gambiae* and *A. funestus,* show a distinct preference for human blood, which is probably one factor leading to the high prevalence of malaria in Africa.

Mosquitoes rely on standing water for their eggs to hatch and the larvae to mature. Therefore, rainfall is a significant factor in malarial spread (Figure 7.2.14). Once the mosquito larvae have matured into adults, they must bite an already infected person and ingest the gametes of the malarial parasite. The gametes form a zygote.

The plasmodium then takes 9–21 days to complete its life cycle, ready to produce gametes, infect the next mosquito and hence the next human host. The length of time depends on the ambient temperature. In cooler areas the process takes longer. Studies of the two species have shown that this part of the mosquito's life cycle cannot occur at temperatures below 15°C for *P. vivax* and below 20°C for *P. falciparum*. The ideal temperature for this stage is above 25°C. Consequently, in areas where temperatures frequently fall below 15°C, transmission of malaria is very unlikely. Figure 7.2.15 shows the mean temperatures in January (Figure 7.2.15a) and in July (Figure 7.2.15b). Temperature and rates of transmission are closely related.

Pathogenic oomycetes

The **oomycetes** (phylum Oomycota) include organisms that cause blight and downy mildew on plants. Long thought of as fungi, the oomycetes are now classified in the kingdom Protista. They have motile cells (with flagella), walls of cellulose, and many cellular processes that are not found in fungi. When spores are released on a leaf, they may be carried in water droplets to other leaves, swim to a germination site, or germinate directly, sending out **hyphae** (thread-like structures) that branch and invade plant tissue. These branching hyphae (also called haustoria) penetrate living cells and absorb nutrients or release enzymes that digest cytoplasm into molecules that can be absorbed. In damp weather, some hyphae grow out through stomata and form spores at their tips. When ripe, spores are blown by the wind to re-infect the same host and to infect other plants.

Members of the oomycetes are important plant pathogens. The genus *Phytophthora* (which means 'plant destroyer') is of particular concern because it has destroyed many crop species and native plants (Figure 7.2.16). There are about 35 species of *Phytophthora*, which infect many crops, including potato, tomato, apple, tobacco plants and citrus trees. In Australia, *Phytophthora cinnamomi* has destroyed tens of thousands of hectares of valuable eucalypt timberland. The spores of *Phytophthora cinnamomi* can survive for years in moist soil, and are attracted to the roots of the plants they infect by a chemical released from the roots.

Phytophthera infestans caused the 1845–1849 potato blight in Ireland. The disease caused the potato crop to fail, resulting in a famine during which more than a million people died of starvation or diseases that thrived in the malnourished population. Up to two million people emigrated from Ireland to escape the famine; many came to Australia.

FIGURE 7.2.16 This eucalypt forest in the Brisbane Ranges National Park in Victoria is infected with *Phytophthora cinnamomi*. Many species of native Australian plants such as the grass trees shown are highly susceptible to this pathogen and rapidly turn brown and die.

Phytophthora has a complex life cycle, with a sexual and an asexual (see Figure 7.2.17) stage. The fungus may be transmitted from plant to plant in water and soil, by wind or by vectors. It thrives under wet conditions, especially where soil is poorly drained. It is easily transported in wet soil attached to boots, tyres or machinery. The motile **zoospores** can swim through soil water to infect new plants. The spores enter the plant through any damaged area of the roots. The spores produce hyphae that grow through the plant, blocking the xylem and phloem, reducing the movement of water and nutrients around the plant and ultimately killing the plant in susceptible species. Figure 7.2.18 shows the specialised hypha (sporangiophore) of *P. infestans* growing out of the stomata of a leaf. At some ends are bulb-shaped structures, (sporangia) which are the spore cases, which will release the **chlamydospores**. These spores can be blown by the wind or transported by other organisms for long distances. When they fall in a suitably moist environment, they mature and release motile zoospores, which continue the cycle of infection.

Only one member of the oomycetes, *Pythium insidiosum*, is known to be pathogenic to mammals, including humans. Infection in humans is rare but when it does occur it causes a serious disease, pythiosis, which is shown in Figure 7.2.19.

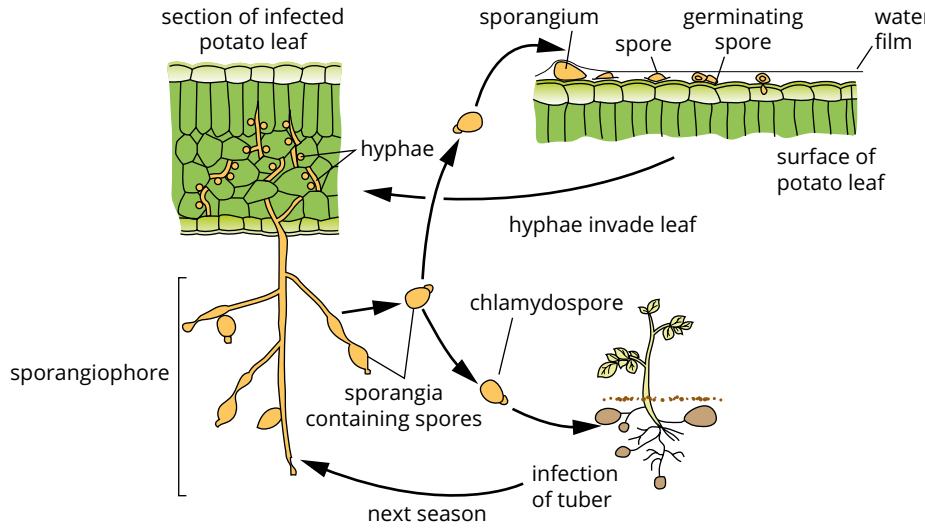


FIGURE 7.2.17 The asexual disease cycle of *Phytophthora*. Spores invade roots and leaves and germinate, and then hyphae grow out of stomata and release more spores to infect other plants.

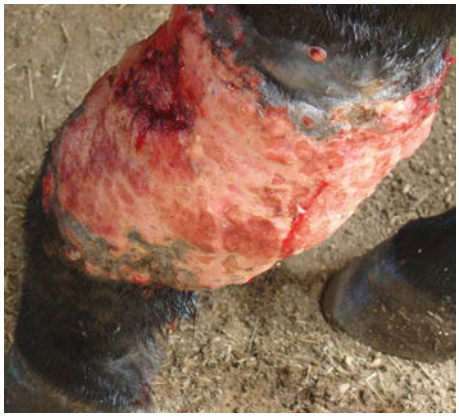


FIGURE 7.2.19 A skin infection caused by *Pythium insidiosum*. In this case, the infection is in a horse but humans and other mammals can also be infected.

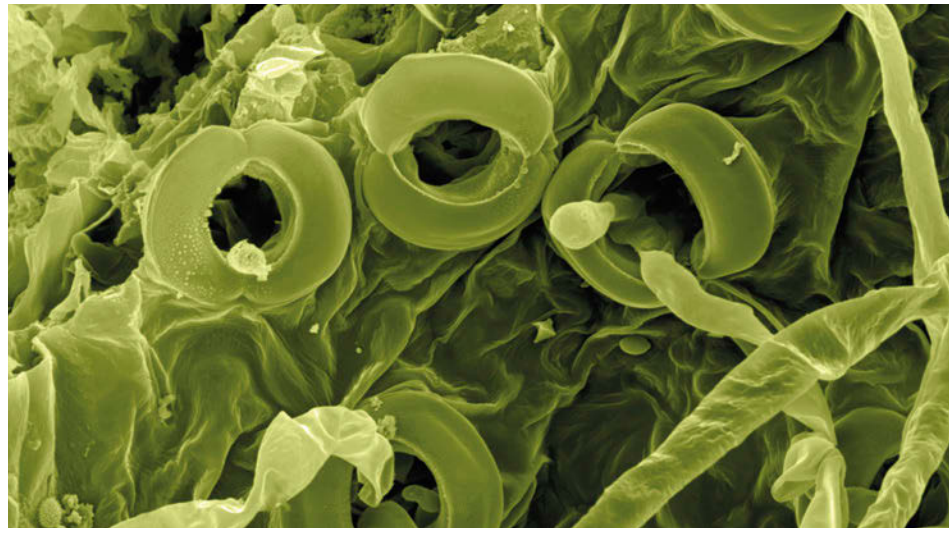


FIGURE 7.2.18 *Phytophthora infestans* hyphae with spore cases attached growing through the stomata of an infected leaf

FUNGI

Fungi are a diverse kingdom of organisms, ranging from the macroscopic to the microscopic (moulds, unicellular yeasts and yeast-like fungi). Fungi can secrete digestive enzymes and other chemicals into their environment to break down organic matter, which can then be absorbed into the fungus. It is these secreted substances that are usually responsible for causing disease in animals and plants. Some fungi, such as the *Amanita muscaria* illustrated in Figure 7.2.20, produce alkaloids, which are biologically active chemicals, some causing disease symptoms due to poisoning if ingested. Fungal cells produce surface glycoproteins and polysaccharides that act as **antigens** (chemicals that trigger an immune response), allowing them to be identified by cells of the immune system.

FIGURE 7.2.20 Many field fungi, such as *Amanita muscaria*, contain toxic alkaloids.

Fungal pathogens

Many fungi are plant pathogens, causing diseases such as leaf spot in eucalypts, rust and ergot in cereals, and Dutch elm disease. In humans, fungi can cause athlete's foot (tinea), ringworm and thrush. A number of fungi are insect-killers. When certain fungal spores land on an insect, they grow through its skin and branch through the insect, eventually killing it (Figure 7.2.21). The hyphae then form fruiting bodies that shoot masses of spores away from the insect.

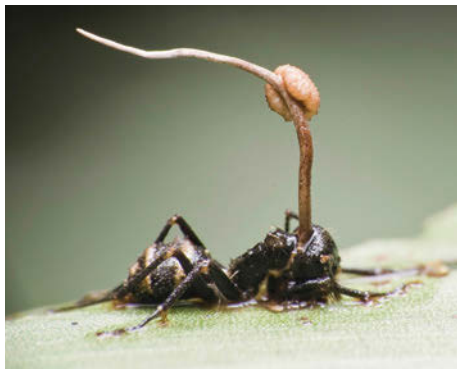


FIGURE 7.2.21 *Ophiocordyceps unilateralis* is a fungus that infects ants.

Only a few fungi are pathogenic to animals. Three main groups cause disease in humans:

- moulds, which are filamentous
- true yeasts, which are unicellular
- fungi-like yeasts, which are like yeasts but may form long non-branching filaments.

The most well known, but not particularly harmful, are the fungi that infect the skin. Different forms of the ringworm fungus cause tinea, which grows in the moist warmth between the toes, and ringworm of the scalp, body and toenails. Thrush, endocarditis and septicaemia are caused by the fungus-like yeast *Candida albicans* (Figure 7.2.22). Direct contact is usually involved in transmission of these skin pathogens. People living with HIV, or other disease in which their immune responses are impaired, often suffer from fungal infections.

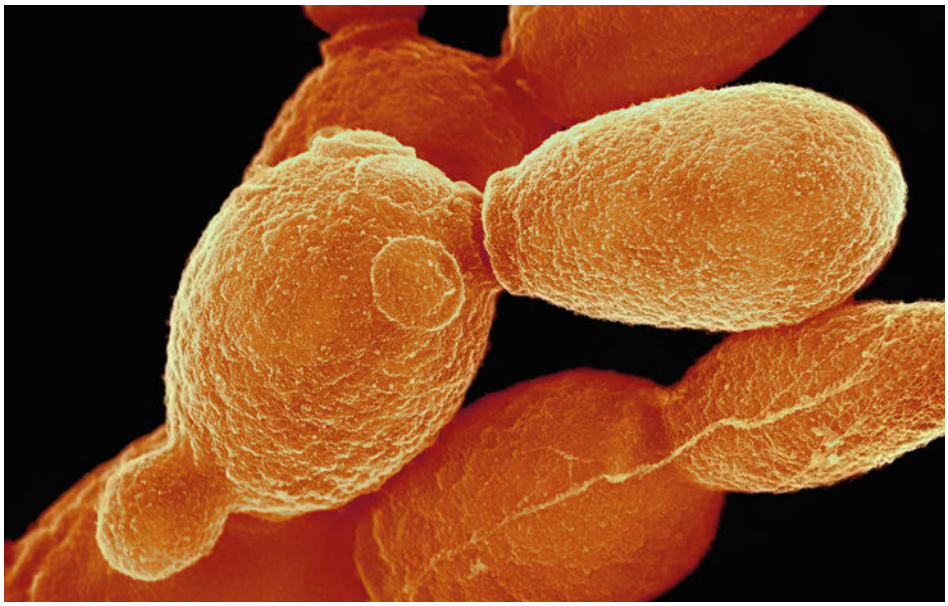


FIGURE 7.2.22 A coloured scanning electron micrograph of the yeast *Candida albicans*, which causes thrush (candidiasis). Depending on environmental conditions, *C. albicans* takes a unicellular yeast-like form or a multicellular filamentous form.

CASE STUDY 7.2.2

Panama disease

Many crop species are susceptible to fungal infections. As recently as 2016, the Queensland banana crop was under threat from Panama disease. This is caused by a strain of the fungus *Fusarium oxysporum* f.sp. *cubense*. Many strains of *Fusarium oxysporum* exist. Some are more pathogenic than others. The different forms are denoted f.sp. (or *formae speciale*).

The *cubense* form of fungus first appeared in Cuba, hence the name. Within *Fusarium oxysporum* f.sp. *cubense* are a number of subgroups or races. The race that infects bananas is Race 4, which has a particular variant that only seems to appear in the tropics, hence Tropical Race 4.

The most popular banana in production was the Gros Michel until the early 1960s when the world crop was devastated by an as yet unidentified strain of *Fusarium*. Searches were made for resistant banana strains and the now popular Cavendish bananas were identified (Figure 7.2.23).

FIGURE 7.2.23 Cavendish bananas now account for around 50% of world banana production. They are highly susceptible to *Fusarium oxysporum* TR4.

In 1989 a new strain of *Fusarium oxysporum* appeared in bananas in Malaysia and Indonesia. This strain, VGC 01213 or Tropical Race 4 (TR4), is highly pathogenic to Cavendish and many other banana varieties. The spread of Fusarium TR4 has been documented and a timeline is shown in Figure 7.2.24. Although identified in 1989 in Malaysia and Indonesia, it is thought that *F. oxysporum* may have been present for some time before then.

Panama TR4 has the potential to wipe out banana production worldwide. The fungus initially gains entry into the plant where roots have been damaged by borers, worms or mechanical damage, or through direct contact of the roots with the roots of other nearby infected plants. Young plants are particularly susceptible to infection. Once in the root, the fungus produces many spores, which are

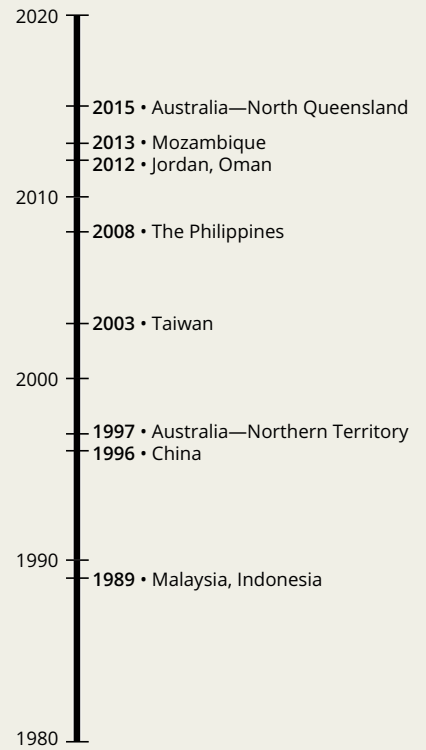


FIGURE 7.2.24 A timeline of the spread of *Fusarium oxysporum* Tropical Race 4 (TR4)

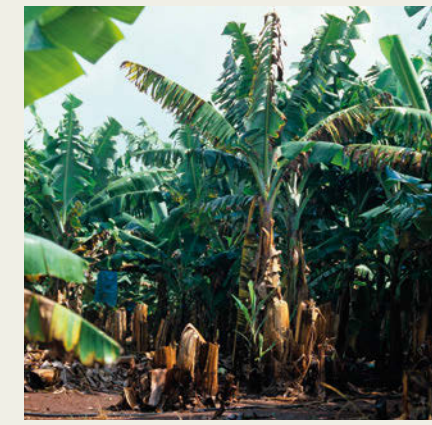


FIGURE 7.2.25 These banana plants are showing the leaf dieback that is symptomatic of *Fusarium* infection.

drawn up the plant in the xylem. Along the xylem are pits that allow water to leave the xylem and move into the tissues. These pits become blocked by the spores, which then geminate and start to grow hyphae into adjacent xylem vessels. The hyphae then produce more spores. The whole of the vascular system becomes impregnated with the fungus, blocking water flow and ultimately resulting in the death of the plant. Banana plants in Figure 7.2.25 are showing signs of the leaf dieback typical of *Fusarium* infection. As the plant dies, the hyphae grow out of the xylem and into the dying and dead tissue, where chlamydospores are produced. These spores end up in the soil where they can lie dormant for many years. Soil testing has shown that fields that have not had banana plants in them for 20 years still contain viable chlamydospores.

Review

1 Describe how *Fusarium* causes the death of the banana plants that it infects.

2 **a** Propose possible strategies that should be undertaken to limit the chances of *Fusarium* spreading from currently infected plantations.

b Argue the likelihood of the proposed strategies for success over the long term (e.g. decades).

CASE STUDY 7.2.3

Black stem rust—a wheat pathogen

Another serious crop-infecting fungus is *Puccinia graminis* (black stem rust), which infects wheat. In the northern hemisphere, this fungus has a complex life cycle involving two hosts and several different types of spores. Thick-walled black spores on wheat germinate after winter and produce new spores (**basidiospores**) in spring. If basidiospores fall on the alternative host (barberry), they germinate and invade the host tissue. They produce haploid fungal spores that fuse and produce a fruiting body. Different spores (**aeciospores**) are then released and dispersed by the wind. If the aeciospores land on a wheat plant, they germinate and invade the wheat plant by entering through stomata on stems or leaves, causing severe damage to the plant. Inside the wheat plant, the aeciospores grow into another type of fruiting body, which produces many spores that re-infect other wheat plants. Late in summer, fruiting bodies form and produce resting spores that become basidiospores the following spring. In Australia, the cycle is limited to the asexual re-infection of wheat and related grasses. The left side of Figure 7.2.26 shows the part of the life cycle of *Puccinia graminis* completed within Australia. The lack of the necessary host plant, barberry, means that the sexual part of its life cycle is unable to occur.

Plant breeders are continually developing new varieties of wheat that are resistant to fungal diseases. This is difficult because the fungi causing these diseases are continually changing, evolving into new strains that can infect the new varieties.

Review

1 **a** State the name given to the process of fusion of the haploid fungal cells.
b Analyse Figure 7.2.26 and identify the type of spores that are formed as a result of sexual reproduction.

2 Explain how the lack of the sexual part of its life cycle will affect the fungus and propose how this could be of advantage to Australian farmers.

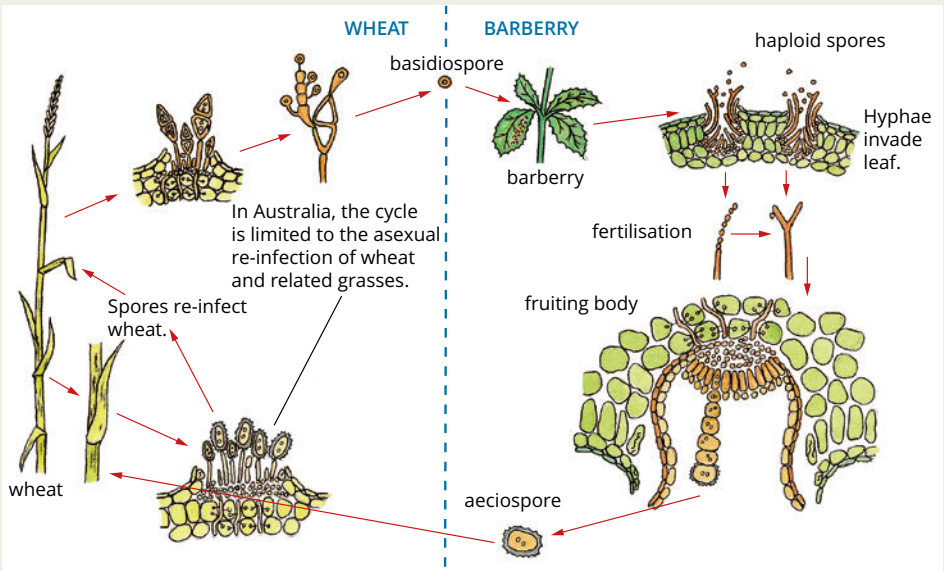


FIGURE 7.2.26 The complete life cycle of *Puccinia graminis* involves two hosts. In Australia, only the asexual part of the life cycle, which occurs in wheat, occurs because of the warmer climate and the lack of the barberry host.

Ergotism

Some fungi produce toxins that can be extremely poisonous to humans and animals. The earliest reported toxic fungus was *Claviceps purpurea*, a parasite that infects the kernel of cereal grains, particularly rye, and produces the substance ergot. It is best known, not for its damage to the rye crop, which is relatively mild, but for its effects on mammals when eaten. Human poisoning (**ergotism**) due to consumption of infected rye grain dates back to before the Middle Ages. There are two types of ergotism. Gangrenous ergotism affects circulation to the extremities, causing gangrene (and some gastrointestinal problems). Convulsive ergotism affects the skeleto-muscular and nervous systems, causing convulsions and brain and spinal lesions.

One of the chemicals in ergot is lysergic acid. This chemical has much in common with the hallucinogen LSD (lysergic acid diethylamide) and many of the psychiatric effects of ergot can be attributed to the lysergic acid. The chemicals produced by ergot also affect blood vessels. They stimulate muscles in arterioles to contract, thereby reducing the diameter of the blood vessel. This reduces blood supply and starves the tissues of oxygen, resulting in cell death. Feet and hands are usually affected first. Digestive tracts may also show symptoms of reduced blood flow, but this is less common. Loss of blood flow to skeletal muscles may result in convulsions caused by the muscles cramping.

Like most poisoning diseases, ergot poisoning is dose dependent. Higher doses result in more serious symptoms. Ergot contains ergotamine, a chemical that is chemically similar to the neurotransmitters serotonin, dopamine and noradrenaline. Its similarity to these important signalling molecules explains its action, because it can take the place of a neurotransmitter and stimulate a response in muscles and organs.

Ergot poisoning is rare in humans today but can cause serious problems for farmers if it infects feed. Its effects on blood flow in the uterus cause females to miscarry. Reduction in blood flow can result in decreased milk production in dairy cattle. Also, sheep and cattle can develop gangrene of the feet, leading to their death.

On the beneficial side, in very small doses ergot has proved useful in the treatment of migraine headaches, and for inducing birth and reducing post-birth bleeding, as it causes both uterine blood vessels and the smooth muscles of the uterus itself to contract.

Most pathogenic fungi do not cause serious illnesses in normally healthy humans, but they can cause serious infections in individuals with compromised immune systems, such as people with HIV or taking immune suppressant drugs, or who are seriously ill with other infections. At times, growth of *Aspergillus* fungi has caused issues in hospitals. In April 2015, an *Aspergillus* infestation forced the closure of the intensive care ward of Ipswich hospital.

OTHER PARASITES

Other parasites also cause disease in humans. Parasites derive nutrition from their host, thereby depriving the host of nutrients. In gaining their nutritional requirements, many parasites damage the host's tissues either by burrowing through them or by directly digesting them as a source of food. A number of phyla contain parasitic members.

The **helminths**, or worms, are distributed over a number of phyla and each phylum contains some parasitic species. There are also a few members of the phylum Arthropoda that are parasites.

Helminths (worms)

Parasitic worms (helminths) of humans and other animals cause destructive diseases of major global socio-economic importance. In particular, parasitic flatworms (trematodes and cestodes) and roundworms (nematodes) have a massive, long-term impact on animal and human health, and cause substantial suffering, particularly in children. Figure 7.2.27 shows the current prevalence of worm infections (Figure 7.2.27a) and the proportion of those infected by country (Figure 7.2.27b). In both prevalence and proportion, developing nations dominate. Helminth infections are relatively uncommon in developed countries.

The World Health Organization (WHO) estimates that 2.9 billion people are infected with worms, mostly transferred from soil (soil-transmitted helminths, STHs) or from eating contaminated food. STHs are contracted from soil contaminated with faeces in areas where sanitation is poor. The incidence of diseases from worms surpasses diabetes and lung cancer in disability adjusted life years (**DALY**s).

Disability adjusted life years (DALYs) is a measure of the reduction in life expectancy due to ill health. It was devised so that differences in life expectancy in different countries due to disease burden could be compared.

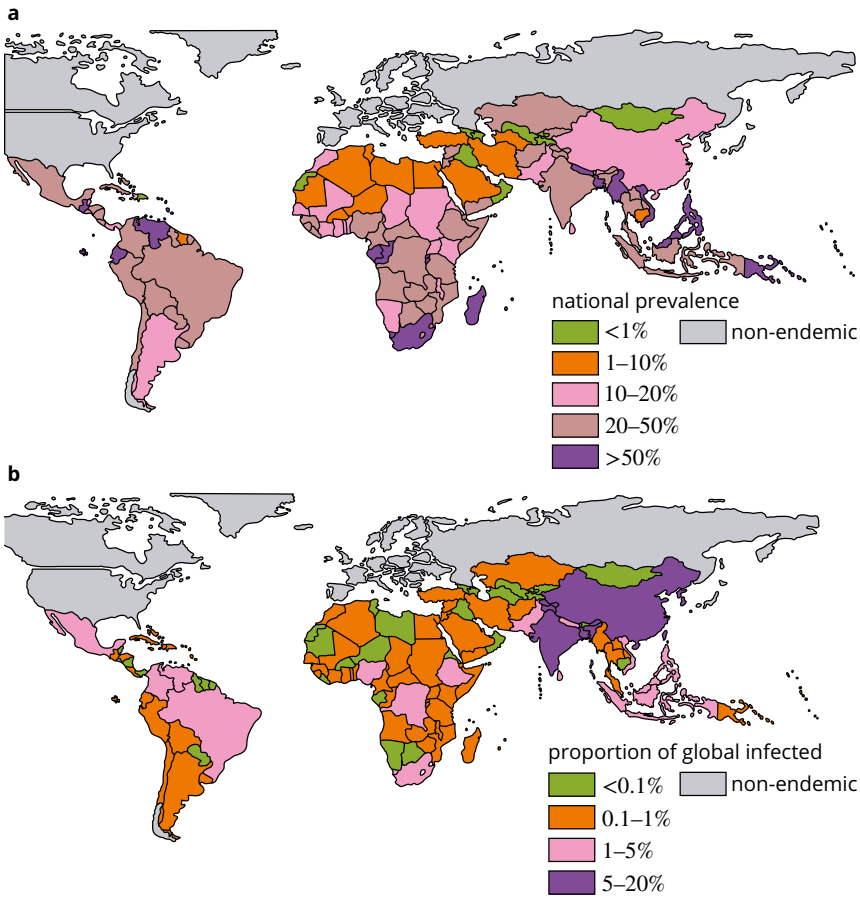


FIGURE 7.2.27 (a) Prevalence by country of infection with helminths and (b) the proportion of the world population infected living in each country. In Australia, helminths are non-endemic.

Parasitic worms include flatworms (phylum Platyhelminthes), such as tapeworms and blood flukes, and roundworms (phylum Nematoda), such as hookworms, dog heartworm, Ascaris and filarial nematodes (which cause elephantiasis). Helminths, which primarily inhabit the digestive tract, absorb nutrients, which can lead to malnutrition in the host. Other helminths consume blood from the host. A large enough infestation can result in anaemia from the depletion of the blood supply.

In plants, roundworms infect roots and are major pests of orchard trees and crops.

Platyhelminthes

Tapeworms are the most highly specialised parasitic flatworms. They are endoparasites that inhabit the gut of humans and other mammals. Adult worms may be up to 10 metres long and are flattened in shape. They have a head, which attaches to the wall of the gut, a neck region, which is the region of growth, and a chain of 'segments' (proglottids), which each contain a set of male and female reproductive organs (Figure 7.2.28). After fertilisation (usually between different segments), each segment matures into a bag of eggs that breaks off and passes out with the faeces.

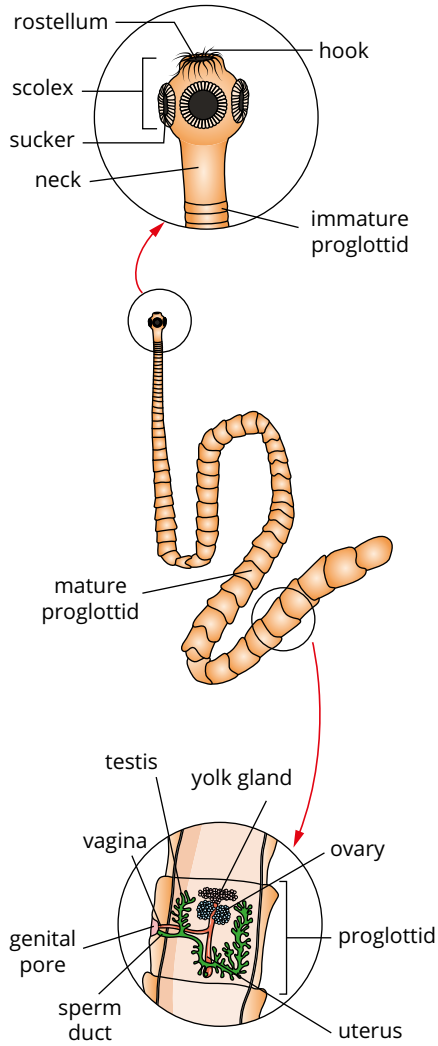


FIGURE 7.2.28 The structure of a tapeworm. Note the maturing segments near the tail that will break off as soon as maturation is complete. These segments are then able to infect a new host.

The blood fluke *Shistosoma mansoni* is another **platyhelminth** known as a trematode. Its life cycle has a snail as the intermediate host (Figure 7.2.29).

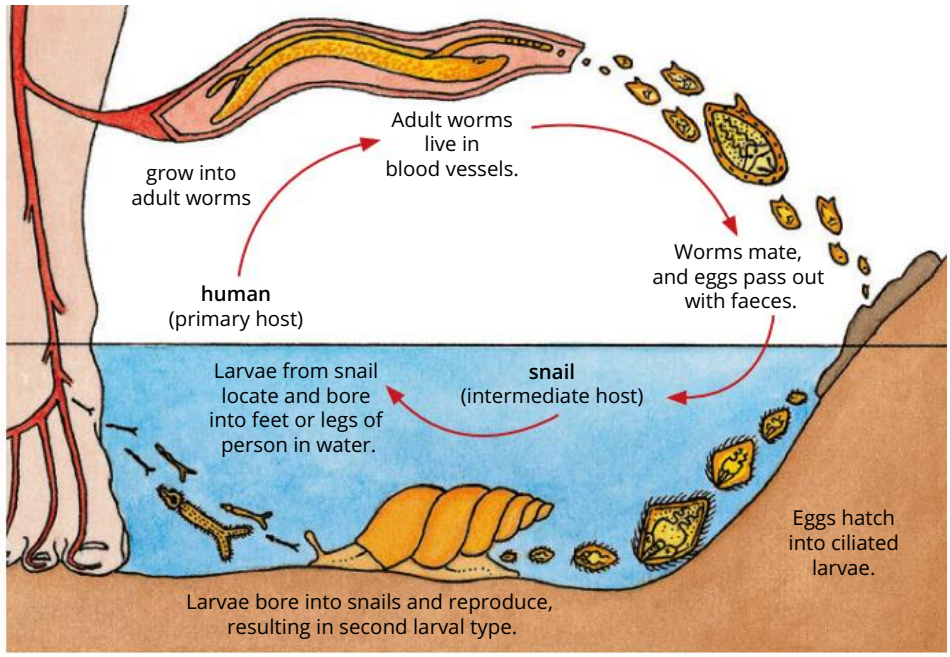


FIGURE 7.2.29 The life cycle of the blood fluke *Schistosoma mansoni*

FIGURE 7.2.30 The internal surface of a dog intestine infested with the hookworm, *Ankylostoma caninium*

Nematodes

Nematodes are known commonly as roundworms, hookworms, threadworms or pinworms. They are present in huge numbers in the environment (millions in a shovel of earth; almost 100 000 in a rotting apple) and are found anywhere that other organisms are found. Some species are extremely widespread while others have very specific requirements and are found in very restricted habitats. Some species live in the guts of animals, such as dogs, as illustrated in Figure 7.2.30.

Although there are both free-living and parasitic nematodes ranging in size from microscopic to over 20 cm in length, the basic body structure of nematodes is virtually the same in every species. They have a simple body plan, lacking either a respiratory or a circulatory system. The pseudocoelom shown in Figure 7.2.31 is a fluid-filled cavity that bathes all of the organs, allowing nutrient, waste and gas exchange to occur. Nematodes have a mouth and anus with a digestive tract that runs the length of their body. There are separate males and females.

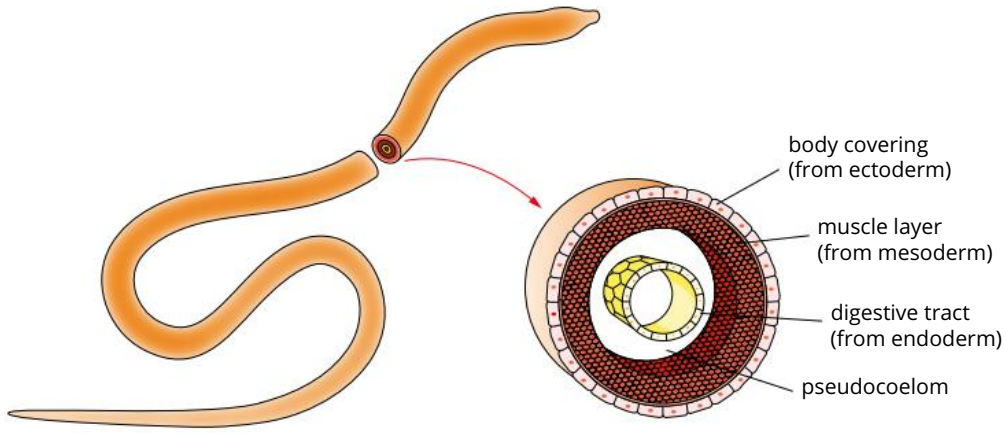


FIGURE 7.2.31 The basic body plan of a nematode. The pseudocoelom allows flow of materials throughout the body and negates the need for a circulatory or respiratory system.

Parasitic nematodes include *Trichinella spiralis*, which causes a disease called **trichinosis** if uncooked, infested pork is eaten. Larvae in infected pork meat hatch out in the gut, where they develop into adult worms. While the adult worms cause no apparent harm and disappear after a few months, the next generation causes severe damage. Sexually mature adults in the gut produce millions of tiny larvae, which migrate through the wall of the intestine and into blood vessels. As they are carried throughout the body, the larvae leave the vessels and burrow into muscle tissues such as the diaphragm, rib muscles, tongue and eye muscles. Many of the symptoms of trichinosis are caused by mechanical damage of tissues as the larvae burrow through them, forming cysts that put pressure on the surrounding tissue. Figure 7.2.32 shows worm-containing cysts in muscle tissue. If cysts form in brain tissue, neurological symptoms can be observed. Fever is a common early symptom of infestation as inflammation reactions occur in response to the damage to body tissues.

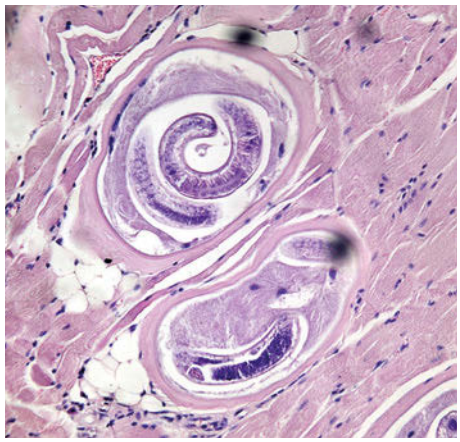


FIGURE 7.2.32 Cysts containing *Trichinella spiralis* worms in muscle tissue.

Another nematode pathogen of humans is *Strongyloides steracolis*. It is endemic in tropical and sub-tropical areas, including areas of northern Australia, where it is particularly problematic in Indigenous communities. *Strongyloides* has two larval stages, **rhabditiform** and **filariform**. Rhabditiform larvae are excreted in faeces, infecting the soil, where they develop into either adults or filariform larvae. The main factor determining whether adults or filariform larvae eventuate is temperature. Lower temperatures (15–30°C) result in adults, while higher temperatures (>30°C) result in more filariforms. The life cycle of *Strongyloides* is illustrated in Figure 7.2.33. Note the two different pathways to infection.

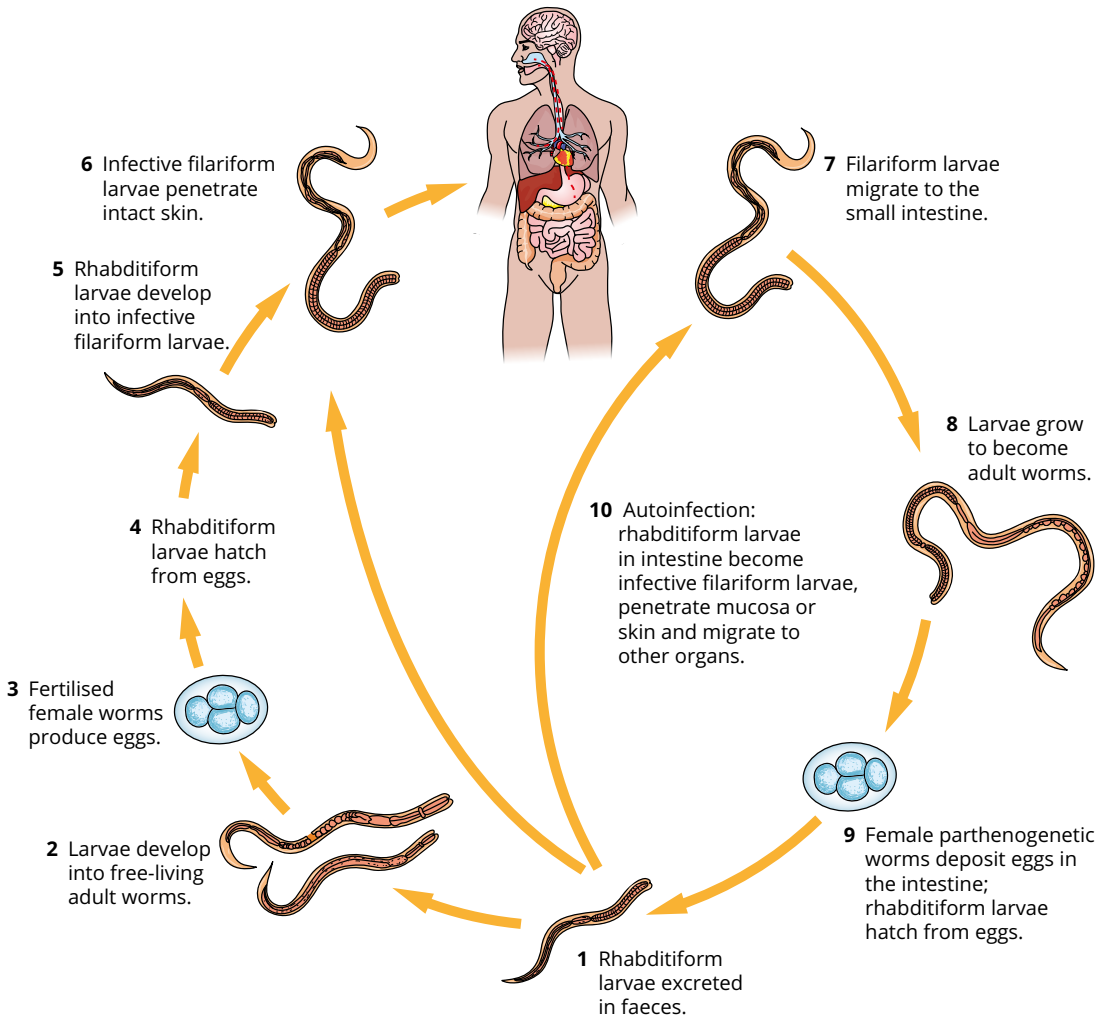


FIGURE 7.2.33 The life cycle of the parasite *Strongyloides*

FIGURE 7.2.34 The mouthparts of many parasitic plant nematodes have a distinctive, needle shaped stylus that is used to puncture the cell walls of the cells. The stylus is clearly visible in this image.

Infection occurs when the filariform larvae penetrate the skin, after which they migrate in the blood to the lungs to be coughed up so that they can enter the digestive tract. The filariform larvae mature into adults in the small intestine. Abdominal pain is a common symptom, mainly caused by normal gut flora invading the surrounding tissues through damaged intestinal lining as the larvae burrow through the walls. Infection with the gut bacteria and the presence of the foreign nematode antigens in the tissues trigger an immune response, which is characterised by a rise in body temperature (fever). If larvae migrate into the lungs, their burrowing causes physical damage to the tissue, resulting in breathing difficulties and chest pain. The adults release eggs, which hatch into larvae and are excreted in the faeces, further contaminating the soil. Spread of *Strongyloides* is common in areas where sanitation is poor.

Some nematodes are major pathogens of crop plants. Plant-infecting nematodes mainly attack roots, and part of their life cycle often takes place in the soil. Female worms lay their eggs in or on host tissues. The eggs hatch and the juveniles feed on nutrients obtained from host tissues, often stimulating tissue growth and gall formation. Nematodes that are parasitic on plants have distinctive mouthparts, with a sharp stylet that is used to puncture the cell wall (Figure 7.2.34). Many nematodes are also vectors (carriers) of other plant pathogens, including fungi, bacteria and viruses.

Arthropods

Insects are major vectors of disease in plants and animals. A few species of insects are parasitic on mammals, including some mosquitoes and fleas. Ticks and mites, including head lice, body lice and the crab louse, are examples of arthropods that infect humans.

In plants, **psyllids** (lerp insects) are small insects that, in their larval stages, induce the formation of galls on leaves (Figure 7.2.35). The larval stages of many psyllid species construct a covering (a lerp) under which they feed on the leaf surface. The saliva from feeding psyllids kills leaf tissue, causing extensive discolouration of the leaf. The saliva of the psyllid or damage to the plant tissue initiates increased production of plant growth hormones. This causes the plant's cells to grow larger or proliferate more quickly. In either case, the tumour-like gall surrounds the pathogen in a swollen mass of cells.

Other species of insects, including aphids, flies, wasps and thrips, also induce the formation of galls on leaves and stems. The shape of the gall indicates the species of insect causing it. Sometimes a second parasitic insect lays its eggs into a gall. The new parasite kills the gall insect as it grows.

FIGURE 7.2.35 Psyllid-induced galls on a lilly pilly leaf

Pioneering studies of disease

A doctor today would never consider even examining a patient without first washing their hands thoroughly, and surgery is performed under sterile conditions to protect patients against the possible invasion by pathogens. This was not the case in the past. During the 18th and early 19th centuries, it was common practice for doctors to go straight from performing autopsies to performing operations, delivering babies or reviewing patients.

The existence of bacteria had been known since the invention of the microscope in 1660 but the link between bacteria and disease was not firmly established until the middle of the 1870s. However, by 1840 some people in the medical profession were beginning to take the first tentative steps towards modern germ theory.

One of the first doctors to consider the idea that there was something in the environment that caused disease was Hungarian doctor Ignaz Semmelweis (1818–1865). Semmelweis was an obstetrician working at the Allgemeines Krankenhaus, a major hospital in Vienna, Austria, when he noticed that there was a distinct difference in the number of women contracting childbed fever (now called puerperal fever) in the two maternity wards at the hospital.

The hospital had two wards: Ward 1 where the patients were cared for by doctors and their medical students and Ward 2 where the patients were cared for by midwives. Semmelweis noticed that the death rate in Ward 1 from childbed fever was more than six times that in Ward 2. He observed both wards carefully, in order to determine what the difference was between the wards. He considered more than one possibility but it was not until another doctor and close friend Professor Jacob Kolletschka died of an illness that displayed symptoms very much like childbed fever that he came up with the answer.

Kolletschka died following an accident. He scratched his hand with a scalpel during the autopsy of a woman who had died of childbed fever.

Semmelweis put the two things together to come up with an answer. The first was the death of his friend following the accident. The second was that on Ward 1, doctors who performed autopsies looked after the women, and the death rates were high; and on Ward 2, midwives, who did not do autopsies, looked after the women and death rates were low. Putting these facts together, Semmelweis hypothesised that 'cadaver particles' on the hands of doctors were transferred to patients and caused childbed fever.

In 1847, Semmelweis instituted rules requiring all doctors to wash their hands thoroughly in chlorinated lime water (mild chlorine bleach) after autopsies and before attending the maternity ward. He also had all medical instruments washed in chlorinated lime water. After these rules were brought into the hospital, death rates of mothers and babies on the doctors' ward (Ward 1) fell from around 12% to just over 2%. Unfortunately, Semmelweis was ahead of his time and his ideas were not well accepted by the establishment. He was not reappointed when his contract ended in 1849. After he left the hospital, hand washing decreased and death rates once again rose. The death rates in the two wards over the relevant period were recorded and are displayed on the graph in Figure 7.2.36.

It was not until later in the 19th century that the work of Louis Pasteur and Joseph Lister established the causes of disease to be closer to our current understanding.

Louis Pasteur established the existence of microorganisms and showed that infectious diseases were caused by microbes.

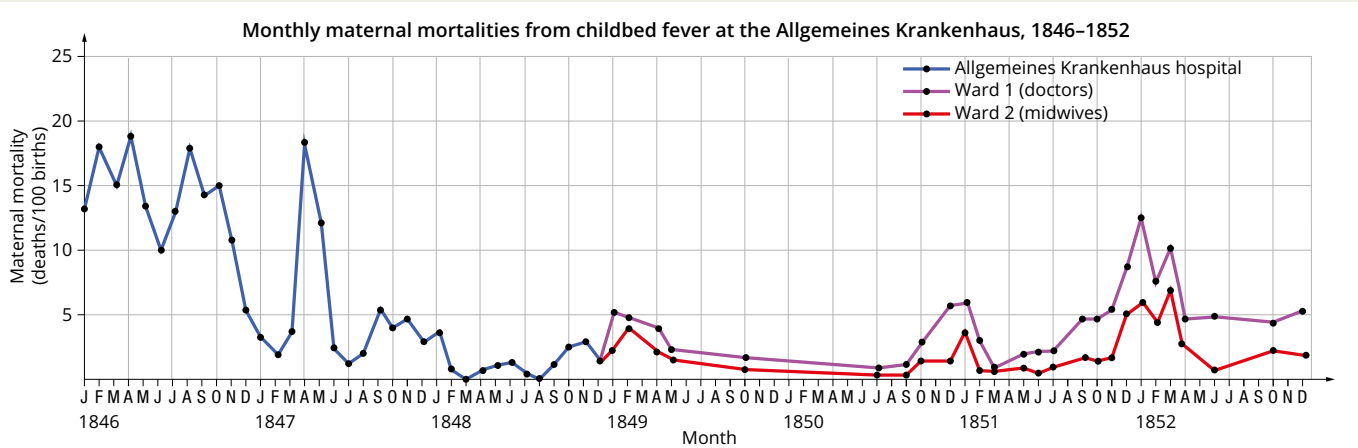


FIGURE 7.2.36 Monthly maternal mortalities from childbed fever at the Allgemeines Krankenhaus between January 1846 and December 1852

Joseph Lister, an English surgeon, observed that when wounds were left open to the air, such as after amputations, almost half the patients died from infection. He also noticed that in wounds that were closed, infection was not nearly so severe. He concluded that infection was due to 'something in the air'. When he heard of Pasteur's experiments showing microbes to be the cause of putrefaction (rotting) of food, he decided they might also be the cause of the infections in his patients.

It was known that carbolic acid was highly poisonous to living organisms, so Lister decided to use it in his hospital wards in the hope that it would kill the 'invisible microbes'. He used it on patients, his own hands and around hospital rooms, and required nurses to use it also. The incidence of infection in his patients was dramatically reduced.

One of the earliest experimental studies that investigated the cause of disease was the work of a German doctor Robert Koch (Figure 7.2.37) and other scientists. Towards the end of the 19th century, with the improvement of the microscope, scientists were able to identify different species of bacteria and protozoa. In Koch's early work, he studied anthrax, a disease of cattle and sometimes humans.

FIGURE 7.2.37 Dr Robert Koch (1843–1910), German bacteriologist, in his laboratory in South Africa

Koch's experimental method involved examining blood samples taken from patients with different diseases, then growing microbes from the blood on nutrient plates. When he injected specific microbes into mice, he found that they developed diseases similar to those of the original patient. As a result of these studies, specific microbes became recognised as the cause of particular diseases.

Koch formulated a set of criteria, known as Koch's postulates, for establishing whether a specific microorganism was the cause of a particular disease. Koch's postulates are:

1 The microorganism should always be found in organisms suffering from the disease, but not in healthy organisms.
2 The microorganism must be cultivated in pure culture away from the body of the infected organism.
3 When this culture is inoculated into a susceptible organism, the organism should develop symptoms of the disease.
4 The microorganism should then be re-isolated from the experimentally infected organism and re-cultured in the laboratory. It should be the same as the original microorganism.

Review

1 For Koch's experimental method, which led to his postulates, identify:
- his working hypothesis
- the experimental variable
- what he measured or observed
- the control.

2 Explain whether Koch's postulates can be applied to non-cellular pathogens.

3 Describe the main contributions of Koch and Semmelweis to our understanding of disease.

4 Propose why Semmelweis had so much trouble having his theories accepted.

7.2 Review

SUMMARY

- Infectious diseases are caused by pathogens, which can be transferred from one organism to another organism.
- Some bacteria, worms, protozoans, fungi and fungus-like oomycetes can cause disease.
- Infection can occur through direct touch or contact with body fluids, by inhaling or ingesting contaminated water or food, through vectors or through medical procedures.
- Insects are vectors for many animal diseases and some cause galls in plants.
- Mosquitoes are one of the most important vectors for animal diseases.
- Virulence is a measure of a pathogen's ability to cause disease. It depends on the characteristics of the pathogen and the host.
- Bacteria are classified according to their traits, which include structure, biochemistry and gram staining.
- Many parasitic pathogens have complicated life cycles involving more than one host.
- Fungi and oomycetes are rarely important animal pathogens but are serious plant pathogens, sometimes destroying large areas of crops.
- Helminths or worms are important human parasites, which can cause serious disease in some individuals.

KEY QUESTIONS

Retrieval

1 Identify four main methods by which diseases can be spread.

2 Describe how an infection with *Phytophthora* causes plant death.

3 Define 'gall' and explain the circumstances under which plants form them.

4 **a** Name a fungus that causes disease in:
i animals.
ii plants.
b Describe how the fungus causes disease in its host.

Comprehension

5 Explain whether all bacteria are pathogenic. Use at least one example to clarify your answer.

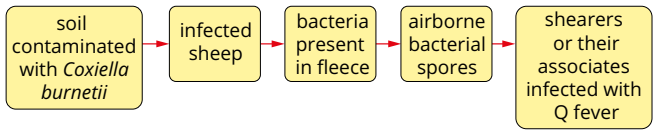
6 Describe how a primary host, an intermediate host and a vector are different.

7 A patient arrives in the emergency department of a hospital with a badly infected cut on their leg. The doctor takes a swab of the wound in order to identify the pathogen that is causing the infection. The swab is sent to the pathology department where the pathogen is cultured and the cultures are examined under a microscope.
The pathologist examines the culture and determines that the pathogen is a bacterium. Having decided that the pathogen is a bacterium, the pathologist must now identify the species of bacteria present.
Outline some features of bacteria the pathologist could analyse and distinguish.

Analysis

8 Explain the significance of gram staining in fighting disease.

9 Q fever is an example of a zoonotic disease. It is caused by a bacterium called *Coxiella burnetii*. In most people it causes a flu-like illness, but in some individuals it can cause liver or heart disease. One pathway for infection is shown here.



Propose three practices that could reduce the chance of infection with the bacterium.

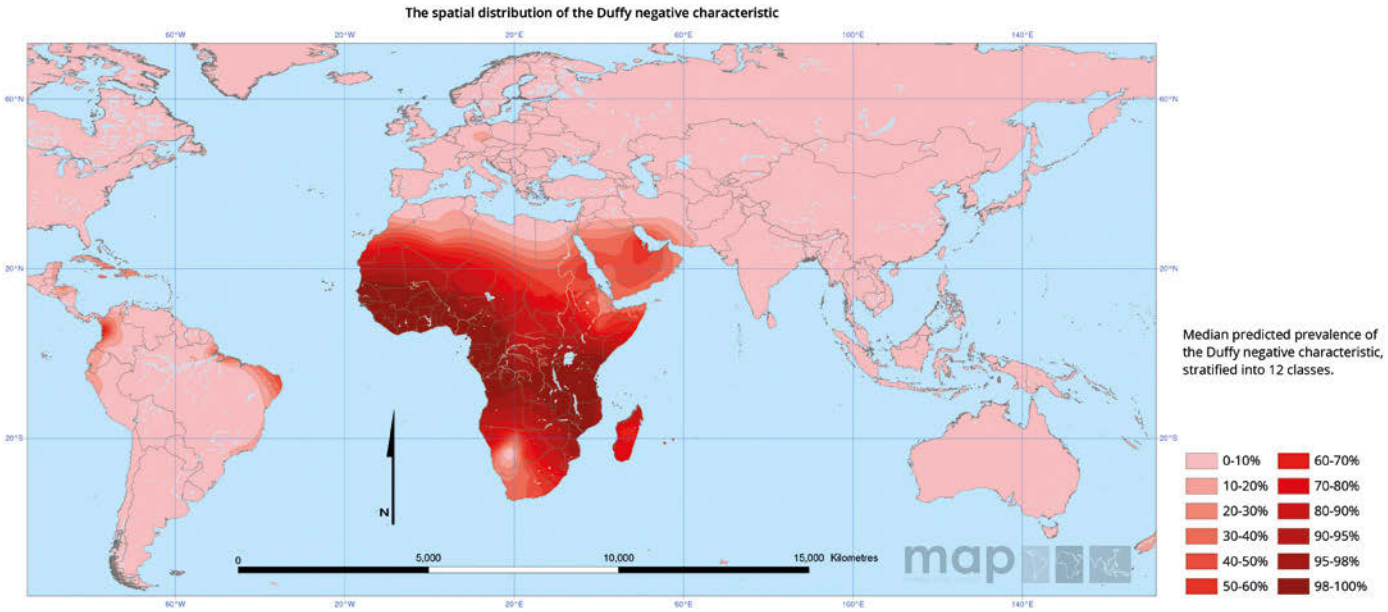
10 Consider the life cycle of the malarial parasite (*Plasmodium*), which involves two hosts, as shown in Figure 7.2.13. Propose intervention strategies to stop disease or symptoms in humans.

11 According to the Centers for Disease Control in the USA, estimates of the survivability of *Anopheles* mosquitoes suggests that the survivor rate is between 0.77 and 0.84 per day, which means 77–84% of the adult mosquitoes survive each day.
a Draw a graph showing the percentage of mosquitoes surviving at each of the (survivor rate) extremes over a period of three weeks. Use the same set of axes.
b Propose why malarial transmission is so unlikely at temperatures below 15°C. Use your graph and the knowledge that you have gained about the life cycle of *Plasmodium* to assist you.

continued over page

7.2 Review *continued*

12 Red blood cells carry surface molecules (antigens) for different blood groups, such as the ABO, MN, Rh and Duffy groups. Malaria merozoites of *Plasmodium vivax* use the Duffy antigen to recognise and attach to red blood cells. Individuals without Duffy antigens (Duffy negative) are at an advantage in regions where malaria is prevalent because the malaria parasite cannot easily enter their red blood cells. The map shows the distribution of the Duffy negative characteristic across the world. Assess whether or not the data in Figure 7.2.12 and the map below support the hypothesis that lacking Duffy antigen assists individuals to resist infection by *P. vivax*.



13 Poultry can be affected by ergot. Studies have been done on the effect of ergot on ducks being grown for the table. The results of one such study are shown in the table below.

		Feed intake (g day^{-1})		Weight gain (g day^{-1})		Feed intake to weight gain ratio (g g^{-1})	
Group	**Ergot intake (g kg^{-1} food)**	**Days 1–7**	**Days 8–14**	**Days 1–7**	**Days 8–14**	**Days 1–7**	**Days 8–14**
A	0	35.1	98.5	25.7	66.6	1.4	
B	1	31.8	94.7	23.4	62.5		
C	10	25.4	78.7	17.2	54.4		
D	15	20.8	48.7	12.5	33.3		
E	20	18.7	38.1	10.7	24.8		

a i Calculate the ratio of feed intake to weight gain by the ducks and use your calculations to complete the table. (The first one has been done for you.)

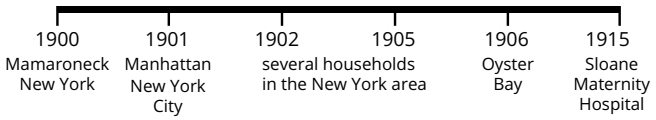
ii Explain what the value of 1.4 means.

b Explain which group is the control in this experiment.

c i Explain whether the claim, 'ergot causes a reduction in feed intake', is supported by the data.

ii Identify a second variable that influences feed intake.

14 *Salmonella typhi* is a bacterium responsible for the disease typhoid fever. Between 1900 and 1907, a woman named Mary Mallon was working as a cook in New York. Mary appeared to be perfectly healthy. A timeline of her working life is shown below.



In 1900, Mary Mallon took a position as the cook in a series of private homes. Around 24 people became ill with typhoid. In 1901, she took a position in Manhattan; several members of the family, along with some of the other staff, became ill. From 1901 to 1906, she moved several times and at nearly all of the new positions, people became ill with typhoid. In 1906, she was working for a family in Oyster Bay on Long Island when 14 of the family became ill. For various reasons, Mary ceased cooking until 1915 when she took a position as cook at Sloane Maternity Hospital in New York. Twenty-five people became infected and two died.

a Explain how Mary could make others ill without showing any signs of disease.

b Explain the significance of Mary's occupation to the incidence of the typhoid outbreaks.

15 Pathogens of animals cause disease by many different pathways, but in plants the disease is often caused through similar mechanisms. Compare how *Agrobacterium* and *Fusarium* cause disease in plants.

16 A study was undertaken in Africa to investigate the relationship of four types of worms and the prevalence of anaemia in their human hosts. All of the hosts were children under the age of 16 years. The data gathered is shown in the table below.

a Evaluate whether the hypothesis that worm infections cause anaemia is supported.

b Evaluate the reliability of this evidence.

Infection	Intensity	Number and percentage of children tested	% Anaemic (95% confidence interval)
Hookworm	No infection	803 (52.7%)	14.0 (11.6–16.3)
	Light infection	691 (45.4%)	12.9 (10.4–15.4)
	Moderate infection	15 (1.0%)	13.3 (0.0–30.5)
	Heavy infection	14 (0.9%)	14.3 (0.0–32.6)
Schistosoma mansoni	No infection	1309 (86.0%)	13.2 (11.4–15.1)
	Light infection	91 (6.0%)	11.0 (4.6–17.4)
	Moderate infection	76 (5.0%)	13.2 (5.6–20.8)
	Heavy infection	47 (3.0%)	25.5 (13.1–38.0)
Trichuris trichiura	No infection	1326 (87.1%)	13.4 (11.6–15.3)
	Light infection	188 (12.3%)	14.4 (9.4–19.4)
	Moderate infection	8 (0.5%)	Not available
	Heavy infection	1 (0.1%)	Not available
Ascaris lumbricoides	No infection	1162 (76.3%)	13.6 (11.6–15.6)
	Light infection	236 (15.5%)	13.1 (8.8–17.5)
	Moderate infection	125 (8.2%)	12.8 (6.9–18.7)
	Heavy infection	0 (0%)	Not available

7.3 Pathogenic molecules

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

- understand that prions are normal proteins that have abnormal folding
- be able to explain how viruses use host cells for replication and then escape from the cell
- understand the role of host cell membrane receptors in viral entry into cells
- understand the role of antigenic drift and shift in viral virulence.

Viruses and prions cause disease in many organisms. Unlike the pathogenic organisms discussed in Module 7.2, viruses and prions are not made of cells, and so are not classified as organisms. Rather, they are known as **pathogenic molecules**.

PRIONS

The smallest of all of the known pathogenic molecules are **prions**. Prions are the only known infectious agents that do not contain genetic material. Prions are proteins that are similar to normal cellular prion proteins (PrP), which are mainly located on the surface of the cells in the central nervous system of an organism. However, unlike PrPs, prions have an abnormal shape (or conformation) (Figure 7.3.1).

Prion diseases have two identifiable causes:

- infection
- genetics.

Infection accounts for 1% of the cases of prion disease, while genetics accounts for 10–15%. The remaining cases of prion disease (84–89%) are classified as sporadic, which means they have no clearly identifiable cause. Sporadic prion diseases may be caused by random mutations in single cells or by a random misfolding of a protein or another as yet unconsidered cause. Regardless of the source of the original misfolded protein, the progress of prion disease remains similar.

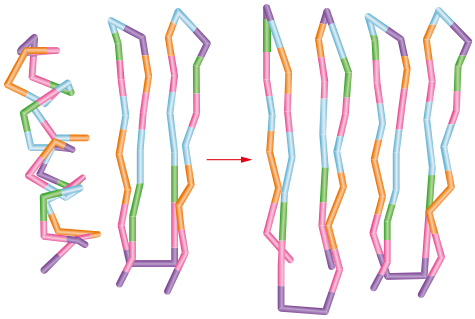


FIGURE 7.3.1 The normal spiral-shaped PrP protein unfolds and refolds into a pleated sheet shape. This makes the proteins clump together, or aggregate, to form masses called plaques, which damage neurons.

Prions stimulate the organism's normal PrP to misfold into the infectious prion form (Figure 7.3.1). The abnormal prion proteins maintain their ability to cause misfolding and thus continue to do damage. As a result of the mechanism by which prions cause disease, the damage to the nervous system develops at an exponential rate. By the time symptoms appear, which may be up to 30 years after infection, considerable damage has been done. The prion proteins build up in the tissues of the nervous system causing plaques. **Plaques** are masses of sticky proteins found in the brain where they lead to neuronal death by means that are still unclear.

Prions are resistant to being denatured, as well as to being broken down by proteases, which normally break down proteins in the digestive tract. Prions cause neurodegenerative diseases in mammals, the first of which to be discovered was scrapie in sheep.

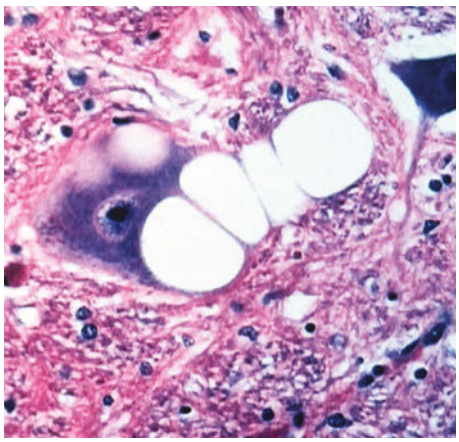


FIGURE 7.3.2 Scrapie is a disease in sheep caused by prions. This light micrograph shows a section through the brain of a sheep infected with scrapie. The large empty vacuoles (white) in the centre show the effects of the disease. As scrapie progresses, the number of empty vacuoles increases and makes the brain tissue appear spongy and destroys neurons. Symptoms of the disease include glazed eyes and body tremors.

In humans, prions cause **Creutzfeldt–Jakob disease (CJD)**. The CJD prions cause vacuoles and misfolded proteins (or plaques) to form in the brain, which kills neurons and makes the brain appear 'spongy' under a microscope. Figure 7.3.2 shows the typical spongy appearance of the brain tissue of a mammal, such as a sheep, affected by a prion disease.

Symptoms of CJD include dementia and sudden muscle contractions, leading to death. The equivalent disease in cattle, bovine spongiform encephalopathy (BSE), commonly known as mad cow disease, has been linked to a human variant CJD (vCJD) through human consumption of BSE-contaminated beef. All forms of CJD have long incubation periods averaging around 10 years but there have been cases where onset of symptoms occurred more than 30 years from exposure. However, once symptoms appear, death generally occurs in less than 18 months.

The normal prion protein (PrP) has two common variants. One variant has the amino acid valine at the 129th position and the other has methionine in that position. The valine variant is designated V, while the methionine variant is designated M. Individuals can be homozygous (VV or MM) or heterozygous (MV). In caucasian populations, 50% of people are MV, 40% are MM and 10% are VV. It has been suggested that possession of the MV genotype partially protects against infection.

Prions elicit an ineffective innate immune response, and the adaptive immune system cannot identify and respond to them. You will learn more more about the innate and adaptive immune systems in Chapter 8. It has been suggested that the reason the adaptive immune system cannot respond to prions is that, despite being abnormal in shape, prions remain very similar to the normal PrP, and any T lymphocytes (a type of white blood cell) that would have responded to normal PrP would have been destroyed to prevent an autoimmune reaction. Another reason could be that prions are unable to be broken down and presented by antigen-presenting cells. You will learn more about adaptive immune responses in Module 8.2.

VIRUSES

Viruses are obligate, intracellular parasites, meaning they cannot replicate outside of cells. A single virus particle is called a **virion**. A virion is composed of genetic material, either DNA or RNA, enclosed in a protein coat, called a **capsid** (Figure 7.3.3). Some viruses also have a covering made of a combination of protein and lipid (a lipoprotein, shown in Figure 7.3.4c).

Viruses come in a variety of different shapes but all have the same basic structure of genetic material enclosed in a protein coat. Figures 7.3.4 and 7.3.5 show some of the varieties of virion shapes.

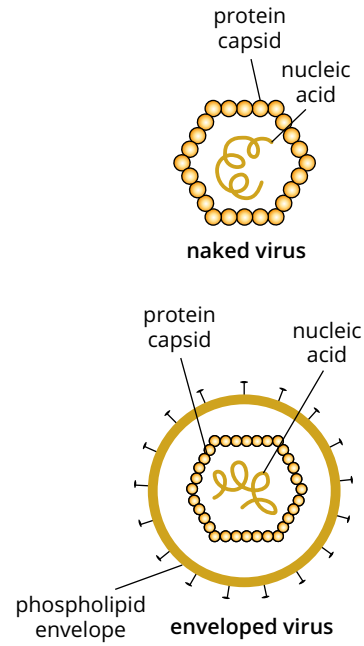


FIGURE 7.3.3 A virus is composed of a nucleic acid core, surrounded by protein molecules and, sometimes, a membrane envelope.

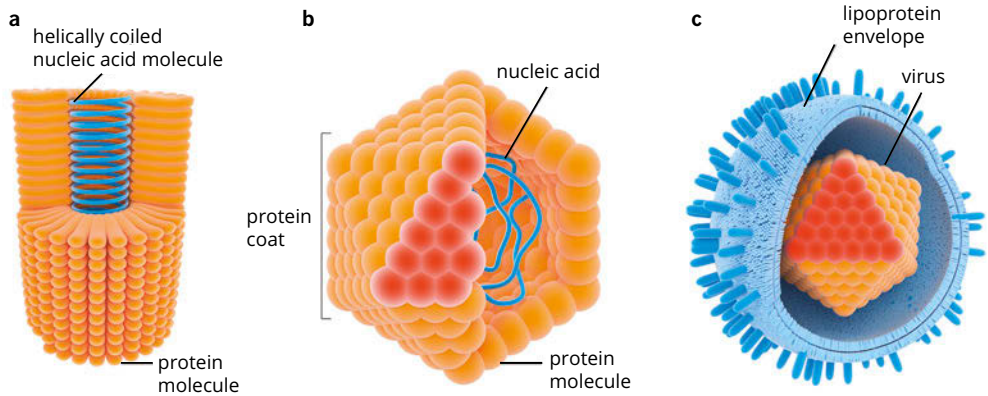


FIGURE 7.3.4 Different structures of virions. (a) A rod-shaped virion with proteins (orange) surrounding a helically coiled nucleic acid molecule (blue). (b) An isometric virion with an icosahedral protein coat surrounding a nucleic acid core (blue). (c) An icosahedral virion (orange) enclosed by a lipoprotein envelope (blue).

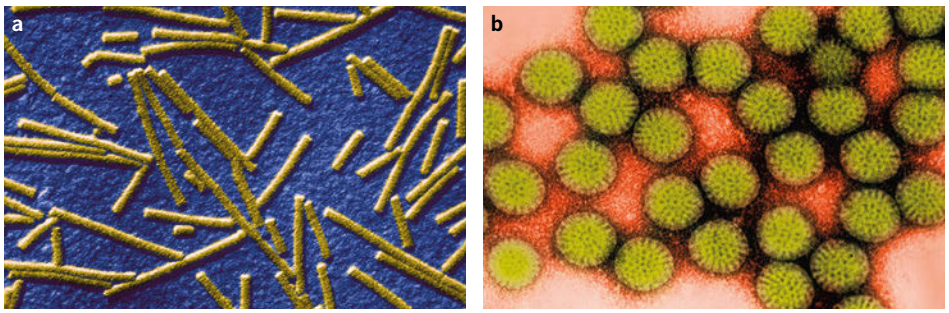
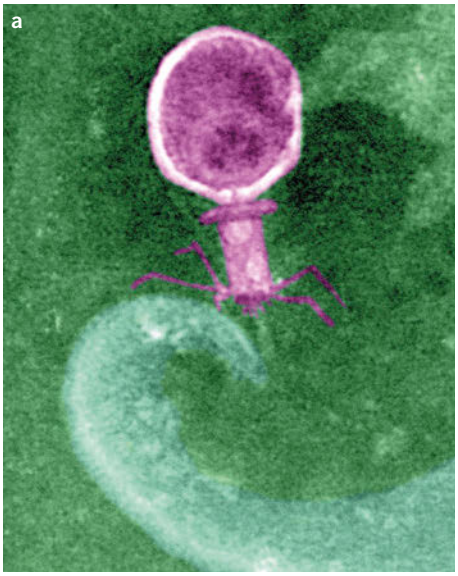


FIGURE 7.3.5 (a) A rod-shaped tobacco mosaic virus. (b) Rotavirus is a major cause of gastroenteritis in children.



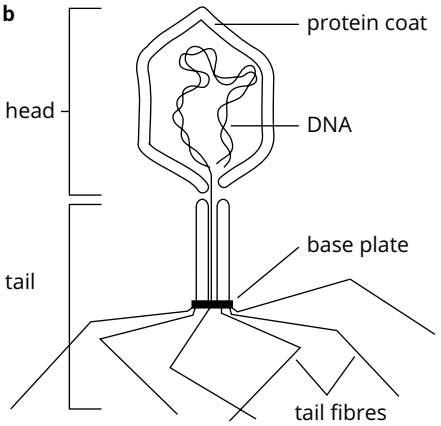


FIGURE 7.3.6 (a) An electron micrograph and (b) a diagram of a T2 bacteriophage. This is a virus that infects bacterial cells.

Viruses infect all types of living things, even bacteria. Viruses that infect bacteria are called **bacteriophages** (Figure 7.3.6).

Viruses that use RNA as their genetic material are known as **retroviruses**. Retroviruses use an enzyme called **reverse transcriptase** to produce DNA, using their RNA as a template once they infect the host cell. Human immunodeficiency virus (HIV), which causes AIDS, is an important retrovirus.

The interaction between a virus and a host cell is specific. The specificity often lies in the attachment and entry processes, which involve viral proteins interacting with receptor molecules on the cell membranes of target cells. For example, the receptor for the influenza virus is a particular glycoprotein on the surface of red blood cells. In Figure 7.3.7, the virus is using one receptor on the cell to attach to the cell and a second receptor (called a co-receptor) to enter the cell by triggering endocytosis by the cell. Other viruses do not have specific attachment sites and enter cells by other means, such as engulfment by phagocytic cells. Once inside a cell, viral nucleic acid must survive the defensive enzymes of the host cell, which normally break up foreign DNA in order to prevent its replication. Some viruses have altered the structure of their DNA so that they are no longer susceptible to destruction by these host cell enzymes.

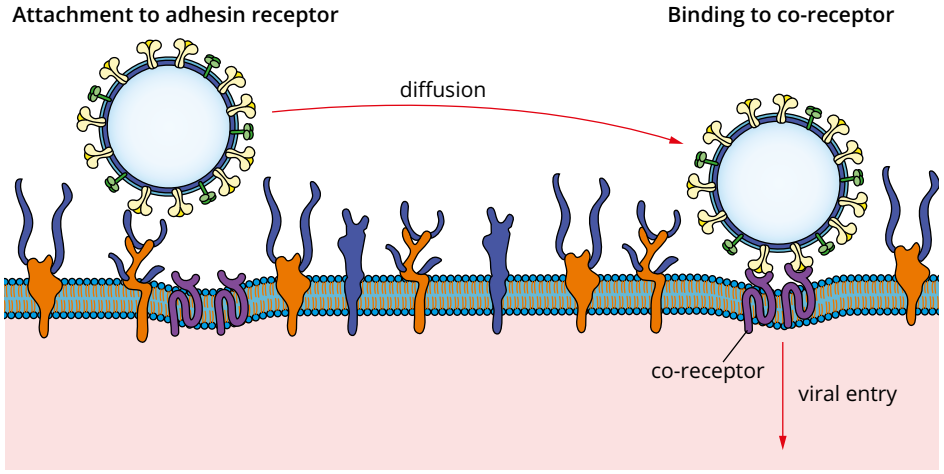


FIGURE 7.3.7 In order to infect a cell, viruses usually interact with a receptor molecule on the outside of the cell membrane. Viruses may use a second receptor to assist with entry into the cell, called a co-receptor.

CASE STUDY 7.3.1

CCR5 and HIV

In 1995, it was observed that a group of people seemed to be highly resistant to infection by HIV. HIV results in immune suppression because it infects one of the crucial cells of the immune system called a helper T lymphocyte. These white cells play a critical role in activating other cells of the adaptive immune response, so when they are invaded by HIV, the immune response is severely compromised and the ability to fight disease is decreased. You will learn more about the adaptive immune response in Chapter 8.

In order to enter the helper T cell, the HIV virus attaches to a receptor on the outside of the cell called CD4. The HIV then uses another protein, called CCR5, to enter the helper T cell. In most people, CCR5 is a large transmembrane protein that extends beyond the membrane both inside and outside the cell, and so can act as a co-receptor site. Figure 7.3.7 illustrates receptors and co-receptors.

Studies showed that some people have a mutation in the gene coding for the CCR5 protein, which makes the protein much smaller than normal. The mutated CCR5 protein is completely enclosed inside the membrane. This makes entry of HIV into the cells via CCR5 unavailable and, as a result, the people with this mutation are almost fully resistant to HIV. Individuals who are heterozygous for the mutation, while not fully resistant, have been shown to be much less likely to be infected by HIV and, if they are infected, the progression of the disease is much slower. One study examined the progression of HIV to AIDS in children who were infected from HIV-positive mothers during pregnancy. Data from this study showed a lower prevalence of infection in children with the CCR5 mutation and slower progression of the disease (Table 7.3.1).

If the virus evades the cell's defence mechanisms, it takes over the cell's metabolic machinery to produce new viruses. Instructions carried by viral nucleic acids direct the cell to produce viral proteins and nucleic acid, which are assembled into new virus particles. For DNA viruses and some RNA viruses, this production process is similar to normal protein production in cells. However, in retroviruses, including some cancer-related viruses and HIV, the process includes a unique step—the production of DNA from viral RNA. This is somewhat backwards because DNA is usually used to make RNA, not the reverse. Hence, the name 'retrovirus' because 'retro' means backwards. This backwards synthesis involves the action of reverse transcriptase. Figure 7.3.8a illustrates this process, using the example of HIV. This provides a window of opportunity for treatment, because a drug that selectively blocks this enzyme does not affect the normal functions of body cells.

Many viruses use the process of budding, which releases enveloped virus particles, occurs slowly and often does not result in the death of the infected cell. This results in a persistent infection of cells, as in the case of the herpes viruses, which cause cold sores and shingles, and HIV. Symptoms of herpes virus appear sporadically when the virus emerges from latency, such as when a person's general health is poor. Budding is shown in Figure 7.3.8b.

When viruses use budding as a means of escape from the host cell, the phospholipid bilayer of their membrane envelope comes from the host cell. However, the recognition molecules associated with it are of viral origin. Influenza viruses and HIV are also enclosed in such envelopes.

Other viruses build up inside the cell until they cause the cell to burst. The rupture of the cell allows the virions to escape and infect other cells. Infected cells that rupture to release the new virus particles are killed in the process.

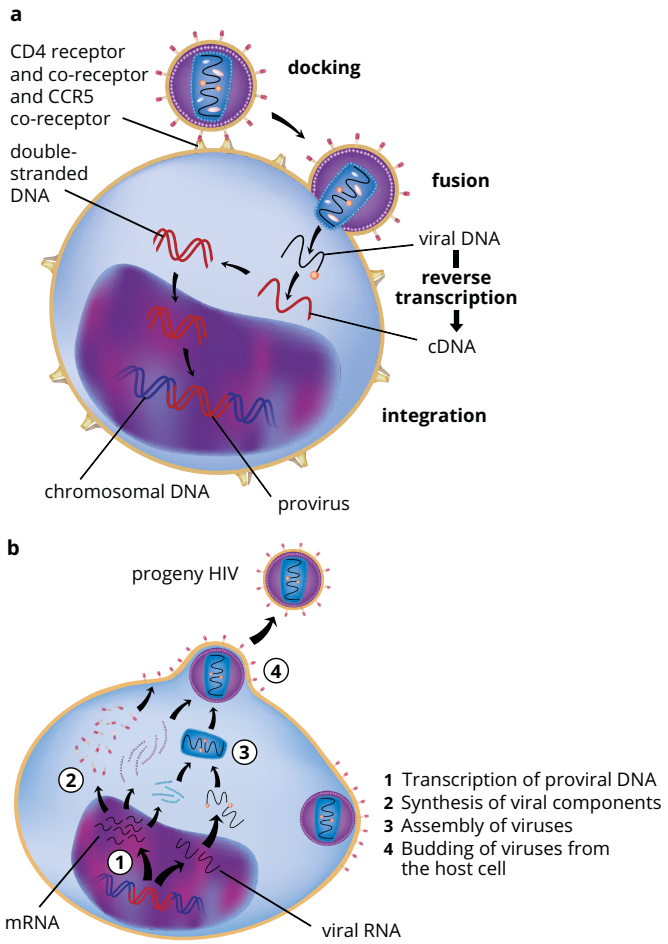


FIGURE 7.3.8 (a) HIV enters cells by attaching to a receptor called CD4. It uses a co-receptor called CCR5. When the viral RNA enters the cell, it is copied into DNA before it is incorporated into the nucleus of the host cell. (b) The host cell then makes new viral particles, which escape from the cell by budding.

TABLE 7.3.1 Progression to AIDS in children prenatally infected with HIV

CCR5 genotype	Speed of progression to AIDS		
	Rapid	Medium	Slow
homozygous normal	17	27	5
heterozygous	1	1	0
homozygous mutant CCR5	0	0	0
total cases	18	28	5

The importance of the CCR5 protein in allowing HIV to infect its host cells was further demonstrated by a case in Germany. In 2007, a patient infected with HIV and suffering from leukaemia was given a bone marrow transplant from a donor who was homozygous for the CCR5 mutation. Six months after the transplant, the recipient was tested for any evidence of HIV genetic material in his leucocytes and they were shown to be free of HIV. Eight years later in 2015, the bone marrow recipient remained free of both leukaemia and HIV.

Both the study of progression in children and the German case involved very small numbers of subjects so any conclusions would need to be considered with caution. Further research and trials need to be undertaken in order to confirm the hypothesis and develop the theory that blocking CCR5 would be a suitable treatment for HIV infection, both from the point of view of effectiveness and safety.

Review

1 Explain why results based on small studies should be treated with caution. Include natural variation and true value in your response (see Chapter 1).

2 From the evidence in Table 7.3.1, write a research question for further investigation.

3 Propose variables in humans that should be considered when conducting further testing, which would build the body of evidence and so the hypothesis can develop into a theory.

Antigens

Once a host has been infected, the host's immune system recognises antigens on the surface of the pathogen. Antigens are specific molecules, usually proteins or carbohydrates. Once these have been identified, the host can mount an immune defence to prevent re-infection. You will learn more about antigens in Chapter 8. However, due to small random genetic changes, some viruses make minor changes to the antigens on their surface. This process is known as **antigenic drift** (Figure 7.3.9a). Usually, the changes in antigen structure are so minor that the host's immune system recognises the virus (if a similar virus has infected the host on a pervious occasion). However, multiple episodes of antigenic drift can result in significant changes in the viral antigens, effectively creating a 'new' virus. However, this takes a long time.

By contrast, **antigenic shift** (Figure 7.3.9b) is a much more abrupt change in the genetic code of a virus due to re-assortment of genes from different viral strains, resulting in significantly different antigens on the coat of the virus. One source of antigenic shift is individuals who are simultaneously infected by two different strains of a particular virus. In this situation, the viruses can swap blocks of genetic material to give them new characteristics.

Antigenic shift can greatly increase the virulence of viruses. It is thought that antigenic shift was responsible for the worst influenza epidemic of all time, the Spanish flu. This influenza epidemic broke out in 1918 as World War I was coming to its end. Initially, because people were focused on the war, the flu did not attract much attention. However, by the end of the pandemic (a countrywide or worldwide disease outbreak, whereas an epidemic is more localised), an estimated one-third of the world's population had been infected and approximately 50 million people (possibly up to 100 million) had died because of it.

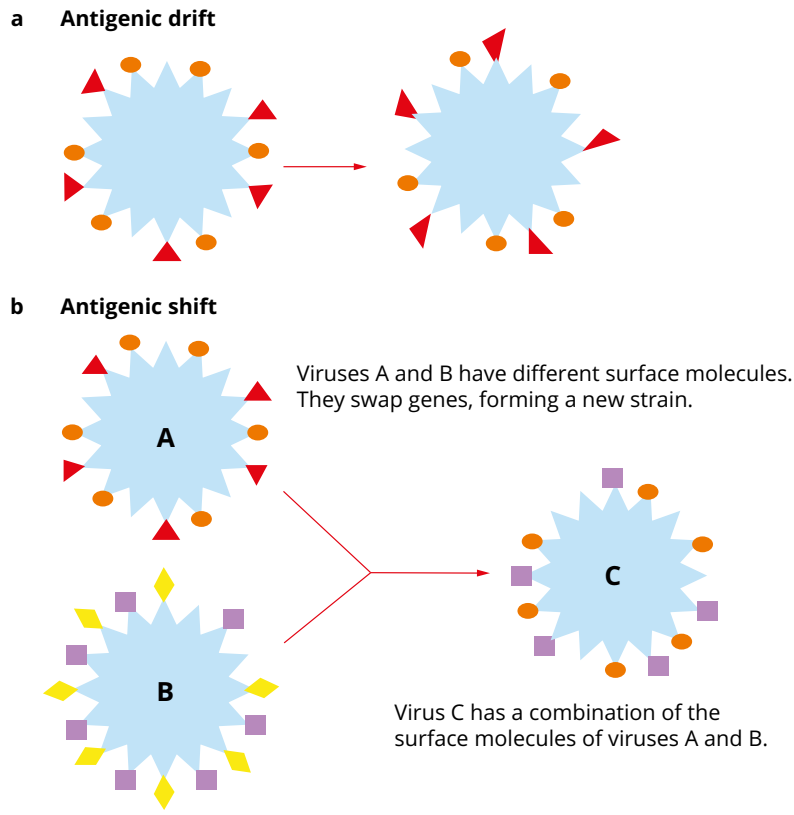


FIGURE 7.3.9 (a) Antigenic drift is a slow process, which occurs as a result of the gradual accumulation of mutations. Initially, the differences are very small, but they accumulate over time. (b) Antigenic shift usually occurs as a result of gene swapping between viral strains and can result in significant changes in the surface molecules of a virus.It usually occurs when two different viruses infect the same host. They can then swap genes and gain very different surface molecules.

This is a mortality rate of between 10% and 20%. Some patients died directly from the influenza and others died from secondary infections, such as pneumonia, contracted while in a weakened state.

While there is no absolute certainty, genetic analysis of samples of the virus suggests that the Spanish flu was caused by an avian (bird-infecting) virus that gained the ability to pass from bird to human through antigenic shift. Antigenic shift can occur when humans and animals live in close proximity.

Recent studies of the Spanish flu virus have given further insight into why it was so virulent. Researchers at the University of Alabama in the USA discovered that the virus contained a protein called NS1, which allowed it to attach to a human cell protein called RIG-1. The human protein RIG-1 is very important because it is needed by the body to trigger an immune response to a viral invasion. By having a protein that binds to RIG-1, the Spanish flu virus could effectively avoid the activation of an immune response and thus replicate completely uncontrolled.

Plant viruses

Plant viruses cause diseases that affect many agricultural crops. There are three main groups: yellows, mosaics and necrotics. Yellow viruses tend to produce yellowing (and other damage to leaves and branches), mosaics produce mottling and spotting, and necrotics cause local or widespread death of plant cells. The vectors for plant viruses are insects, such as leaf-hoppers and aphids. Yellow viruses tend to persist in insects, whereas mosaics do not. Some viruses require an incubation period of a few days within an insect before they are infective, but what takes places during this period is not understood.

COMBATING PATHOGENS

Many pathogens, both organisms and molecules, rely on contact or poor sanitation to spread between hosts. This is mostly due to pathogens either being immobile or having limited mobility, relying on aid to spread from one host to another. Good hygiene is an important means of limiting the spread of most pathogens. This includes regular hand washing and bathing, proper disposal of contaminated materials, such as tissues, and sensible precautions to stop the spread of airborne particles, such as covering the mouth when coughing.

Transmission of body fluids between individuals is a very important mechanism for infection. Blood, semen, saliva and vaginal secretions are all fluids that can potentially pass pathogens between individuals. Where pathogens are spread by biting insects, insect repellents, bed netting and avoiding areas where the vectors congregate are helpful. You will learn more about mechanisms of transmission and combating disease as individuals, communities and globally in Chapter 9. The inter-relatedness between the vast number of variables involved are explored through epidemiological concepts.

When infection has occurred, treatment is available for many of the cellular pathogens. Bacteria can be treated with **antibiotics**, which are chemicals that disrupt bacterial metabolism and/or their reproduction. Fungal infections and worm infestations in humans are generally treated with chemicals toxic to the parasite. There are treatments for some viruses, which slow their replication or disrupt their ability to escape from the host cell to infect other cells, but no treatments are available for prions.

CASE STUDY 7.3.2

Avian influenza 2003

Influenza viruses are normally classified by the variants of two proteins: **haemagglutinin** (H) and **neuraminidase** (N). Haemagglutinin is a surface protein of the virus that assists it to attach to potential host cells and gain entry. There are 18 known variants of this protein. Neuraminidase is an enzyme that allows the viral particles to escape from the host cell and there are nine variants of it. Influenza strains are named according to the variants of these two proteins. For example, the H1N3 strain has both variant 1 of haemagglutinin and variant 3 of neuraminidase.

In 2003, a H5N1 variant of avian flu crossed to humans and caused worldwide panic because mortality was so high (possibly 60%). Table 7.3.2 shows the cumulative number of confirmed human cases of H5N1, including deaths, between 2003 and 2011. Scientists have postulated that as with the earlier Spanish flu, the H5N1 virus was particularly virulent because large parts of the population had not been exposed to any similar viruses. The viral strain that had been responsible for seasonal flu outbreaks for many years prior to 2003 had been either H1N1 or H3N2 strains.

It was initially thought that the H5N1 flu first crossed to humans in Vietnam because that was where the first large-scale outbreak was reported (Table 7.3.2). Common farming and poultry practices in Vietnam result in all or most family members coming into contact with the farmed animals. People in close contact with infected domestic birds were also infected. There was no evidence of person-to-person transmission at that stage.

More extensive studies showed that H5N1 had first appeared in China in wild birds and then in poultry.

After its initial evolution, H5N1 spread throughout Asia and Europe. There were also outbreaks in Africa. The virus was identified in several migratory bird flocks. It is postulated that the virus was spread by migratory birds to local domestic birds, and then from the poultry to humans. Figure 7.3.10 shows the possible migratory paths of birds that may have carried the virus. Nearly all of the infected people had been in direct contact with sick birds or their faecal matter. There were a small number of cases of family members becoming infected possibly by person-to-person transmission but this is not certain.

It is unusual for a virus that infects an animal to infect humans, and when it does the virus is normally unable to spread from human to human. Widespread culling of infected birds and strict quarantine of infected people stopped the virus acquiring the ability to easily transfer between people and averted a crisis. However, the potential for an animal virus crossing to humans and creating another pandemic of equal or worse severity than the Spanish flu of 1918 remains an ever-present danger.

Review

1. Propose why H5N1 was not seen in humans in Europe even though it occurred in both wild and domestic birds.
2. Explain why scientists cannot be certain that family groups caught the infection as a result of person-to-person contact.

TABLE 7.3.2 Cumulative number of confirmed human cases (C), including deaths (D), for avian influenza A (H5N1) reported to WHO, 2003–2011 (laboratory cases only). All dates refer to onset of illness.

Country	2003		2004		2005		2006		2007		2008		2009		2010		2011		Total	
	C	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D
Azerbaijan	0	0	0	0	0	0	8	5	0	0	0	0	0	0	0	0	0	0	**8**	**5**
Bangladesh	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	**3**	**0**
Cambodia	0	0	0	0	4	4	2	2	1	1	1	0	1	0	1	1	8	8	**18**	**16**
China	1	1	0	0	8	5	13	8	5	3	4	4	7	4	2	1	0	0	**40**	**26**
Djibouti	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**	**0**
Egypt	0	0	0	0	0	0	18	10	25	9	8	4	39	4	29	13	32	12	**151**	**52**
Indonesia	0	0	0	0	20	13	55	45	42	37	24	20	21	19	9	7	7	5	**178**	**146**
Iraq	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0	**3**	**2**
Lao People's Democratic Republic	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**2**	**2**
Myanmar	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**	**0**
Nigeria	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	**1**	**1**
Pakistan	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	**3**	**1**
Thailand	0	0	17	12	5	2	3	3	0	0	0	0	0	0	0	0	0	0	**25**	**17**
Turkey	0	0	0	0	0	0	12	4	0	0	0	0	0	0	0	0	0	0	**12**	**4**
Vietnam	3	3	29	20	61	19	0	0	8	5	6	5	5	5	7	2	0	0	**119**	**59**
Total	**4**	**4**	**46**	**32**	**98**	**43**	**115**	**79**	**88**	**59**	**45**	**33**	**73**	**32**	**48**	**24**	**49**	**25**	**565**	**331**

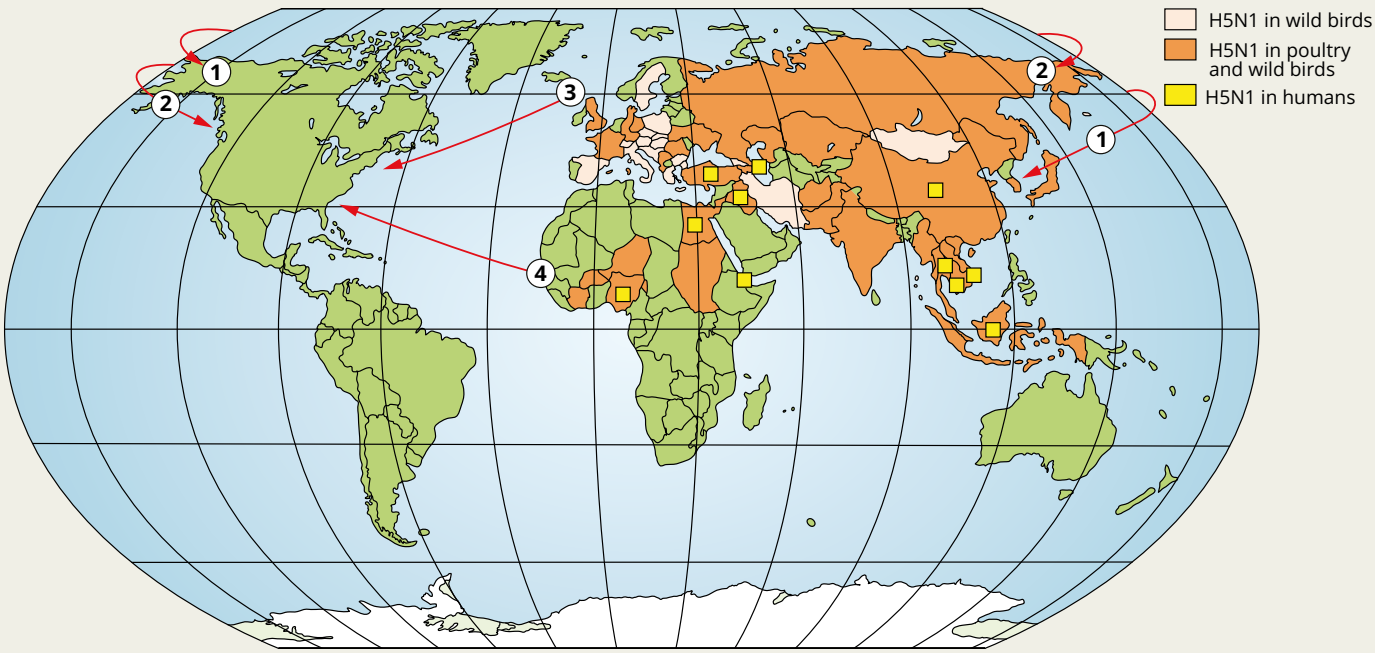


FIGURE 7.3.10 The actual and potential spread of the H5N1 strain of avian influenza A. Arrows indicate the known routes of wild bird migration. (1) Summer in Alaska, winter in East Asia. (2) Breeding in East Asia, winter in North America. (3) Breeding in Northern Europe and Iceland, winter in North America. (4) Birds carried by storms from West Africa to North America.

7.3 Review

SUMMARY

- Prions and viruses are both infectious molecules that do not have all of the characteristics of living organisms.
- Prion diseases are caused by PrP proteins that are abnormally folded.
- An important prion disease in humans is Creutzfeldt–Jabob disease (CJD).
- Some individuals have genetic traits that appear to give them resistance to prion infection.
- Viruses are infectious particles that consist of nucleic acids covered in a protein capsid.
- Some viruses use RNA rather than DNA. These are called retroviruses and include HIV.
- Viruses may escape from host cells by cell rupture or by budding.
- Genetics plays a role in determining the virulence of viral diseases. The CCR5 mutation in humans appears to offer protection from HIV infection.
- Viruses change over time, slowly by antigenic drift or quickly by antigenic shift.
- Influenza viruses can cause major pandemics when they are new to humans because they have been transmitted from animals, like birds, to humans.
- Plant viruses fall into three main types: yellows, mosaics and necrotics.
- Plant viruses are often transmitted by insects.

KEY QUESTIONS

Retrieval

1 Define:
- **a** bacteriophage
- **b** retrovirus
- **c** prion
- **d** antigen.

Comprehension

2 State two ways prions are different from viruses.

3 Identify the difference between an epidemic and a pandemic.

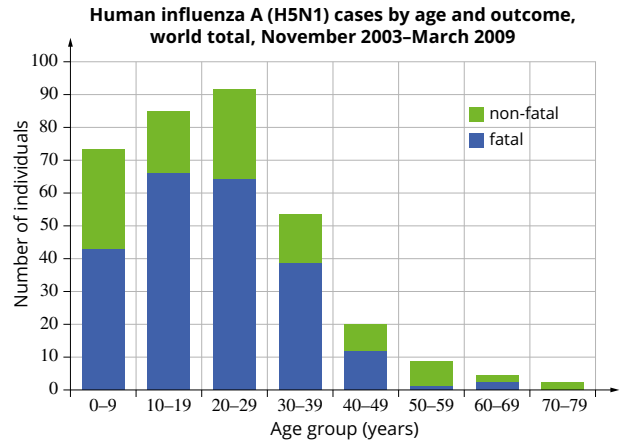
4 Explain why the incubation period of prion diseases is so long.

5 State how the PrP protein of an individual who has the MV genotype differs from that of someone who has the W genotype.

Analysis

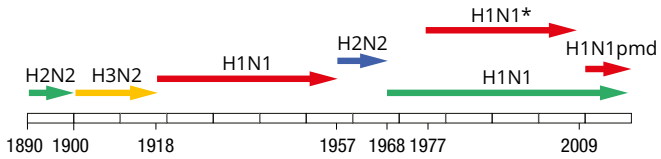
6 Between the late 1950s and 1985, children who were identified as having conditions that would result in them being significantly shorter than average were treated with human growth hormone (HGH) to increase their height as adults. Until 1985, the source of HGH was the pituitary glands of human cadavers. In 1985, the first case of Creutzfeldt–Jakob disease attributable to cadaver-derived HGH was diagnosed, leading to its use being stopped. Today, HGH is produced by genetically engineered bacteria. Up until 1985, approximately 30 000 people were treated with HGH; of those people, 139 developed CJD.
Calculate the chance of an individual treated with HGH from cadavers subsequently developing CJD.

7 During the 2003 Avian flu (H5N1) outbreak, stringent quarantine precautions were taken. Not only were infected people and their contacts quarantined but in many countries, including Australia, people arriving from affected countries were screened for any signs of fever and were quarantined if any was found. The reasons for these stringent precautions are suggested by the data in the graph, which shows global H5N1 cases by age and outcome, from November 2003 to March 2009.



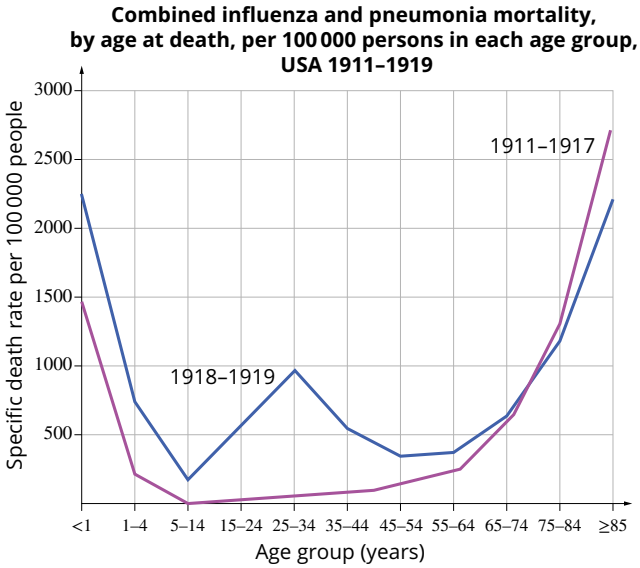
Consider why governments took such extreme precautions. Refer to the data in your answer.

8 Study of human tissues from past disease outbreaks has shown that waves of influenza have been with us for hundreds of years (at least). Some recent pandemics are shown in the diagram.



* Probably reintroduced from a laboratory from the H1N1 circulating from 1918 until 1957

Most influenza pandemics show a typical pattern of infection and mortality. The young and elderly are generally more likely to die. The following graph shows the fatality rate in the USA for the influenza pandemics of 1911–1917 and for the Spanish flu pandemic of 1918–1919.



The Spanish flu pandemic was very unusual in its distribution of fatalities. It has been hypothesised that the unusual pattern for the 1918 flu was due to older individuals having some level of immunity because of a previous influenza exposure and that people in their late teens and 20s had not been exposed to the relevant strain or anything like it. Consider the data in the diagram and the graph.

a Explain the evidence that supports this hypothesis.

b During the epidemic, death rates for 45–54 year olds was low at around 375 per 10 000. Extrapolate the death rate that would have occurred without the protection that 45–54-year-old people had.

Investigating the effect of antibiotics on bacterial growth

Research and planning

Aim

To investigate the effect of antibiotics on bacterial growth.

Rationale (scientific background to the experiment)

Like all living organisms, bacteria require nutrients in order to grow and reproduce. Within laboratories, colonies of bacteria can be grown on agar plates–Petri dishes that contain a gelatinous substance. Agar plates can also contain bacterial growth inhibitors, such as antibiotics. Different kinds of bacteria are affected by different antibiotics and growth inhibitors. Scientists can identify bacteria based on the appearance of bacterial colonies, and the type of agar on which they grow.

In addition to agar plates, scientists can use Mastrings or Multodiscs to identify bacteria. Mastrings or Multodiscs are commercially produced discs impregnated with a variety of different antibiotic substances. A Mastring comprises a central ring that has a series of satellite rings coming off it. Each satellite on the Mastring contains a different antibiotic that is identified by either a colour or a letter code or both. When bacterial growth is inhibited, clear zones are visible around the satellite. These clear zones are called inhibition zones. Bacterial growth (or inhibition zones) at each satellite enables scientists to identify antibiotics that can be used to kill bacteria.

Timing

2 × 60 minutes, 48 hours apart

Materials

- 3 sterile, prepared nutrient agar Petri dishes
- broth cultures of *Escherichia coli* (*E. coli*) and *Staphylococcus albus* (*S. albus*)
- 2 sterile swabs in container
- marking pen
- fine forceps
- parafilm strips
- access to incubator set at 30°C
- 2 sterile Mastrings
- disposal bags
- paper towel
- disinfectant
- access to material for washing hands
- Bunsen burner

Method

Risk assessment

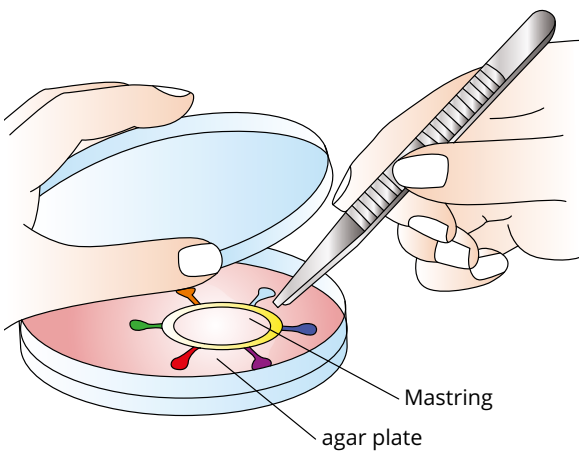
Assessment of risks include chemical hazards and physical hazards. Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

Part A Day 1

1 Collect three sterile nutrient agar Petri dishes. Keep the lids in place and use a marker pen to label the three dishes 'A', 'B—*E. coli*,' and 'C—*S. albus*'. Use initials or another code to identify your Petri dishes from other students' Petri dishes. Label the underside of the dish only, and write at the perimeter of the dish rather than the middle.

2 Collect a container of each of the two bacteria and two sterile swabs. Your teacher will demonstrate how to prepare a 'lawn culture' of the bacterium. Use the swabs to prepare bacterial cultures of *E. coli* and *S. albus* in Petri dishes B and C, respectively. Immediately replace the lids. Place the used swabs in a disposal bag.

3 Collect two Mastrings. Use fine forceps to place one Mastring in the centre of Petri dish B. Replace the lid. Repeat this procedure for Petri dish C.
Note: Sterilise the tips of a pair of forceps by flaming in a Bunsen flame. Allow to cool.
Transfer one Mastring to each of the coated nutrient agar plates, gently pressing the lobes of the disc onto the surface of the plates. Re-sterilise the forceps in between testing different bacterial cultures.



4 Seal each of the Petri dishes with a single layer of parafilm strips.

5 Set the Petri dishes in the incubator. The Petri dishes should be placed upside down, with the agar on the top. This prevents the growth of bacteria being disrupted by drops of condensation.

6 Incubate the Petri dishes at 30°C for 48 hours or at room temperature for 3 days. This will depend on your class timetable and teacher discretion.

7 When all equipment is put away, wipe down your bench with paper towel and disinfectant. Then wash your hands thoroughly.

Part B Day 2

8 Collect your three Petri dishes for observation. **Do not open the dishes**.

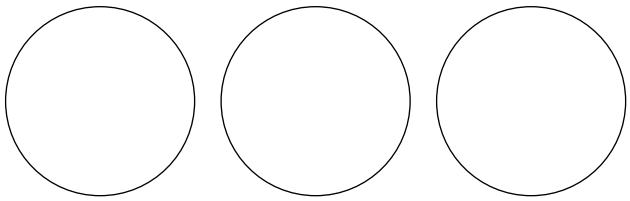
9 Prepare detailed drawings of what you see in each Petri dish. Include appropriate labelling as well as a description of your observations. Measure the inhibition zones around each satellite.

10 Place all Petri dishes in the disposal bag provided. Wash your hands thoroughly.

Analysing

Raw data

1 Copy the circles and space below to record your observations of the Petri dishes. Label each drawing and include a title.



Processed data

2 Look carefully at Petri dishes B and C that include the Mastring. Use your observations to complete the results table.

Record of results

Disc code	Antibiotic on disc	Observations of bacterial growth around disc (diameter of inhibition zone, mm)	
		E. coli	*S. albus*

➤ 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

3 Explain the purpose of Petri dish A.

4 Suggest a hypothesis being tested by this activity.

5 Explain why it is important to ensure the Petri dishes remain sealed.

6 Are all of the inhibition zones the same size? Account for any differences in the size of the inhibition zones.

7 Compare the sensitivity of the bacterial species to the range of antibiotics used.

8 Imagine you are working in a hospital and a patient was infected with *E. coli*. Considering the bacterial sensitivity of both *E. coli* and *S. albus*, suggest which antibiotic you would prescribe and explain why.

9 Identify two potential errors encountered in the procedure. Suggest how these could be minimised if the procedure were modified.

➤ Reflect and check that your analysis demonstrates these characteristics

- ☐ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis
- ☐ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships
- ☐ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis

Interpreting and communicating

Conclusion

1 Summarise the relationship between bacteria and antibiotics.

Evaluation

2 Explain whether the potential errors you identified above had a significant effect on your conclusions. In other words, do you consider the level of uncertainty caused by the potential errors reasonable? You may like to consider what impact an error would have if this experiment was being used in a hospital to administer antibiotics.

Improvements

3 If you were to repeat this experiment, identify the steps that you would do differently. Consider how you:
- **a** might change the methodology.
- **b** might improve your technique.
- **c** could reduce error and uncertainty.

4 Describe the shape of the inhibition zones. Suggest a method to measure the area of the inhibition zones.

Extension

5 Search the internet to identify a range of antibiotics that are used to treat common infections.

6 Regular use of antibiotics has resulted in some bacteria developing resistance to antibiotics. Bacteria that are resistant to multiple antibiotics have been termed 'super bugs' in the media. Search the internet to discover how antibiotic-resistant bacteria, or super bugs, are controlled to prevent major outbreaks of infection.

➤ 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

07

KEY TERMS

adhesin
aeciospore
allele
antibiotic
antibody
antigen
antigenic drift
antigenic shift
bacteriophage
basidiospore
capsid
capsule
carrier
chlamydospore
chromosome
contagious
Creutzfeldt–Jakob disease (CJD)
DALY
disease
Duffy
ectoparsite
endoparasite
endotoxin
epidemic
ergotism
exotoxin
filariform
fungus
gall
gram stain
haemagglutinin
helminth
heterozygote advantage
heterozygous
homozygous
hypha
incubation period
infectious
intermediate host
karyotype
macrophage
merozoite
mutation
nematode
neuraminidase
oomycete
parasite
pathogen
pathogenic molecule
pili
plaques
plasmodium
platyhelminth
primary host
prions
prostaglandin
psyllid
retrovirus
reverse transcriptase
rhabditiform
trichinosis
vector
virion
virulence
virus
zoonose
zoospore

KEY QUESTIONS

Retrieval

1 Kwashiorkor and scurvy are both deficiency diseases. Deficiency diseases are caused by:
- **A** viruses
- **B** bacteria
- **C** prions
- **D** malnutrition

2 It would be true to say of the bacterial capsule that it:
- **A** contains peptidoglycans and lipopolysaccharides.
- **B** allows the bacterium to attach to its host.
- **C** is important in allowing the bacterium to avoid phagocytosis by leukocytes.
- **D** is common to all bacteria.

3 *Legionella* infection is caused by a bacterium that often contaminates air-conditioning cooling plants. The most likely method of disease spread of *Legionella* is:
- **A** vectors
- **B** airborne
- **C** body fluids
- **D** contaminated food

4 Helminth infection by *Strongyloides steracolis* in some remote areas of northern Queensland is a serious problem. The most effective way for individuals to reduce their chances of becoming infected is:
- **A** frequent hand washing.
- **B** using toilets connected to sewage treatment plants.
- **C** periodically using anti-helminthic medications.
- **D** wearing shoes.

5 Identify the incorrect statement about viruses.
- **A** They use the host cell for reproduction.
- **B** They are significantly smaller than bacteria.
- **C** They all contain DNA.
- **D** They consist of some nucleic acid enclosed in a protein coat.

6 Haemagglutinin is important to the replication of influenza viruses because it plays an important role in:
- **A** attachment to the host cell.
- **B** incorporating the DNA of the virus into the host's DNA.
- **C** production of viral enzymes like neuraminidase.
- **D** release from the host cell.

7 Define:
- **a** disease
- **b** pathogen
- **c** virus

8 List the ways in which disease-causing bacteria are spread.

Comprehension

9 Using one or two sentences, distinguish between infectious and non-infectious diseases.

10 In a particular area, two strains of influenza virus have been circulating: H1N2 and H3N6. These influenzas have not caused major concern except for the elderly and in people whose immune systems are weak or compromised. Unexpectedly, there is a rapid increase in the number of young and previously healthy people presenting to hospital with influenza. A study of the virus shows it to be a H3N2 strain. This virus is likely to have arisen as a result of:

A antigenic drift
B antigenic shift
C large numbers of people catching the virus from birds
D a poorly targeted vaccination program.

11 Compare pathogenic bacteria and fungi.

12 Explain the significance of both adhesins and pili in bacterial infection.

13 Compare viruses and prions.

Analysis

14 Twin studies are important in determining the contributions of genetics and environment to disease. The following table shows the data collected from a series of twin studies in which pairs of identical and fraternal twins were examined for their body weight. BMI stands for body mass index and is calculated by dividing weight, in kilograms, by height, in metres squared. The column 'corr' is the correlation in BMIs between the two twins in each pair. It is a measure of how well the BMI of one twin matches the BMI of the other twin.

a Assess if a genetic component exists for BMI.

b i Calculate the standard deviation for the BMIs of female identical twins.

ii Males and females have different proportions of body fat and muscle. An equal volume of muscle weighs more than fat. Considering this information, propose why analysing male/female twin pairs is unlikely to provide useful information about the contributions of the effects of genetics and environment.

Adult identical twins						Adult fraternal twins								
Male/Male			Female/Female			Male/Male			Female/Female			Male/Female		
No. pairs	Mean BMI	Corr	No. pairs	Mean BMI	Corr	No. pairs	Mean BMI	Corr	No. pairs	Mean BMI	Corr	No. pairs	Mean BMI	Corr
1186	15.7	0.84	1429	15.40	0.84	1292	15.7	0.49	1204	15.50	0.50	2644	–	0.48
808	15.3	0.81	925	15.00	0.80	859	15.3	0.46	750	15.10	0.50	1633	–	0.45
474	15.0	0.79	544	14.80	0.88	497	15.0	0.64	437	14.90	0.57	947	–	0.48
630	15.2	0.88	738	15.30	0.88	645	15.3	0.58	580	15.40	0.54	1200	–	0.55
488	16.3	0.86	577	16.40	0.85	425	16.3	0.56	422	16.40	0.51	874	–	0.47
341	16.9	0.86	373	17.40	0.90	288	17.1	0.55	279	17.50	0.49	554	–	0.51
64	17.6	0.87	174	18.83	0.89	47	17.6	0.39	149	18.69	0.47	261	18.87	0.44
129	17.3	0.85	142	20.56	0.89	77	17.3	0.48	123	20.17	0.41	204	22.57	0.29
96	16.4	0.87	148	21.43	0.88	67	16.6	0.64	98	21.52	0.31	204	22.57	0.29
132	15.9	0.85	319	19.80	0.88	80	15.9	0.48	595	15.79	0.59	126	20.00	0.31
48	15.6	0.89	784	15.84	0.85	38	15.5	0.31	517	15.75	0.55	1010	15.79	0.54
120	15.4	0.83	720	15.64	0.81	67	15.5	0.45	593	17.26	0.52	819	15.75	0.45
139	15.3	0.91	804	17.08	0.88	95	15.5	0.55	735	17.83	0.48	950	17.26	0.45
110	15.5	0.91	823	17.75	0.86	71	15.7	0.35	354	17.60	0.50	1329	17.83	0.42
98	16.0	0.88	377	17.50	0.79	69	16.1	0.46	330	19.50	0.49	734	_	0.41
118	16.3	0.88	356	19.20	0.81	73	16.4	0.43	309	21.10	0.39	666	_	0.38
104	16.6	0.88	334	20.70	0.77	69	16.9	0.56	–	–	–	595	_	0.33
5085	**16.0**	**0.86**	**9567**	**17.57**	**0.85**	**4818**	**16.2**	**0.49**	**7475**	**17.50**	**0.49**	**14 750**	**18.83**	**0.43**

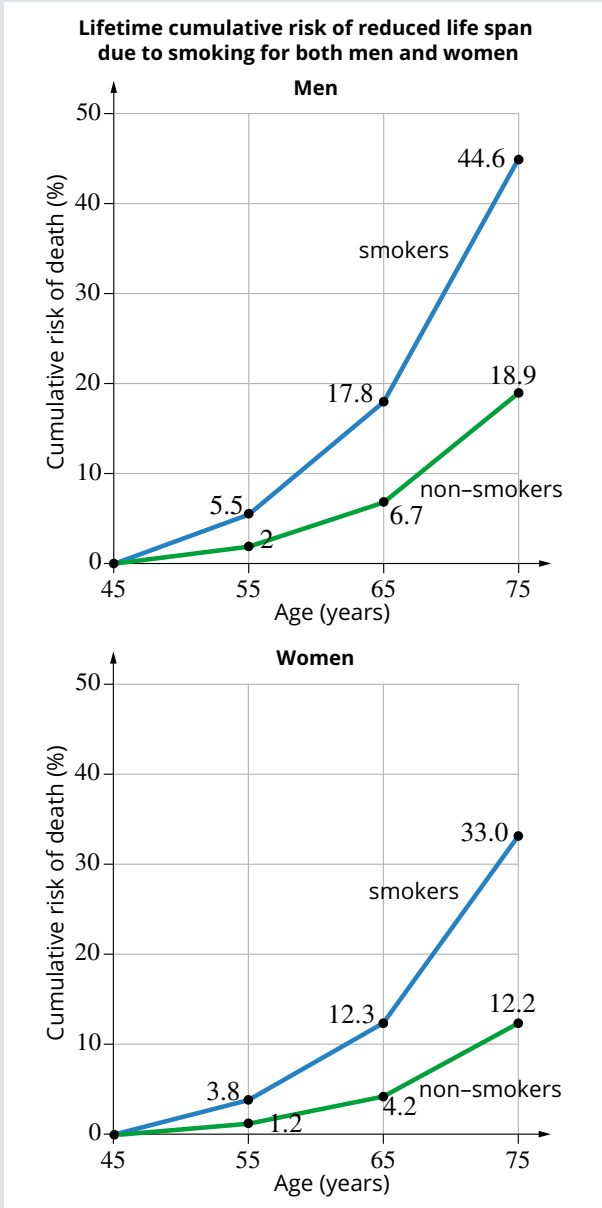
15 The lifetime cumulative risk of reduced life span due to smoking for both men and women is shown in the following graphs.

a Determine the number of years a 65-year-old smoking female has lost, assuming that by comparing equivalent cumulative risk of death (%) between smokers and non-smokers, the number of years lost due to smoking is revealed.

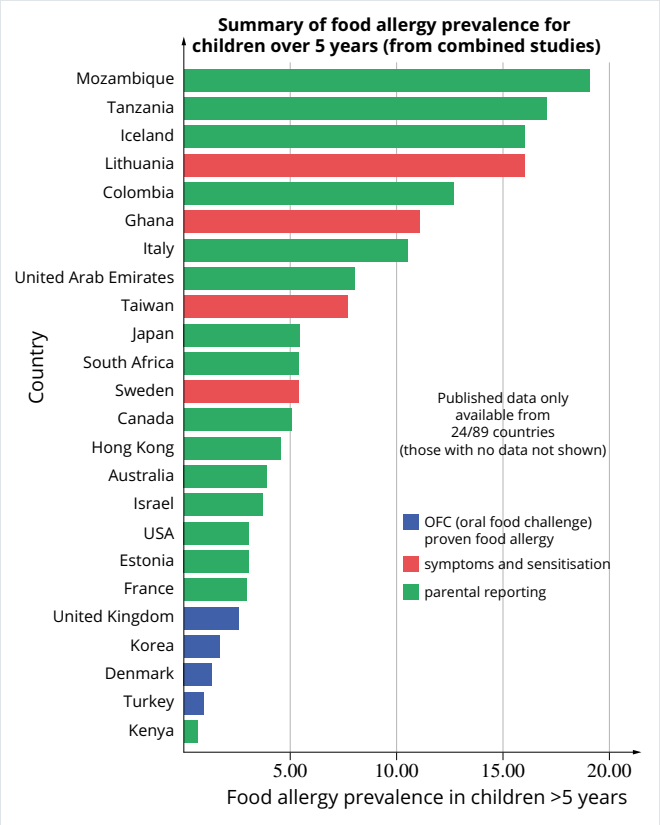
b Calculate the difference in chance of death by age 75 of a male smoker compared to a non-smoker of the same age and sex.

c Determine whether the cancer mortality trends for Australia are worsening, on the basis of the data in the table below.

	Actual number of deaths	Rate (deaths per 100 000 people)
1984	26 645	212.3
1989	30 555	214.4
1994	34 134	212.6
1999	35 575	194.2
2004	38 489	184.6
2005	38 836	181.6
2010	43 216	196.2
2012	42 961	189



16 Food allergies have become a significant source of disease in Australia in the last few decades. Many theories have been advanced to explain what seems to be a sudden and rapid increase. The following graph shows the incidence of food allergies in school-aged children in a range of countries across the world. Data is not available for all countries.



a Explain which of the two countries' data is likely to be the more reliable measure of the incidence of food allergies in their children, between the United Kingdom and Italy.

b The following data on food allergies was collected in the USA. Four thousand people were tested or interviewed for the survey.

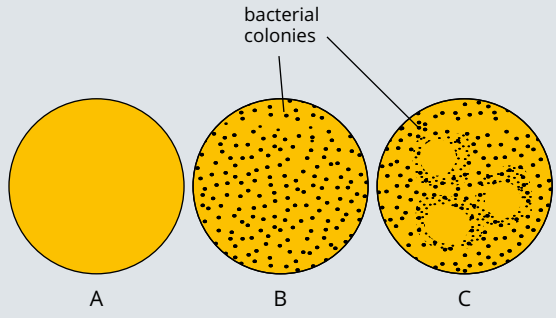
	Type of report	Year		
		2001	2006	2010
percentage of allergies reported by adults	self-reported	9.1	14.9	13
	medically diagnosed	5.3	7.6	6.5

i Discuss what the data suggests about the accuracy of self-reporting.

ii Explain whether there is any evidence that allergies among adults in the USA is increasing.

17 In a particular study, the chances of dying from a particular form of heart attack (myocardial infarction) between 1999 and 2008 had decreased by a probability of 0.82 in which the 95% CI range was from 0.67 to 0.99. Explain what this means.

18 A medical student studying the impact of antibiotics on pathogenic bacteria set up the following experiment. Three sterilised nutrient agar plates were prepared. Plate A remained sealed with nothing added to it. Plate B was exposed to bacterial spores and then sealed. Plate C was treated with three drops of a chemical (X) that was being tested for its antibiotic properties. Plate C was then also exposed to bacterial spores and sealed. All three plates were incubated at 37°C for 24 hours and then examined for the growth of bacterial colonies. The results are shown in the following diagram.



a State the hypothesis that was being tested in this experiment.

b i Identify which plate or plates act as the control.

ii Explain the function of a control.

c Draw a conclusion from the results.

d Explain how the reliability of the results could be increased.

e Further research into chemical X was undertaken to investigate the most effective concentration. Several sterile plates were obtained and labelled (20, 30, 40, 50, 60) and three drops of chemical X were added to each plate before it was exposed to bacterial spores, sealed and incubated as before. Each of the plates contained a different concentration of chemical X, as shown in the following table. After incubation, the diameter of the circle of inhibited growth for each drop was measured. This diameter was taken to indicate the effectiveness of chemical X.

	Concentration of chemical X (µg/100 mL)				
	20	**30**	**40**	**50**	**60**
diameter of inhibition (mm)	12.4	12.9	17.1	17.6	17.9
	12.1	13.2	17.3	17.5	17.7
	12.6	12.7	17.9	17.7	17.7
mean diameter of growth inhibition (mm)					

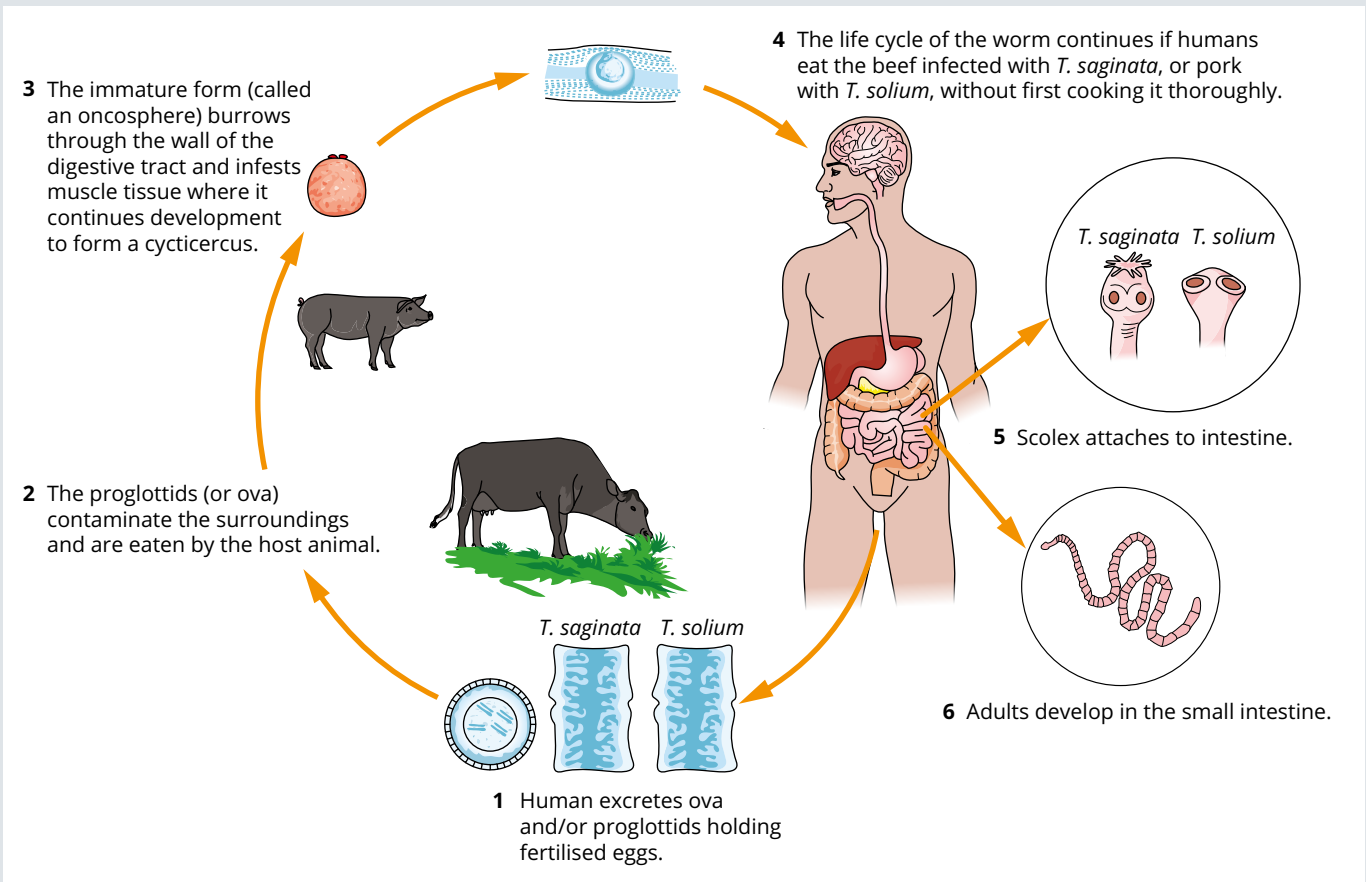
i Calculate the mean for each concentration and use your results to complete the table.

ii Identify one assumption that is being made in drawing conclusions from the result.

iii When the testing of chemical X moved to phase 1 human trials, it became clear that about 19% of patients developed minor nausea as a side effect at concentrations over 35 µg/100 mL. The nausea increased to mild as the concentration of chemical X increased, and more people were affected. Explain which concentration should be used in the second stage of the human trials.

19 It has been observed that gram-negative bacteria are more likely than gram-positive bacteria to be involved in episodes of toxic shock (caused by endotoxins or exotoxins, or both), the most severe form of blood infection, in hospital intensive care units where patients are under specialised treatment. Explain this observation.

20 The life cycles of *Taenia saginata* (beef tapeworm) and *T. solium* (pork tapeworm) are shown below. Identify the primary and intermediate hosts, giving reasons for your decision.



21 Argue which conditions are more likely to facilitate the spread of plant diseases caused by fungi and members of the Oomycetes.

22 Many diseases, caused by both bacteria and viruses, have incubation periods ranging from several days to months or even years. Explain how this assists the pathogen to spread.

23 The following table shows data collected by WHO on H5N1 (bird flu) infection in wild and domestic birds and humans 2003–2010. Numbers are for human cases. Coloured boxes represent animal outbreaks: light blue boxes represent sporadic and/or seasonal outbreaks notified in poultry; grey boxes represent poultry outbreaks reported throughout the year in domestic birds; white boxes represent no avian outbreak reported.

Country	Nov 2003–Dec 2005	2006	2007	2008	2009	To 1 July 2010	Total
Azerbaijan	0	8	0	0	0	0	**8**
Bangladesh	0	0	0	1	0	0	**1**
Cambodia	4	2	1	1	1	1	**10**
China	9	13	5	4	7	1	**39**
Djibouti	0	1	0	0	0	0	**1**
Egypt	0	18	25	8	39	19	**109**
Indonesia	20	55	42	24	21	4	**166**
Iraq	0	3	0	0	0	0	**3**
Laos	0	0	2	0	0	0	**2**
Myanmar	0	0	1	0	0	0	**1**
Nigeria	0	0	1	0	0	0	**1**
Pakistan	0	0	3	0	0	0	**3**
Thailand	22	3	0	0	0	0	**25**
Turkey	0	12	0	0	0	0	**12**
Vietnam*	93	0	8	6	5	7	**119**
Total	**148**	**115**	**88**	**44**	**73**	**32**	**500**

* With a high degree of seasonal and geographical variation
Source: Data collected by the epidemic intelligence team at Institut de Veille Sanitaire from postings on the websites of the World Health Organization, the World Organization for Animal Health and other authoritative sources in the 15 countries.

It has been proposed that bird flu spread from wild birds to domestic poultry and from domestic poultry to humans.

a Analyse the data in the table above and identify the evidence that supports the hypothesis that humans caught the flu from domestic poultry.

b The following table shows the distribution of deaths from H5N1 by age and sex.

Age group (years)	Male	Female
<5	13	8
5–9	19	13
10–19	18	31
20–29	18	27
30–39	17	16
40–49	5	6
>50	6	5

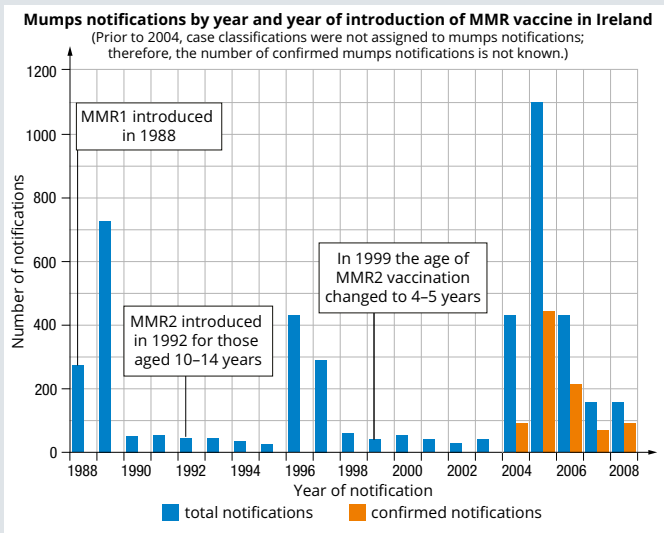
i Draw a graph of the data in the table.

ii The way the data is displayed is somewhat misleading. Explain how the data is misleading.

iii Explain whether the data suggests that either sex is more susceptible to bird flu.

iv The data given is from a WHO report. WHO does not collect data itself. It relies on self-reporting from affected countries. Explore the reliability of the data presented.

24 Mumps is caused by a virus. A vaccination (MMR) has been available since the early 1980s. The vaccination was introduced in Ireland in 1988. Once the vaccination was introduced, reporting of suspected cases became mandatory. The incidence of reported cases is shown in the following graph. From 2004, suspected cases were tested to confirm diagnosis. This did not take place before 2004.



a State the percentage of total notifications that were confirmed in 2006.

b Discuss the reliability of mandatory reporting of suspected cases, in considersation of testing to confirm mumps.

Knowledge utilisation

25 Scientists have proposed a link between exposure to benzene and the development of leukaemia in children. Describe the study that researchers should undertake to provide data to support this proposal.

26 In Australia, the prevalence of infection with threadworms (nematodes) is much higher in children under the age of 10 years than in adults. Argue why this is the case. Consider the life cycle of the nematode in your answer.

27 It has been suggested that the filarial forms of the helminth *Strongyloides stercoralis* are attracted to the potential host by chemicals in sweat called urocanic acid. Design an experiment to test this hypothesis. Identify the independent and dependent variables in your experiment and state what results would support the hypothesis.

28 AIDS is an infectious disease that has reached pandemic proportions. Discuss the nature of this pandemic. In your answer, include the type of pathogen, its method of causing disease, its method of transmission, and its method of infecting tissues. Also suggest a possible treatment.

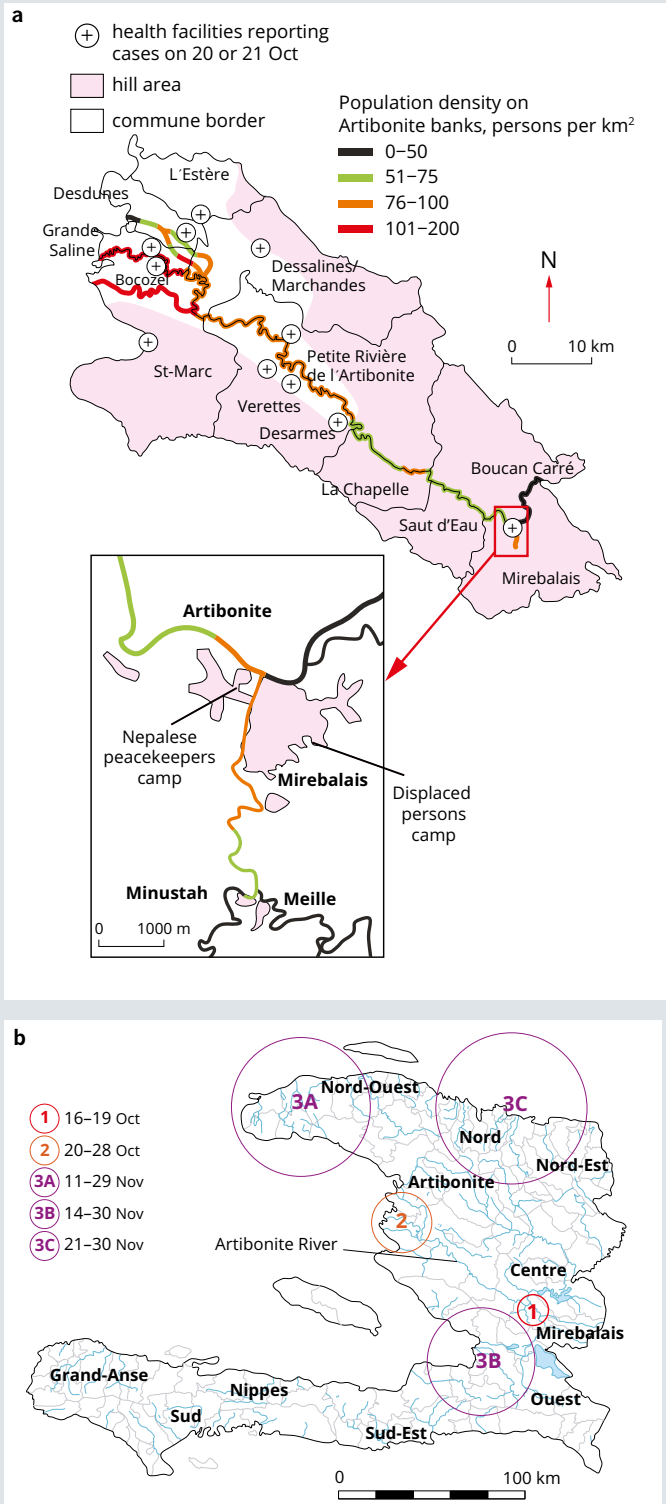
29 Cholera is a serious disease caused by the bacterium *Vibrio cholera*. The disease is characterised by diarrhoea, vomiting and cramping. If untreated, severe dehydration and shock occur. Mortality can be as high as 50%.

In 2010, the island of Haiti was shaken by a major earthquake that destroyed much of the infrastructure on the island, including electricity, sewage and water treatment plants. This left most people relying on untreated river water for all of their water needs. Many people were buried by falling buildings and so there was a large influx of people from many countries to assist, to find survivors, help with the provision of medical attention and maintain law and order.

Within weeks of the earthquake, a cholera epidemic broke out in Haiti. This was very surprising to everyone because there had not been any cases there for many decades.

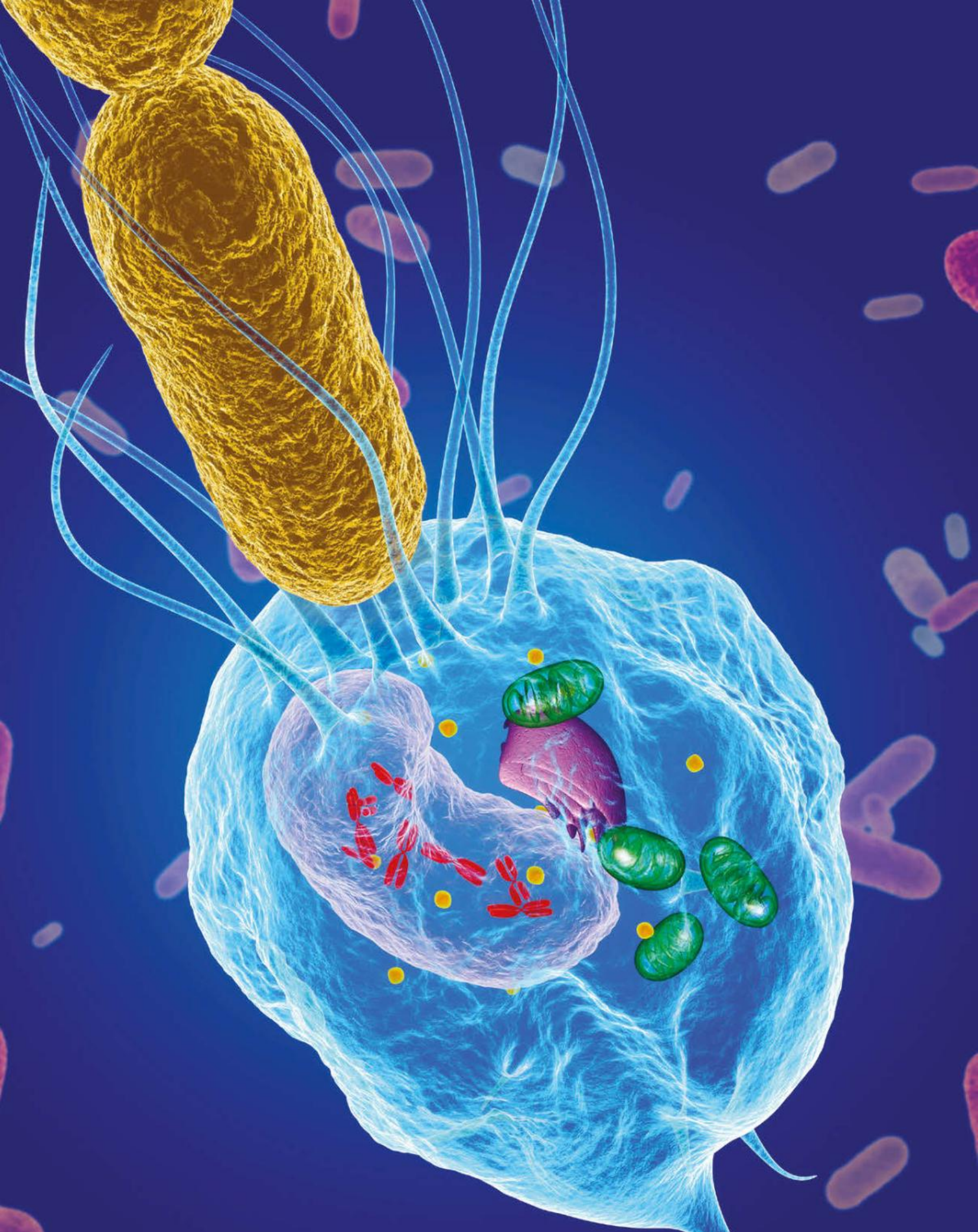
The following diagrams show the location of health centres reporting cholera cases on 20 or 21 October 2010, and the progress of the epidemic between its commencement on 16 October through to 30 November, when it had become widespread in Haiti.

a Design a better distribution of the health facilities in order to more effectively limit the spread of disease in times of disaster. Justify your design using the maps supplied, the information provided and your research and knowledge of disease.



(a) Location of health centres reporting cholera cases on 20 October or 21 October 2010 (b) progress of epidemic to 30 November 2010

b In 2016, another major outbreak of cholera occurred in Haiti. Research the event that caused the outbreak. Explain why there were fears it could be worse than the 2010 outbreak.



CHAPTER

08 The immune response

In this chapter, you will learn about how plants and animals resist infection by pathogens, and the physiological responses that they have when the barriers fail. You will learn about the innate and adaptive immune responses in mammals and how antibodies are made and long-term immunity is created. You will also learn about vaccination and how it stimulates immunity.

Syllabus subject matter

Topic 2 • Infectious disease

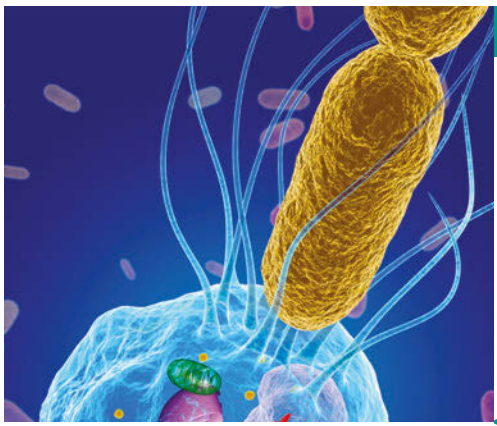
IMMUNE RESPONSE AND DEFENCE AGAINST DISEASE

- understand how pathogens (bacterial and viral) can cause both physical and chemical changes in host cells that stimulate the host immune responses (introduction of foreign chemicals via the surface of the pathogen, production of toxins, recognition of self and non-self)
- recognise that all plants and animals have innate immune responses (general/non-specific) and that vertebrates also have adaptive (specific) immune responses
- recall examples of physical defence strategies (barriers and leaf structures) and chemical defence strategies (plant defensins and production of toxins) of plants in response to the presence of pathogens
- recall that the innate immune response in vertebrates comprises surface barriers (skin, mucus and cilia), inflammation and the complement system
- describe the inflammatory response (prostaglandins, vasodilation, phagocytes) and the role of the complement system
- explain the adaptive immune responses in vertebrates—humoral (production of antibodies by B lymphocytes) and cell-mediated (T lymphocytes)—and recognise that memory cells are produced in both situations
- interpret long-term immune response data
- analyse the differences and similarities between passive immunity (antibodies gained via the placenta and via antibody serum injection) and active immunity (acquired via natural exposure to a pathogen or through the use of vaccines) for both naturally and artificially acquired immunity.

SCIENCE AS A HUMAN ENDEAVOUR

- Discuss the factors influencing organ donor suitability, organ transplant, immunosuppression and rejection with the focus on the physiological immune responses and evaluation of individual, social and cultural considerations.

8.1 Innate immunity



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

- understand the role of antigens in immune responses
- know how animals and plants use physical and chemical barriers to the resist the entry of pathogens
- be able to describe the steps in the innate immune response in animals and plants
- be able to name and describe the roles of the cells involved in the innate response
- recognise the importance of the major histocompatibility complex in identifying self and non-self.

Antigens are unique molecules, or parts of molecules, that can elicit an immune response, and so play a crucial role in immunity. The mechanisms by which organisms defend against pathogens and identify non-self antigens are multiphase and, in many instances, quite complex. These defence mechanisms include barriers that help prevent infection, and immune responses to the pathogens that breach these barriers.

The defence mechanisms of plants and most invertebrates seem to be confined to **innate immunity**. Innate responses are non-specific and do not create immunological memory, so the response to subsequent infections is the same as the first response. Vertebrates have innate responses, like plants and invertebrates, but also have an adaptive, or specific, immune response, which is modified on each exposure to the pathogen, and which is highly specific to the particular pathogen.

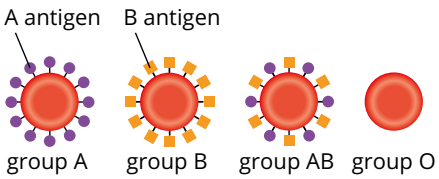


FIGURE 8.1.1 The A and B blood group antigens are carbohydrate molecules attached to proteins and lipids in the cell membrane and displayed on its surface.

ANTIGENS

Antigens are substances that, upon entering the body, can evoke an immune response. Antigens can be classified as self or non-self, and an organism's cells, especially immune system cells, can usually differentiate between self and non-self antigens and respond accordingly. Any antigen that elicits an immune response is more properly known as an **immunogen**. However, in the context of an immune response it is still common to simply refer to them as antigens.

Antigens are expressed or presented on the surface of the plasma membrane of cells, where they act as recognition sites for the immune system. However, not all antigens are attached to a cell; for example, some antigens, such as toxins released by bacteria, circulate freely in body fluids. The immune system can normally distinguish antigens that are expressed by its own cells from those that are not, and respond accordingly.

An example of antigens is the cell membrane complex carbohydrates of the human ABO blood group. It is the structure of the cell membrane carbohydrate that makes the A antigen different from the B antigen. The presence or absence of A and B antigens on the surface of red blood cells determines whether your blood group is A, B or AB. Group O blood has neither A nor B antigens on the surface of red blood cells. Figure 8.1.1 shows the four major blood groups. Proteins on the surfaces of virus particles or cells also act as antigens, as can be seen in Figure 8.1.2.

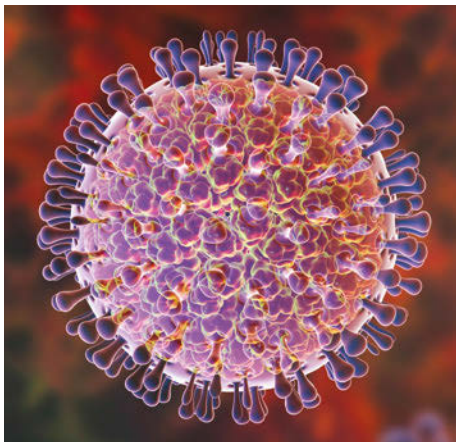


FIGURE 8.1.2 An artist's impression of rotavirus, a virus that is a common cause of gastroenteritis and diarrhoea in infants. Proteins on the surface of the virus act as antigens, which are recognised by the body's immune cells.

Antigens normally present on cells of the body are self-antigens and should not elicit an immune response. The lack of response to self-antigens is called tolerance, or **self-tolerance**. If self-tolerance breaks down and the immune system responds to self-antigens, it results in autoimmune diseases.

Some substances almost never trigger an immune response. For example, stud earrings are often made of gold because gold does not normally elicit an immune response. Other substances almost always stimulate an immune response. These include poison ivy (a plant) resin, the venom from insect bites, transplanted tissues, and pathogen-associated molecules. There are also some substances, such as various pollens and antibiotics, that sometimes cause a response. The response in this case is an over-reaction to antigens that are of no danger to the body. These antigens are called **allergens**, and the reaction to them is an allergic reaction.

BARRIERS TO INFECTION

Organisms have a number of **first-line defences** (or barriers) that provide innate resistance against pathogens, including:

- physical barriers, such as skin or bark
- chemical barriers, such as the lysozyme enzymes in saliva and other body secretions
- microbiological barriers, namely **microflora**.

Plant barriers to infection

Like vertebrates, plants have natural barriers to invasion by pathogens, but, unlike vertebrates, they don't have an adaptive immune system. Plants also lack mobile immune cells that can travel to the site of infection, so every plant cell has to respond to pathogens and use molecules to signal other cells during infections, resulting in non-specific responses. Plants have both physical and chemical barriers as their first lines of defence.

Physical barriers

Plants have a large variety of physical barriers to prevent pathogens from entering their tissues. Physical barriers include:

- cell walls that provide strength and flexibility
- dense cuticles on the outside layers of epidermal tissues, which are made of cutin and other waxes. The thicker the cuticle, the harder it is for pathogens to enter the cells
- thick layers of bark that also prevent pathogen entry
- lignified cell walls. Lignin is the main constituent of wood. It is dense and impervious to water. Lignin is difficult for insects to chew through and if undamaged is impenetrable to pathogens
- the ability to close stomata to deny pathogens entry. Stomata are the pores through which gas exchange takes place. Such openings are an ideal entry point for pathogens so the ability to close them when under attack is beneficial. A stomata is shown in Figure 8.1.3
- vertical positioning of leaves, which means water is unable to collect on the surface of leaves. This prevents infection by pathogens that are reliant on water for motility.

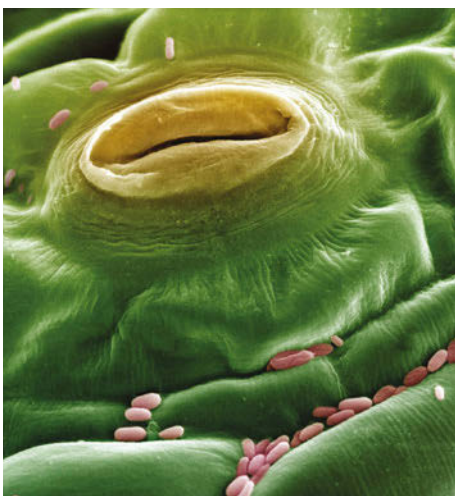


FIGURE 8.1.3 A scanning electron micrograph of a single stomata on the surface of the leaf of a tomato plant. Stomata can close to prevent bacteria (pink, rod-shaped structures) entering and infecting the plant.

Chemical barriers

Plants possess specific genes called resistance genes (R). Resistance genes code for proteins (R proteins), which switch on a plant's defences when it recognises a specific molecule produced by the pathogen. The specific pathogen molecules are generally proteins, known as AVr or avirulence proteins, and are coded for by AVr genes in the pathogen. They are avirulence genes because the presence of their protein product stimulates such a rapid and overwhelming response by the infected plant tissues that the pathogen is rapidly destroyed and disease does not eventuate.

A plant can mount an immune response if a pathogen enters the plant's tissue, either by responding to AVr proteins or through pathogen-recognition pathways. However, in many cases, immune responses are not required because the initial barriers to infection have held.

When the physical barriers are breached, plants make a range of toxic chemicals that help defend against infection. Many of these chemicals are usually present in the plant tissues, although their levels may increase when the plant is attacked by a pathogen. Toxic chemicals produced by plants in response to pathogens include saponins, terpenes, phenolics, alkaloids and cyanogenic glycosides.

Saponins have soap-like properties and, like soaps, they break down lipids, and so disrupt the cell membranes of pathogens.

Terpenes make up many of the essential oils found in plants. Pyrethrins are terpenes that are used in insecticides. Phytoectysones are terpenes that mimic the hormones involved in insect moulting and cause disruption to larval development, increasing mortality, and thus reduce infestation.

Phenolics include flavonoids, tannins and phytoalexins. Phytoalexins and many flavonoids have antibiotic properties. They disrupt cellular metabolism in the pathogen. Tannins are water-soluble chemicals that are highly toxic to plant pathogens. Tannins are stored in vacuoles until required. They bind to salivary proteins and digestive enzymes such as trypsin. This can result in the death of the pathogen through inadequate energy intake. The effects of tannins on bacterial growth are shown in Table 8.1.1. Tannins are effective against even antibiotic-resistant bacterial strains.

Alkaloids are toxic to many organisms, ranging from bacteria to humans. Many alkaloids are highly toxic to fungi, bacteria and insects. Their toxicity is usually dose dependent. Caffeine, nicotine, morphine, capsaicin and atropine are all alkaloids. Some alkaloids are used in low doses as drugs, such as atropine, which is used as a cardiac stimulant in minute doses but is lethal in large doses.

Cyanogenic glycosides are compounds that break down to form hydrogen cyanide (HCN). Hydrogen cyanide is extremely toxic to all eukaryotic cells because it disrupts ATP production in the mitochondria by blocking the electron transfer chain. This quickly leads to cell death.

TABLE 8.1.1 Zone of inhibition of tannins extracted from green tea on growth of selected bacteria. An antibiotic was used as a control. Paper discs were soaked in tannin extract or antibiotic

Mass (mg) tannin per disc	Zone of inhibition (mm)				
	Vancomycin-resistant *Staphylococcus aureus*	Methicillin-resistant *Staphylococcus aureus*	*Bacillus coagulans*	*Shigella flexneri*	*Listeria monocytogenes*
2	0.2–1.5	<0.1	2.0–4.5	0.2–1.5	0.2–1.5
3	2.0–4.5	0.2–1.5	2.0–4.5	0.2–1.5	0.2–1.5
4	2.0–4.5	0.2–1.5	2.0–4.5	2.0–4.5	2.0–4.5
5	2.0–4.5	2.0–4.5	5.0–7.0	2.0–4.5	2.0–4.5
Antibiotic control	5.0–7.0	5.0–7.0	>8	>8	2.0–4.5

If all previous defences fail to prevent pathogens from infecting the plant, cell-mediated defences can involve self-destruction of infected or damaged cells, which helps to limit a pathogen's access to nutrients and, in turn, limit the spread of the pathogen to the rest of the plant. Many plants also produce a hypersensitive response when invaded by parasites, such as nematode larvae or bacteria. This response involves the rapid breakdown of cells around the parasite and the release of toxic substances. This may kill the invader but it also signals surrounding tissues to increase their levels of resistance to infection.

Animal barriers to infection

Animal barriers to infection are generally different from plant barriers but are just as effective. Unbroken skin and body secretions are among the most important strategies used by animals to prevent pathogens entering the body. These are the first line of defence against disease. Figure 8.1.4 shows the major physical and chemical barriers to infection.

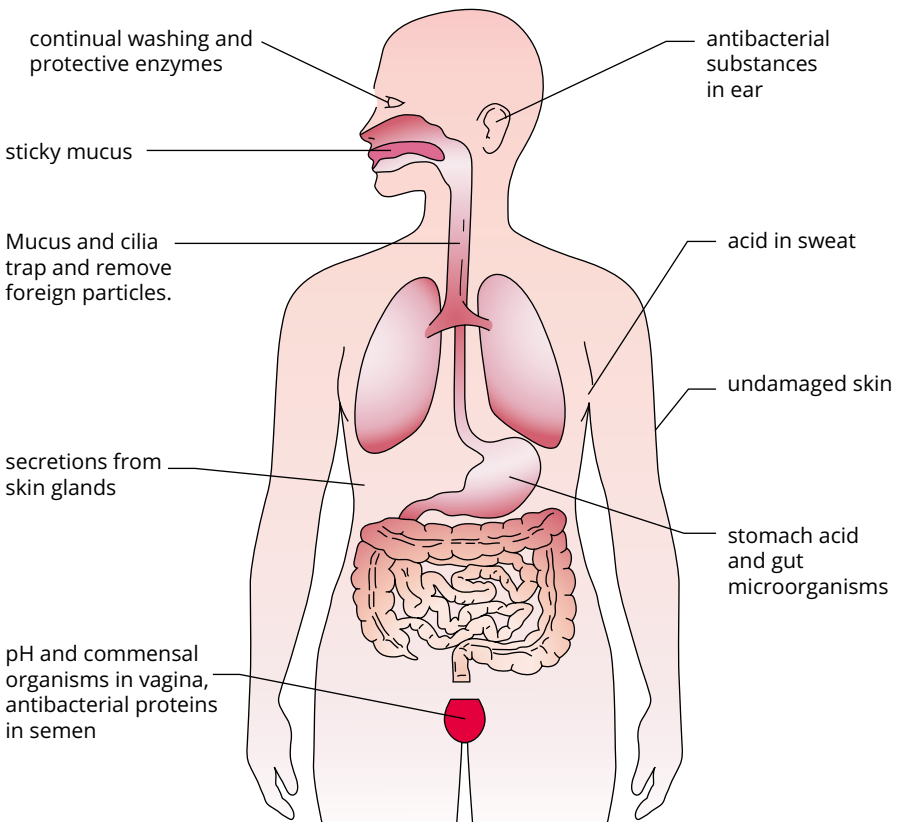


FIGURE 8.1.4. Some of the physical and chemical defence mechanisms that prevent foreign organisms from gaining access to the human body

Physical barriers

In animals, epithelial cells create a physical barrier that prevents pathogens from entering the organism. Epithelial cells line the skin, as well as the respiratory, gastrointestinal and urogenital tracts. They are joined tightly by specialised membrane proteins to form a continuous barrier against pathogens.

In addition to toughened (keratinised) unbroken skin, physical barriers to pathogens in animals include mucus-secreting membranes. Invading organisms are trapped in mucus and membranes lined with cilia sweep foreign bodies away (e.g. those that line the airways of mammals). These can be seen in Figure 8.1.5.

Chemical barriers

External chemical barriers in vertebrates include lysozyme enzymes and toxic metabolites, such as lactic acid and fatty acids, which are found in secretions such as tears, sweat and saliva. Here, they have protective functions and provide a generalised defence; for example, by destroying bacterial cell walls.

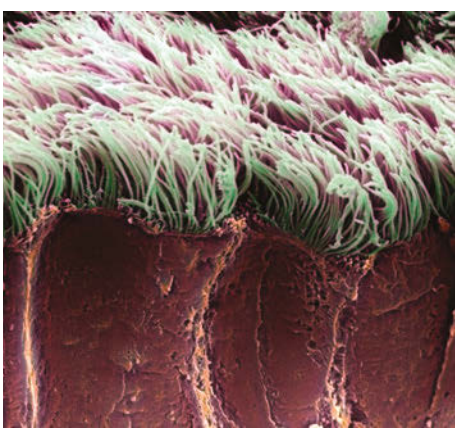


FIGURE 8.1.5 A coloured scanning electron micrograph of the mucous membrane (or bronchial epithelium) that lines the major airways of the lung. Mucus traps potential pathogens and foreign particles, and the rhythmic movement of hair-like cilia moves bacteria and other particles away from the lung and towards the throat.

Other chemical barriers include stomach acid and digestive enzymes, which are primarily involved in the digestion of food, but also kill many pathogens. The fluid in the lungs contains proteins that act as surfactants. Surfactants are 'detergent-like' substances found in lung secretions that lower the surface tension of lung fluids and prevent the alveoli from collapsing on exhalation. They are also antimicrobial because they coat the pathogens, making it easier for the pathogens to be eliminated by macrophages. In female mammals, the lining of the vagina is coated in acidic secretions that serve several functions, including defence against pathogens.

Microbiological barriers

In healthy people, non-pathogenic bacteria, referred to as normal flora, are found on the skin, and in the mouth, nose, throat, lower part of the gastrointestinal tract and the urogenital tract. The presence of normal flora prevents the growth and colonisation of other bacteria because normal flora competes with other bacteria for space and resources, and produces chemicals that lower the pH of the micro-environment.

If you take a course of antibiotics, you can disrupt the normal flora of your intestine and reproductive tract, because the antibiotics do not discriminate between beneficial normal flora and harmful bacteria. This can disturb the normal function and predispose you to various infections until the levels of normal flora return to their pre-treatment values. For example, the use of antibiotics can allow the growth of yeast infections. Yeasts are fungi and are not affected by most antibiotics. The yeast *Candida albicans* is generally present in most humans in the mouth and gut and in the vagina of females. Disruption to the normal bacterial suite, which keeps the size of the yeast colony under control, can result in the disease thrush.

In healthy people, competition between all of the natural flora keeps bacterial numbers in balance. However, in people with weakened immune systems, normal flora can sometimes grow unchecked and cause disease.

INNATE IMMUNE RESPONSES

If pathogens manage to breach the first line of defence, they are immediately met by attacking cells and molecules. This line of defence is known as the **innate immune response**.

The innate immune response exists in all organisms, and its persistence over millions of years of evolution indicates its fundamental importance. Even if the innate immune response cannot eliminate a pathogen, it is still critical for keeping infections under control until the adaptive immune response (see Module 8.2) starts working, which can take up to several days.

Innate immune responses in vertebrates:

- are non-specific—they do not target a specific antigen
- are rapid—they occur within hours
- are present in all animals
- are fixed responses—they do not adapt
- do not lead to an immunological memory of the pathogen that caused the infection.

Plant responses to infection

The main response of plants to infection is a chemical response. Plants make a variety of chemicals that disrupt pathogen reproduction. Some of these chemicals are present in plant tissues all of the time (the chemical barrier), whereas others are only produced during infection or potential infection. The plant response is triggered when plant cells recognise certain molecules, such as certain lipopolysaccharides, or other common cell wall components, which form the cell walls of pathogens. These are called **microbe-associated molecular patterns (MAMPs)** and are recognised by **pattern recognition receptors (PRRs)**. Plants use hormone-like chemicals, such as jasmonic acid and salicylic acid, to activate their responses in the recognition pathways. The plant response pathway is summarised in Figure 8.1.6.

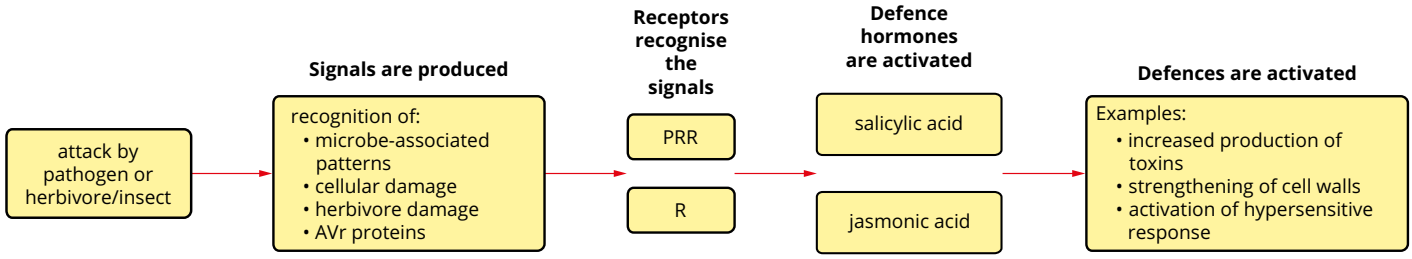


FIGURE 8.1.6 Plants recognise attack by pathogens or plant-eating organisms and mount defences that strengthen natural barriers and increase production of toxic and signalling chemicals.

Plants produce a range of proteins and enzymes that provide defence against pathogens. Because it requires a lot of energy to produce these substances, most plants only make them when under actual attack by a pathogen.

Among the proteins produced by plant tissues are:

- **defensins**, which are small proteins that act against digestive enzymes and are also thought to act against microbes by disrupting the cell membrane. Many of these proteins are rich in the amino acid, cysteine. Bread wheat, shown in Figure 8.1.7, can produce defensins
- **protease inhibitors**, which inhibit enzymes such as trypsin, an important digestive enzyme
- **digestive enzyme inhibitors**, which are proteins that block normal digestion. They include enzymes, lectins, which block the digestion of starch by insects, and ricin, which is so toxic that 0.2 mg is enough to kill an adult human
- **hydrolytic enzymes**, which break down cell walls. Chitinases break down chitin, the main constituent of fungal cell walls and insect exoskeletons. Glucanases break the chemical bonds between the molecules that form glucans, which comprise the cell walls of members of the oomycetes. Lysozymes are enzymes that can digest bacterial cell walls.

In many plants, recognition of a pathogen may also activate enzymes that strengthen the cell wall as a barrier to infection and cause surrounding cells to thicken their cell walls. Many plants also undergo cell-mediated responses when all other pathways have failed. These responses can result in the self-destruction of the infected tissues, the hypersensitive response, in an attempt to wall off the pathogen and so protect the rest of the plant.

FIGURE 8.1.7 Bread wheat (*Triticum aestivum*) contains small cysteine-rich proteins that act as plant defensins to inhibit the growth of bacteria and fungi.

WS 2.2.3

Animal responses to infection

Like plants, animals can recognise and respond to pathogens through the identification of **pathogen-associated molecular patterns (PAMPs)**. In vertebrates, this response includes a large range of responses and involves many specialised cells, especially white blood cells (or **leukocytes**).

The vertebrate response to pathogens is probably the most complex of all organisms. It includes both innate and adaptive components. The **adaptive immune response** provides long-term immunity to pathogens through the creation of immunological memory. The adaptive response is modified on each subsequent infection and becomes more effective each time. Many different types of cells are involved in both the innate and adaptive responses in vertebrates. In this section, the focus is on the innate response of mammals, especially humans.

Defensive molecules

Complement proteins and cytokines are defensive molecules involved in both the innate and adaptive immune responses.

The **complement system** comprises more than 30 **complement proteins** that circulate in the blood and help kill foreign cells. They exist in body fluids in an inactive form, and are activated as part of the non-specific immune response to certain antigens and carbohydrates on the surfaces of some bacteria and parasites.

When the first protein is activated, it triggers a cascade of reactions, each protein activating the next in the cascade.

The signals that activate the complement cascade include antigen–antibody complexes of the immune response and carbohydrates on the 'foreign' surfaces of some bacteria and parasites. Activated complement proteins have a number of important actions, such as:

- attracting and enhancing the activity of phagocytic cells, which assists them to recognise and engulf foreign material
- forming attack complexes to destroy bacteria directly by punching holes in bacterial membranes and causing them to **lyse** and release their contents, which attracts phagocytes to the site of infection. This is shown in Figure 8.1.8
- contributing to inflammation by increasing local permeability of capillaries and attracting phagocytes.

The complement system is a part of the innate immune response but it can be recruited by the adaptive response through the binding of anitbody–antigen complexes to certain complement proteins.

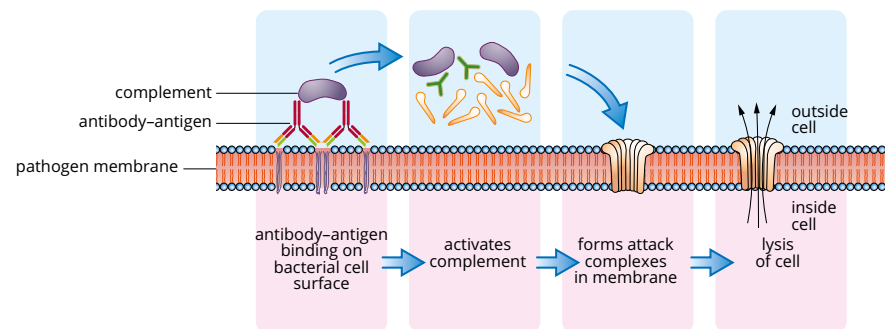


FIGURE 8.1.8 Complement proteins activated by antigen–antibody complexes are also involved in specific (adaptive) immune responses.

Cytokines are small signalling molecules used by the immune system. They coordinate many aspects of immune responses. Cytokines can be peptides, proteins or glycoproteins, and are released by body cells in response to cell damage or the presence of pathogens. There are many different cytokines and they trigger a variety of responses, both non-specific and specific. For example, cytokines can promote the rapid increase of lymphocytes, induce inflammation and fever, activate macrophages and regulate cells in the adaptive immune response. Interferons and chemokines are two examples of cytokines, and they each have different functions.

Interferons are a class of cytokines that are produced by, and act on, a host cell infected by a virus. Interferons stimulate the infected cells to produce enzymes that break down viral RNA and proteins that block translation. This limits viral replication and release from the cell. Interferons also attract natural killer cells, which release cytotoxic peptides to kill the virus-infected cell. Interferons are non-specific and act against any virus. However, viruses vary widely in their susceptibility to interferons. Many viruses can evade interferon-induced defences and the more virulent viruses may be able to inhibit the production of interferon.

Interferons are an important defence against viruses, but play a smaller role in combating bacterial and parasitic infections. Interferons also regulate the immune system in a number of ways, such as enhancing T lymphocyte activity.

Chemokines are a group of cytokines that act as chemical attractants (or chemo-attractants). Chemokines are important for attracting leukocytes to sites of infection and inflammation.

Cells of the innate immune response

Leukocytes are immune cells that are present in blood and other tissues. Leukocytes have pattern recognition molecules, also known as toll-like receptors (TLRs) on their surface, which are able to recognise PAMPs. Different TLRs recognise different PAMPs. For example, TLR-2 recognises the lipoproteins and peptidoglycan of gram-positive bacteria, TLR-4 recognises lipopolysaccharides of gram-negative bacteria, TLR-5 recognises bacterial flagellin, and TLR-7 and TLR-8 recognise single-stranded viral RNA.

The cells of the innate immune system of mammals include:

- macrophages
- neutrophils
- monocytes
- dendritic cells
- natural killer cells.

Natural killer cells identify and kill somatic (body) cells that have been infected by viruses. They do this by producing chemicals called **perforins**, which perforate the cell membrane, or introducing **granzymes** into the cell. Granzymes are enzymes that cause the cell to undergo cell suicide.

Macrophages, neutrophils, monocytes and dendritic cells are all **phagocytes**. Phagocytes engulf pathogens through the process of phagocytosis. You can see examples of phagocytes in Figures 8.1.9 and 8.1.10.

TLRs on the phagocyte interact with a microbe's PAMPs to cause a series of changes inside the cell, and activate the phagocyte. Once activated, the phagocyte engulfs the microbe, with the plasma membrane forming a vacuole called a **phagosome** around it. Then a lysosome containing digestive enzymes fuses with the phagosome, forming a **phagolysosome**, which breaks down the foreign material. The fragments can then be expelled from the cell by exocytosis. Exocytosis is the release of substances enclosed within a vesicle to the outside of a cell. It occurs by fusion of the vesicle with the plasma membrane.

Table 8.1.2 on page 354 shows a more detailed list of the leukocytes involved in the innate immune response and indicates whether they are involved in phagocytosis, antigen presentation or the release of cytokines that promote inflammation. You will learn more about cytokines later in this module.

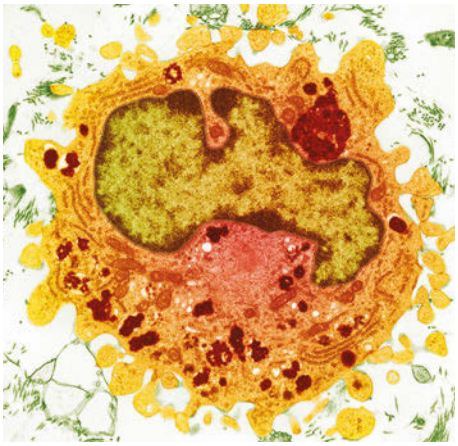


FIGURE 8.1.9 A coloured transmission electron micrograph of a macrophage. Macrophages are cells of the innate immune response in vertebrates that recognise and engulf foreign material.

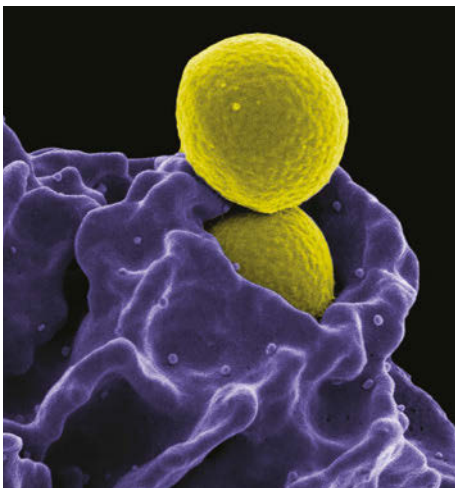
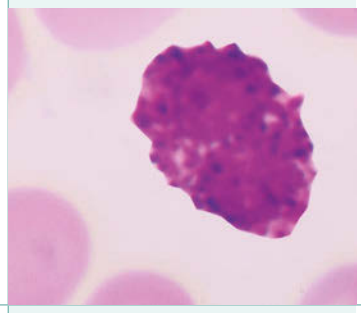
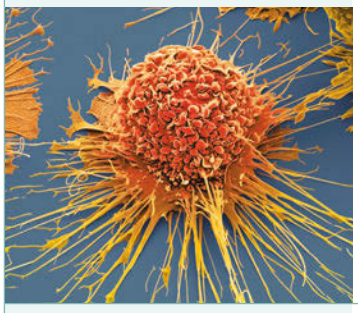
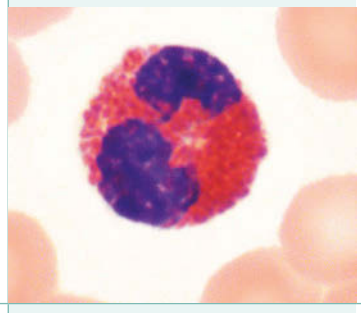
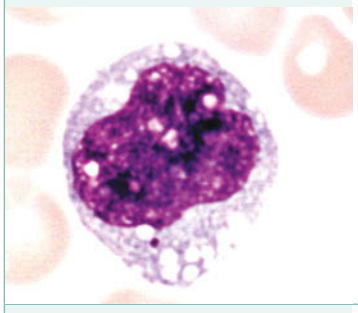
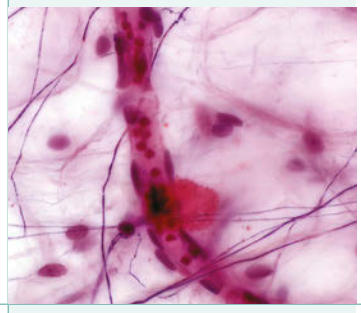
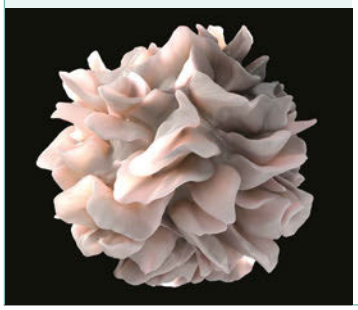
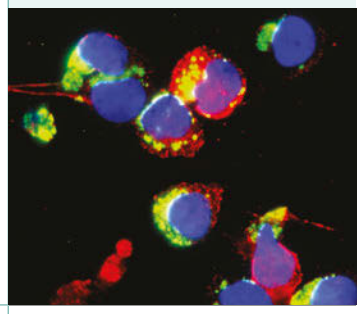


FIGURE 8.1.10 Phagocytes are a key part of the innate immune response. This neutrophil (purple) is engulfing *Staphylococcus aureus* bacteria (yellow), which it then phagocytoses.

TABLE 8.1.2 A more detailed list of the leukocytes involved in the innate immune response and their functions

Cell type	Function	Cell type	Function
neutrophil (granulocyte) 	• phagocytosis • releases antimicrobial compounds, such as defensins and hydrogen peroxide, which disrupt bacterial and fungal membranes • releases cytokines that attract other immune cells and cause inflammation	basophil (granulocyte) 	• releases histamine, which contributes to inflammation and therefore blood vessel dilation • has a limited role in phagocytosis
macrophage 	• phagocytosis • antigen presentation • releases cytokines	eosinophil (granulocyte) 	• antigen presentation • releases cytokines and cytotoxic chemicals • has a limited role in phagocytosis • found in large numbers in parasitic infections
monocyte 	• phagocytosis	mast cell (granulocyte) 	• plays a key role in inflammation, and therefore blood vessel dilation, by releasing histamines • has a limited role in phagocytosis Mast cells stained red/pink with haematoxylin and eosin stain
dendritic cell 	• phagocytosis • antigen presentation • has many grooves that increase surface area and permit contact with a large number of other cells	natural killer 	• recognises virus-infected and cancerous cells • releases cytotoxic chemicals from granules, such as perforin, which makes holes in cell membranes, triggering apoptosis and cell death of virus-infected cells and abnormal cells • releases cytokines to attract and activate cells of the adaptive immune system An immunofluorescent light micrograph of natural killer cells: cytotoxin granules (green), nuclei (blue), cytoplasm (red)

Inflammatory response

Inflammation is the accumulation of fluid, plasma proteins and leukocytes that occurs when tissue is damaged or infected. Inflammation results in heat, pain, swelling, redness and loss of function at the site of infection and may involve body-wide effects such as fever.

Inflammation is often triggered by substances released from damaged cells, by **histamines** released by stimulated **mast cells** and by **platelets**. Mast cells are stationary granular cells located in the walls of blood vessels, gut and lungs. Platelets are membrane-bound fragments of huge white blood cells (**megakaryocytes**) located in the bone marrow. Platelets are about half the size of red blood cells and have no nucleus or DNA. Megakaryocytes 'pinch off' thousands of platelets during their life and release them into circulation where they remain for about 10 days. They are important in wound healing and blood clotting.

The interaction between leukocytes (especially phagocytes) and pathogens may also trigger the inflammatory response that results from the production, activation or release of peptides and proteins such as complement proteins and cytokines.

Acute inflammation involves phagocytes, and occurs soon after infection as part of the innate immune response. Inflammation can also involve lymphocytes and occur later as part of the adaptive immune response.

A number of steps are involved in the initiation of an inflammatory response to infection. These steps are shown in Figure 8.1.11.

1 Bacteria or other pathogens breach the barriers of the first line of defence; for example, through an open cut or wound in the skin.

2 Injured cells release cytokines (chemokines) that attract neutrophils, and mast cells release histamine, which increases **vasodilation** (blood vessel dilation) and permeability. The dilated, more permeable blood vessels allow leukocytes and fluid containing peptides and proteins such as complement proteins to enter the infected tissue. Platelets release clotting factors at the site of the wound.

3 Neutrophils migrate towards the cytokines and are activated, causing the neutrophils to recruit macrophages and secrete factors, such as defensins and hydrogen peroxide, that degrade and kill pathogens; for example, by damaging bacterial cell membranes.

4 Macrophages become activated and secrete cytokines and, along with neutrophils, phagocytose pathogens and debris at the site of infection. This may lead to pus, which is fluid containing leukocytes, dead pathogens and cell debris.

5 The inflammatory response continues until the pathogen is eliminated and the wound has healed.

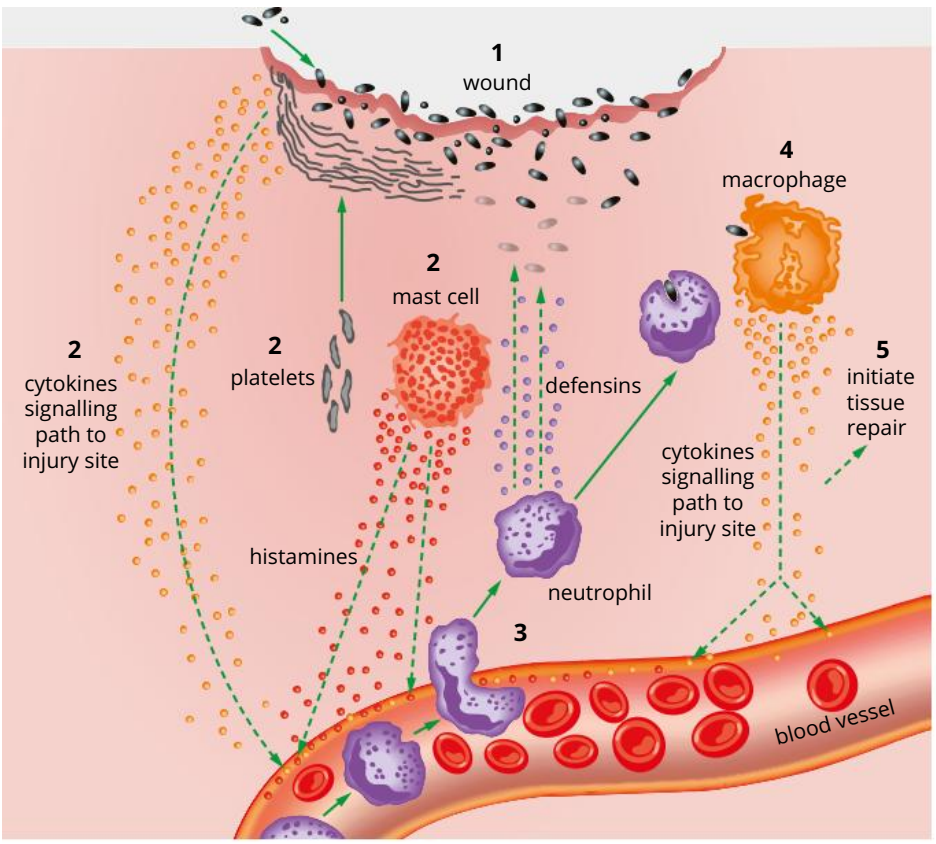


FIGURE 8.1.11 The process of inflammation. (Cell colours are for illustrative purposes only.)

Fever

Fever is one common consequence of inflammation. In humans, normal body temperature is about 37°C. Fever occurs when body temperature is above normal. The increase in body temperature results when the regulated body temperature set point in the hypothalamus of the brain is set to a higher level by inflammatory cytokines, including prostaglandins.

Fever slows the replication of bacteria and viruses by shifting the temperature away from their optimal range, and so allows more time for other defences to intervene. Additionally, moderate increases in temperature increase the activity and proliferation of leukocytes, so fever also improves the immune response.

Prostaglandins

Prostaglandins are a group of lipid compounds with hormone-like effects that are involved in many processes. For example, they help to control reactions that cause pain, fever and the healing process and significantly contribute to inflammation. Prostaglandins are involved in stimulating blood vessel dilation (vasodilation). Where pathogens are present and releasing toxins, prostaglandins mediate increased blood flow (through vasodilation) and chemical signals that summon white blood cells. As long as pathogens are present and releasing toxins, prostaglandins will continue to be produced and add to the inflammatory process.

Major histocompatibility complex and antigen presentation

All body cells have **major histocompatibility complex (MHC)** proteins on the surface of their cell membranes. The MHC proteins, also called **human leukocyte antigens** (HLA), are found on the surface of your body's cells, presenting self or non-self antigens to **lymphocytes** (a type of leukocyte primarily involved in the adaptive response; you will learn more about lymphocytes in Module 8.2). MHC proteins are coded for by a gene region, containing over 200 genes, found on chromosome 6.

MHC proteins play a fundamental role in immunity. They are a critical link between the innate and adaptive responses because they are involved in antigen presentation. Two classes of MHC proteins that are important in antigen presentation are MHC class I (MHC-I) and MHC class II (MHC-II). All body cells, except red blood cells, usually have MHC-I markers; however, cells that have been invaded by viruses normally lack MHC-I proteins. The absence of these markers can be recognised by certain cells of the innate immune system, such as natural killer cells, which then initiate the destruction of the infected cell by releasing cytotoxic chemicals, such as perforin and granzyme.

The two classes differ in structure and function because they are specialised to present different types of antigens, and so elicit different responses.

Some phagocytes, particularly macrophages and dendritic cells, act as **antigen-presenting cells (APCs)**. When APCs phagocytose a pathogen, fragments of digested antigen are linked to MHC-I proteins on the cell membrane, as shown in Figure 8.1.12. The phagocyte then displays, or presents, this pathogen-derived antigen to other cells in the immune system.

In this way, the adaptive immune response is initiated. There are a number of different types of lymphocytes involved in the adaptive response. You will learn more about the cells of the adaptive response in Module 8.2.

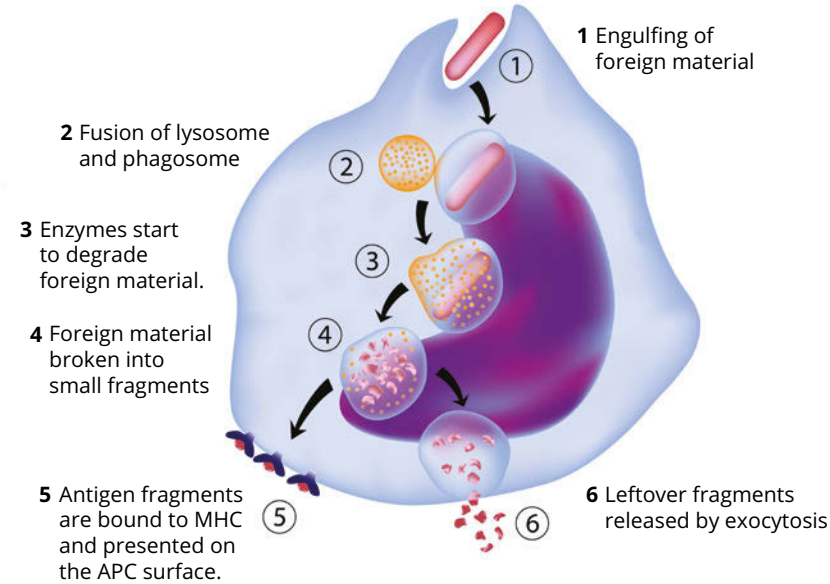


FIGURE 8.1.12 Phagocytosis and antigen presentation in an antigen-presenting cell (APC). APCs communicate with other immune cells by presenting antigens or fragments of antigens on their cell surface.

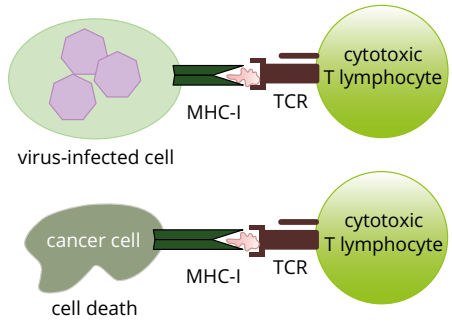


FIGURE 8.1.13 Infected or cancerous cells present antigens on MHC-I to the T cell receptors (TCRs) of cytotoxic T lymphocytes. Cytotoxic T lymphocytes then release cytotoxins that kill the virus-infected cells and cancer cells.

MHC-I proteins also communicate with a type of lymphocyte called a **cytotoxic T lymphocyte (T_C)** about the proteins being produced within each cell, such as non-self viral antigens produced by virus-infected cells. If a T_c lymphocyte reacts to the antigen being presented, it becomes activated and releases toxic peptides (perforin and granzyme) that damage the target cell membrane and induce apoptosis. Figure 8.1.13 shows this process.

MHC-II proteins can be conditionally expressed on all cells, but are most commonly found on the surface of APCs such as dendritic cells, macrophages and B cells, which are cells of the adaptive response. MHC-II presents antigens that originated extracellularly and have been processed after phagocytosis. This presentation of antigens activates the **helper T lymphocytes (T_H)** of the adaptive immune response, linking the innate and adaptive immune responses as the APC and T_H cell interact. Figure 8.1.14 shows this interaction.

Once the antigens are presented, T_H lymphocytes are activated, and secrete cytokines that activate and attract other immune cells to the site of infection, as shown in Figure 8.1.15.

You will learn more about the adaptive immune response and the role of T_H cells in Module 8.2.

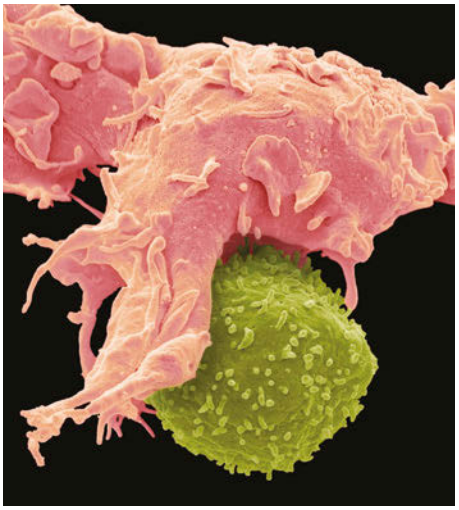


FIGURE 8.1.14 A coloured scanning electron micrograph showing the interaction between a macrophage (pink) and a helper T lymphocyte (light green).

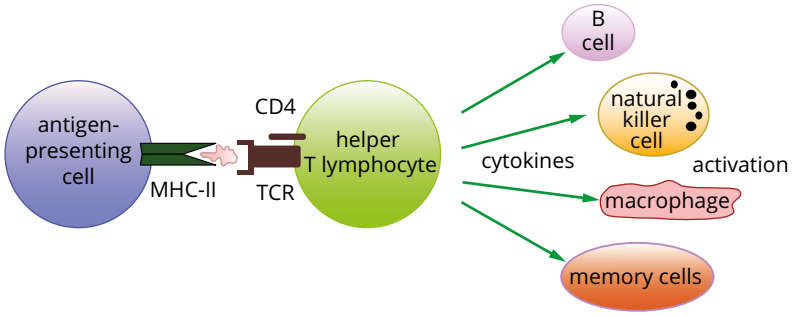


FIGURE 8.1.15 Antigen-presenting cells present antigens on MHC-II to helper T lymphocytes via the T cell receptor (TCR). The CD4 co-receptor assists recognition and signalling. Helper T lymphocytes release cytokines to help activate a range of immune cells.

8.1 Review

SUMMARY

- Antigens are molecules, or parts of molecules, that are identified by cells of the immune system as self or non-self.
- Antigens are usually composed of one or more polypeptide chains, but may be carbohydrates, nucleic acids or lipids.
- Antigens are found on the surface of cells or free in body fluids.
- Most foreign molecules are identified as non-self antigens and elicit an immune response.
- Self-antigens do not usually elicit an immune response.
- Pathogens are a source of non-self antigens.
- Plants have physical barriers against invasion by pathogens; these include thick cuticles.
- Plants have chemical defences, which may be present in their cells all of the time, such as tannins, or which may be produced when the plant is under attack, such as defensins.
- Vertebrates have a range of non-specific defences against pathogens, including intact skin, phagocytes, complement proteins, natural killer cells and a variety of chemicals, such as interferons.
- Interferons are produced by virus-infected cells. Interferons make surrounding cells more resistant to viruses by interfering with viral reproduction.
- Interferons belong to a group of signalling molecules called cytokines.
- Cytokines are the communication molecules of the immune system.
- The complement system causes the lysis of bacteria, which increases the activity of phagocytes and promotes inflammation.
- Natural killer cells are a part of the non-specific immune response; they are active against virally infected cells and cancer cells.
- Phagocytes are leukocytes that engulf and digest pathogenic antigens and then display those antigens attached to MHC-II markers to the cells of the adaptive response.
- Inflammation increases blood flow to an area of infection, bringing more leukocytes, complement proteins and platelets to the area.
- Fever, associated with inflammation, inhibits bacterial growth and enhances the activity of immune system cells, especially phagocytes.
- Vertebrates have a group of genes called the major histocompatibility complex (MHC), which code for MHC-I and MHC-II proteins, which are used for displaying antigens and identifying self and non-self.

KEY QUESTIONS

Retrieval

1 Define ‘antigen’.

2 Describe how phagocytes link the innate and adaptive immune responses.

3 State the specific mechanisms by which natural killer cells kill virally infected somatic cells.

4 Draw the process of inflammation that occurs when bacteria enter skin through an open wound. Label key white blood cells and the molecules they produce in response to the pathogen, and number the steps involved in the inflammatory response.

Comprehension

5 Compare the physical barriers in plants with those in animals.

6 Explain how the increased permeability of capillaries, which occurs during inflammation, helps to defend against pathogens.

7 Explain what is meant by self-tolerance. In your answer, explain why it is necessary.

8 Mild infections such as the common cold are a regular experience of children attending childcare. One symptom of these infections is a mild fever (up to 39°C). The usual treatment given to children is a medication such as paracetamol, which reduces their temperature to normal.
Explain why reducing the body temperature of a patient with a mild fever may prolong the infection.

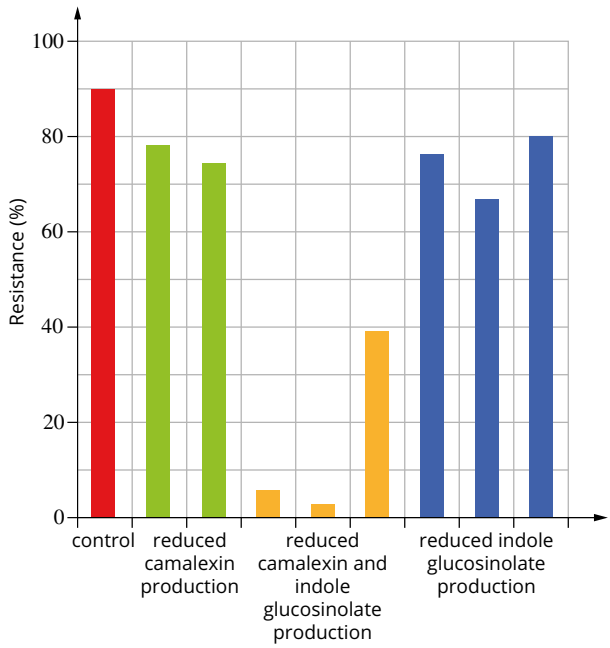
9 A patient requires a blood transfusion. The only blood available is either group B or group O.
- **a** If the patient is blood group A, explain which blood should be used for the transfusion.
- **b** Explain whether you would have chosen differently if the patient had been group AB.

10 After a course of antibiotics, some doctors advise their patients to consume a probiotic, which contains bacteria. Explain the potential benefits.

Analysis

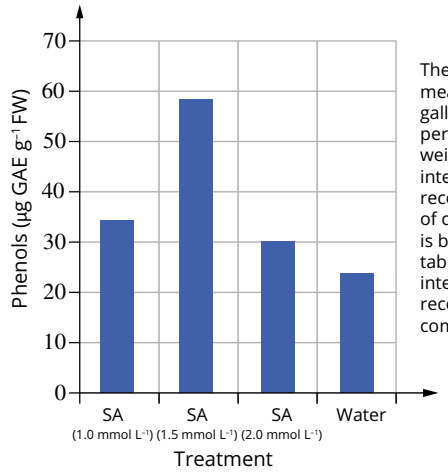
11 Indole glucosinolate and camalexin are phenols involved in protecting plants from pathogens. The graph shows the resistances to infection of plants with mutations, which result in reduced camalexin production, reduced glucosinolate production or reduced production of both.

Using only this data, draw conclusions about the contributions of these two chemicals to plant resistance to infection.



12 It has been suggested that salicylic acid is involved in stimulating the pathway leading to the production of phenols—chemicals that defend plants from attack by pathogens and herbivores.

The graph shows the results after a group of plants were sprayed with salicylic acid (SA) at various concentrations.



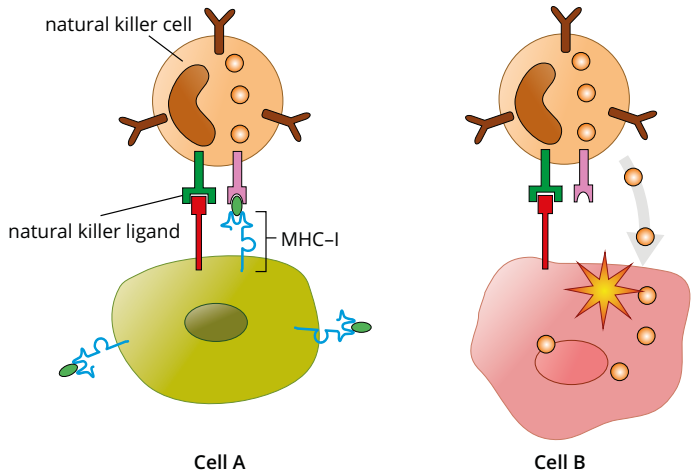
The unit μg GAE g^{-1} FW means micrograms of gallic acid equivalent per gram fresh weight. It is an internationally recognised measure of concentration that is based on a standard table issued by an internationally recognised scientific committee.

a Describe the features of the graph that support the contention that salicylic acid promotes the production of defensive chemicals in plants.

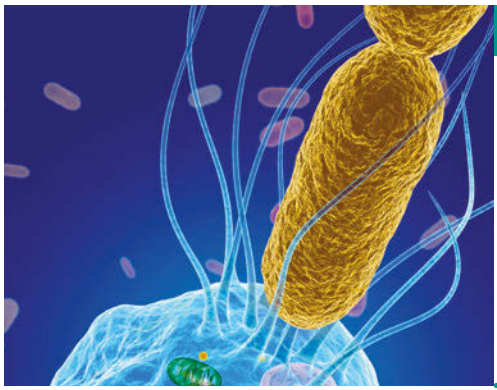
b Identify the concentration of salicylic acid that is most effective and state how you know this.

13 The diagram shows a natural killer cell interacting with two different cells that it has encountered in the body.

Examine the diagram carefully. Explain, using evidence, which cell is being killed and how the natural killer cell identified that the other cell was not a threat.



8.2 Adaptive immunity



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

- know the names and roles of the various cells involved in immune responses
- understand the difference between innate and adaptive immunity
- understand the role of antibodies in the adaptive response
- understand how humoral and cell-mediated immune responses provide protection against pathogens
- understand how the immune system identifies which cells to target during immune responses.

FIGURE 8.2.1 Each B lymphocyte produces antibodies for a specific antigen.

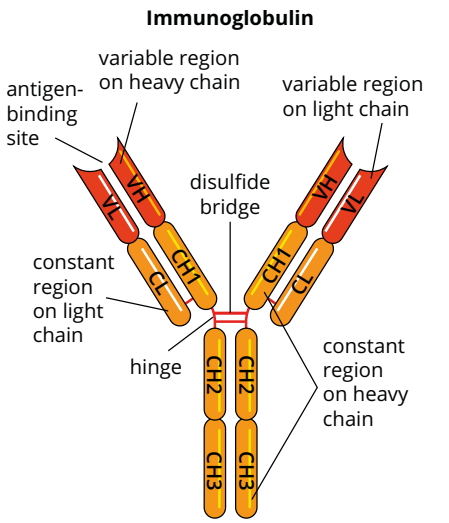


FIGURE 8.2.2 The structure of a basic unit of an antibody. Antibodies have two long heavy (H) chains and two short light (L) chains. Both heavy and light chains have variable (V) and constant (C) regions. Naturally produced antibodies consist of two identical variable regions that are specific for a particular antigen. The constant region can bind to and initiate other immune components, such as the complement proteins.

You will recall from Module 8.1 that that if a vertebrate's first line of defence is breached by a pathogen, that pathogen is met with a non-specific innate immune response. If this innate immune response is not successful in eliminating the invader, vertebrates also have an additional adaptive immune response to pathogens.

There are two distinguishing features of **adaptive immunity**. The adaptive immune response is specific. On recognising a specific foreign antigen, cells of the adaptive immune system implement an array of defensive mechanisms. The adaptive immune response involves immunological memory. This means that after the first encounter with an antigen, subsequent encounters result in faster and stronger responses.

Adaptive immunity involves **B lymphocytes**, a number of different types of **T lymphocytes** and antibodies. Figure 8.2.1 shows a B lymphocyte. B lymphocytes and T lymphocytes are types of white blood cells that are important in the adaptive immune response. B lymphocytes produce antibodies, which are proteins that bind to specific antigen molecules.

ANTIBODIES

Antibodies, also known as **immunoglobulins (Ig)**, are produced by B lymphocytes and released into the blood and lymph fluid. When an organism is first exposed to a new foreign antigen, it reverse engineers the protein structure of the antigen. It then changes one or some of many immunoglobulin genes in the B lymphocytes, so it is then able to produce a protein with complementary binding sites (an antibody) to the foreign antigen. Each antibody is specific to only one type of antigen. Pathogens can have many different antigens so each pathogen can stimulate the production of many different types of antibody.

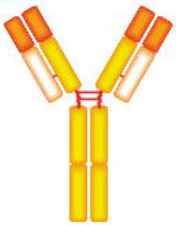
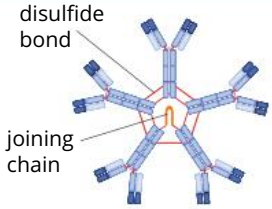
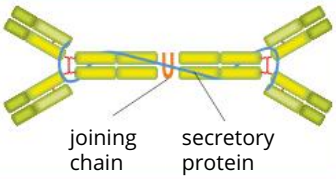
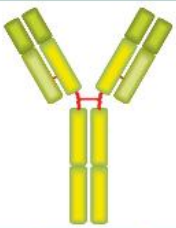
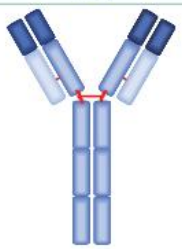
Antibody structure

The basic unit of an antibody molecule is a Y-shaped protein, formed by four polypeptide chains: two long **heavy chains** and two short **light chains**, as shown in Figure 8.2.2. The amino acid sequences that form the top of the 'arms' of the Y-shaped antibody are known as the **variable regions**. The variation of these variable regions allows antibodies to bind to different antigens. The two variable regions are identical antigen-binding sites and attach to identical antigens. The single 'stem' of the Y-shaped antibody is a conserved sequence in all antibodies and is called the **constant region**. The constant region recruits other components of the immune system.

Mammals have five main classes of antibody molecules with different structures and functions. Antibodies may act singly (monomers), in pairs (dimers) or in groups of five (pentamers). Antibodies IgG, IgE and IgD are all monomers but differ in the structure of their constant regions. IgA is a dimer and IgM is a pentamer.

Different classes of antibodies are also found in different body fluids and tissues. The different classes of antibody also play different but overlapping roles in immunity. For example, both IgG and IgA have a role in protecting newborn babies. IgG can cross the placenta and IgA is found in breast milk so that as levels of IgG from the mother decline, the newborn still has some protection. Table 8.2.1 summarises the roles and structure of the five classes of antibody and Figure 8.2.3 illustrates a three-dimensional visualisation of the structure of antibodies.

TABLE 8.2.1 Structure and function of mammalian immunoglobulins

Class	Half-life in serum (days)	Presence	Functions	Structure
IgG	21	Blood, lymph and extracellular fluid; most circulating antibodies (>80%); crosses placenta	agglutination, complement activation	
IgM	10	Blood and lymph; produced early in infection response	agglutination, complement activation	
IgA	6	Secretions such as tears, saliva and milk	mucosal immunity	
IgD	3	Blood and lymph; mostly present on B lymphocyte surfaces; small amount in circulation; binds to basophils and mast cells	functions not well understood; possible role in regulating innate immune responses	
IgE	2	Blood and lymph; attaches to mast cells	involved in allergic reactions	

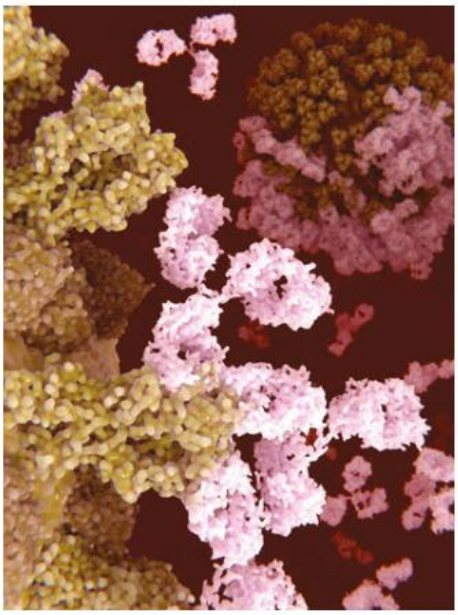


FIGURE 8.2.3 A digital illustration of antibodies (pink) binding to specific antigens on the surface of influenza virions.

Antibody functions

Antibodies do not directly destroy pathogens, but carry out several important mechanisms to interfere with the function of the pathogen. The major functions of antibodies are:

- neutralisation of toxins—antibodies bind to toxins produced by bacteria or other organisms, blocking the action of the toxin
- neutralisation of pathogens—antibodies bind to antigens on the surface of the pathogen that are required for entry into host cells, thus preventing pathogen invasion of host cells
- activation of the complement
- **agglutination**—antibodies bind to antigens on the surface of cells and form **antigen–antibody complexes**, which activate phagocytes and the complement cascade, leading to antigen/cell destruction. Agglutination is an advantage because it immobilises that pathogen and facilitates the phagocytosis of large numbers of pathogen particles at the same time
- **precipitation**—antibodies bind to soluble antigens, causing them to become insoluble and precipitate out of solution.

The major functions of antibodies are summarised in Figure 8.2.4.

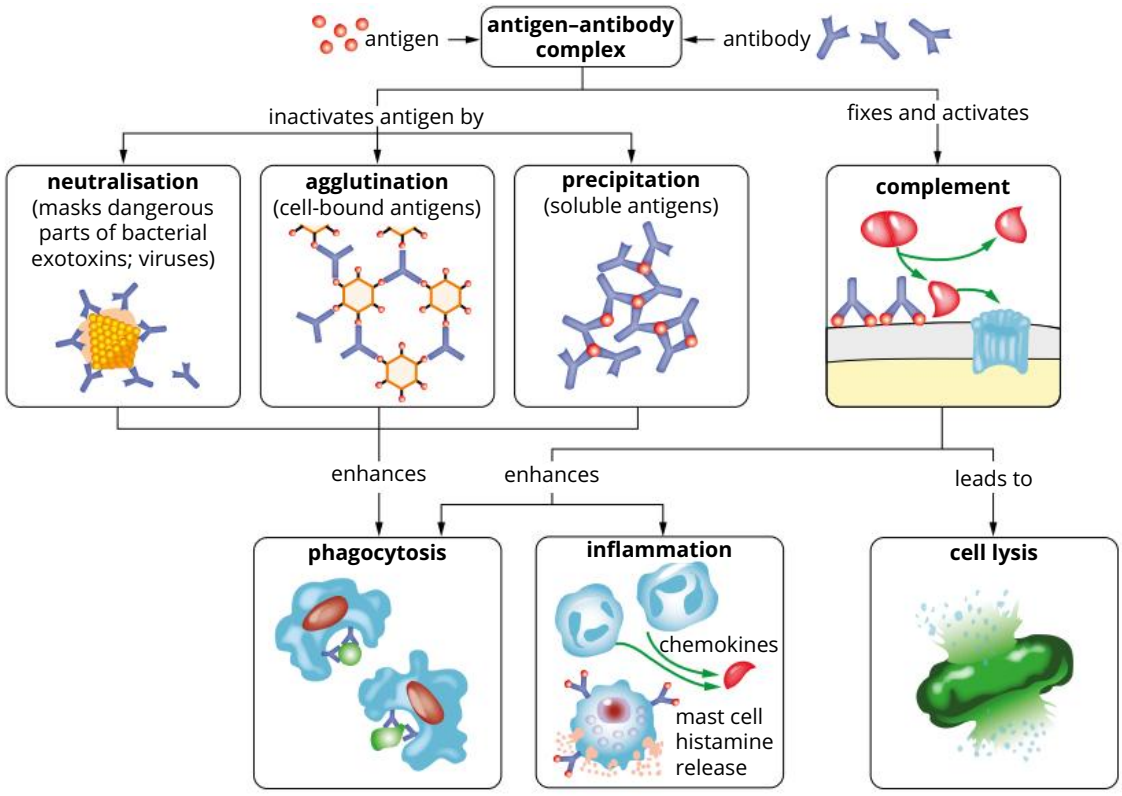


FIGURE 8.2.4 Antibodies function in a number of different ways to help eliminate pathogens.

MECHANISMS OF ADAPTIVE IMMUNE RESPONSES

A large part of the specificity of the immune response is achieved by having cells with specific receptors. Each lymphocyte has a different receptor. Receptor production is controlled by the MHC genes. Because these genes are constantly rearranged, there are many different receptors, each on a different lymphocyte, and each one is specific to a particular antigen. The shape of a receptor matches a molecule found on the specific pathogen.

The cells of the adaptive immune response are lymphocytes. Lymphocytes are white blood cells, which are formed in the bone marrow of long bones. These lymphocytes include B lymphocytes and a variety of T lymphocytes.

There are two mechanisms of adaptive immunity:

- **humoral immunity**, in which macromolecules, such as complement proteins, and antibodies produced by B lymphocytes, are secreted into the extracellular fluid
- **cell-mediated immunity**, which involves the action of T lymphocytes and phagocytes.

The processes of the adaptive response are mediated by cytokines, the signalling molecules of the immune system. One important group of cytokines involved is the **interleukins**.

Cells of the adaptive immune response

B lymphocytes originate and begin differentiating in the bone marrow and complete their maturation in the peripheral lymphoid organs and tissues, especially lymph nodes. Figure 8.2.5 illustrates the structures of the lymphatic system. At any one time, there are billions of B lymphocytes circulating in the blood.

There are a variety of T lymphocytes and each has a specific role to play in the immune response.

- Helper T lymphocytes (T_H) do not directly kill pathogens, but they assist the immune response by secreting cytokines that promote inflammation and activate macrophages and B lymphocytes.
- Cytotoxic T lymphocytes (T_C) recognise and kill foreign, infected or abnormal host cells by releasing toxic compounds (Figure 8.2.6).
- **Memory T lymphocytes** differentiate into memory T lymphocytes that are antigen-specific. The memory T lymphocytes persist after the infection is resolved, to ensure a prompt response should the same pathogen re-infect the organism.
- **Regulatory T lymphocytes** (also known as suppressor T cells or TREGS) suppress the immune response after the infection has been defeated.

Initial adaptive immune response

Adaptive immunity relies on antigen recognition. APCs engulf, process and display antigens to B and T lymphocytes, which are part of the adaptive response. The APCs display the antigens attached to MHC-I proteins.

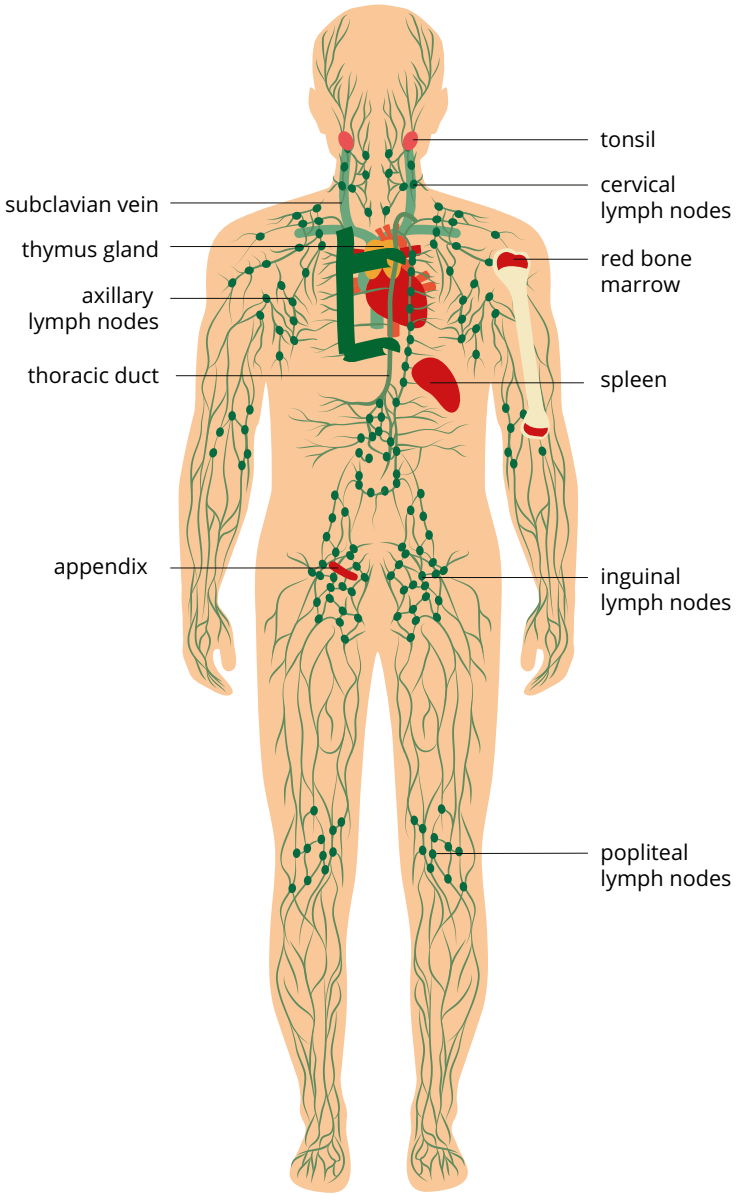


FIGURE 8.2.5 The main structures of the lymphatic system

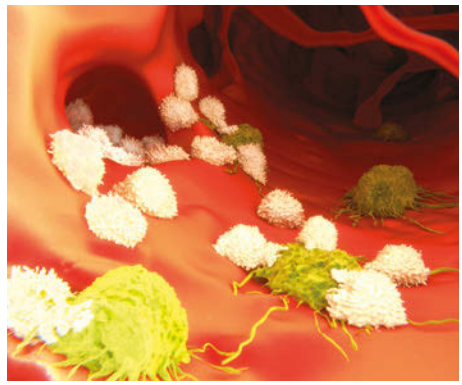


FIGURE 8.2.6 A digital illustration of cytotoxic (white) T lymphocytes attacking migrating cancer cells (yellow)

When a T_H lymphocyte meets an antigen-presenting cell with an antigen that matches its receptor, that T_H cell becomes activated. This is shown in Figure 8.2.7.

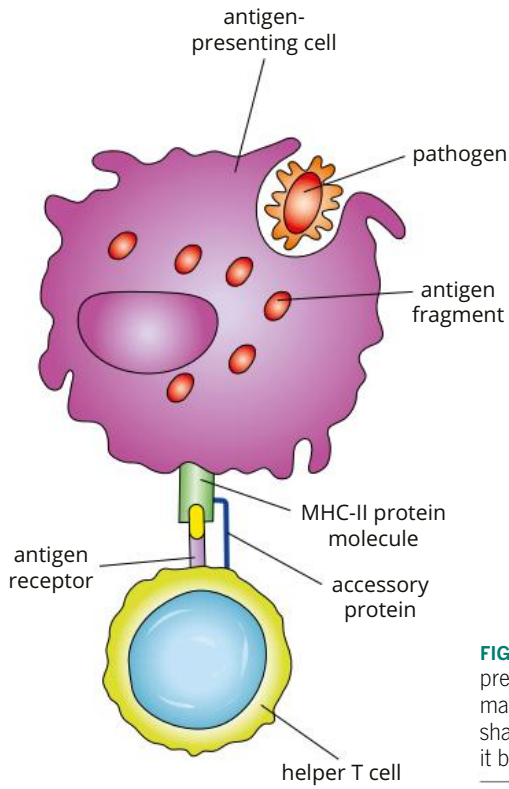


FIGURE 8.2.7 An antigen-presenting cell presenting to a T_H attached to its MHC-II marker. The T_H cell has a receptor with a shape complementary to the antigen and it becomes activated.

Once the T_H cell is activated, it either activates a B lymphocyte, starting the humoral pathway, or activates a T_C lymphocyte and the cell-mediated pathway.

Humoral immunity targets antigens in the tissue fluids or attached to cells, and involves B plasma cells, whereas cell-mediated immunity focuses on infected or defective cells and involves T_C cells. Most lymphocytes are similar in appearance, but have different functions, as shown Figure 8.2.8.

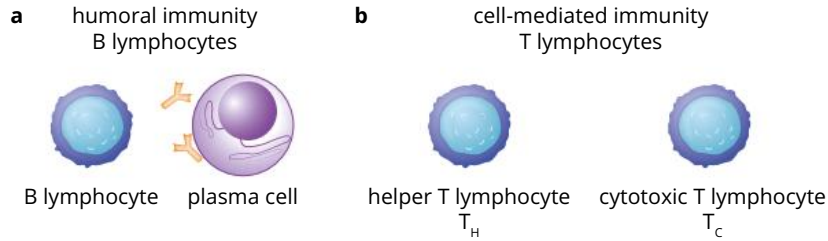


FIGURE 8.2.8 (a) B lymphocytes are involved in humoral or antibody-mediated immunity. They originate in bone marrow and mature in the peripheral lymphoid organs and tissues. (b) T lymphocytes are involved in cell-mediated immunity. They originate in bone marrow and mature in the thymus. Except for plasma cells, the different types of lymphocytes look very similar under a microscope. The only way to identify them is by their different surface proteins.

Humoral immunity

Humoral immunity involves proteins present in body fluids such as blood, tissue fluid and lymph. It is mediated by B lymphocytes.

Both T lymphocytes and the antibodies produced by B lymphocytes can recognise the presence of non-self antigens. The receptors on B lymphocytes are membrane-bound antibodies that recognise free antigens or antigens that are on the surface of a pathogen. Antibodies can also be secreted by the B lymphocytes. Figure 8.2.9 illustrates the different types of antigen receptors.

The term 'humoral' derives from medieval times, when body fluids were called humours.

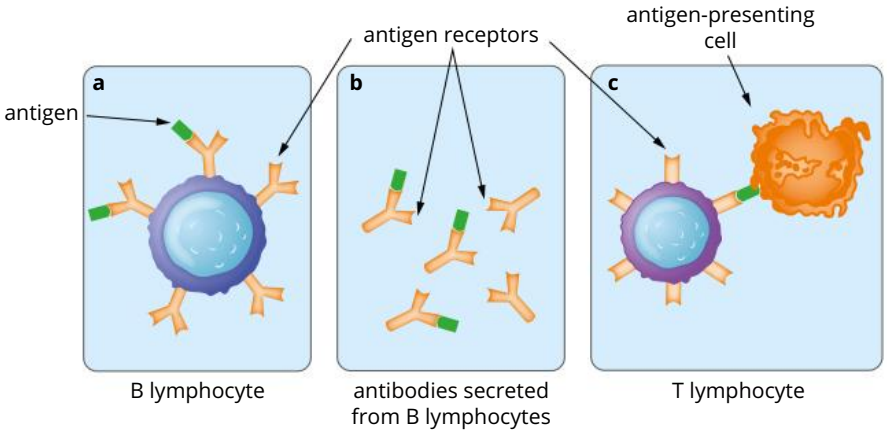


FIGURE 8.2.9 Antigen receptors on immune cells. Antibodies are antigen receptors that may be (a) bound to the plasma membrane of B lymphocytes or (b) secreted from B lymphocytes. (c) T lymphocytes have their own type of receptors that recognise antigens presented by specialised antigen-presenting cells.

When a B lymphocyte meets and binds to a specific antigen, it becomes 'primed'. Then when the B lymphocyte meets a T_H cell, which has the appropriate receptor, and has been activated by being presented with the same antigen by an APC, the B lymphocyte starts to proliferate. Cytokines released by the helper T lymphocytes regulate this process.

The identification and activation of the particular lymphocyte with the specific receptor for the particular antigen is called **clonal selection**. Once a lymphocyte has been selected, it proliferates, creating clones of the initial lymphocyte with the specific receptor for the antigen. This process is called **clonal expansion**.

Following activation, B lymphocytes proliferate rapidly to form many new clones. These clones differentiate to form either plasma cells or memory B lymphocytes. Plasma cells are essentially 'factories' specialising in antibody production, as shown in Figure 8.2.10. The antibodies produced are specific to the antigen that activated the B lymphocyte. A plasma cell can produce 2000–10 000 antibody molecules per second.

A lymphocyte that is mature but which has not yet come in contact with the antigen specific to its receptor is described as 'naive'.

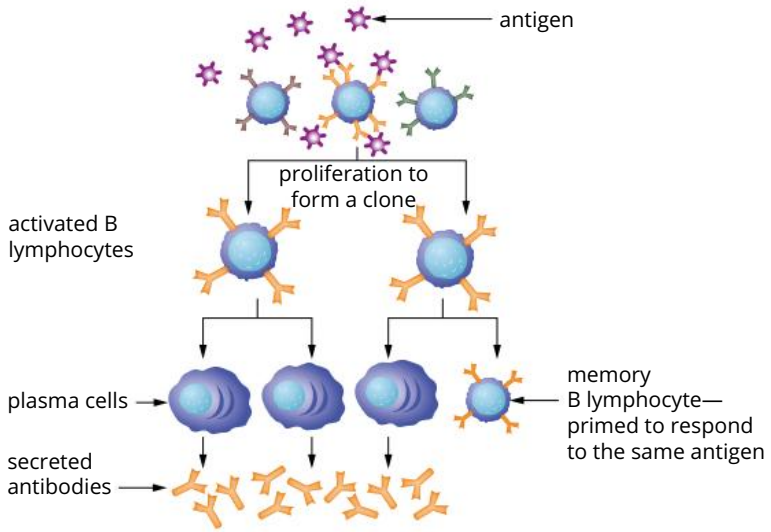


FIGURE 8.2.10 Many B lymphocytes differentiate into plasma cells, which produce and secrete antibodies for immune protection. Others become memory B lymphocytes and are retained in lymph nodes. Helper T lymphocytes are often involved in activating B lymphocytes to produce antibodies.

Memory B lymphocytes are one source of immunological memory. They remain in lymphoid tissues for long periods (even for the lifetime of the animal) and are responsible for the immunity that often follows infection or vaccination. These cells can divide rapidly and give rise to new plasma cells if secondary exposure to the antigen occurs.

The millions of antibodies produced by plasma cells bind to the antigens attached to the pathogen or molecules released by the pathogen and thereby inactivate them (Figure 8.2.11).

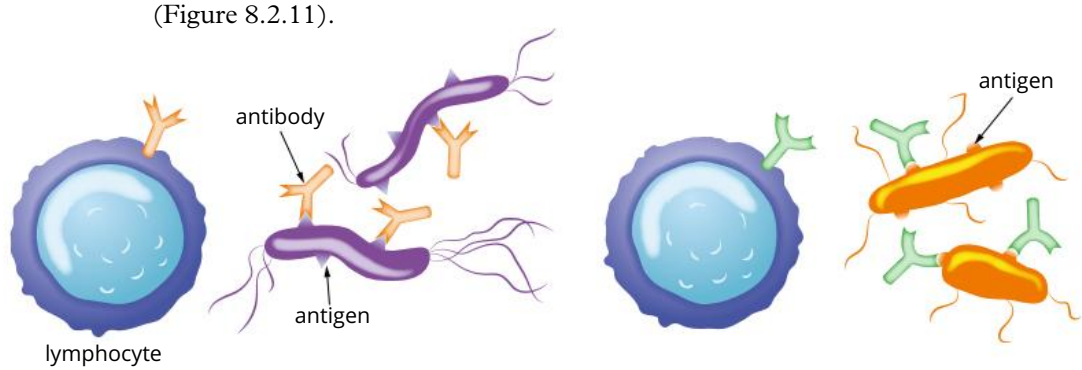


FIGURE 8.2.11 Antibodies specific to a foreign antigen bind to it, helping to eliminate the invading pathogen.

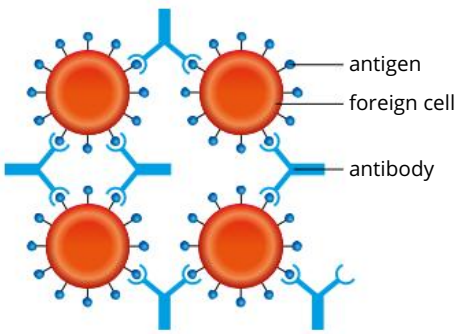


FIGURE 8.2.12 Antibodies have two attachment sites that can attach to two different pathogens, using the same antigen, and link them together (agglutinate), immobilising them and making it easier for phagocytes to engulf the pathogens.

Antibodies can also form cross-links between pathogens, such as bacteria, clumping them together and making it easier for phagocytes to engulf them. This is shown in Figure 8.2.12.

Clonal selection theory

An almost infinite number of different antigens exist, and the immune system can produce lymphocytes specific to each antigen upon exposure. The clonal selection theory explains how lymphocytes are able to produce a large number of antibodies specific to an antigen.

When B and T lymphocytes form, each has a receptor that reacts to a single antigen. The clonal selection theory states that a specific antigen only activates a lymphocyte with a receptor that specifically recognises that antigen. Recognition occurs when a part of the antigen, called the **epitope**, attaches to the receptor. This attachment occurs because the receptor and epitope are complementary in shape. Once activated, the lymphocyte proliferates into a clone of millions of effector cells dedicated to eliminating the specific antigen that stimulated the immune response. These effector cells are called **plasma cells**. Figure 8.2.13 illustrates this process.

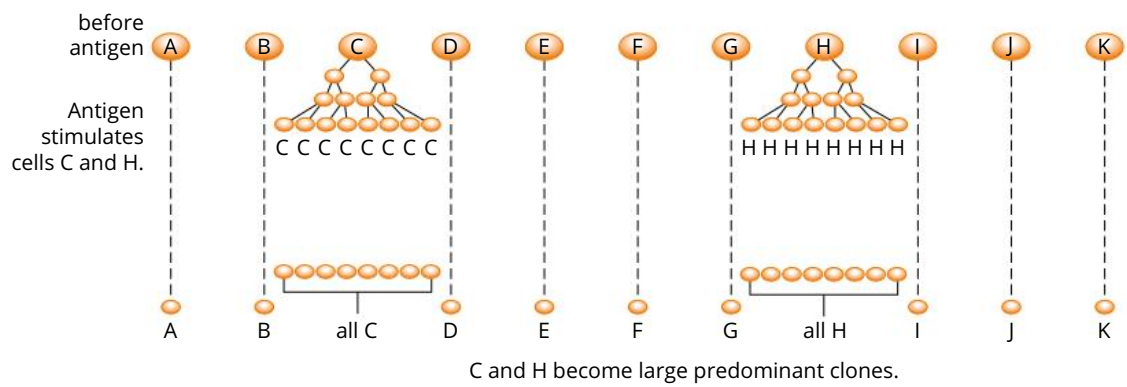


FIGURE 8.2.13 The clonal selection theory and expansion. Lymphocytes that encounter or interact with an antigen, such as lymphocytes C and H, begin to proliferate. This increases the number of lymphocytes with identical receptors, or clones, for the specific antigen that was first encountered.

Cell-mediated immunity

Unlike humoral immunity, which involves B lymphocytes, cell-mediated immunity is regulated by T lymphocytes. Depending on their function, T lymphocytes are classified as helper, cytotoxic, memory or regulatory T lymphocytes.

The response is mediated by the **T cell receptors** (TCRs). TCRs are central to the function of T lymphocytes in the adaptive immune response (remember that T lymphocytes are also known as T cells). TCRs are made up of two polypeptide chains. Like antibodies, TCRs have a variable and constant region, as shown in Figure 8.2.14. Unlike antibodies, which have two antigen-binding sites, TCRs have only one antigen-binding site.

TCRs do not bind to antigens on pathogens, as B lymphocyte receptors do; instead, they bind to fragments of antigens that are displayed or presented on the surface of APCs. Receptor binding triggers signal transduction in the T lymphocyte, resulting in proliferation, cytokine release and activation of cytotoxic function.

T lymphocytes check the antigens of cells they come into contact with in the body, differentiating between cells that belong to the organism (self) and cells that are foreign (non-self). Remember that during their development, lymphocytes that react to self-antigens are normally destroyed. This inability of lymphocytes to respond to self-antigens is known as self-tolerance.

All nucleated cells have surface proteins that present peptide antigens of the proteins being synthesised in that cell. These antigens are presented to cytotoxic T lymphocytes by MHC-I molecules. APCs are specialised for presenting antigens. When an APC engulfs a pathogen, the antigens of the pathogen are broken into small peptides in the cell. These antigen fragments bind to MHC-II molecules inside the cell. The antigen–MHC-II complexes then move to the cell surface to present the antigens to helper T lymphocytes. The TCRs on the helper T lymphocytes recognise the antigen–MHC-II complex. The bone marrow produces millions of different immature T lymphocytes and each has a TCR that is a unique shape that is complementary to only one antigen. Joining the TCR with its unique antigen attached to the MHC marker on the APC initiates signal transduction within the immature T lymphocyte, which then proliferates. The newly formed T lymphocytes differentiate to become helper T, cytotoxic T, memory T or regulatory T lymphocytes, all of which possess the unique receptor that is complementary to the antigen presented by the APC.

The newly formed helper T lymphocytes then activate the cytotoxic T lymphocytes. The whole process is regulated by cytokines. This process is shown in Figure 8.2.15.

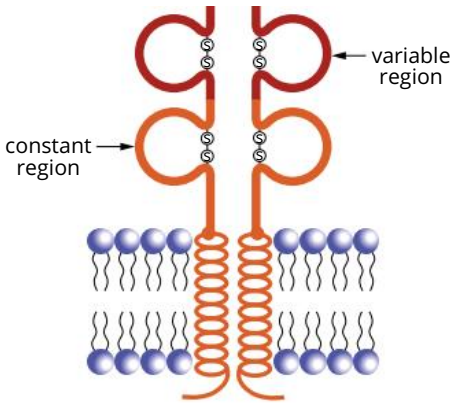


FIGURE 8.2.14 The structure of the T cell receptor (TCR), which is found on helper T and cytotoxic T lymphocytes and binds to fragments of antigen

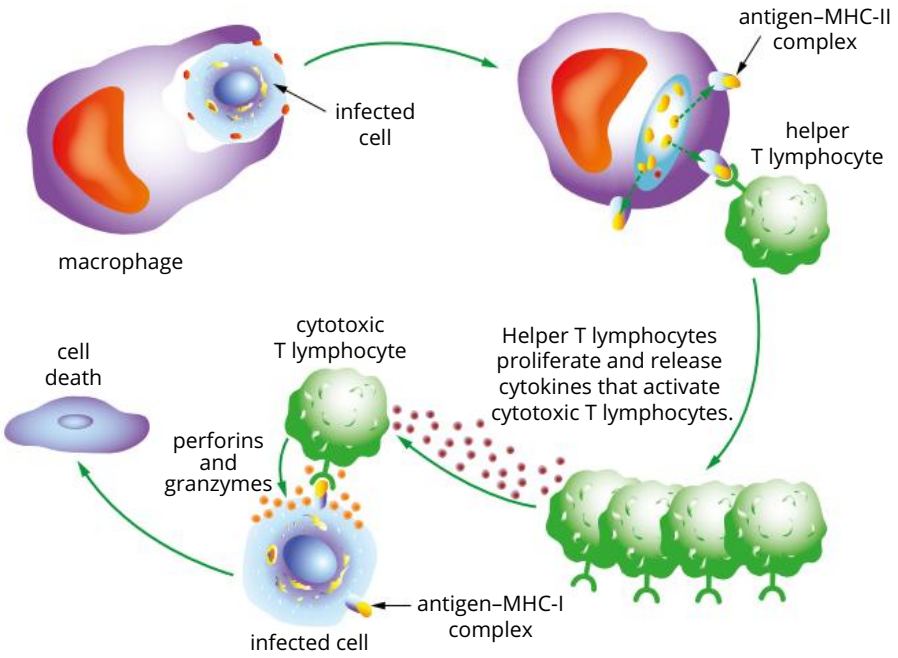


FIGURE 8.2.15 T lymphocytes are activated in cell-mediated immunity. Infected cells are detected and destroyed by cytotoxic T lymphocytes.

The processes of the adaptive immune response are illustrated together in Figure 8.2.16.

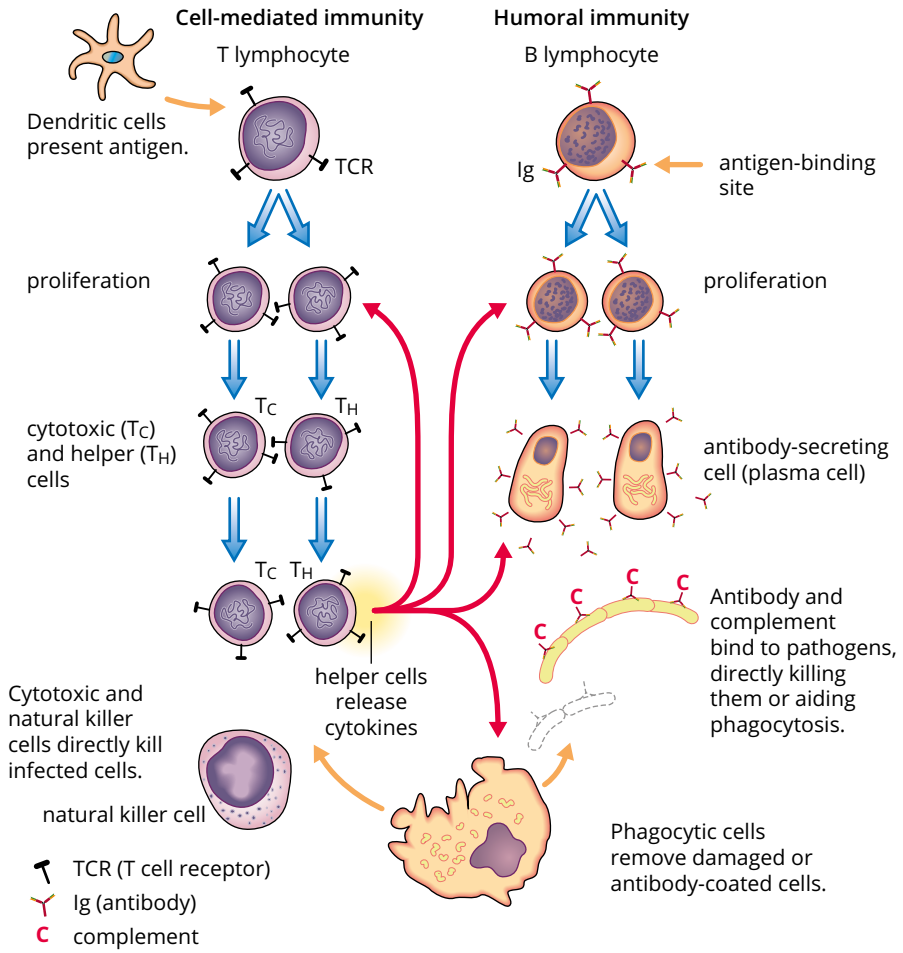


FIGURE 8.2.16 A summary of cell-mediated immunity and humoral responses

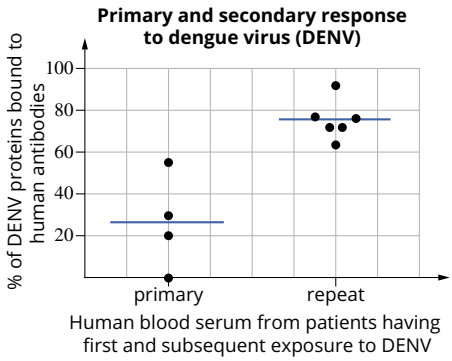


FIGURE 8.2.17 Antibody levels after infection by dengue fever virus (DENV) on initial exposure and subsequent exposure. The secondary response to dengue virus antigens is stronger than the primary response, as shown by the greater binding between human antibodies and the dengue virus antigens.

Immunological memory

The response arising from the first encounter of a T or B lymphocyte with a specific antigen is known as the **primary immune response** (Figure 8.2.17). After the initial exposure, B and T lymphocytes form B and T memory lymphocytes. IgM antibodies are the predominant antibodies produced in a primary response.

Once formed, lymphocytes constantly circulate between lymphoid tissues, especially lymph nodes, and the bloodstream. Each lymphocyte moves from the lymphoid tissue into the blood and back again about 50 times per day. This maximises the chance of a particular lymphocyte meeting and recognising its complementary antigen if that antigen enters the body.

The response arising from subsequent encounters with the same antigen is known as the **secondary immune response**. Lymphocyte proliferation and production of antibodies occurs much more quickly during the secondary immune response because the existing memory lymphocytes, which were produced during the first encounter and which remain for months or years, allow faster proliferation of the required lymphocytes (those with the receptor specific to the antigen). IgG antibodies are the predominant antibodies produced in the secondary response.

A secondary antibody response is stronger than the primary response. This has been shown by many experiments. Figure 8.2.17 shows the results of patients' antibody levels after infection by dengue virus. Some patients were experiencing the virus for the first time while others were having secondary exposure. Blood samples were taken from the patients and their blood serum was incubated with dengue virus particles and the percentage of cross-linking between the antibodies and the virus particles was determined. Figure 8.2.18 summarises the primary and secondary immune responses. You will learn more about the immune response in Module 8.3.

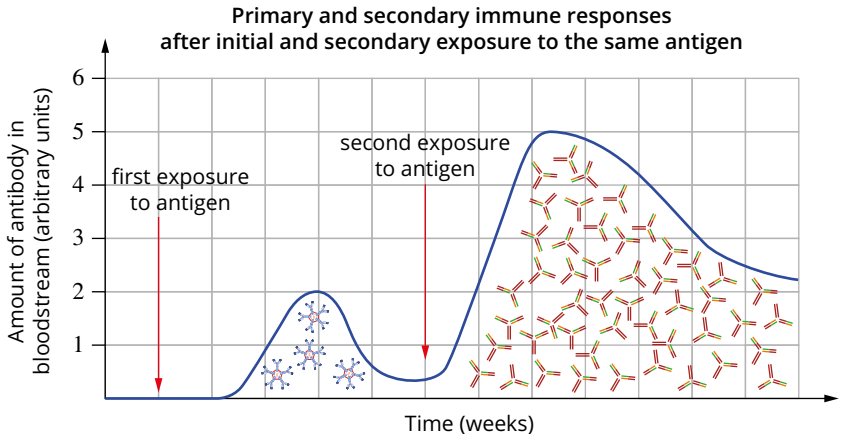


FIGURE 8.2.18 Primary and secondary immune responses after initial and secondary exposure to the same antigen

WS 2.2.4 WS 2.2.5

8.2 Review

SUMMARY

- Vertebrate immune responses are specific and involve memory cells.
- Specific defence is provided by an adaptive immune system.
- Specific immune responses involve lymphocytes, called B and T lymphocytes, which are made in the bone marrow.
- Adaptive immunity is divided into the humoral and cell-mediated responses.
- The adaptive response is initiated when phagocytes present antigens to helper T cells.
- The humoral response is enacted by B lymphocytes, which undergo clonal expansion and produce specific antibodies after being activated by T_H cells.
- Antibodies are proteins that cause neutralisation, agglutination and precipitations of pathogens and their toxins.
- The cell-mediated response is enacted by T lymphocytes against cancer cells, transplanted cells and cells infected by viruses.
- Once activated both B lymphocytes and T lymphocytes produce memory cells during clonal expansion during the initial infection.
- Memory cells remain in the body for long periods of time and provide a faster, stronger immune response to subsequent infections involving the same antigen/pathogen.

continued over page

8.2 Review *continued*

KEY QUESTIONS

Retrieval

1 List five functions of antibodies.

2 Draw an antibody. Label the heavy and light chains, the variable region, the disulfide bridges and the antigen-binding sites.

3 Draw a table of the different types of T lymphocyte and their function.

Comprehension

4 Contrast a naive B lymphocyte with a B plasma cell.

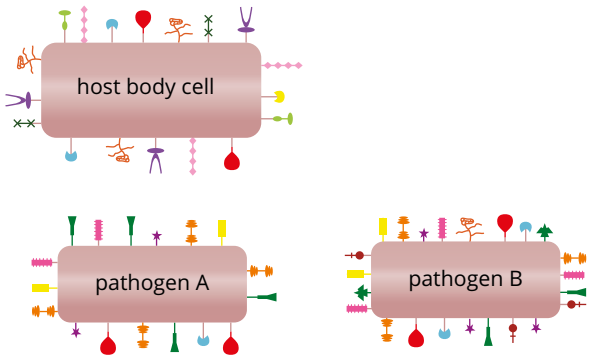
5 Explain why the secondary immune response is faster and greater than the primary immune response.

6 Draw a schematic outlining the sequence and mechanisms of humoral immunity.

7 Draw a schematic outlining the sequence and mechanisms of cell-mediated immunity.

Analysis

8 An organism that has cells with self-antigens as shown below is invaded by two different but related pathogens.

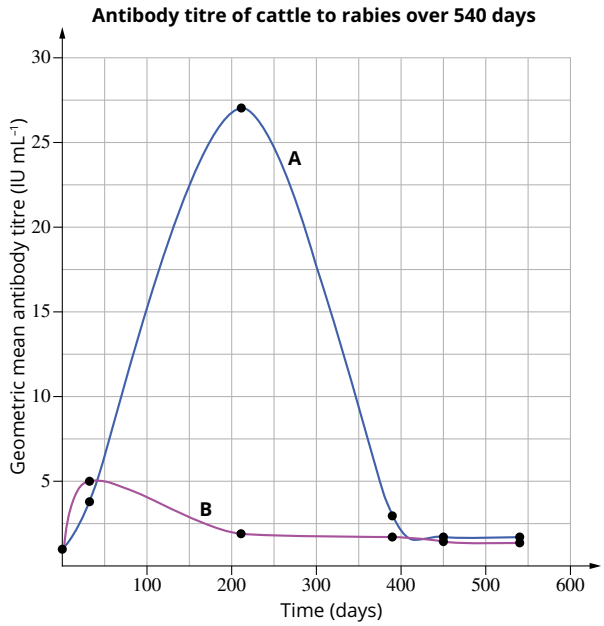


a State the number of different antigens present on the membrane of pathogen A compared to the host cell.

b Explain how many antibodies to pathogen B the host organism could make.

c Identify which pathogen, A or B, results in the higher number of antibodies being produced by the host. Justify your answer.

9 An experiment was performed to determine the effectiveness of a vaccine against rabies in stimulating the production of antibodies in cattle. Two groups, A and B, of cattle were assessed. Both groups were first exposed to the virus on day 0, then only one of the groups was exposed again on day 120. Antibody titres were measured on days 0, 30, 210, 390, 450 and 540. The results are shown in the following graph.



a Deduce which result, A or B, represents the group that was exposed only once. Explain your response.

b i Explain why interpolation of the antibody titres for group A between days 30 and 210 would be unreliable.

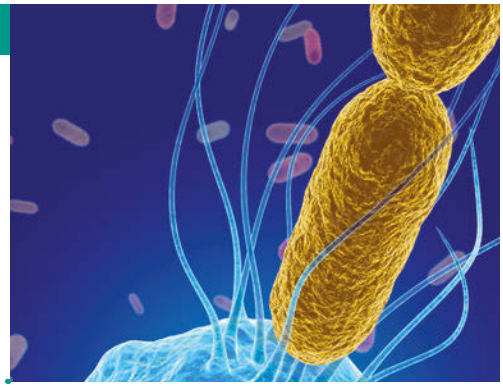
ii Predict what a scientist who measured the antibody titre of group A would measure if they sampled at day 100.

c Along with increased production of antibodies, T lymphocyte concentration would be expected to rise significantly, especially in the group having two exposures to the pathogen. Explain.

8.3 Immunity

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

- understand that passive immunity occurs when individuals acquire antibodies from another organism
- understand that active immunity is obtained when an individual makes memory lymphocytes and their own antibodies
- understand that vaccination has significantly decreased the world burden of disease
- recognise that immunisation rates need to be high in order to provide the community with herd immunity.



In Modules 8.1 and 8.2, you learnt about the physical, chemical and microbiological barriers that help prevent infection, as well as the innate and adaptive immune responses that provide immunity against invading pathogens that bypass these first line defences. In this module, you will learn that immunity can be active or passive, natural or artificial. You will also learn that vaccination (Figure 8.3.1) is an example of artificial active immunity, and about the role of vaccination programs in creating herd immunity and preventing disease.

Immunity is active or passive depending on the origin of the immune response. **Active immunity** results from an organism encountering antigens and then making their own B and T memory lymphocytes. These lymphocytes can last for a long time, even an entire lifetime. **Passive immunity** is generated when antibodies pass from one organism, which made them, to another organism by natural or artificial means.

FIGURE 8.3.1 A baby being vaccinated. The vaccine stimulates an adaptive immune response that protects against infection.

PASSIVE IMMUNITY

Passive immunity is acquired when antibodies made in one organism are transferred to a different individual. Passive immunity generally lasts for less time than active immunity. This is because the transferred antibodies last for a limited time in the organism receiving them. Passive immunity occurs naturally when antibodies pass from mother to fetus through the placenta before birth or through breast milk once the baby is born. **Artificial passive immunity** can be created when antibodies that were made by another person, or an animal such as a horse or rabbit, are injected into an individual.

Natural passive immunity

Natural passive immunity involves the passive transfer of antibodies from mother to fetus, or from mother to breast-feeding baby. These maternal antibodies provide protection to the baby for weeks or months, while the baby's own immune system is developing. The newborn baby relies heavily on these antibodies during the first months of life because its immune system is not fully developed.

IgG is the only class of antibody that crosses the placenta in significant amounts. The level of IgG crossing is determined by a number of factors, including the IgG concentration in the mother's blood, the gestational age of the fetus, the integrity of the placenta, and the nature of the antigen that caused the generation of the antibody. Figure 8.3.2 shows a typical profile of IgG in a healthy fetus with a healthy mother.

The concentration of placenta-derived maternal IgG antibodies lowers over the first 9 months of the baby's life. However, antibodies continue to be passed to the infant through breast milk. As can be seen in Table 8.3.1 on page 372, IgG antibody levels are nearly as high in breast milk as in the mother's blood but IgA and IgM levels are only about half.

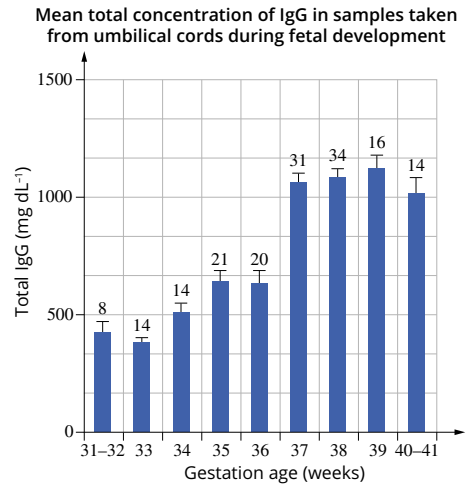


FIGURE 8.3.2 Antibodies are passed from mother to fetus. The numbers above the bars indicate the numbers of samples taken.

TABLE 8.3.1 Relative antibody levels, determined by enzyme-linked immunosorbent assay (ELISA)

Antibody class	Mean relative maternal concentration in breast milk (±SD)	Mean relative maternal blood serum concentration (±SD)	*P* value
IgG	0.045 ± 0.031	0.052 ± 0.017	0.852
IgA	0.039 ± 0.0075	0.0613 ± 0.0205	0.167
IgM	0.036 ± 0.010	0.052 ± 0.014	0.085

ELISA

ELISA (enzyme-linked immunosorbent assay) is a process that can be used to determine the concentrations of proteins such as enzymes, hormones and antibodies. When an ELISA is performed, the antigen for the antibody is adhered to a clear polystyrene plate, as shown in Figure 8.3.3.

FIGURE 8.3.3 An ELISA plate being used to test for HIV antibodies. Many wells appear clear, indicating a negative result. Six plates indicate positive results. A darker colour indicates a higher antibody concentration.

Once the antigen is fixed, the material containing the antibody to be assayed (measured) is added. The antibody binds to the antigen, such as an MHC marker (controlled by the HLA genes). A second antibody is then added, which is designed to adhere to the heavy chain of a human antibody. Finally, an enzyme, fluorescent marker or radioactive marker that also binds to the designed enzyme is added. The plates are washed between each step to remove any unbound material. The plates can be read by a **spectrophotometer**, a specialised measuring instrument. In many cases, the enzyme causes precipitates to form in the well or the colour to deepen, increasing the light absorbency in the well. The light absorbency or optical density (OD) can be determined and it gives a measure of the concentration of the assayed antibody. A deeper colour indicates a higher antibody concentration. There are a number of slight variations of this process depending on the exact material to be assayed. Figure 8.3.4 illustrates one of the most common variants.

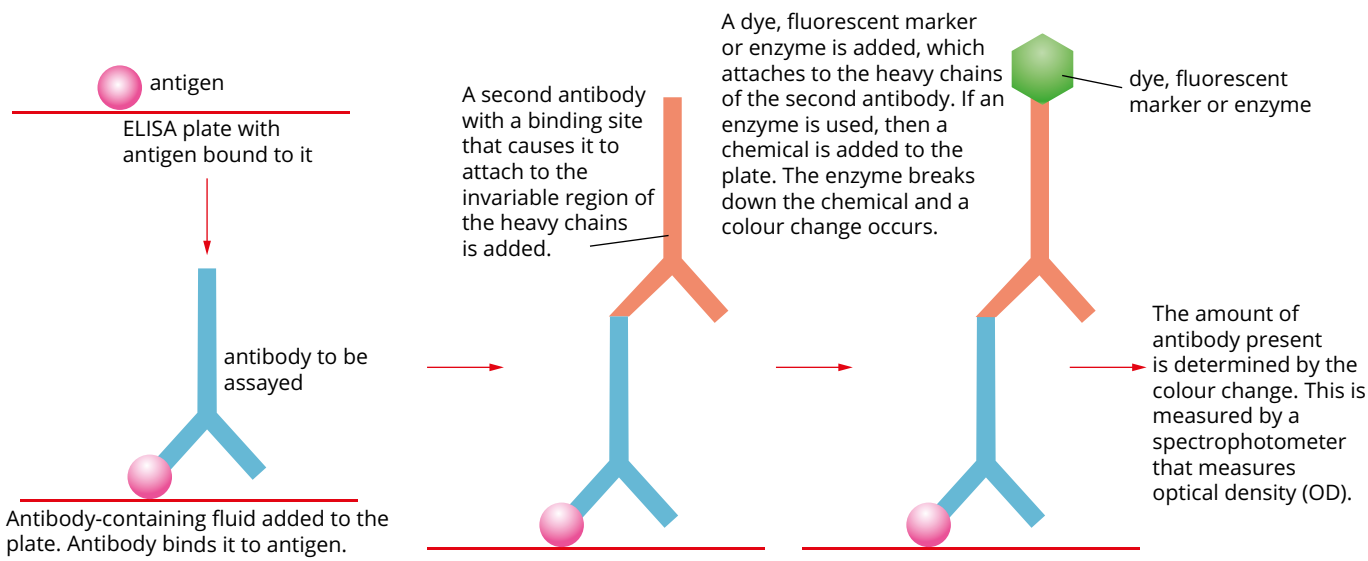


FIGURE 8.3.4 When ELISA is used to measure the concentration of antibodies in a solution or serum, the antibody to be measured is sandwiched between the antigen specific to the antibody and another antibody designed for the purpose.

An ELISA plate can identify whether an antibody is present or not, as in the HIV test shown in Figure 8.3.3. It can also show the relative amounts of antibody present between two groups. Figure 8.3.9 shows the results of an experiment in which the antibody production of a control group was compared to an experimental group. If the specific concentration of the antibody present is required, then before completing the experiment a standard curve is prepared by doing the test using known concentrations of the antibody and plotting the results on a graph. The experimental results can then be compared to the standard curve to quantify the amount of antibody present.

When an antigen is to be assayed, the process is basically the same, but an antibody that is specific to the antigen is bound to the plate, then the antigen is added. Finally, a second antibody that has the marker attached that also binds to the antigen is added and the results are read in the same way as for antibody assays.

Haemolytic disease of the newborn

Passive immunity as a result of antibodies crossing the placenta is usually an advantage to the fetus, but sometimes those antibodies can damage the fetus. **Haemolytic disease of the newborn** is caused by maternal antibodies attacking the blood of the fetus.

You will recall from Module 8.1 that blood cells have A and B antigens on their surface, which results in the blood groups A, B, AB and O. More than 100 different antigens have been identified on the surface of blood cells; another one is the Rh, or rhesus, protein, which was first seen in rhesus monkeys. People either have the rhesus antigen (Rh^+) or do not have the protein (Rh^-).

Haemolytic disease of the newborn occurs when a mother's immune system makes antibodies that cross the placenta and attack the red blood cells of her fetus. This occurs when the mother has rhesus blood type Rh^-. She lacks the rhesus antigen (or D antigen) on her red blood cells (Figure 8.3.5). When an Rh^- mother has an Rh^+ baby, the mother is likely to develop an adaptive immune response to the Rh antigen, as fragments of fetal red blood cells cross the placenta during birth (Figure 8.3.6a).

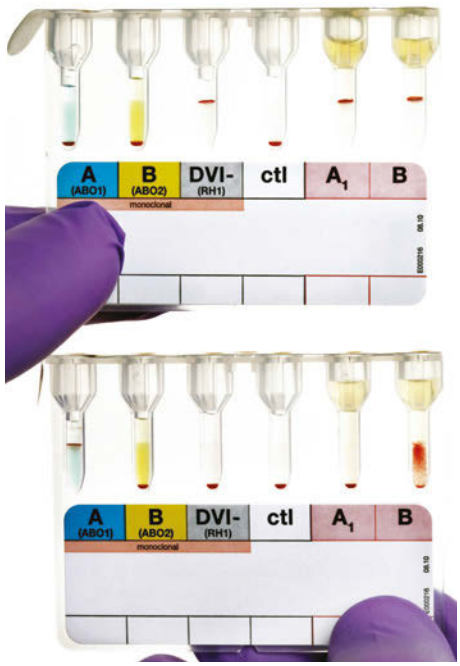


FIGURE 8.3.5 Laboratory tests showing an Rh^+ result (top), in which there is D antigen present on red blood cells (third vial from the left), and an Rh^- result (bottom), in which there is a lack of D antigen.

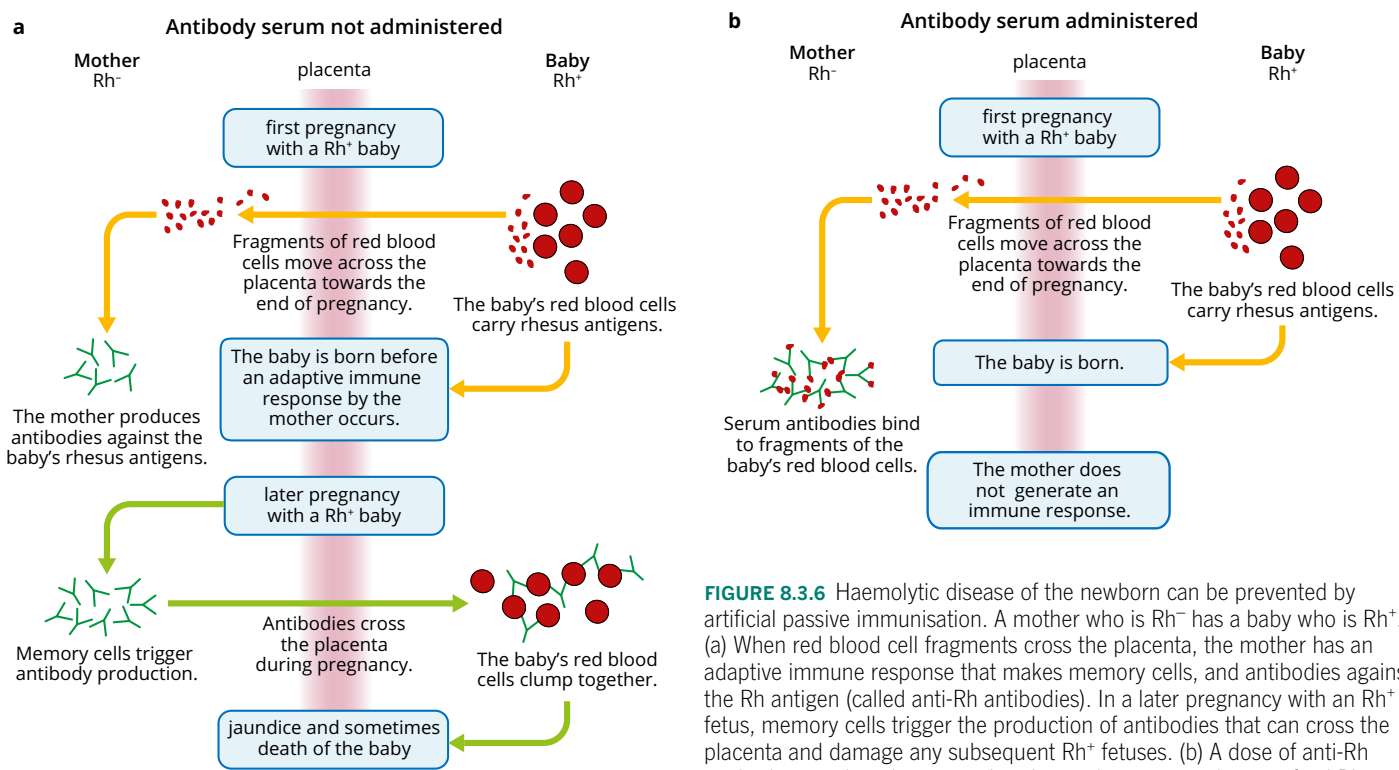


FIGURE 8.3.6 Haemolytic disease of the newborn can be prevented by artificial passive immunisation. A mother who is Rh^- has a baby who is Rh^+. (a) When red blood cell fragments cross the placenta, the mother has an adaptive immune response that makes memory cells, and antibodies against the Rh antigen (called anti-Rh antibodies). In a later pregnancy with an Rh^+ fetus, memory cells trigger the production of antibodies that can cross the placenta and damage any subsequent Rh^+ fetuses. (b) A dose of anti-Rh antibodies can be administered to the mother to neutralise any fetal Rh antigens before an immune response occurs, protecting any future Rh^+ fetus.

If the same Rh^- woman has another pregnancy with an Rh^+ baby, her memory cells triggers the production of antibodies that cross the placenta and damage the baby's blood cells, causing them to develop haemolytic disease of the newborn (from *haemo*, meaning 'blood', and *lysis*, meaning 'breakdown'). In each subsequent pregnancy with an Rh^+ baby, more memory cells and antibodies are made and the situation worsens.

To prevent the mother having an adaptive immune response and producing anti-Rh antibodies during her first pregnancy, she is given a dose of anti-Rh antibodies (Figure 8.3.6b on page 373). These administered antibodies neutralise any fetal Rh antigens before an adaptive immune response by the mother occurs. The benefits of giving the mother IgG antibodies within 72 hours of the birth have been demonstrated in a number of studies. Table 8.3.2 shows the results of an early study in Canada that proved the benefits of giving IgG antibodies to women who were Rh incompatible with their babies after they gave birth.

TABLE 8.3.2 Haemolytic disease of the newborn prevention trial (March 1967 – January 1968)

	Given Rh IgG after birth	Not given Rh IgG after birth
Rh^- mothers in trial	1216	500
No. mothers with maternally created antibodies 6–9 months after birth	0	36 (7.2%)

Finally, many factors influence whether haemolytic disease of the newborn occurs, including the ABO blood type of the mother and fetus. Some of these factors are not fully understood and are the subject of ongoing research.

Artificial passive immunity

Artificial passive immunity is the process of giving an organism antibodies that have been made by another organism. The process of giving IgG antibodies to mothers of Rh-incompatible babies is one example of artificial passive immunity.

To provide artificial passive immunity, the antibodies are usually given by injection of **antiserum**. Antiserum is serum that contains specific antibodies. **Serum** is the fluid portion of blood that remains after blood cells and material involved in blood clotting have been removed, as illustrated in Figure 8.3.7. Serum contains antibodies, as well as other substances. When the transferred antibodies from the antiserum bind to the antigens on the pathogen or toxin, they form an antigen–antibody complex. This complex inhibits the pathogen or toxin before it does much damage.

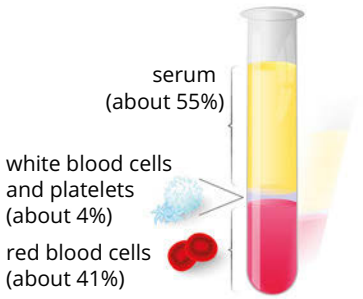


FIGURE 8.3.7 Serum is the fluid portion of blood that remains after blood cells and clotting factors (platelets) have been removed. Antiserum is serum containing specific antibodies injected to treat or protect against disease.

Artificial passive immunisation can be a useful way of treating an infection by a pathogen, or a bite or sting by a venomous animal, when death is likely to occur before the primary immune response has had time to develop. For example, a tetanus antiserum protects against tetanus in at-risk patients, such as those with a deep or dirty puncture wound. The antiserum contains antibodies specific for the toxin, called antitoxins, which bind to the tetanus toxin, inhibiting its function. However, introducing antibodies to contain the threat before the person's adaptive immune response can be mobilised means the protection provided is only temporary, as no immunological memory is formed. In order to achieve long-term immunity, active immunity is required.

ACTIVE IMMUNITY

Active immunity comes from having memory B and T lymphocytes and the ability to make one's own antibodies in response to antigens. Immunological memory is highly specific to the antigens present on a particular pathogen or molecule. Active immunity develops in healthy individuals when foreign antigens are processed by phagocytes and the adaptive response is initiated.

Active immunity can be acquired naturally when someone is infected by a pathogen, becomes ill and then recovers. Active immunity can be also be achieved artificially through vaccination. Once active immunity is achieved, it is maintained for a long time, even for the person's lifetime.

Natural active immunity

For most diseases, active immunity is achieved through natural exposure to the disease, illness and recovery, and thus is **natural active immunity**. The large number of pathogen antigens generated during the illness usually results in a strong immune response. For most pathogens, one bout of illness is enough to provide long-term immunity.

Once active immunity is achieved, subsequent exposure to the same antigen results in a secondary response, which is both faster and greater than the initial immune response. Figure 8.3.8 shows the primary and secondary responses to challenge by an antigen. The secondary response is so much larger than the primary response that it needs to be measured on a logarithmic scale (not linear). Also note the time lag before the primary response shows antibody production. This does not occur with the secondary response, which is immediate. The main reason for this difference is the large number of memory cells that were formed during the first exposure to the antigen.

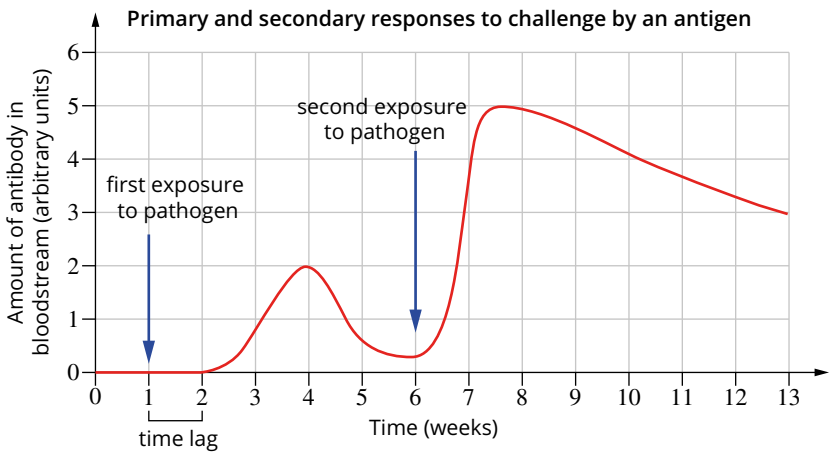


FIGURE 8.3.8 A subsequent infection with the same infectious agent will trigger a secondary immune response. The secondary immune response is faster and stronger than the primary immune response.

Many experiments have demonstrated that antibody levels increase with secondary exposure to pathogens. In one experiment, two groups of newborn mice were used to investigate the development of antibodies to *Leishmania* parasites.

Leishmania parasites are the cause of a serious disease called leishmaniasis. The parasite is spread by an insect vector. As a part of the investigation, mice in the experimental group were exposed to the infected vectors once a week for 5 weeks. Mice in the control group were not exposed to the pathogen. Throughout the experiment, blood samples were taken and tested for IgG antibodies to *Leishmania*, using ELISA. Both groups were exposed to the pathogen at week 27 and their antibody titres were determined one week later. It can be seen in Figure 8.3.9 on page 376 that the mice that had been previously exposed showed a gradual increase in IgG antibodies over the first few weeks and after the exposure at week 27 showed a steep increase in antibodies that was not seen in the control group. This supports the theory that a second exposure results in a faster and stronger response.

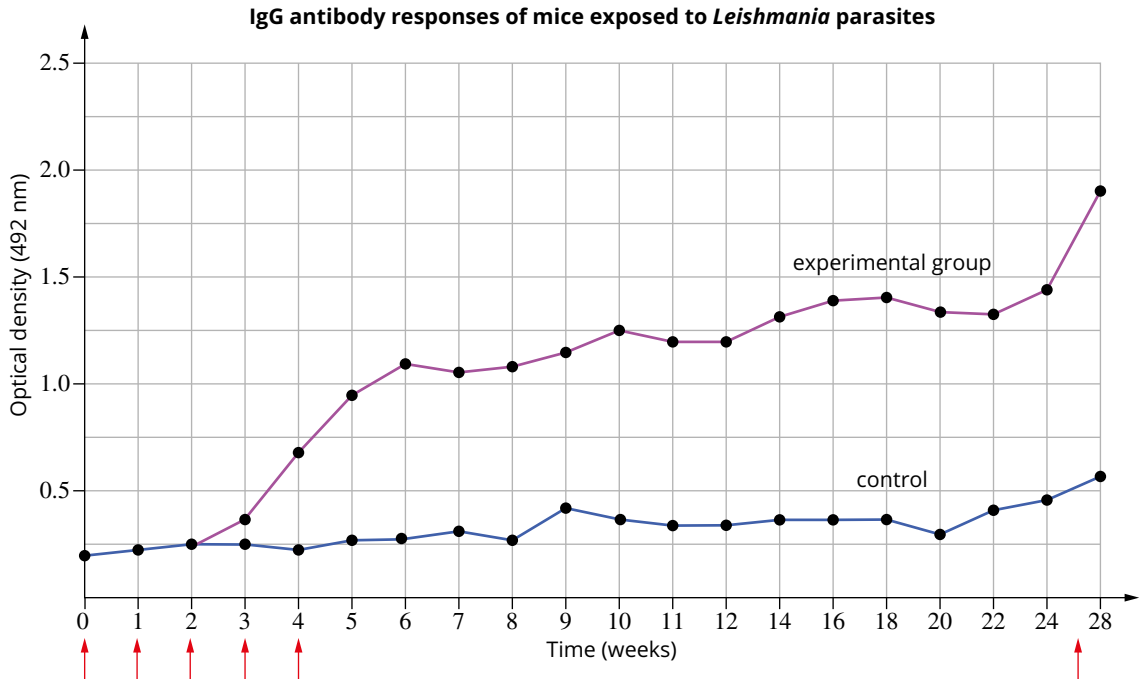


FIGURE 8.3.9 IgG antibody responses of mice exposed to *Leishmania* parasites (indicated by the arrows). Note that the graph for the experimentally bitten group (at 27 weeks) shows that a second exposure to an antigen produced a much quicker and stronger response than the initial exposure, which takes a long time to build up. Optical density is a measure of antibody concentration provided using ELISA. (Note: *x*-axis is not to scale.)

Artificial active immunity or vaccination

Active immunity is immune protection provided by an individual's own adaptive immune response. It can be primary (slow) or secondary (fast).

Artificial active immunity results from the administration of antigens to induce an adaptive immune response.

Preparations that artificially introduce the antigens of the pathogen to the immune system are called **vaccines**. The process of presenting a vaccine to the body is **vaccination** (also called **immunisation**). The antigens in the vaccine can be in the form of altered, weakened or killed pathogens, such as bacteria or viruses, or inactivated toxins or proteins produced by the pathogen.

Vaccines must be highly specific to initiate an adequate immune response that results in an immunological memory. Increased understanding of microbiology and immunology has led to the development of very safe vaccines that induce the desired immune response while producing minimal side effects.

There are different methods of producing vaccines.

Live attenuated vaccines

Live attenuated vaccines involve a living microbe that has been weakened in the laboratory, usually through repeated culturing. The advantage of live attenuated vaccines is that a single dose usually provides long-lasting immunity because the vaccines induce a strong adaptive immune response that produces many types of antibodies directed against multiple antigens.

The disadvantages of live attenuated vaccines are that although they are safe for most people, they may cause disease in people with weakened immune systems. Also, they may cross the placenta in pregnant women and damage the fetus.

Attenuated vaccines are more commonly used for viruses than for bacteria, because bacteria have thousands of genes and thus are much harder to control. Attenuated vaccines are used against measles, mumps, rubella and polio.

Inactivated vaccines

Inactivated vaccines, also known as **killed vaccines**, contain microbes that have been inactivated by heat, radiation or chemicals. The advantages of inactivated vaccines are that they result in the production of many different antibodies because they contain many different antigens. Inactivated vaccines can safely be used in people who have weakened immune systems.

The disadvantage of inactivated vaccines is that they stimulate a relatively weak immune response compared to live, attenuated vaccines, so they require booster doses to achieve and maintain long-term immunity. **Adjuvants** can be added to inactivated vaccines to help boost the immune response. Adjuvants are chemicals such as aluminium phosphate and aluminium hydroxide that stimulate a stronger immune response against antigens administered at the same time.

Most vaccines against bacteria are inactivated vaccines. Examples of inactivated vaccines are the inactivated rabies and hepatitis A vaccines.

Subunit vaccines

Like inactivated vaccines, **subunit vaccines** do not contain any live microbial components. Unlike inactivated whole-cell vaccines, subunit vaccines contain only parts of microbes selected for their ability to induce an adaptive immune response. Subunit vaccines can contain a fraction of an antigen, a single antigen or multiple antigens. These antigens can be proteins, detoxified toxins or polysaccharides. Subunit vaccines that contain multiple antigens induce a broader immunity, because they induce the production of antibodies directed against multiple antigens.

Subunit vaccines have the same the advantages as inactivated vaccines in that they are safer, more stable and easier to store than live, attenuated vaccines. However, subunit vaccines also share the disadvantages of inactivated vaccines in that that they require multiple doses and an adjuvant to improve the strength of the immune response.

Subunit vaccines are made by growing the pathogen in the laboratory and chemically extracting the antigens, or by using **recombinant DNA technology**. An example of a recombinant subunit vaccine is one that has been genetically engineered to produce a purified component of the protein coat of the virus that causes foot-and-mouth disease. Recombinant DNA technology can also be used for live vaccines, to genetically modify microbes so that they elicit an immune response but do not cause illness.

A **toxoid vaccine**, a type of non-recombinant subunit vaccine, uses toxins inactivated by formalin (called toxoids) to stimulate an adaptive immune response. Although the toxoid is inactivated, it remains similar enough to the original toxin that the immunological memory for the toxoid is also effective for the toxin. For example, *Clostridium tetani* is a bacterium that produces a neurotoxin that causes tetanus, and the inactivated toxin is used in the vaccine for tetanus. *Clostridium tetani* is illustrated in Figure 8.3.10. Another example of a toxoid vaccine is the diphtheria vaccine. Toxoid vaccines often require multiple doses to achieve immunity.

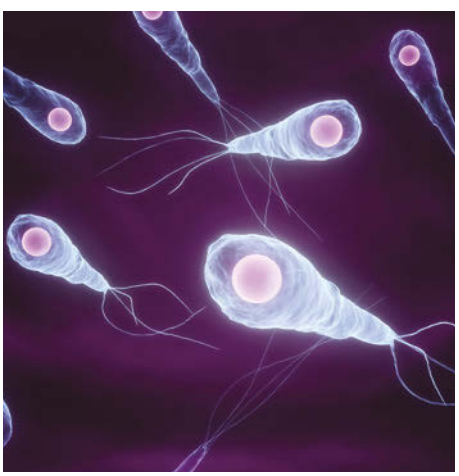


FIGURE 8.3.10 A digital illustration of *Clostridium tetani*, the bacterium that produces a toxin called tetanospasmin. The toxin acts on the central nervous system, causing muscle spasms that can result in convulsions, difficulty breathing and abnormal heart rhythms.

Immunisation programs

Vaccination introduces the antigens from the pathogen to a person's immune system, generating an immune response where both antibodies and memory cells are formed. The reduced concentration of antigens presented in this way often means more than one challenge to the immune system is required in order to generate sufficient memory cells for protection from the wild pathogen. For this reason, the immunisation schedule for many diseases involves booster injections. These present the antigens to the immune system again.

The recommended vaccination schedule for Queensland is shown in Table 8.3.3. Table 8.3.3 shows that vaccination programs do not commence until babies are at least 6 weeks old. This is because vaccination is unlikely to prove successful before that age. Maternal antibodies present in newborn infants inactivate the antigens in the vaccination before the infant's immune system can mount a response. Figure 8.3.11 shows the antibody levels for different types of antibodies in the fetus and infant. Note that fetuses can begin producing IgM antibodies by approximately 3 months gestation.

TABLE 8.3.3 Recommended vaccination schedule for Queensland

Recommended age for vaccination	Vaccines
Birth	Hepatitis B
6 weeks	• DTPa-hepB-IPV-Hib • Pneumococcal • Rotavirus
4 months	• DTPa-hepB-IPV-Hib • Pneumococcal • Rotavirus
6 months	• DTPa-hepB-IPV-Hib • Pneumococcal
12 months	Measles, mumps, rubella (MMR) *Haemophilus influenzae* type B–meningococcal C
18 months	Measles, mumps, rubella, chickenpox (varicella) (MMRV) Diphtheria, tetanus, pertussis,
4 years	DTPa-IPV
Year 7	DTPa-IPV
Year 10 students and 15–19 year olds	Meningococcal ACWY
65+ years	Pneumococcal
70 years	*Varicella zoster* (shingles)
71–79 years	*Varicella zoster*
Pregnant women from 28 weeks of pregnancy	Adult diphtheria, tetanus
Also recommended for Aboriginal and Torres Strait Islanders	
12 months	Hepatitis A
18 months	• Pneumococcal • Hepatitis A
15–49 years	Pneumococcal
50+ years	Pneumococcal

DTPa-IPV = diphtheria, tetanus, pertussis, poliomyelitis.
DTPa-hepB-IPV-Hib = diphtheria, tetanus, pertussis, hepatitis B, poliomyelitis, *Haemophilus influenzae* type B.

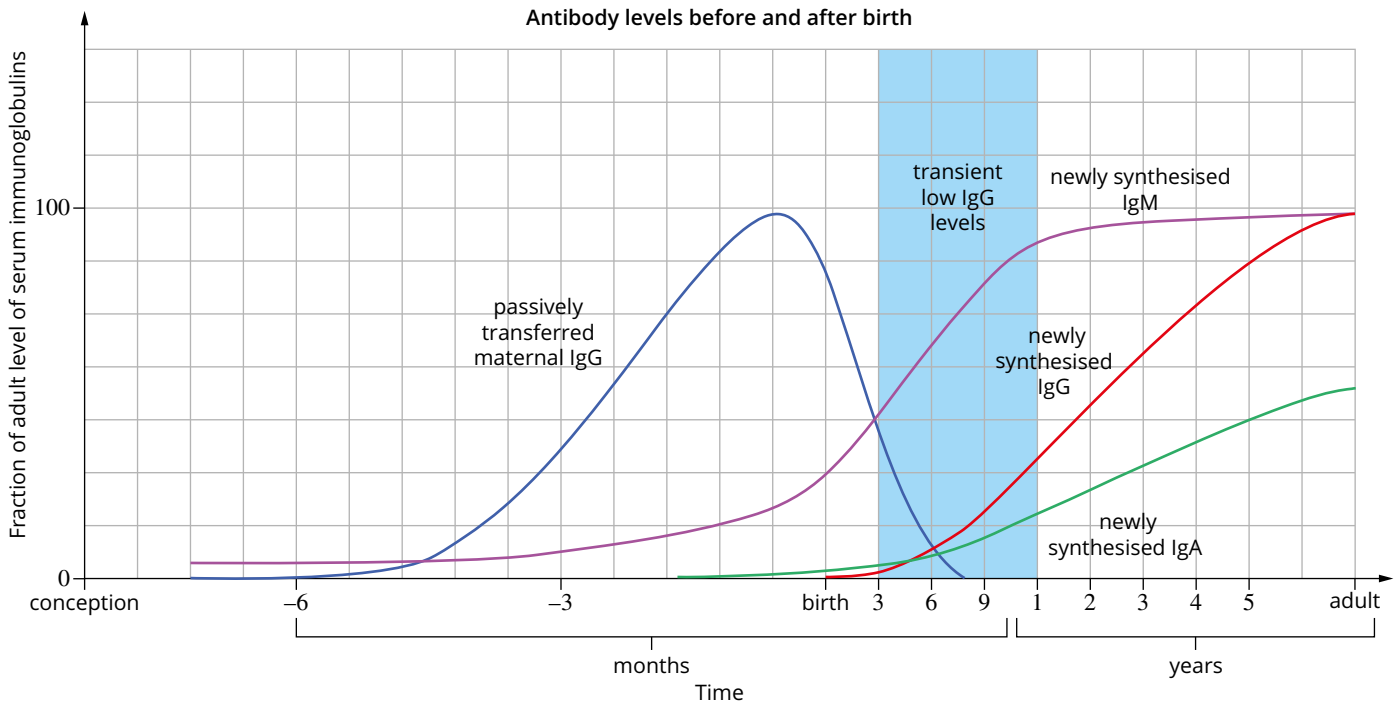


FIGURE 8.3.11 Antibody levels before and after birth

Vaccine effectiveness

As can be seen from the vaccination schedule in Table 8.3.3, some vaccines, such as MMRV, are effective with one dose whereas others require multiple doses to maintain immunity. This is because the life span of the memory cells that produce the antibodies needed for active immunity is very variable.

For example, antibodies against *Bordetella pertussis* (whooping cough) do not last throughout life. In a study in Thailand, it was shown that despite a significant infant vaccination program, covering 95% of all infants, by age 11 years nearly 50% of the population were antibody negative and at risk of developing *Bordetella pertussis* infection (Figure 8.3.12).

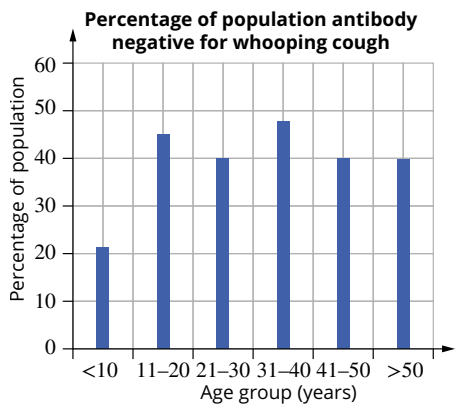


FIGURE 8.3.12 The percentage of Thai population with negative antibody titres for *Bordetella pertussis* (whooping cough).

Unlike memory cells for whooping cough, influenza memory cells seem to be very long lived. In a recent study, survivors of the 1918 H1N1 influenza pandemic were tested for immunity to the virus, which had recently been isolated from preserved tissues. The individuals, now in their nineties, supplied blood samples, which were incubated with samples of the virus that caused the epidemic. The blood serum contained antibodies that bound tightly to the virus even though the survivors had not been to exposed to it for over 80 years.

Influenza (or flu) viruses undergo antigenic drift relatively quickly. Antigenic drift is a change in the genes of the virus. When antigenic drift occurs, the antigens on the virus change. As antibodies are highly specific to their antigen, the immunity developed to the strains circulating in one year often won't provide protection against the newly evolved strains circulating in the population in future years. This is true whether you have caught the flu and developed natural active immunity, or have received a flu vaccine and developed artificial active immunity.

To keep up with antigenic drift, new flu vaccines are released every year. Although it is a single injection, each new flu vaccine is a cocktail of vaccines for different influenza strains. The decision on which strains to vaccinate against is based on what strains are predicted to be the most common in the coming flu season. However, sometimes the most common strains are not the expected ones, in which case the flu vaccine provides little protection. This is most likely if the virus experiences antigenic shift, swapping genes with another strain of virus.

i Strains of influenza A virus are named according to their two surface proteins: haemagglutinin (H) protein and neuraminidase (N) protein. There are 18 haemagglutinin subtypes (H1–H18) and 9 neuraminidase subtypes (N1–N9).

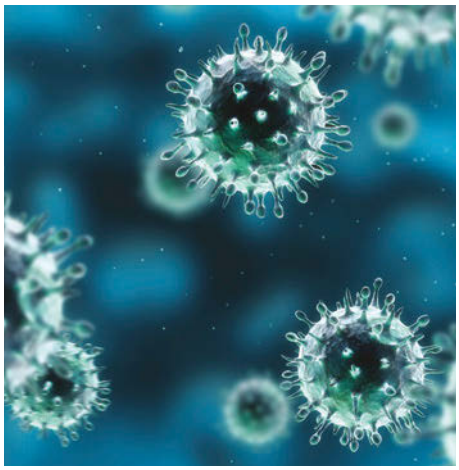


FIGURE 8.3.13 A digital illustration of the H1N1 strain of swine influenza virus

Morbidity is the state of being diseased or in ill health. Mortality is a measure of death rate.

In 2009, a new H1N1 pandemic strain of influenza (Figure 8.3.13) infected humans. The 2009 strain was sufficiently different from the 1918 H1N1 strain that exposure to the earlier virus gave little protection. Minimal protection was seen in some patients who had had influenza vaccinations for a number of years, suggesting that some earlier versions of seasonal flu may have had some commonalities with the new strain.

Even though regular booster vaccines are needed for some diseases, the introduction of routine vaccinations has reduced the mortality and morbidity of disease in Australia and throughout the world.

Vaccination has had the greatest impact on mortality in developing countries. In economically developed countries, where nutrition is good and people can easily access high-quality health care, death rates from most infectious diseases were decreasing even before vaccination. Good hygiene and sanitation also significantly limited the spread of disease. For example, measles had a death rate of around one death per 100 cases before vaccinations began, and by 1990 had fallen to one death for every 2000 cases. However, in developing countries, where children are often malnourished and may be infected with other parasites, such as malaria and helminths, mortality rates range between one in 200 and one in 17 under normal conditions to one in three in times of war or social disruption.

According to the World Health Organization, there were 134 200 deaths from measles in 2015. However, with about 85% of the world's children receiving at least one dose of measles vaccine, around 20.3 million deaths were prevented. The effect of vaccination on the incidence of measles in a developing area of the world, Latin America and the Caribbean, can be seen in Figure 8.3.14. Plummeting incidence rates mean the numbers of deaths also decrease even if rates per individuals infected do not improve.

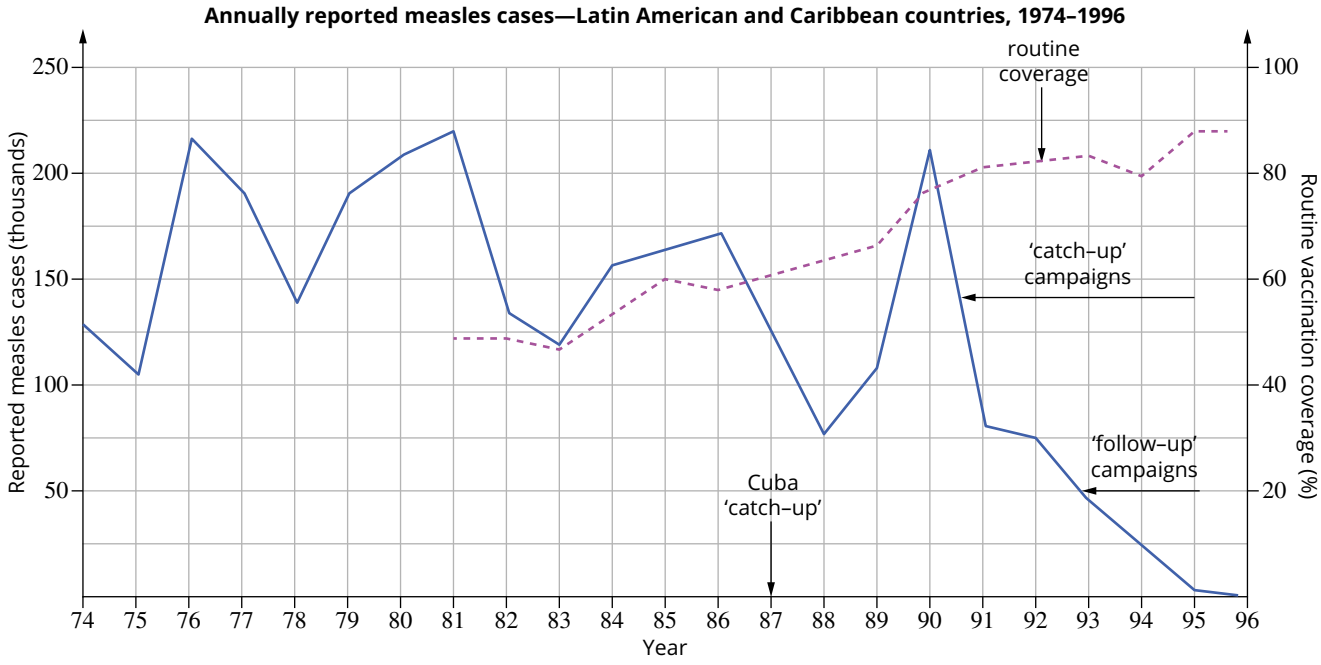


FIGURE 8.3.14 Annually reported measles cases in Latin American and Caribbean countries 1974–1996. The number of reported cases of measles in the Caribbean and Latin America decreased significantly as vaccination rates increased, indicating the effectiveness of vaccination programs.

The greatest success story for vaccination is smallpox. Smallpox was caused by the *Variola* virus. It was a terrible disease with a high mortality rate of around 30%. It was highly infectious and spread through droplets in the air. Those who survived were usually very disfigured by scarring left when the pox healed.

Smallpox virus was a good candidate for eradication by vaccination. It was a terribly feared disease that people would take almost any measure to avoid. It had a short incubation time and the symptoms (pox or blister-like sores) were distinctive, so outbreaks could be quickly identified and contained. Figure 8.3.15 shows a person suffering from smallpox. Also, it was entirely confined to humans, which is essential if a disease is to be eradicated because if animals are a source of the disease, the only way to eradicate it is to eradicate the animal reservoir as well. A disease is eradicated when it has been removed from the world.

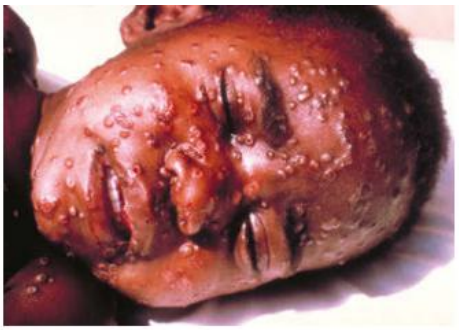


FIGURE 8.3.15 This person is suffering from a mild case of smallpox. Note the many smallpox pustules that cause scarring as they heal. Most people would be covered in pustules over most of their body.

In 1980, the world was declared smallpox free (Figure 8.3.16). It had been eradicated. Today, the only source of *Variola* virus is in two high-security laboratories at the Centers for Disease Control and Prevention in Georgia, USA, and the State Research Centre of Virology and Biotechnology (VECTOR Institute) in Koltsovo, Russia.

The most recent disease that is being targeted for eradication is polio, which is caused by poliovirus. Eradication of this virus is close. As a result of a worldwide vaccination effort, numbers of people infected annually have fallen from 350 000 to 42 cases in 2016. Only three countries are known to have had cases of wild-type infection: Pakistan, Afghanistan and Nigeria. Each of these three countries is currently in a state of internal turmoil, which has disrupted vaccination programs.

WS 2.2.6 WS 2.2.7

GLOBAL SMALLPOX ERADICATION

Years on the map indicate the year smallpox was eradicated in that place; smallpox was never widespread in Australia.

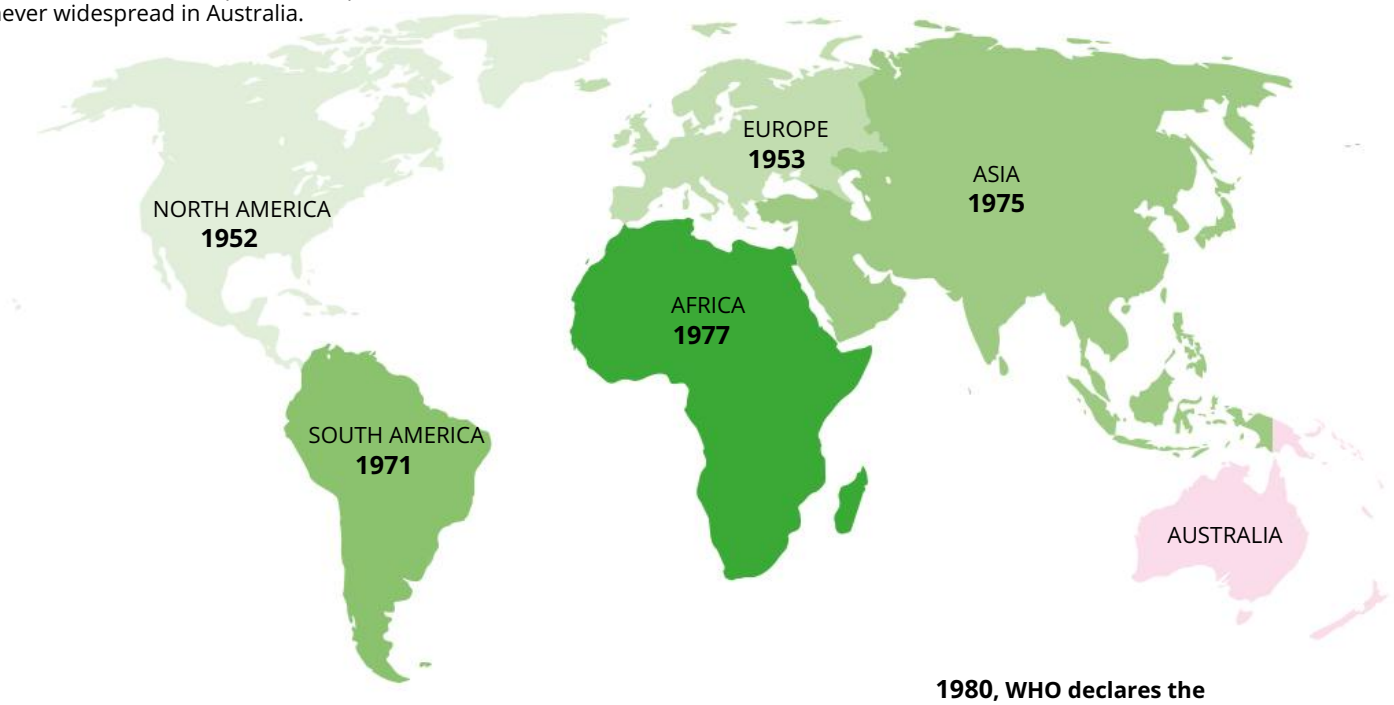


FIGURE 8.3.16 The timeline for the eradication of smallpox in the world. It was finally declared eradicated by the World Health Organization (WHO) in 1980, 3 years after the last reported case in Africa.

Herd immunity

Immunisation is critical, not only for the person immunised, but also for the wider community. For an immunisation program to be successful, a sufficient number of people need to be vaccinated, This is called **herd immunity** and is shown in Figure 8.3.17. The more people who are vaccinated, the less chance there is of an infectious agent spreading throughout a population, because there are fewer potential carriers. Herd immunity is essential for protecting people who cannot be vaccinated or who have suppressed immune systems. This includes newborn babies, pregnant women, the elderly, people suffering from an immune disease and people taking immunosuppressant medication.

FIGURE 8.3.17 The effectiveness of herd immunity. (a) With no immunisation in a community, infectious diseases spread easily. (b) With some immunisation in a community, infectious diseases spread less easily. (c) When most of the community is immunised, there are few carriers or infected people and minimal spread of infectious diseases. This is known as herd immunity.

Breakdown of herd immunity: whooping cough

Immunological memory for some pathogens reduces over time, thereby reducing the herd immunity of immunised populations. An example of the breakdown in herd immunity in Australia is the recent spike in cases of whooping cough, a disease caused by the bacterium *Bordetella pertussis*. Although it only causes a persistent cough in adults, approximately one in 200 babies under the age of 6 months who become infected die. Babies cannot be vaccinated until they are 6 weeks old and they are not fully protected by this vaccine until about 6 months of age.

One of the reasons for this breakdown in herd immunity is that not enough people get booster vaccinations. A public education campaign has been implemented to encourage adults to receive a booster vaccination to maintain herd immunity against whooping cough. New parents are offered the booster vaccination when their baby is born, and are encouraged to recommend the vaccination to family and friends who will be in close contact with their baby.

In Australia, vaccination rates are among the best in the world but even here the rates fall short of the 95% that is considered necessary to fully provide herd immunity. As can be seen in Table 8.3.4, even Tasmania, which has the highest percentage of fully immunised children, has still not reached the target of 95% although rates of immunisation by age five have increased since 2005. Failure to achieve the targets leads to outbreaks of disease, such as the measles outbreak that occurred in Western Sydney in 2016.

TABLE 8.3.4 Rates of full immunisation of children by age 5 years in Australia by state from 2005 to 2017

State/territory	2005	2006	2007	2008	2009	2010	2017
Australian Capital Territory	78.42	83.53	87.57	86.17	85.32	89.41	93.52
New South Wales	71.89	78.72	83.74	76.58	80.61	87.60	93.48
Victoria	76.74	80.98	85.65	83.11	85.48	90.07	93.77
Queensland	76.93	82.29	83.83	81.24	82.22	88.22	93.48
South Australia	72.60	76.50	80.47	74.38	77.48	85.61	93.39
Western Australia	72.48	77.40	80.31	77.77	79.75	85.36	91.45
Tasmania	75.15	80.50	83.89	80.60	82.92	90.07	94.06
Northern Territory	75.95	78.80	83.61	81.40	81.80	85.77	92.39
Australia	**74.42**	**79.83**	**83.71**	**79.39**	**81.97**	**88.02**	**93.32**

Throughout Australia, immunisation rates of children (by 5 years of age) vary by area from the protective rates required to achieve herd immunity. Western New South Wales and Murrumbridgee, NSW, have protective rates that achieve herd immunity at 96.1% and 96%, respectively. The protective rates in North Coast, NSW (90.3%), Perth North, Western Australia (90.6%), Perth South, WA (90.8%), and Gold Coast, Queensland (90.8%), have concerning rates that are below what is required to achieve herd immunity.

Organ transplantation

The first successful organ transplant took place on 23 December 1954. A kidney was transplanted from Ronald Herrick into his identical twin. An identical twin is an ideal donor because there is no danger of rejection of the organ.

Herrick's twin lived a further 8 years after receiving his transplant. He was luckier than most organ recipients in those early days when most lived for only a few months or even a few days. Organ rejection was a major issue.

Organ rejection occurs when the recipient's immune system recognises the organ as non-self because the human leucocyte antigen system (HLA) markers on the organ and those of the recipient do not match. The HLA system is a series of genes that code for the major histocompatibility complex (MHC) markers present on cells, and which identify the cells to the immune system as self or non-self.

More than 200 genes are involved in determining the HLA system and most of these genes have multiple alleles. More than 7400 different alleles have been identified so far, and more are being discovered all the time. Figure 8.3.18 shows the discovery of HLA alleles from 1987 to 2012.

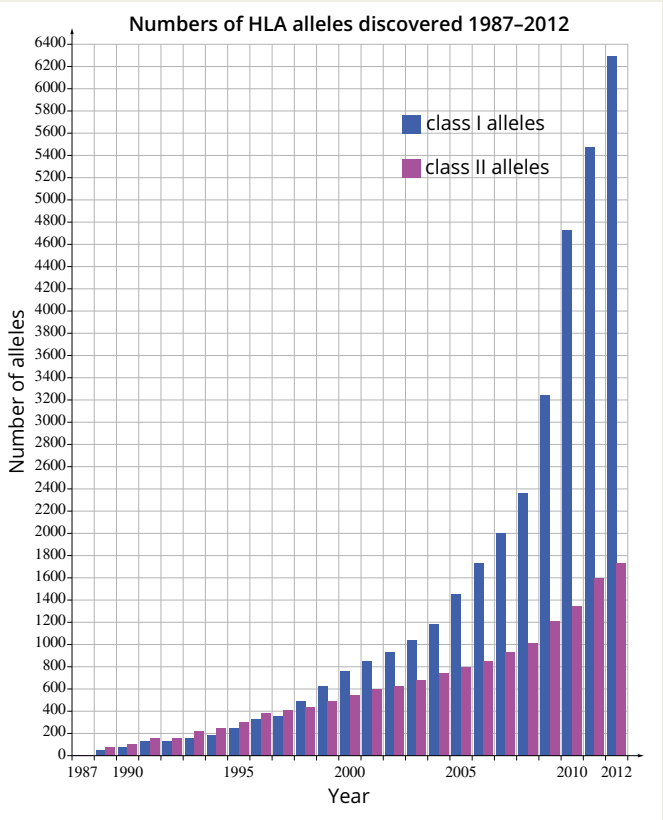


FIGURE 8.3.18 The increasing number of HLA alleles discovered from 1987 to 2012

Luckily, not all 200 genes need to be matched for a successful transplant. There are a few crucial matches required. The genes involved are named by a system of letters and numbers. The most important ones are HLA-A, HLA-B, HLA-C, DRA and DRB. Also important are DQA1, DQA2, DPA1 and DPB1. Most organ donation centres match HLA-A, HLA-B and HLA-C, along with DRB and a few also consider the DQ sites in determining suitable matches between donors and recipients. Most transplant centres insist on at least six matches for a transplant to take place. The matching requirements are shown in Figure 8.3.19.

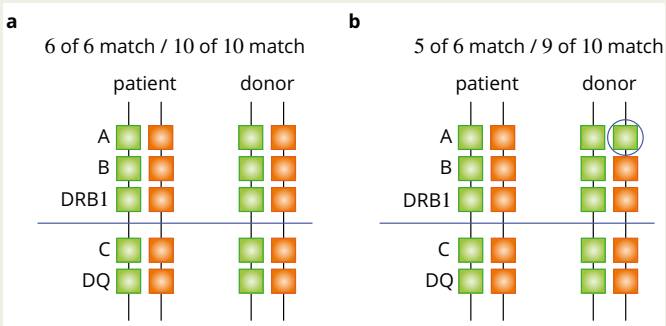


FIGURE 8.3.19 (a) All 10 of the patients' alleles match the donor. This would be a perfect match and have the highest chance of long-term success. (b) This shows one mismatch. This degree of matching would still constitute a viable transplant, but would have a greater chance of rejection in the future.

The HLA system was not identified until 1967, but once it was, the understanding that matching HLA genes was necessary resulted in a major advance in transplants. The lives of most recipients were extended for more than a few weeks.

The next advance was the discovery and development of the antirejection drug cyclosporine by Swiss scientists Jean Borel, Hartmann Stähelin and a team of scientists. One major cause of failure of the transplanted organ is attack by cytotoxic T lymphocytes. These cells of the immune system are activated to destroy foreign and damaged cells in the body. Once the T_c cells are activated, they destroy the cells of the transplant. After this destruction occurs, a second transplant has a much lower chance of success. The production of antibodies against the HLA markers of the donor organ means there are fewer options for matches for a second transplant.

Cyclosporine greatly reduced the chances of rejection. This drug was first extracted from the fungus *Tolypocladium inflatum* in 1971. It was under investigation for use as an antibiotic. It was not until 1976 that its immunosuppressive abilities were discovered, and it was 1983 before it was used to treat rejection in transplant patients. Cyclosporine had the advantage that it reduces the activity of lymphocytes, especially T cells, but does not supress the entire immune system. It appears to act by blocking the release of pro-inflammatory cytokines by T cells, thereby reducing the co-option of T_c cells and, to a lesser extent, naive B cells to reaction against the foreign HLA markers.

Even with the advances that have taken place in understanding transplant rejection, about 50% of all transplanted organs are rejected within 12 years. The next step in organ transplant technology would be to identify ways of stopping any activation of the immune response by stopping the stimulation of the innate immune system. The mechanisms of the role of the adaptive response in organ rejection have been the subject of considerable research and are fairly well known, but the role of the innate response is still poorly understood.

Recently, a team of scientists discovered that mice produce a molecule called SIRP-alpha, which binds to a receptor on monocytes (immature macrophages). This triggers the cascade that starts off the innate response, and from there the adaptive response follows. This is significant in organ transplants because humans also produce SIRP-alpha and it comes in different variants. It may be that matching of SIRP-alpha as well as HLA would greatly reduce the chances of immune response generation. In addition, blocking of the interaction between SIRP-alpha and the monocyte receptor stopped the activation of the innate immune response, so this discovery opens another possible area of research. It may be possible to find a drug that blocks the receptor but does not completely shut down the immune response.

One issue with immunosuppression is that it leaves the patient open to infection and cancers. The immune system protects against both and a complete inactivation would almost certainly result in death very quickly. Patients on immune suppression therapy have higher rates of cancer because T_c cells also kill abnormal body cells and they are more prone to infection as the response to many pathogens, especially viruses, is ineffective. Despite the problems associated with organ transplants, for most recipients the benefits outweigh the disadvantages and their most pressing concern is how long they have to wait until an organ becomes available.

In many countries, the organ donor system is an opt-out one in which people are assumed to agree to be a donor unless they specifically refuse. In Australia, we have an opt-in system. A person wanting to be an organ donor must register their wishes on the Organ Donor Registry and make sure that their family is aware of their choice.

Australia has a lower rate of organ donation than most other countries, according to the number of organs surgically transplanted through donation programs. In 2015, Australia was ranked 20th in the world. However, Australia has a high success rate and it is a recognised world leader in providing care for transplant patients. Many reasons have been suggested for the low rate of organ donations in Australia, including our opt-in system. Some people disagree with an opt-out system because they say it opposes the altruistic nature of organ donation and may increase the distress of families at the death of their relative. Also, an opt-out system in Australia is unlikely to increase the supply of organs. Currently, there are around 6 million people registered as organ donors. This is a large proportion of the population, and much higher than most countries.

Donor program reviews by professional associations indicate that hospitals can improve systematic processes that include the identification of potential donors, family consent and family communication and education to minimise the number of refusals.

Improvements in hospital procedures can largely solve the first two problems but the issue of why families refuse needs to be researched. It may be that the third issue is a consequence of the other two and that good hospital procedures and having well-trained staff who can approach families in a caring and sensitive way would reduce the number of refusals. There is some data to suggest that this might be the case (Table 8.3.5).

The significant difference between Melbourne's Alfred hospital and other major trauma centres suggests that something about the hospital is a factor in determining organ donation rates. Even with good hospital procedures, there will still be families who will refuse to donate organs for transplant.

TABLE 8.3.5 Organ donation in major Australian hospitals in 2015 from deceased donors

Hospital	Number of deceased donors
Alfred Hospital (Vic.)	37
Royal North Shore Hospital (NSW)	21
Royal Melbourne Hospital (Vic.)	20
Royal Adelaide Hospital (SA)	20
Sir Charles Gairdner Hospital (WA)	18
Princess Alexandra Hospital (Qld)	15
John Hunter Hospital (NSW)	15
Monash Medical (adults) (Vic.)	14
Flinders Medical Centre (SA)	14
Royal Perth Hospital (WA)	14
Austin Hospital (Vic.)	13
Gold Coast Hospital (Qld)	12
Canberra Hospital (ACT)	12
Westmead Hospital (NSW)	10
Royal Brisbane Hospital (Qld)	9
Nepean Hospital (NSW)	9
St George Hospital (NSW)	9
Cairns Hospital (Qld)	7
Gosford Hospital (NSW)	7
Liverpool Hospital (NSW)	7
Prince of Wales Hospital (NSW)	7
Royal Prince Alfred Hospital (NSW)	7
Fiona Stanley Hospital (WA)	7
Nambour Hospital (Qld)	6
Prince Charles Hospital (Qld)	6
St Vincent's Hospital (NSW)	6
Wollongong Hospital (NSW)	6
Albury Hospital (NSW)	5
Geelong Hospital (Vic.)	5
St Vincent's Hospital (Vic.)	5
Royal Hobart Hospital (Tas.)	5

In Brazil, a study of family members who had refused to permit organ harvesting found that refusals fell into three main groups.

1 Families honouring the deceased person's wishes of not wanting to be an organ donor. No amount of training of hospital staff will change these decisions.
2 Family religious beliefs. The researchers, however, decided that these were actually cultural beliefs because all of the religions cited support organ donation as an act of charity. A proper approach to this group by a well-trained staff member who understands the culture of the family may result in a higher rate of donation.
3 Families not being familiar with hospital procedures and understanding the patient's condition. The families did not have a good understanding of brain death. They assumed that the patient could wake up or be saved by medical intervention. In some cases, the family mistrusted the hospital staff because they felt they were being pressured to 'pull the plug' on their family member quickly so the hospital could get hold of the organs. Better trained, more empathetic staff could have a major impact on the supply of organs for transplant.

With the current rate of organ donation in Australia, many people on the waiting lists will die before a suitable organ becomes available. In 2016, a record number of 1447 Australians received an organ transplant from 503 donors, which was an improvement on the previous year. However, with about 1400 people on the waiting list for a suitable organ at any one time, a larger supply is needed to ensure better matches.

Review

1 Explain why transplant patients have an increased risk of developing cancer.
2 One area of research in organ transplantation is the growth of new organs from stem cells from the person needing the organ. Compare immune system considerations between the current organ transplantation option and proposed adult stem cell organ transplantation.
3 Organ donation is at a fairly low rate in Australia, not because of a lack of registered donors, but in part because families of suitable candidates refuse permission. Discuss the reasons for and against giving permission for a family member's organs to be used for transplantation.

8.3 Review

SUMMARY

- Immunity is active or passive.
- Naturally acquired active immunity results from surviving an infection by a pathogen.
- Artificially acquired active immunity arises as the result of the introduction of specific antigens into the body, usually by injection.
- A vaccine is a preparation that contains antigens from a pathogen and which induces active immunity in the recipient.
- Vaccines can contain live attenuated pathogens, killed pathogens, antigens from pathogens or toxoids produced by pathogens.
- Vaccines provide effective protection from disease, giving protection against influenza and are responsible for the eradication of smallpox.
- Artificial passive immunity involves the administration of a serum containing antibodies made in another organism.
- Natural passive immunity occurs when antibodies pass from mother to baby across the placenta or in breast milk.
- Haemolytic disease of the newborn occurs when the mother has made antibodies to the fetal blood and these antibodies cross the placenta during pregnancy.
- ELISA (enzyme-linked immunosorbent assay) is a process used to identify the concentration of antibodies in a solution. It uses optical density.
- Herd immunity occurs when a sufficiently large proportion of a population has immunity to a specific pathogen so that the chances of a non-immune individual coming in contact with an infectious individual is remote.
- Close matching of HLA factors increases the chance of the success of organ transplants.

KEY QUESTIONS

Retrieval

1 **a** Define 'passive immunity'.
b Describe the two ways in which passive immunity is produced.

2 Explain why smallpox was a good candidate for disease eradication.

3 Explain the function of adjuvants. Include a definition of adjuvant in your answer.

Comprehension

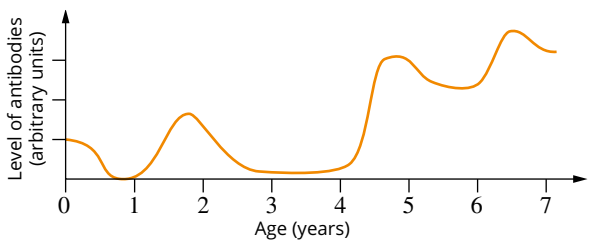
4 Distinguish between eradication and elimination in terms of disease.

5 Describe under which circumstances passive immunity would be artificially induced.

6 Identify which type(s) of immunity provide long-term protection from disease.

Analysis

7 The following graph shows the levels of measles antibodies in a child from birth to 7 years of age.



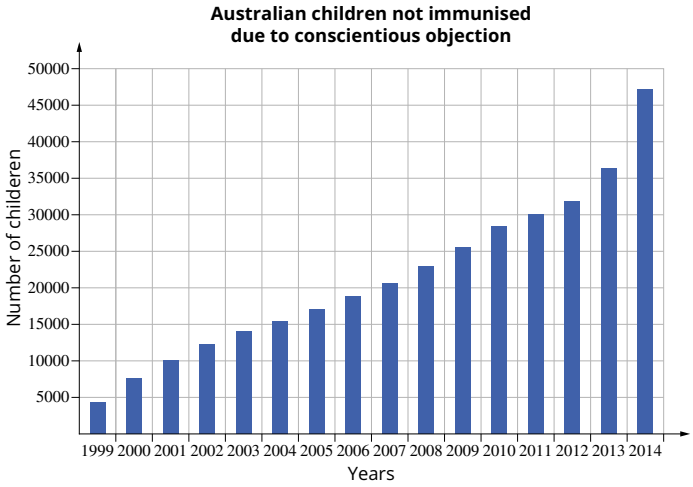
a This child had antibodies against the measles virus at birth. Explain how.
b Explain why the antibody levels dropped to zero in the months following the birth.
c The child was immunised against measles at 1 year of age and again at 4 years of age.
i Assess with conceptual justification the results of the 1-year and 4-year immunisations.
ii Draw a conclusion about the level of antibodies between the ages of 3 and 4 years.

continued over page

8.3 Review *continued*

d At 6 years of age, antibody production increases greatly again, but no vaccination had occurred. Infer an explanation.

e In Australia, the number of measles infections in children has been increasing recently, with a jump in 2015–2016. Argue why, using the data in the following graph.



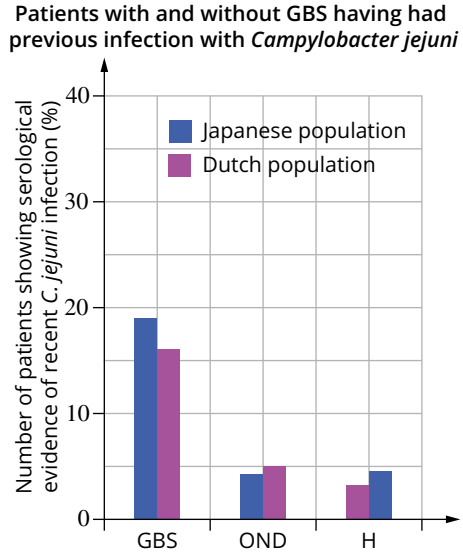
8 Compare natural and artificial active immunity.

9 Guillain–Barre syndrome (GBS) is a neurological disease. It is characterised by paralysis, which occurs when an autoimmune reaction causes damage to nerves by the patient's own immune system. GBS generally follows a previous infection. It is not confined to any particular sex or age group.

It has been suspected for some time that one trigger for the development of GBS is infection with the bacterium *Campylobacter jejuni*. *C. jejuni* is a common cause of food poisoning. Some people can be infected and remain asymptomatic.

Some researchers have suggested that previous infection with *C. jejuni* is more likely to result in the development of GBS among Asian populations than among European populations. A study was undertaken to investigate this proposal. Patients from The Netherlands and Japan with GBS were assessed by ELISA assays to determine whether they had been infected with *C. jejuni* previously. A group having other neurologically based diseases (OND) was included, as were a healthy group (H).

The Japanese subjects were 88 with GBS, 27 OND and 56 H and the Dutch subjects consisted of 132 GBS, 42 ONO and 30 H. The results are shown in the following graph.



a Propose reasons for including the OND and H groups in the study.

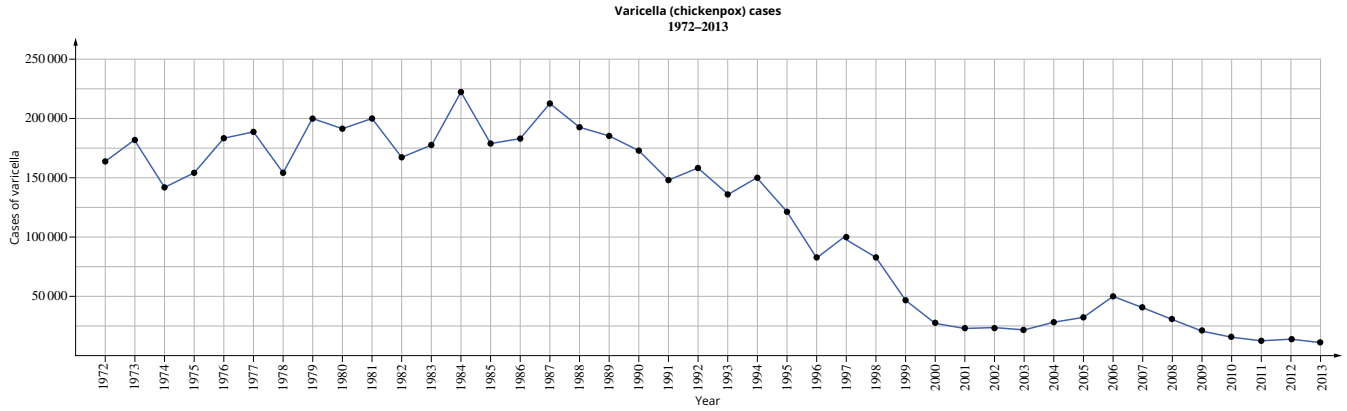
b Draw a conclusion regarding the hypothesis, 'People with Asian ethnicity are more prone to GBS following *C. jejuni* infection'.

10 Consider the two graphs below for incidence (a) and mortality (b) from chickenpox (varicella) in the USA. The varicella vaccine was introduced in 1995. That year, there were 120 624 cases of varicella, and 115 deaths from varicella.

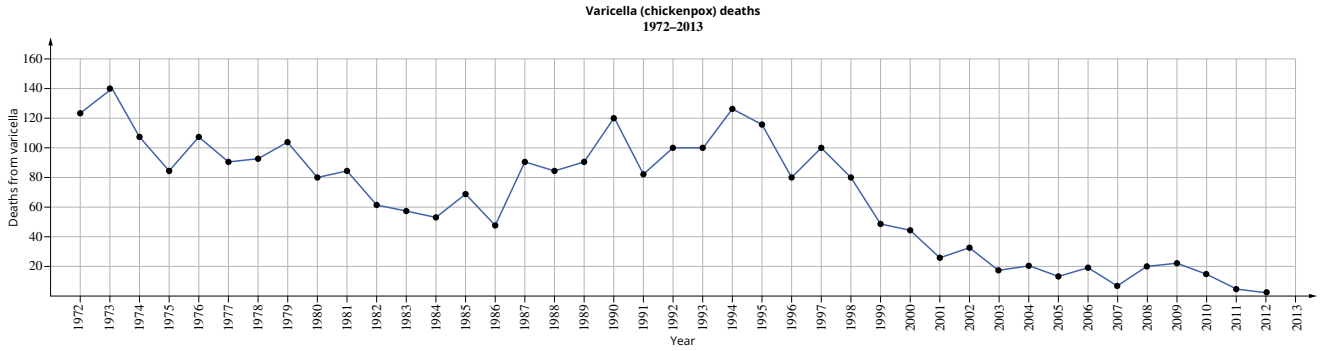
a Determine the death rate per 1000 cases of varicella in 1995.

b Estimate the average number of varicella cases per year before the introduction of vaccinations.

a



b



Chapter review

08

KEY TERMS

active immunity
adaptive immune response
adaptive immunity
adjuvant
agglutination
alkaloid
allergen
antigen–antibody complex
antigen-presenting cell (APC)
antiserum
artificial active immunity
artificial passive immunity
B lymphocyte (B cell)
cell-mediated immunity
chemokine
clonal expansion
clonal selection
complement protein
complement system
constant region
cyanogenic glycoside
cytokine
cytotoxic T lymphocyte (T_c)
defensin
digestive enzyme inhibitor
ELISA (enzyme-linked immunosorbent assay)
epitope
fever
first-line defence
granzyme
haemolytic disease of the newborn
heavy chain
helper T lymphocyte (T_H)
herd immunity
histamine
human leukocyte antigen
humoral immunity
hydrolytic enzyme
immunisation
immunogen
immunoglobulin (Ig)
inactivated vaccine
inflammation
innate immune response
innate immunity
interferon
interleukin
killed vaccine
leukocyte
light chain
live attenuated vaccine
lymphocyte
lyse
major histocompatibility complex (MHC)
mast cell
megakaryocyte
memory T lymphocyte
microbe-associated molecular pattern (MAMP)
microflora
natural active immunity
natural passive immunity
passive immunity
pathogen-associated molecular pattern (PAMP)
pattern recognition receptor (PRR)
perforin
phagocyte
phagolysosome
phagosome
phenolic
plasma cell
platelet
precipitation
primary immune response
protease inhibitor
recombinant DNA technology
regulatory T lymphocyte
saponin
secondary immune response
self-tolerance
serum
spectrophotometer
subunit vaccine
T cell receptor (TCR)
T lymphocyte (or T cell)
terpene
toxoid vaccine
vaccine
vaccination
variable region
vasodilation

KEY QUESTIONS

Retrieval

1 Identify the chemical that is not produced by plants in response to infection by a pathogen.
- **A** saponins
- **B** lignins
- **C** terpenes
- **D** phenolics

2 Classify the type of immunity provided by vaccination.
- **A** artificial passive
- **B** natural active
- **C** artificial active
- **D** natural passive

3 Identify the statement that can most accurately be applied to the secondary immune response.
- **A** A small amount of antibody would be found in the blood serum of the patient.
- **B** It requires a large dose of the antigen in order to provoke an immune response.
- **C** It occurs with a time lag that is shorter than the primary response.
- **D** It results in large numbers of IgD molecules.

4 Identify the type of antibody found in the highest concentration in the blood of a newborn baby.
- **A** IgA
- **B** IgG
- **C** IgE
- **D** IgD

5 Identify which of the following must be present on an antigen-presenting cell membrane, in order to activate a T_H cell.
- **A** IgM
- **B** MHC-I markers
- **C** MHC-II markers
- **D** IgG antibodies

6 List three barriers to infection used by:
- **a** plants.
- **b** animals.

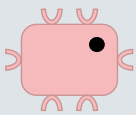
7 Identify the cells that display MHC-I markers.

8 Define 'self-tolerance' and describe how it is achieved.

Comprehension

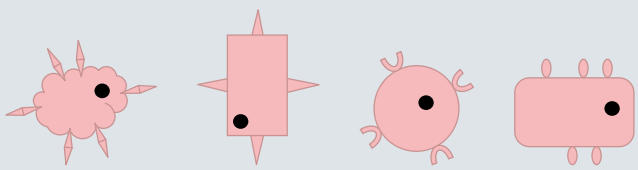
9 In a particular community, avian influenza strain H3N2 and a human strain H1N1 have been circulating. Without any warning, there is a sudden increase in people arriving at hospital emergency departments with influenza. The strain is analysed and found to be a new strain H3N1. This new strain is likely to have arisen as a result of:
- **A** lack of people in the population having vaccination.
- **B** antigenic shift.
- **C** antigenic drift.
- **D** the development of antibiotic resistance by the influenza virus.

10 Lymphocytes recognise cells as non-self because the foreign cells have antigens that are complementary in shape to their receptors for detecting foreign antigens.
- **a** Explain what is meant by the word 'complementary' in this context.
- **b** A lymphocyte (cell Z) with its receptor is shown below.



cell Z

Explain which of the cells, A, B, C or D, will be identified as non-self by the lymphocyte.



cell A cell B cell C cell D

11 Cassava provides a significant proportion of the daily kilojoule intake for over 600 million people throughout the world. In both Africa and India, cassava crops are regularly attacked by the cassava mosaic virus (CMV). One important method of protecting crop production is to use cassava varieties that show a natural resistance to CMV. Propose one feature the CMV-resistant varieties of cassava plant could have that non-resistant plants do not.

12 Upon first exposure to an antigen, there is a lag time before antibody production. Explain why this occurs.

13 Chédiak–Higashi syndrome is a rare inherited disorder of the immune system in which the proteins that regulate the joining of lysosomes with endosomes in phagocytes are defective.
- **a** Name the defective structure.
- **b** The failure of lysosomal breakdown of engulfed bacteria seriously undermines not only the innate immune response, but also the adaptive immune response. Explain why.

14 On occasion, the blood bank in Melbourne advertises for donors who have recently recovered from chickenpox. The blood bank takes a blood donation from these people and then separates the blood by a centrifuge into the blood serum and blood cells. The blood cells may be injected back into the donor. The serum is then purified and some of the proteins are extracted.
- **a** Name these proteins.
- **b** These proteins are given to patients. Identify the group of patients that is most likely to be in need of these proteins.
- **c** Explain why the extraction of these proteins does not affect the donors' future immune response to chickenpox exposure.
- **d** Explain whether the injection of these proteins gives the recipients long-term immunity.

15 In a family of two children, child X, the elder, receives the whooping couch vaccination whereas the younger, child Y, does not. Child Y contracts pertussis (whooping cough) 2 years later and recovers in hospital and now both children have developed immunity against pertussis.
- **a** Compare the response of the B and T lymphocytes and antibodies when child Y contracts pertussis.
- **b** Considering that both children develop an immunity to pertussis, explain why it is advisable for children to be vaccinated.
- **c** Child Z from another family is currently undergoing chemotherapy and is immune-suppressed as a result. Discuss why her parents are concerned about some children not being vaccinated against pertussis.

Analysis

16 Chemical pesticides are highly polluting, so studies have been done to find more environmentally friendly options to protect crops from pathogens. In one study, leaf extracts from five species of medicinal plant were tested for their ability to inhibit the growth of eight highly pathogenic species of fungus. The results are shown in the table below.

Identify the species that would be the most useful source of fungicide. Justify your choice.

Effect of plant extracts on growth of various fungi

Plant species	Inhibition (%) of fungus at different concentrations of leaf extract											
	Aspergillus niger			*Aspergillus flavus*			*Aspergillus terreus*			*Aspergillus fumigatus*		
	10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%
Ocimum sanctum	30.00	45.00	60.00	13.63	27.27	51.17	35.00	50.00	62.50	10.52	26.31	47.37
Mentha arvensis	25.00	40.00	50.00	18.18	31.81	68.82	20.00	41.66	66.67	21.05	41.36	73.69
Cymbopogon citratus	20.00	25.00	30.00	09.90	36.36	33.34	12.50	20.83	33.34	05.26	36.84	57.90
Eucalayptus globulus	10.00	35.00	40.00	13.63	22.72	41.67	16.66	25.00	41.67	31.57	42.10	63.16
Tridax procumbens	05.00	20.00	30.00	09.90	13.63	22.73	08.33	20.83	29.17	00.00	10.52	15.79
	Penicillium citrinum			*Fusarium oxysporum*			*Alternaria alternata*			*Curvularia lunata*		
	10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%
Ocimum sanctum	11.76	23.52	41.18	37.50	50.00	62.50	27.77	33.33	50.00	15.78	31.57	42.11
Mentha arvensis	29.41	47.05	67.71	41.66	54.00	62.50	38.88	50.00	66.67	36.84	47.36	63.16
Cymbopogon citratus	05.88	11.76	29.42	29.00	37.50	58.33	22.22	27.77	38.89	05.63	10.52	21.05
Eucalyptus globulus	05.88	23.52	35.30	12.50	20.83	33.34	11.11	33.33	44.45	21.05	26.31	42.11
Tridax procumbens	11.76	23.52	35.30	20.83	37.50	50.00	16.66	38.88	50.00	15.78	15.78	10.53

17 Saponins are a group of chemicals that defend plants against attack by pathogens. An investigation to examine one type of saponin, avenacin, was undertaken to investigate the research question, 'Will the absence of avenacin result in an increase in plant disease?'.

A group of plants from the species *Avena strigosa* were mutated so they could not produce avenacin. They were allowed to mature and were then exposed to spores of the pathogenic take-all fungus (*Gaeumannomyces graminis*).

The results of one study with the mutant plants are shown in the following table. Plants were examined 21 days after infection with the fungal spores. Wild-type plants do not have reduced avenacin production. Plants marked by * have reduced avenacin levels and other mutants lack any avenacin. Each group contained a large number of genetically similar plants.

Draw conclusions about the effectiveness of avenacin in combating fungal infections in plants.

Plant group	Disease rating, % seedlings			
	No disease	Low disease	Moderate disease	Severe disease
Wild type (not mutant)	100	0	0	0
A	0	25	12	63
B	28	28	28	16
C*	62	38	0	0
D	31	44	6	19
E	12	71	17	0
F	27	40	33	0
G	6	44	50	0
H*	56	38	6	0
I*	74	21	5	0

18 Chickenpox (varicella) is a disease caused by the *Herpes zoster* virus. Vaccination has been a part of the childhood immunisation schedule in Queensland since 2005. The vaccine is currently administered at 18 months of age.

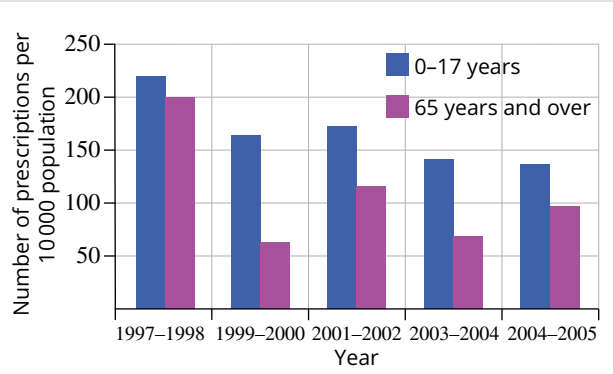
a Explain why 18-month-old children in Queensland do not contract the chickenpox disease from the vaccine containing a live virus.

b Before the vaccination program, it was common for the eldest child in a family to develop chickenpox in their kindergarten or first year of school. After the eldest child's infection, the younger children would then develop the disease, but breastfeeding babies in the family rarely caught chickenpox and even if they did it was generally very mild. Explain this observation.

c Since the introduction of chickenpox vaccine to the immunisation schedule, there has been an increase in the incidence of chickenpox among adults. Infer why this is occurring.

19 Research in the USA has shown that the common cold costs the US economy around $25 billion each year in lost productivity. The cost of the common cold to Australia would be proportionally similar. The major issue with the common cold is that there are many different strains of the rhinoviruses that cause colds.

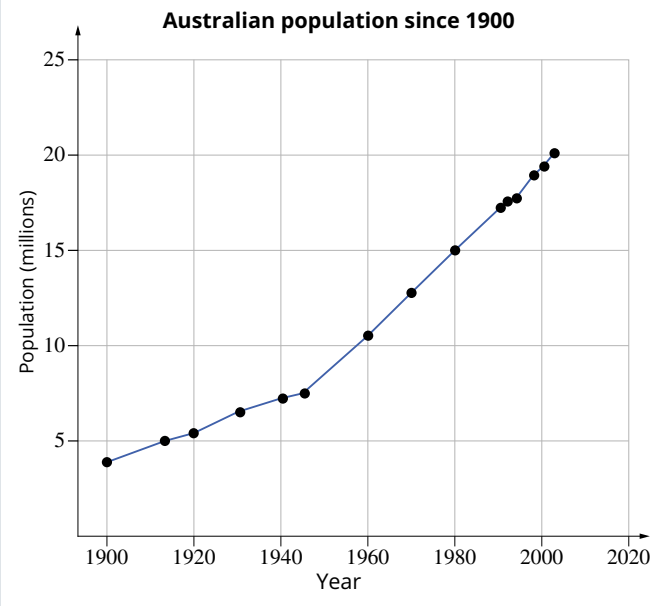
a The graph below shows the number of prescriptions for antibiotics issued in the USA as treatment for the common cold.



i Discuss the use of antibiotics for the treatment of the common cold.

ii Determine which group was most likely to receive a prescription for antibiotics to treat their cold, according to the data in the graph.

b The following graph shows the population of Australia from 1900 to 2005.



i Assuming that Australia's rate of issuing prescriptions for a cold is similar to that of the USA, use the information in the graphs to estimate how many people in Australia received a prescription for the common cold in 2000.

ii Each prescription for a course of antibiotics costs the Australian government approximately $20.00. Calculate how much money was wasted in 2000.

20 After World War I, a Spanish flu pandemic swept the world. More than 20 million people died. The Spanish flu was unusual because many of the fatalities occurred among young people with healthy immune systems. Modern medical opinion is that most of these deaths were caused by acute respiratory distress syndrome initiated by a 'cytokine storm'.

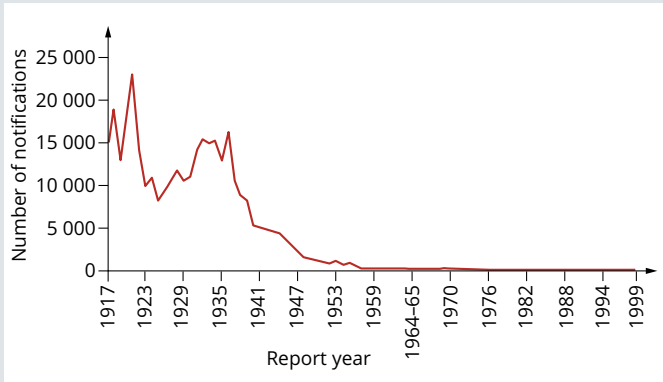
Cytokine storms occur as a result of positive feedback between macrophages and the cytokines.

Draw a flow chart to show how a cytokine storm can eventuate and cause death.

21 Diphtheria is a potentially fatal disease caused by either *Corynebacterium diphtheriae* or *C. ulcerans*. About 10% of infected individuals die. For this reason, diphtheria is one of the diseases for which children are vaccinated. The first vaccinations became available in 1921. By 1929, contacts of people with diphtheria were being vaccinated. School-based vaccination programs began in 1932.

Diphtheria is still a major health issue in some countries. Fewer than 10 cases have occurred in Australia in the last 10 years, all of which have been linked to overseas travel. The last recorded death from diphtheria in Australia was in 2011.

The graph shows the incidence of diphtheria in Australia between 1917 and 1999.



a Evaluate the effectiveness of the vaccination program in Australia.

b Explain why, despite the high incidence of diphtheria in some other countries and the ease of international travel, only isolated cases and no outbreaks of diphtheria have occurred in Australia in the last 10 years.

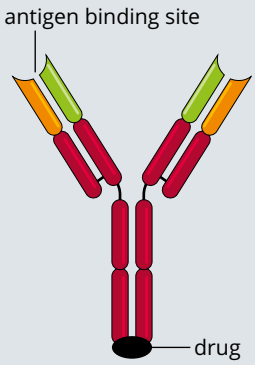
Knowledge utilisation

22 Traditional cancer treatments have many side effects. This is because the drugs are highly toxic to cells and kill many healthy, non-cancerous cells as well as the cancer. Rapidly dividing cells such as hair follicles and the linings of the digestive tract are affected very badly.

Researchers have sought ways to make anticancer drugs more specific to cancer cells. Cancer cells have unique features that set them apart from other body cells so scientists tried to to exploit these differences to devise new treatments.

An important advance was the development of monoclonal antibodies. Monoclonal antibodies are artificially constructed antibodies with antigen-binding sites that allow them to attach to cancer cells with a much higher affinity than to normal body cells.

One group of researchers suspect that monoclonal antibodies can increase the efficacy and reduce the side effects of a commonly used anticancer drug by attaching the drug to a monoclonal antibody that has a binding site specific to an antigen that is expressed only on cancer cells.



The results of a preliminary trial comparing administration of the drug attached to the antibody with conventional administration are shown in the table below.

Propose an extension of this experiment. Provide a rationale for your extension.

Tumour response to antibody-boosted or conventional drug treatment

Patient number	Antibody or conventional therapy	Tumour size at start of treatment (mm^3)	Tumour size after one round of treatment (mm^3)	Change in tumour size (mm^3)	Change in tumour size (%)
1	antibody	12.5	9.6	–2.9	–23.2
2	antibody	23.9	15.5	–8.4	–35.1
3	antibody	54.2	26.8	–27.4	–50.6
4	antibody	46.8	27.9	–18.9	–40.4
5	antibody	53.6	56.4	+2.8	+5.2
6	conventional	54.8	48.5	–6.3	–11.5
7	conventional	84.1	66.9	–17.2	–20.5
8	conventional	36.9	30.8	–6.1	–16.5
9	conventional	56.1	49.1	–7.0	–12.5
10	conventional	38.9	31.5	–7.4	–19.0

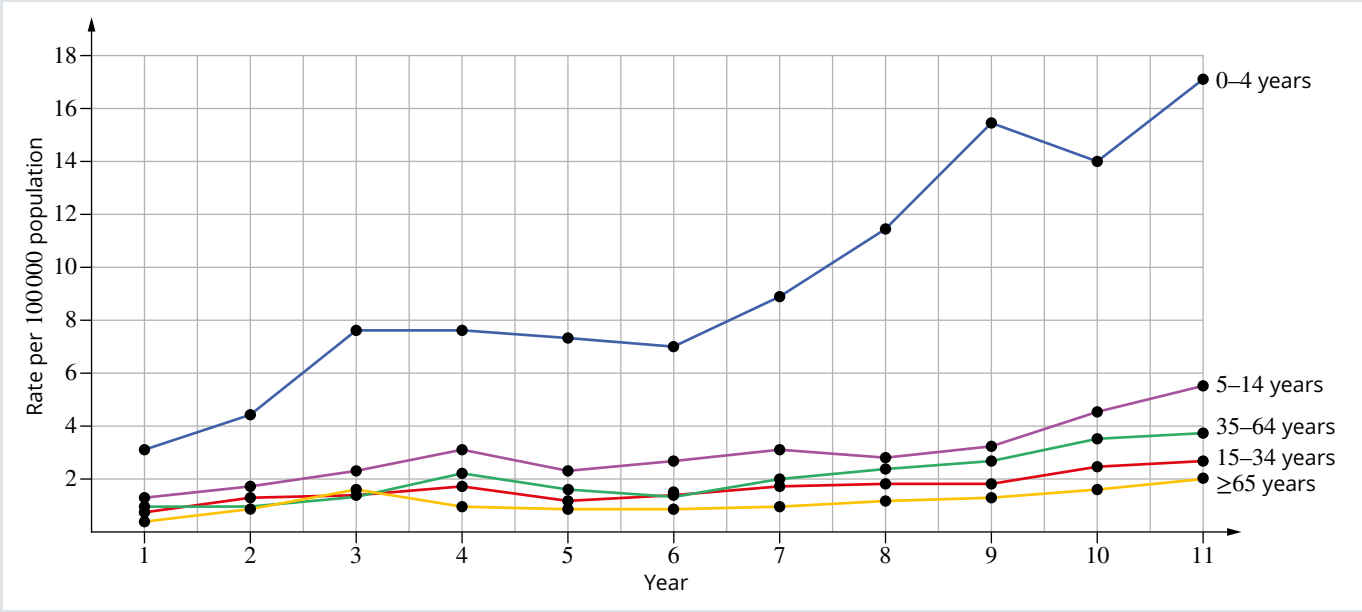
23 Allergic reactions are a life-threatening problem caused by the immune system. They occur when the immune system forms antibodies to antigens that do not pose a threat to the body. These antibodies attach to a type of immune system cell found in many tissues, called a mast cell. An allergic reaction occurs when the mast cell releases large amounts of histamine because the antigen (e.g. peanut or pollen) attaches to the antibodies on the cell. The production of large amounts of histamine can cause inflammation throughout the body, called anaphylaxis.

a Create a theoretical treatment for peanut allergy in Australia that is appropriate to the population. Provide a rationale with your proposed treatment.

b i Compare the approximate number of hospital admissions per 100 000 in each age group in year 11 to that in year 1.

ii Assess whether all individuals maintain their allergic reactions throughout their life and propose a theoretical reason.

c A group of scientists think that they have developed a vaccine that would protect people at risk from developing allergic reactions to peanuts. Design an experiment, using mice that have a genetic tendency to peanut allergy, that would allow the scientists to test their new drug. State the results that would show that the vaccine is a success.



24 Japanese encephalitis virus (JEV) is a mosquito-transmitted disease. The most important vectors are mosquitoes in the genus *Culex*, especially *C. tritaeniorhynchus* and *C. vishnui*. JEV is of major public health importance in an area that extends from Japan to India.

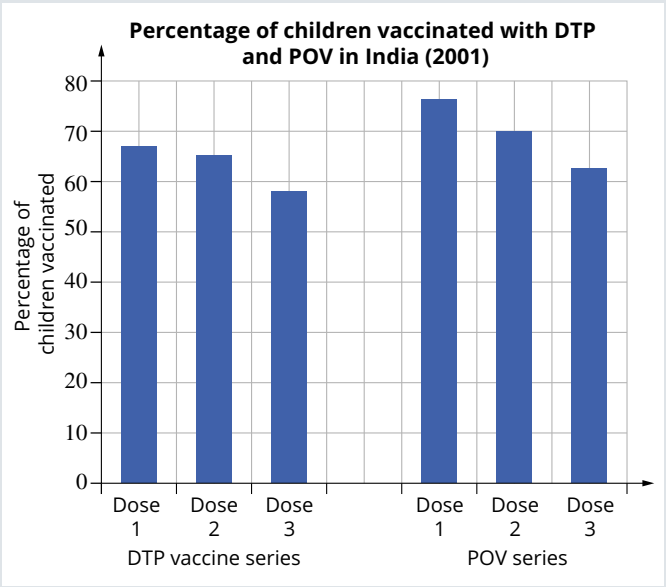
Most individuals do not suffer major symptoms but in a few cases encephalitis (brain inflammation) develops and these patients have a 30% mortality rate. In one epidemic in 1924, 6000 people were infected, of whom 60% died. Children are at much higher risk of serious consequences, and fetal infection through the placenta from infected mothers has been observed. Severely affected individuals who survive may suffer brain damage, paralysis and/or deafness.

People in urban areas are less at risk because of the lower mosquito numbers and strategies that reduce the chances of being bitten, such as mosquito nets and insect repellents.

A government in eastern Asia is considering adding JEV vaccination to its childhood vaccination schedule. There is a vaccine available for JEV. It comes in two different forms. One form is given as a single dose and the other is given in three doses, two administered a week apart followed by a booster at one year. Both methods require a booster, of one dose, at year 3.

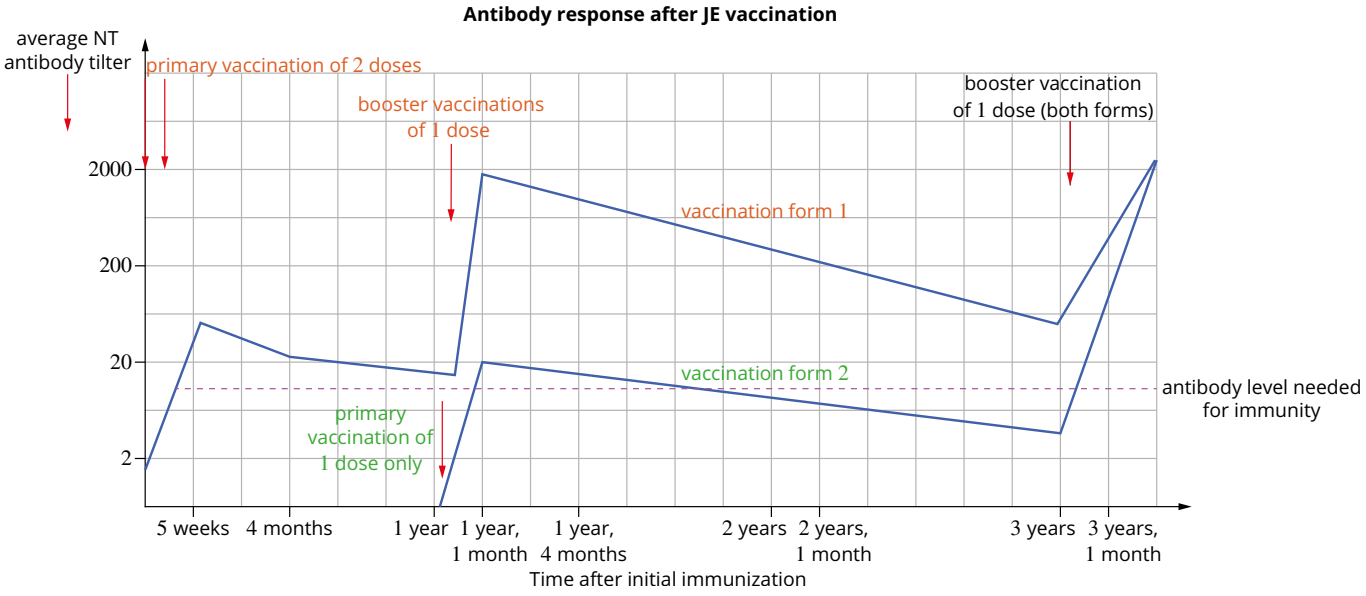
The antibody response of both options is shown in the graph. The dashed line represents the antibody level that is needed for protection from the virus.

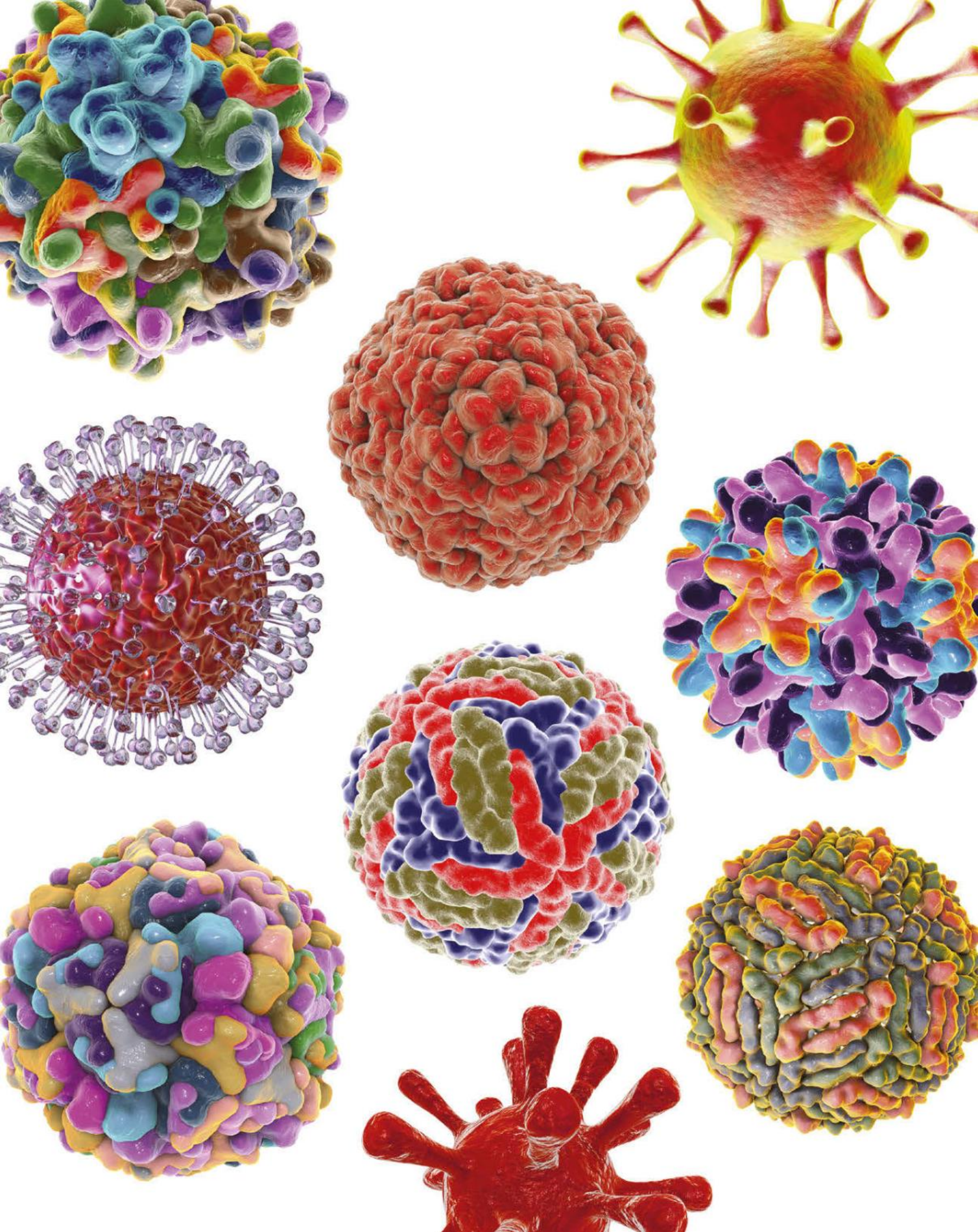
Issues with the giving of the vaccination include cost (40 cents per dose) and the number of children who fail to complete the full series. Studies in India, which has a similar demographic to the country in question, on the drop-out rates for multidose vaccines, namely diphtheria/tetanus/pertussis (DTP) and polio oral vaccine (POV), are shown in the following graph.



When the vaccination program begins, initially 54 000 000 children under the age of 15 years will need to be vaccinated in a catch-up program. Thereafter, it is estimated that 3 150 000 children will need vaccination each year.

Prepare a recommendation for the east Asian government that outlines a vaccination program for their population. Provide a rationale for the JEV vaccination program.





CHAPTER

09 Disease patterns

Epidemiology is the study of diseases, how they are transmitted, and how they might be controlled. Epidemiologists analyse disease patterns. Epidemiologists predict and control the spread of disease, by modelling and analysing transmission through communities and regions and across continents.

This chapter enables the use of knowledge from previous chapters on disease and pathogens in a range of case studies. To develop models of disease transmission, this chapter introduces transmission concepts, mechanisms of transmission and methods of prevention.

The case studies provide in-depth and extensive learning activities that afford opportunities to use knowledge, incorporating retrieval and comprehension of knowledge, as well as analyse and interpret evidence. Various Queensland Biology syllabus assessment objectives have been used to design the questions and tasks for each case study. It is envisaged that with data available in these chapters, various opportunities to apply and utilise knowledge and scientific skills beyond the questions and tasks prescribed can be developed. The case studies will develop skills to address all assessment objectives across all assessment instruments.

Syllabus subject matter

Topic 2 • Infectious disease

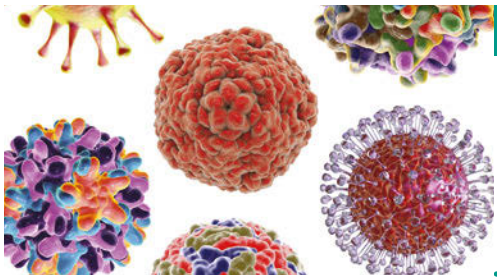
INFECTIOUS DISEASE

- identify from given data and describe the following modes of disease transmission: direct contact, contact with body fluids, contaminated food, water and disease-specific vectors.

TRANSMISSION AND SPREAD OF DISEASE (EPIDEMIOLOGY)

- recognise that the transmission of disease is facilitated by regional and global movement of organisms
- identify the interrelated factors affecting immunity (persistence of pathogens within host, transmission mechanism, proportion of the population that is immune or has been immunised, mobility of individuals in the affected population)
- analyse these factors to predict potential outbreaks
- evaluate strategies to control the spread of disease
  - personal hygiene measures
  - community level: contact tracing and quarantine, school and workplace closures, reduction of mass gatherings, temperature screening and travel restrictions
- make decisions and justify them in regard to best practice for the prevention of disease outbreaks based on the critical analysis of relevant and current information
- interpret data for the modelling of the spread of disease using secondary data or computer simulations.

9.1 Transmission and populations



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

- model and predict disease transmission
- understand general ideas and models based on transmission and spread of disease, and measuring the spread of disease
- understand and consider factors such as pathogen persistence, mechanism of transmission and immunity.

The number of pathogens that exist in the world around you, including those on your body, is immeasurable. Fortunately, the microbiome on your body is relatively stable and pathogens usually need to gain access to the internal environment to cause disease.

FIGURE 9.1.1 Ultraviolet (UV) light being used to show bacteria on a person's hands. The person has applied gel to their hands and then washed them. Under UV light, the gel fluoresces (green) to indicate areas that have not been adequately cleaned. The UV light shows most species of bacteria regardless of whether they are harmful (pathogenic) or harmless.

TRANSMISSION AND SPREAD OF DISEASE

Disease itself cannot be transferred from one organism to the next; rather it is the pathogen that causes the disease that is transferred. You will recall from Module 7.2 the various ways in which pathogens can be transferred from one person to another, resulting in the transmission of disease. There are many mechanisms of transmitting pathogens and the spread of disease becomes more complex the more people and organisms that are involved.

The spread of disease within a community is related to many factors, including population density and movement, personal and communal hygiene, immunity and environmental factors, mechanism of transmission and category of pathogen being spread. Epidemiologists sometimes study the spread of disease categorically to reduce the complexity. For example, when studying environmental factors, categories may include:

- water supply
- **sanitation** facilities
- food
- climate.

Each one of these environmental factors can be further analysed into more specific categories and then defined more discretely into measurable variables. Water supply factors can be analysed more specifically as inadequate excretion from disposal facilities, poor hygiene practices (such as hand washing, Figure 9.1.1), removal of used water from living premises, amount of stagnant water, or delivery of fresh water. Climate factors can be analysed further as flooding, heavy rains, excessive stagnated water and detritus, airstreams and wind.

The ability of pathogens to spread from one host to another and then through a community and global populations is continully developing. Even though much is known about pathogens, including their structures, chemistry, genetics, virulence and pathogenicity, we are still discovering more about them every year. Their ability to survive, the environments they can withstand, molecular intereactions with hosts and environment are a few examples. Living pathogens require a medium to survive while being transferred and this usually includes water and nutrients. Non-living pathogens do not require water or nutrients. However, because they are not capable of movement, they are often transferred through mediums such as water, food, body fluids and direct contact of surfaces. As long as the non-living pathogens remain structurally sound, and are not denatured by heat or extreme conditions, they will remain pathogenic.

Living organisms are the perfect vectors to transport and spread pathogens and transmit disease: they have a reasonably stable temperature, contain water and fluid, are a source of nutrients, and typically move regularly. Of all the vectors that spread disease to new populations, humans are the most potent. To develop an understanding of human influence on disease transmission, research into international movement showed that in the 1990s, 500 million people travelled across international borders on commercial flights. The same research showed that over a 200-year period, the average daily distance travelled by the typical French population increased 1000-fold, and that in 40 years the number of people who exited or entered Australia increased 100-fold. Figure 9.1.2 shows the traffic of the world's population in recent times.

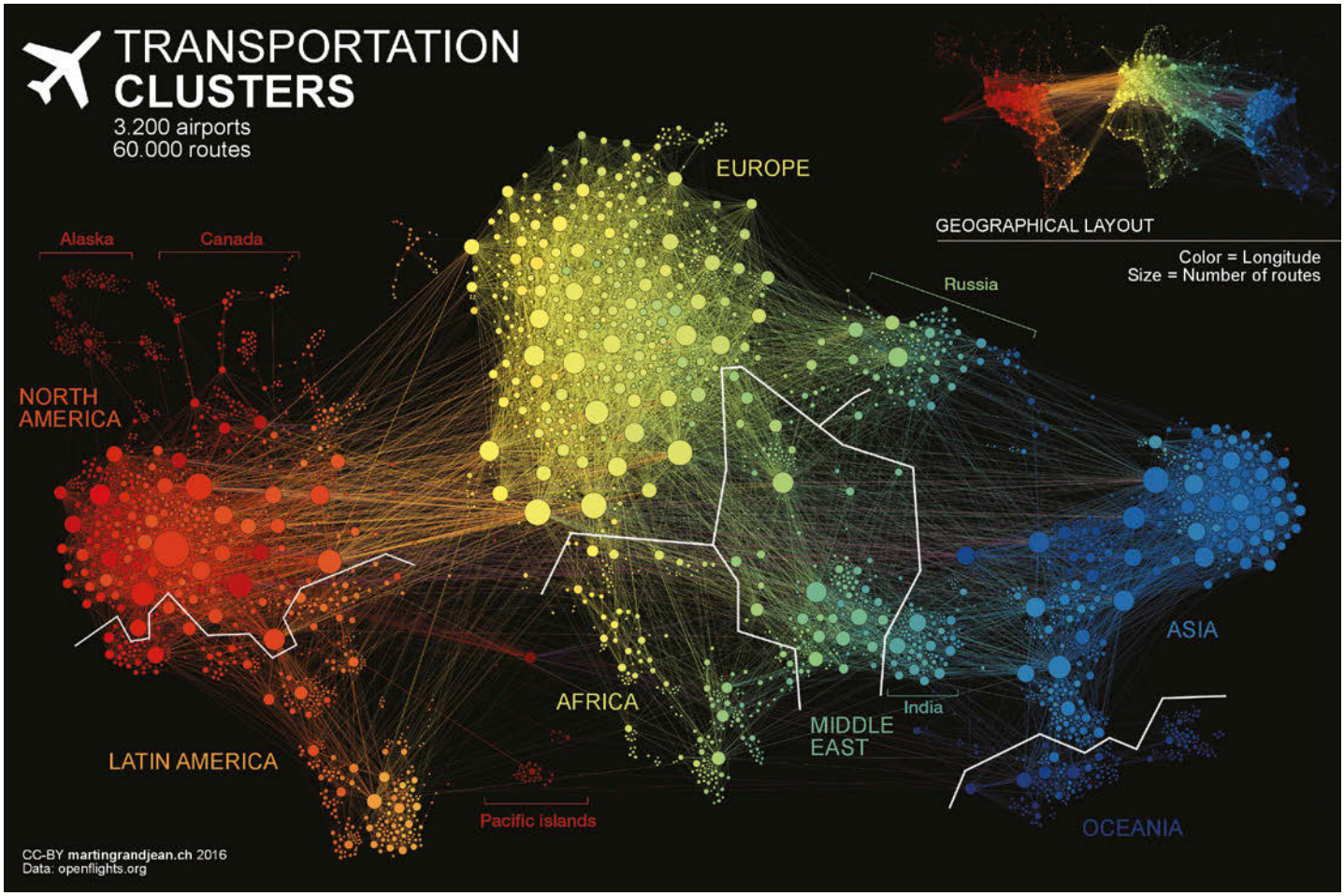


FIGURE 9.1.2 This map displays the 60 000 flight routes of 2016 (shown by size of the circle at each hub), representing the global reach of air travel (or longitude—indicated by the colour). It is estimated that the number of daily flights was in excess of 100 000 in 2014, equating to more than 8 million people travelling by air.

Table 9.1.1 outlines a few of the pathways in which disease has been shown to spread because of human activity.

TABLE 9.1.1 A few of the recorded pathways in which diseases have been known to spread

Pathway	Vector	Direct/ indirect	Transmission mechanism
fishing routes	human	both	• person-to-person (skin–skin) • contaminated object (surface–orifice) • animal-to-person (fluid transfer) • person-to-person (fluid transfer)
trading routes	human	both	• person-to-person (skin–skin) • contaminated object (surface–orifice) • animal-to-person (fluid transfer) • person-to-person (fluid transfer)
	human and snail	indirect	• vector (human–snail–human)
migration	human	both	• person-to-person (skin–skin) • contaminated object (surface–orifice) • person-to-person (fluid transfer) • fluid transfer (through food, water supply, ventilation)
	insect (sandfly)	indirect	• fluid transfer (through food)
shipping	human	both	• skin–skin • surface–orifice • fluid transfer (human–human)
	insect (mosquito)	indirect	• fluid transfer
	various introduced organisms	indirect	• environmental reservoir • food and drinking water
infrastructure	human	indirect	• airborne (ventilation systems) • food and drinking water

Table 9.1.1 is not an exhaustive list of recorded pathways for disease transmission. Importantly, of all vectors and disease transmission pathways, humans are the most common.

Mechanism of transmission

To survive, all living pathogens need a source of nutrients and many require a specific source. Many living pathogens that cause disease must infect new people, animals or plants. As disease causes the malfunctioning of processes in a living host, if the disease persists in the host, then often it is only a matter of time before the host dies. For living pathogens, the mechanism of transmission must sustain life until a new host is found. Some pathogens are highly resistant to environmental factors and can remain alive under harsher conditions for longer than other pathogens. For example, the spores of *Bordetella pertussis*, the bacterium that causes whooping cough, can survive for many days in the environment. Non-living pathogens are usually limited by fewer environmental factors in transmission.

The mechanisms of transmission are grouped into two distinct categories: direct and indirect contact. **Direct contact transmission** is when disease is transferred from an infected person to a **susceptible** person through physical contact. Direct contact includes person-to-person (direct touch or exchange of body fluids) and **droplets** (fluid droplets sprayed by coughing, sneezing or speaking). Figure 9.1.3 shows some examples of methods of direct contact transmission. **Indirect contact transmission** is when disease is transferred to a susceptible person where no physical contact has been made. Indirect contact includes airborne transmission, contaminated objects, food and drinking water, animal-to-person contact, vectors and environmental reservoirs.

Person-to-person transmission

The skin or affected body parts have pathogens present that are transmitted directly through hands, clothes, hair or any other contaminated material through physical contact. If the pathogen requires an internal or wet environment to live, it will enter the body through broken skin, **mucous membranes** (e.g. lips) or an orifice. Often these infections are associated with poor personal hygiene.

Because transmission must be through direct physical contact, the pathogens do not travel very far, as their motility is limited. Transmission is achieved directly through the actions of the host. Transmission through person-to-person contact can be traced through very small transmission distances and usually to people of regular contact, such as family members, carers or perhaps work colleagues. Disease **clusters** appear in or around the home of the infected, and the homes of their family members or friends, carers or work colleagues (Figure 9.1.3).

FIGURE 9.1.3 (a) Skin-to-skin contact or breathing the same droplets from exhaled air cause direct contact transmission. (b) Skin-to-skin contact, droplets, direct contact of clothing or sharing eating and drinking utensils can result in direct contact transmission. (c) Large numbers of sick people in a small area can result in direct contact transmission through clothing and droplets (breathing and coughing).(d) Sharing of facilities at the same time will result in skin-to-skin contact and direct contact transmission through droplets (breathing and perhaps coughing or sneezing). (e) Couples easily transmit disease through direct contact of clothes, skin-to-skin contact and body fluid transfer when kissing or through sexual relationships.

Droplet transmission

FIGURE 9.1.4 Sneezing ejects and transfers droplets 1–2 metres, demonstrating direct contact transmission of disease.

When an individual talks, coughs or sneezes, small droplets of mucus, which contains pathogens, are expelled or ejected (Figure 9.1.4). When droplets reach a susceptible individual, the person may inadvertently transfer the pathogen to a skin opening, mucous membrane or an orifice (e.g. using their hands to scratch an itch).

Droplet transmission depends on the distance the droplets travel when ejected. The distance the droplet travels depends on the size of the droplet and the ejection velocity. A transfer distance of 1–2 metres is typical for droplets, and droplet transmission under 2 metres is considered direct contact transmission.

Disease clusters for droplet transmission are similar to person-to-person contact, although it is possible for more friends or work colleagues to become infected. Usually when an infected individual becomes aware of their illness, they remain at home, minimising the chance of transfer. This can result in a cluster similar to person-to-person contact because only family, close friends or carers spend time with infected individuals once they are aware.

Airborne transmission

If a pathogen can remain in the air for a long period of time and can travel more than 1–2 metres, it is classified as airborne. Airborne pathogens can travel further than pathogens carried by droplets, usually transferring diseases within closed facilities or buildings to other parts or rooms. They can also remain in the air for a long time, so pathogens can be transferred to susceptible individuals after an infected person is gone. Often pathogens are carried on dust or fine particles, known as aerosols, and can travel large distances over long periods of time.

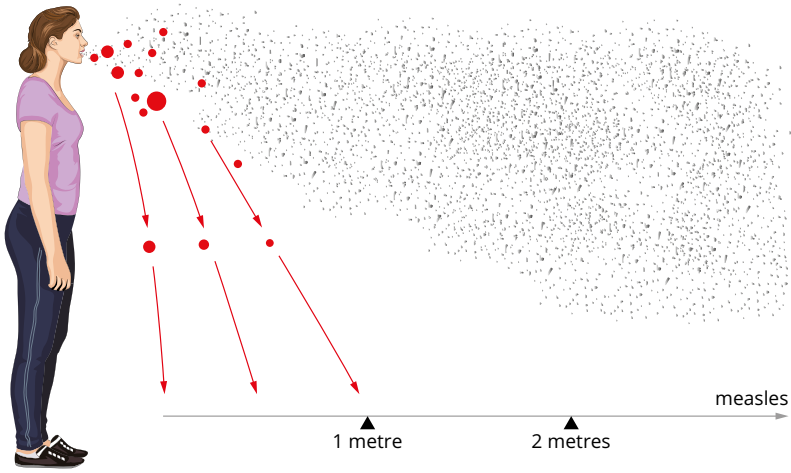


FIGURE 9.1.5 Measles (rubeoloa) virus is an airborne pathogen that is found in tiny droplets and remains in the air for extended periods of time and can travel large distances.

Disease clusters for airborne pathogens can often be found at locations where infected individuals have visited. Often a person will visit a site while infectious but before symptoms are present. This means transfer can occur at many locations and affect many people following an infected person's movements. The clusters can be traced along movement patterns and may develop a time line. Measles (rubeoloa) virus is an airborne pathogen that is found in tiny droplets that remain in the air for extended periods of time and can travel large distances of up to 10 metres (without assistance from wind or airflow). Figure 9.1.5 illustrates the transfer of the measles virus.

Transmission through contaminated objects

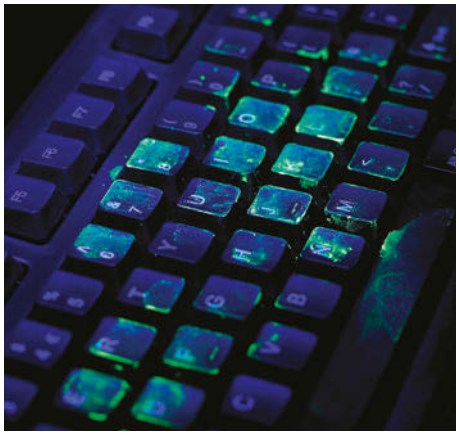


FIGURE 9.1.6 Ultraviolet light showing bacteria (illuminated in green) on a computer keyboard

Infected individuals can eject droplets or touch inanimate objects, transferring the pathogen to the object. Some of these objects allow the pathogen to live or can transfer infectious pathogens to susceptible individuals. Objects or materials that can carry pathogens are called **fomites**. Fomites do not sustain living pathogens indefinitely and the window of opportunity for infection is limited. When a susceptible individual touches the fomite and receives the pathogen, they then usually need to transfer the pathogen to a point of entry for transmission to occur. A computer keyboard is an example of a fomite (Figure 9.1.6), transferring bacteria from an infected person to another. The recipient may then transfer the bacteria to an opening by rubbing their eyes or nose.

Although disease transmission and spread through fomites can be traced, it is difficult to assert with confidence. Health and disease organisations and professionals can ascertain the presence of pathogens at a location, but many variables affect whether it was transmitted. Such variables include personal and organisational hygiene practices, climate, airflow facilities, and possible effective contact.

Transmission through food and drinking water

Food and water (especially drinking water) are known as vehicles to transport pathogens (Figure 9.1.7). The sharing of food and water with an infected person, including before they realise they are infected, can transmit disease directly to the internal environment of a susceptible person. Poor sanitation methods (both personal hygiene and community infrastructure) allow pathogens to be transported great distances.

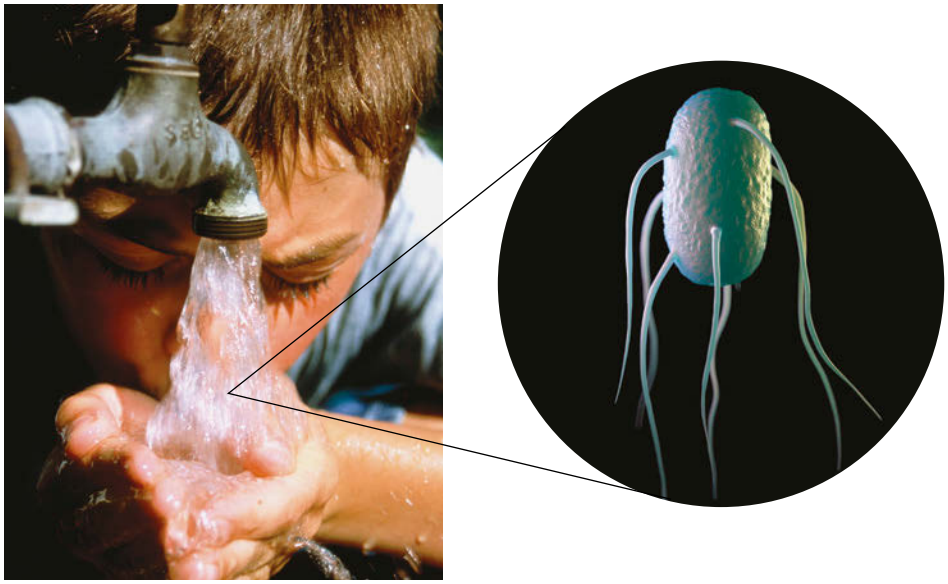


FIGURE 9.1.7 This boy is drinking water contaminated with *Salmonella* bacteria. Many countries do not have clean or filtered drinking water; disease from unboiled water is common.

Animal-to-person transmission

Animal-to-person contact transmission of infection is similar to person-to-person direct contact. Some pathogens can infect and cause disease in both animals and humans. The transfer may occur through a scratch or bite as well as from skin to skin. Figure 9.1.8 shows the results of two animal bites.

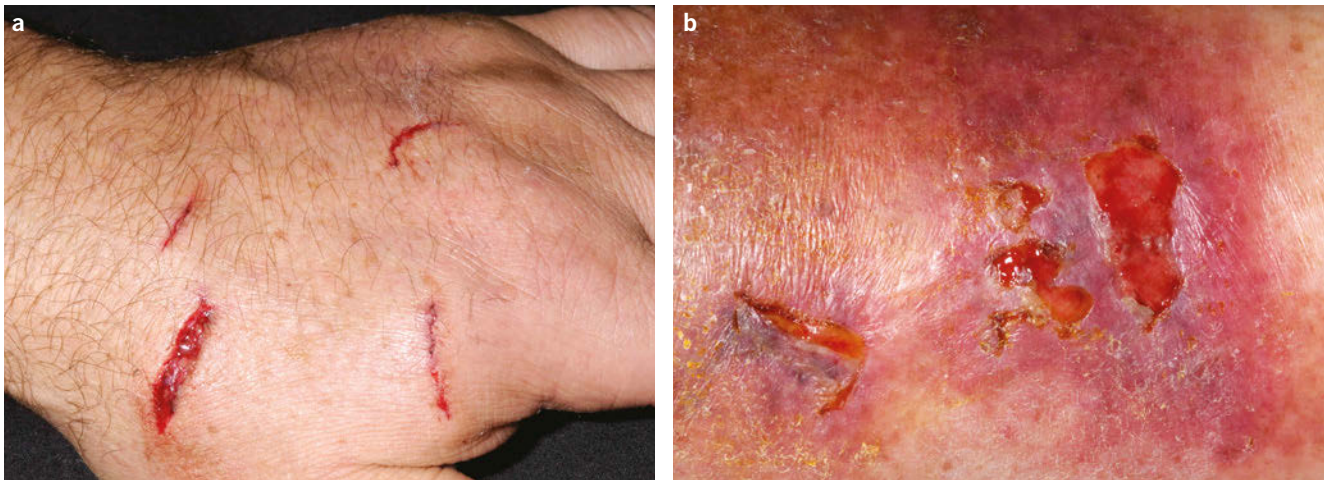


FIGURE 9.1.8 (a) This animal bite has resulted in a slight infection. (b) This bite has caused a mild infection.

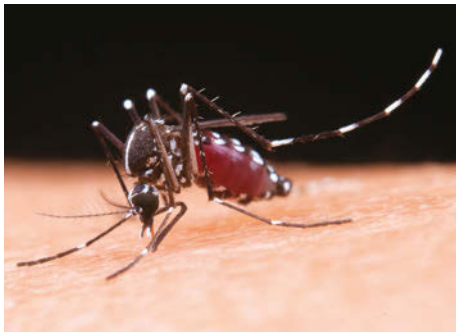


FIGURE 9.1.9 Mosquitoes can carry numerous pathogens because they feed on the blood of hosts, transferring blood containing pathogens from one person to another.

Vectors

Vectors are organisms that transfer a pathogen from an infected individual to a susceptible individual. Common vectors are insects such as mosquitoes (Figure 9.1.9), ticks, fleas and lice, also rats, cattle, cats and dogs. Often vectors carry the pathogen but are not diseased. Insects often draw fluid (e.g. blood) from an infected host and then move on to another person who may be susceptible, thus transferring the pathogen.

Researchers are interested in the route of vector transmission, some of which can be quite complicated. For example, pathogens from infected individuals can be found in fecal matter or waste, which vectors may access or feed on. Pathogens are then transferred when the vector comes into contact with a susceptible host. Other routes involve vectors increasing in number during certain seasons, or when particular environmental conditions exist. Some routes include vector-to-vector transfer before reaching a human host. As human population density increases, so does the number of possible links in the transmission chain, enabling pathogens, and the disease, to spread further.

To consider disease transmission via vectors, the life cycle of the vector also needs to be studied. As such, treating disease spread by vectors can be significantly influenced by treating the vector itself. For example, the *Plasmodium* parasites that cause malaria are spread by mosquitoes; the use of insect repellent and guarding against mosquitoes in malaria-prone environments helps to reduce the spread of malaria. The Lyme disease cycle in Figure 9.1.10 illustrates how the bacterium *Borrelia burgdorferi* is transferred through the tick vector. The cycle is complex and involves many organisms and opportunities to transfer to humans. This cycle is 2 years long and is seasonal, with the seasons colour-coded in the diagram: spring (green), summer (yellow), autumn (orange) and winter (blue-grey). In some instances, the complexity of the transmission route can also include a vector transferring the pathogen to fomites or other animals, which eventually come in contact with a susceptible human.

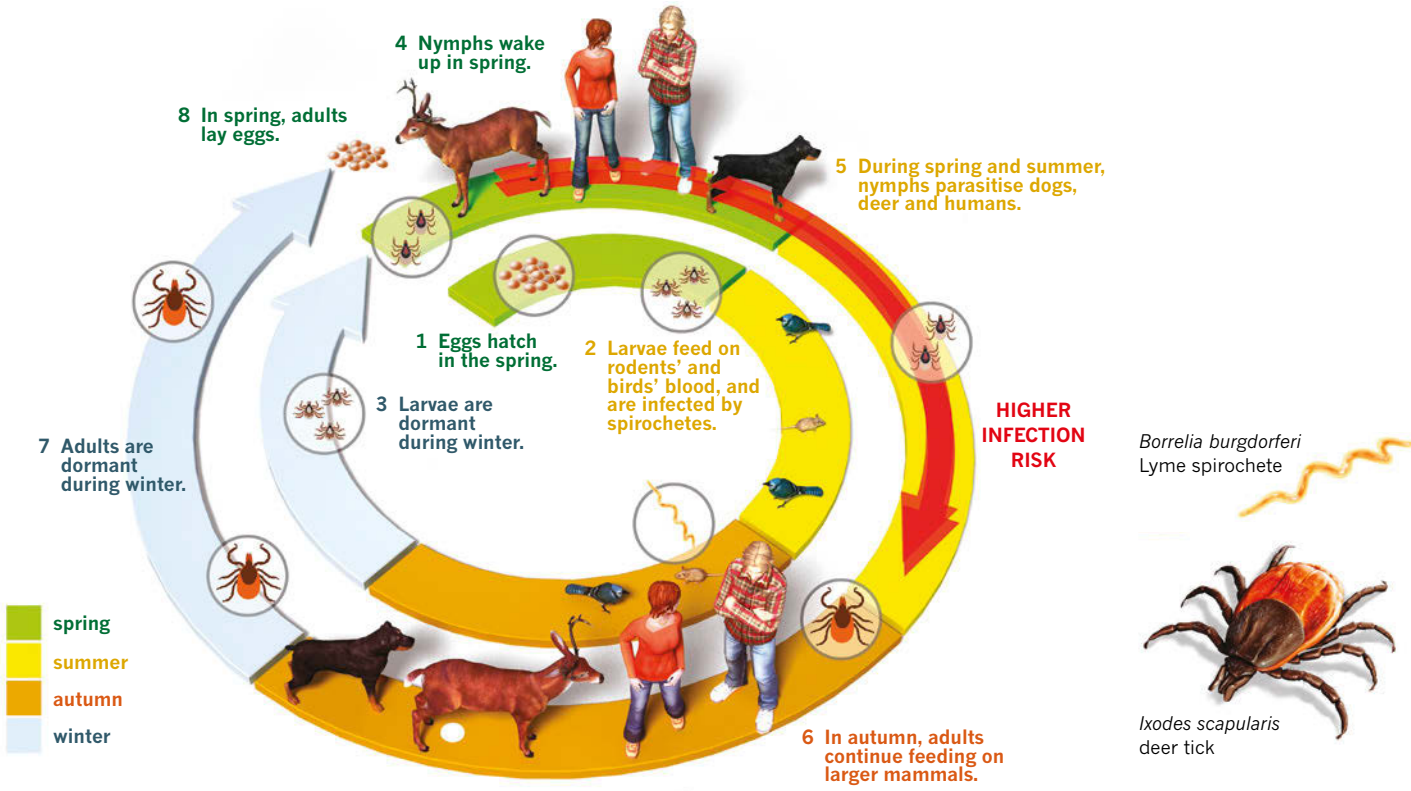


FIGURE 9.1.10 Diseases that are transferred through vectors can have complex cycles and pathways. This Lyme disease cycle illustrates how the bacterium *Borrelia burgdorferi* (right) is transferred through the tick vector.

Disease clusters for vector-spread pathogens can be found around communities with poor sanitation, and near vector population hot spots and breeding grounds. The most prolific vectors are humans. The increasing regional and global movement of humans is causing new patterns of disease clusters and transmission routes.

Environmental reservoirs

Reservoirs in the environment can be anything that can harbour or store pathogens or vectors, such as the water reservoirs in Figure 9.1.11. Soil, water and vegetation can all harbour pathogens or vectors, which can be transmitted to people either directly or indirectly. As this is location based, clusters of disease typically occur in relation to a location.

Regional spread of disease

The spread of disease in local regions has always been considered closely linked to distance. An example of the relationship between distance and disease transmission is the Philadelphian typhoid epidemic in the USA in the late 1800s to early 1900s. Clusters of typhoid formed along water supply infrastructure and in households, maintaining a correlation between the source and distance. In recent times, the spread of disease has increasingly correlated to transport systems, including road networks and airports. Disease is also known to spread through social networks, and spread is affected by accessibility to source, infrastructure contamination and transport of the pathogen. Factors that can affect the rate of infection and transmissibility include temperature and humidity, precipitation, airflow and ventilation, hygiene practices, and human behaviour.

Disease vehicles can cause both localised and regional clusters of infected individuals. The clusters may follow infrastructure systems (as occurred during the Philadelphian typhoid epidemic discussed above). Clusters can also be seen along travel routes (air and sea where food is served or shared) or in places of large gatherings (e.g. cruise ships and conferences).

FIGURE 9.1.11 Water reservoirs provide both nutrients and a reproductive environment for pathogens and vectors.

Usually the spread of disease is due to many factors, and research into a local case at the location of outbreak reveals numerous methods and mechanisms of transmission that are often unique to the case. Although the exact details of all transmissions in a case cannot be determined, models are developed based on recorded data to infer a likely scenario and plausible explanation. Many similarities are found between cases, though it is rare to find two identical cases of disease transmission. Hence, distance is often (though not always) a factor that is most often strongly correlated to disease transmission. Data must be analysed, along with maps and transport systems to try to interpret and understand the methods and spread of disease.

Global spread of disease

As modes of transport, including air, sea and land, continue to develop, the speed of travel increases as well as the number of people travelling. This means all vectors, especially humans, and pathogens are moving further, faster and in greater numbers. Notable increases in transport are shown in Table 9.1.2. Advances in transport have also caused a noticeable increase in the global contact of flora and fauna between continents and regions, especially by individuals from wealthy nations. Growth across the globe in human migration, tourism and economic activity is leading to continual increases in the movement of both disease vectors and the number of diseases.

TABLE 9.1.2 Increases in worldwide transport and associated vectors

Transport industry	Increase	Time	Transported vectors and/or disease
commercial airline passengers	9% per year	since 1960	• severe acute respiratory syndrome (SARS) • cholera • influenza • yellow fever • dengue • malaria
airfreight	about 9% per year	since 1960	
shipping	27%	since 1993	• fleas • lice • kissing bugs • mosquitoes (especially *Aedes aegypti*, *Culex pipiens complex*, *Aedes albopictus*)

MEASURING THE SPREAD OF DISEASE

Organisations concerned with local and worldwide disease and health include the World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC). WHO and the CDC have published many articles correlating global economic activities, as well as tourism and human migration, to an increasing number of cases in the movement of both disease vectors and the diseases they carry worldwide. Historically, trade routes, seaports, exploration and travel by horseback or on foot through villages have been strongly correlated to the spread of disease and **pandemics** (outbreaks of diseases across large regions). Animal vectors can also contribute to or sometimes cause pandemics.

Rate of disease transmission: R_0

Because of the complexity of disease spread, transmission is usually measured first by the incidence of infections and rate of disease spread, not the mode of transmission or other factors. The ability of a disease to spread, and how infectious it is, is measured by the basic **reproduction number (R_0)** (pronounced 'R nought'). R_0 is a measure (or estimation) of how many people will contract a disease from the person who is the primary source. R_0 is the number of **secondary infections** produced by a single case of infection, in a population where the disease does not exist and therefore where individuals in the population are vulnerable. This is shown in Figure 9.1.12.

R_0 is measured by counting the number of secondary cases following the introduction of an infection into a totally susceptible population. If R_0 is 7, it means that approximately seven people will become infected from coming into contact with a diseased person. Subsequently, every new case of the disease will result in seven new secondary cases. The R_0 of several infectious diseases can be seen in Table 9.1.3. R_0 can be used to predict outbreaks and pandemics. When:

- $R_0 > 1$, then transmission is increasing and an outbreak is possible
- $R_0 \approx 1$, then transmission is stable
- $R_0 < 1$, then transmission is decreasing and the disease is going into extinction (in the local region).

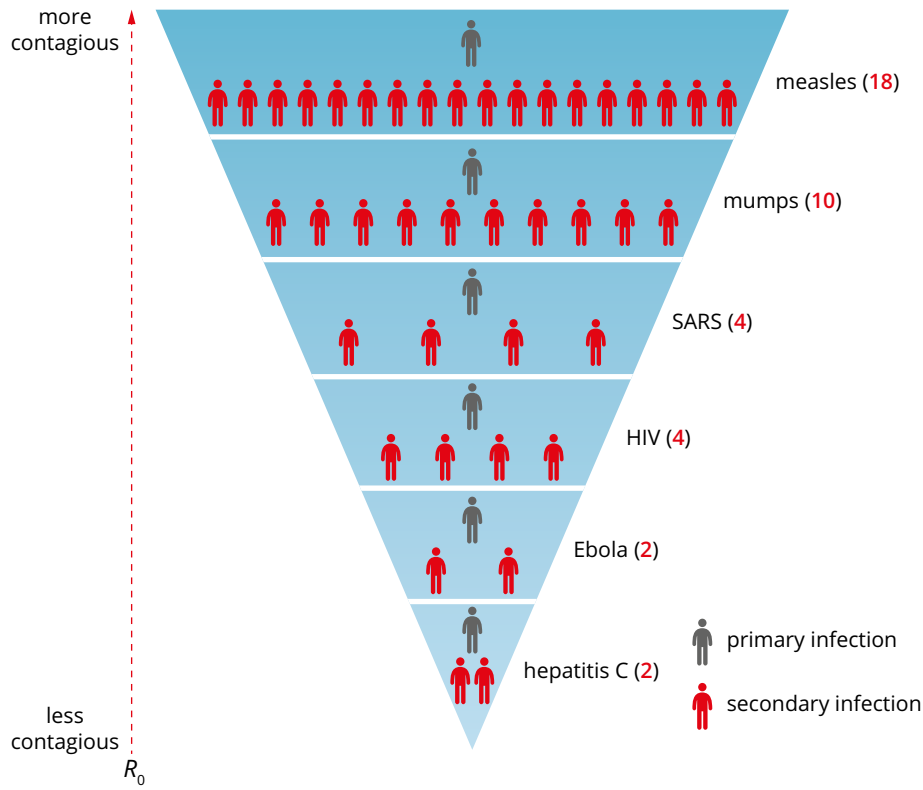


FIGURE 9.1.12 R_0 for some diseases. The numbers of secondary infections that are typically caused by a single person are shown in parentheses.

TABLE 9.1.3 Estimated R_0 values for some well-known or common infectious diseases

Disease	Mechanism of transmission	R_0
measles	airborne	12–18
diphtheria	droplet	6–7
small pox	airborne	5–7
rubella	airborne	5–7
mumps	airborne	4–10
HIV/AIDS	person-to-person	2–5
pertussis (whooping cough)	airborne	5.5
SARS	airborne	2–5
influenza (1918 pandemic strain)	airborne	2–3
Ebola (2014 Ebola outbreak)	person-to-person	1.5–2.5

Disease does not always spread when people come into contact with or are in proximity of transmission. Only some people may fall ill, resulting in a secondary infection, as shown by the R_0 values.

Several factors affect the rate of secondary infections, and the calculation of R_0 depends on the:

- length of time an individual is infectious
- probability of transmitting the infection to a susceptible individual during a single contact
- rate of new individuals contacted.

The estimated R_0 is not always the same for a specific disease across locations or over time. This is because the factors that effect the calculation of R_0 change. For example, a disease may have a larger R_0 value in a densely populated area than in a sparsely populated area. Also, different strains of the same disease may have different levels of **virulence**, which will affect the calculated R_0. Standards of hygiene, education and infrastructure can also affect calculated R_0 values. Likewise, not all individuals who fall ill require medication or seek medical aid, so some R_0 values are measured from recorded cases while others are estimated. Table 9.1.4 shows the R_0 values for two strains of influenza at different times and locations.

TABLE 9.1.4 Estimated R_0 for the H5N1 strain of the influenza virus

Year(s)	Subtype	Location	R_0
1976	H1N1	New Jersey, USA	1.20
2004–2006	H5N1	Vietnam	0.00
2004–2006	H5N1	Indonesia	0.00
2005	H5N1	Turkey	<1
2009–2009	H5N1	Indonesia	0.1–0.25
2006	H5N1	Indonesia	1.14

Pathogen persistence

One of the many factors that influence the spread of disease is the persistence of pathogens to infect a host. Within a host, pathogens can lie dormant for extended periods of time and remain inactive until triggered, or they can have various periods of time in which they are infectious. Each pathogen has its own infectious characteristics due to reproduction rates, toxicity, virulence and other factors. Tables 9.1.5 and 9.1.6 show the length of time some bacterial and viral pathogens persist.

When analysing a case of disease transmission, it is very important to identify the pathogen. It is important to know the pathogen and understand its characteristics and mechanisms of transmission. Knowing such factors helps researchers studying patterns in the spread of disease.

REDUCING TRANSMISSION

You will recall that in Chapter 8 specific details about innate and adaptive immunity as well as vaccinations and immunisation were explained. Immunity and immunisation programs have been shown to decrease disease transmission and decrease the spread of disease through communities as well as across regional and international borders. Many methods and strategies are used to decrease the transmission and spread of disease, including medicine and personal health care, disinfectants and aseptic techniques, personal hygiene and infrastructure sanitation, food and water supply, using pesticides and killing vectors. However, the most effective method and strategy to control the transmission and spread of disease has been immunisation.

TABLE 9.1.5 The length of time various bacteria can remain pathogenic on inanimate objects

Bacterium	Disease(s) caused by bacterium	Duration of persistence
Acinetobacter spp.	pneumonia, meningitis	3 days to 5 months
Bordetella pertussis	whooping cough	3–5 days
Campylobacter jejuni	campylobacteriosis	up to 6 days
Clostridium difficile (spores)	*C. difficile*	5 months
Chlamydia pneumoniae, C. trachomatis	chlamydia	≤30 hours
Chlamydia psittaci	chlamydia	15 days
Corynebacterium diphtheria	diphtheria	1 week to 6 months
Escherichia coli	gastroenteritis	1.5 hours to 16 months
Helicobacter pylori	peptic ulcers, gastritis	≤90 minutes
Klebsiella spp.	pneumonia	2 hours to >30 months
Listeria spp.	listeriosis (food poisoning)	1 day to months
Mycobacterium bovis	tuberculosis (TB)	>2 months
Mycobacterium tuberculosis	tuberculosis (TB)	1 day to 4 months
Neisseria gonorrhoeae	gonorrhea	1–3 days
Proteus vulgaris	urinary tract infections	1–2 days
Salmonella typhi	typhoid fever, food poisoning, gastroenteritis	6 hours to 4 weeks
Staphylococcus aureus, including methicillin-resistant *S. aureus* (MRSA)	impetigo, food poisoning, cellulitis, toxic shock syndrome	1 week to 7 months
Streptococcus pneumonia	meningitis, peritonitis, sinusitis	1–20 days
Vibrio cholera	cholera	1–7 days

TABLE 9.1.6 The length of time various viruses can remain pathogenic on inanimate objects

Virus	Duration of persistence
adenovirus	7–90 days
astrovirus	7–90 days
coronavirus	3 hours
SARS associated virus	3–4 days
coxsackie virus	>2 weeks
cytomegalovirus	8 hours
echovirus	1 week
hepatitis A virus (HAV)	2 hours to 60 days
hepatitis B virus (NBV)	>1 week
human immunodeficiency virus (HIV)	>1 week
Herpes simplex virus, type 1 and 2	4.5 hours to 8 weeks
influenza virus	1–2 days
norovirus and feline calici virus (FCV)	8 hours to 1 week
papillomavirus 16	>1 week
papovavirus	8 days
parvovirus	>1 year
poliovirus type 1	4 hours to 8 days
poliovirus type 2	1 day to 8 weeks
pseudorabies virus	≥7 days
respiratory syncytial virus	up to 6 hours
rhinovirus	2 hours to 7 days
rotavirus	6–60 days
vacciniavirus	3–20 weeks

Population/herd immunity

You will recall that Chapter 8 explained how innate and adaptive immunity develops to form antibodies that provide a highly tuned response to infection by pathogens. Individual immunity can minimise or prevent disease even when acquiring a pathogen. Immunity that is achieved by a critical portion of a community (i.e. a critical number of the population) that results in most individuals in the community being protected against a disease is called **community immunity**, or herd immunity (see Module 8.3). The critical number of the population required to achieve herd immunity depends on many factors, such as the R_0, population susceptibility and mechanism of transmission.

Herd immunity is achieved by exposing a critical portion of the community to a pathogen, or modified strain of a pathogen, so each individual develops a personal immunity. Personal immunity decreases the time a pathogen is infectious within a host and also decreases the number of pathogens that reproduce within the host. Together, these factors decrease the ability to infect and spread a disease, helping to maintain the health of the wider community.

Because many factors influence disease transmission and humans are the most potent vectors, human preventative measures are the most successful way of combating disease transmission. Research shows the most effective, efficient and safe way to achieve this is through vaccines. The more people who are vaccinated, the less chance there is of an infectious pathogen spreading throughout a population. Herd immunity results in less disease in the community, less severe infections (in general) and protection for individuals for whom other methods of protection are too risky, including the young, elderly, pregnant, ill and **immunosuppressed**. Achieving immunity of a critical portion of a population changes the status of the population from susceptible to protected.

Figure 8.3.17 (Module 8.3) shows how herd immunity works. An infectious person will come into contact with people through their daily schedule. Depending on the R_0, a number of secondary infections will occur. R_0 decreases significantly when large portions of a community are immunised, thus protecting most of the community.

The people in a population who are at higher risk of disease and benefit from herd immunity are:

- young children—their immune systems (innate and adaptive) are still developing as they grow, and disease often strikes this portion of the population with greater severity and higher **morbidity** rates
- the elderly—their immune systems become less efficient and effective as people get older and so elderly people are more susceptible to disease
- pregnant women—a large immune system response during pregnancy can cause deformities or fatally harm the growing baby
- individuals who are already ill—these people have a suppressed immune system (which can also be caused by medication), so are more susceptible to disease.

For these reasons, herd immunity can protect most people in a community.

In 1980, WHO declared that one of the world's deadliest diseases, smallpox, had been eradicated as a result of vaccines and herd immunity. Smallpox (variola virus) is transmitted by droplets (direct contact transmission). The last known natural case was in Somalia in 1977.

Immunisation coverage

Immunisation coverage is the proportion of the population that has been vaccinated against a particular disease. Epidemiological studies and organisations attempt to calculate the immunisation coverage required to protect the rest of the community as illustrated in the example in Figure 9.1.13.

Figure 9.1.13 displays **herd immunity thresholds** required to protect a community from disease outbreaks in common diseases. The R_0 values are provided as a range due to the multiple variables involved in disease transmission. Even though many variables are involved, the R_0 value is somewhat consistent across numerous communities and continents. Also notable is the correlation between R_0 and herd immunisation threshold.

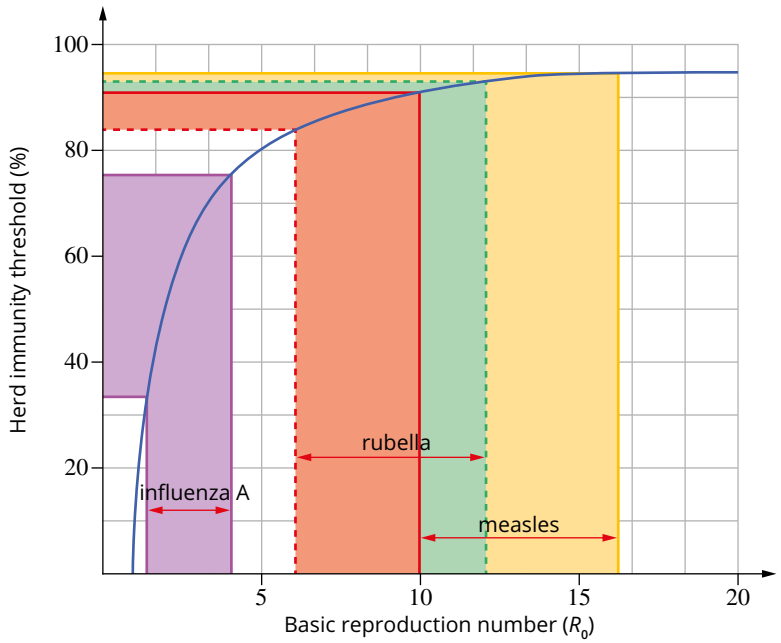


FIGURE 9.1.13 Using typical R_0 values across numerous community cases of disease spread for influenza A, rubella and measles, immunisation coverage has been estimated (modelled) in order to determine a proposed critical portion of the community (herd immunity threshold) that would protect the rest.

PA 2.2.1

TABLE 9.1.7 Calculated estimates for the immunisation coverage needed in a population to protect the community from outbreaks

Disease	R_0	Herd immunity threshold (%)
diphtheria	6–7	85
measles	15–16	83–94
mumps	4–7	75–86
pertussis	12–17	92–94
polio	5–7	80–86
rubella	6–7	83–85
smallpox	5–7	80–85

Table 9.1.7 illustrates the correlation between vaccination (immunisation) coverage and R_0 values for common diseases.

Table 9.1.8 shows the result of a study of the spread of mumps across numerous primary schools in the Netherlands. There is a general trend in the overall attack rate (number of people diagnosed with the disease per population sample) that correlates with the vaccination coverage. As can be seen from the data, the correlation between overall attack rate and vaccination coverage is similar to the estimates of R_0 in Table 9.1.7. The data implies that herd immunity can be achieved at about 78% vaccination coverage or higher.

TABLE 9.1.8 The spread of disease (mumps) across ten primary schools in the Netherlands

	Number of people	Number infected	Vaccination coverage	Attack rate in unvaccinated people	Attack rate in vaccinated people	Overall attack rate
All schools	2493	510–1342	0.62	0.68 (485/709)	0.03 (25/952)	0.31
School 1	432	205–369	0.12	0.86 (204/237)	0.03 (1/31)	0.76
School 2	338	135–289	0.13	0.82 (131/160)	0.17 (4/24)	0.73
School 3	259	68–159	0.42	0.72 (68/94)	0 (0/74)	0.40
School 4	184	40–70	0.54	0.53 (37/70)	0.04 (3/84)	0.26
School 5	130	13–33	0.75	0.46 (13/28)	0 (0/82)	0.12
School 6	263	28–171	0.76	0.70 (19/27)	0.10 (9/93)	0.23
School 7	194	6–43	0.78	0.19 (6/31)	0 (0/126)	0.04
School 8	227	3–27	0.79	0.05 (2/41)	0.01 (1/162)	0.01
School 9	258	6–119	0.93	0.18 (2/11)	0.03 (4/134)	0.04
School 10	208	6–62	0.93	0.30 (3/10)	0.02 (3/142)	0.04

CASE STUDY 9.1.1

Measles outbreak in Western Sydney, April 2017

In April 2017, the New South Wales Government department of health (NSW Health) reported a measles outbreak in Western Sydney. The number of confirmed cases of locally acquired measles cases associated with the outbreak was 16.

The cause of the locally acquired cases was most likely a single person who was infected with the disease in Indonesia and spent time in the Western Sydney region while infectious.

In the latest case, a man who was infected by an earlier case at Quakers Hill on 28–30 March, spent time in Lawson, Strathfield and Leichhardt on 10 April, and later on 14 April went to the Blue Mountains Hospital where he was isolated and recovered.

On the day of 10 April, he visited the Uniting The Marion Aged Care Facility in Leichhardt, the Me Oi Vietnamese restaurant in Strathfield, and the Lawson shops in the Blue Mountains. He revisited the shops on 13 April. Typical infections result in a rash on day 14, and infected people are usually contagious from 4 days before until 4 days after the onset of the rash. The infected individual presented themselves to the hospital on 14 April, the third day he had a rash.

Vicky Sheppeard, director of communicable diseases with NSW Health, released a press statement regarding this case, stating that isolation of infected individuals is the best method to combat any further outbreak.

Review

1. State the mechanism of transmission for measles. (Hint: Use Module 9.1.)
2. Outline the range of dates from Table 9.1.9 in which people could have been infected and contracted the measles in this case.
3. Predict the susceptible populations from Table 9.1.9 that could be at risk from this case. Support your prediction with adaptive immunity concepts.
4. NSW Health issued a statement releasing the details of all locations visited by the latest case (Table 9.1.9). Knowing that the infection was transmitted in Quakers Hill, explain why it was important to release this information.
5. Write an appraisal of Vicky Sheppeard's press release regarding isolation by detailing implications and limitations.

TABLE 9.1.9 The timeline of all locations visited by the latest infected case of measles in Western Sydney

Date	Location
18 April	Casula Central Medical Centre and Chemist Warehouse, Casula approx. 10am
15 April	Blacktown Hospital, approx. 7.30–8 pm
13, 15 and 17 April	Liverpool Westfield, including an optometry practice
14 April	Rashays, Darling Harbour (later in the afternoon)
14 April	Powerhouse Museum (early afternoon)
10 and 13 April	Lawson shops, Lawson
10 April	Uniting The Marion Aged Care Facility, Leichhardt
10 April	Me Oi Vietnamese restaurant, Strathfield
8 April	Virgin flight VA965, Sydney to Brisbane
7 April	Local train and bus travel in western Sydney area
28 March to 4 April	Auburn area, including Pharmacy 4 Less
3 April	NAS Advanced Medical Centre, Auburn
1 April	Michel's Patisserie, Auburn
1 and 2 April	The Children's Hospital emergency department
1 April	Fairfield Hospital emergency department
28–30 March	Wyndham College, Quakers Hill
28–30 March	Local train between Flemington and Quakers Hill
26 and 31 March	Fairfield District Medical Centre
26 and 28 March	Tweed Hospital emergency department, Tweed Heads
26 March – 11 am–12.30 pm	Hillsong Church, Bella Vista

CASE STUDY 9.1.2

Measles outbreak originating from Disneyland, USA, December 2014

Figure 9.1.14 shows the confirmed cases of measles reported to the California Department of Public Health from a single original infection. All cases were traced back to the original infection in Disneyland on 16–21 December, in which rash onset was 16 December.

A total of 110 California residents were confirmed to have measles between 27 December and 8 February. Thirty-nine visited one or both of the two Disney theme parks during 17–20 December, where it is thought they were exposed to measles. Thirty-four are secondary cases from the first wave of 38 infections, while 37 have an unknown exposure source. Twenty-six of the 34 secondary cases were household or close contacts, and eight received the virus in a community setting. Five of the California patients reported being in one or both of the two Disney theme parks during their exposure period outside of 17–20 December, but their source of infection is unknown.

Among this outbreak of the 110 patients, a total of 96 were either unvaccinated or had unknown or undocumented vaccination status for measles. Within this group, there were 12 infants who were too young to be vaccinated. The infected patients were of various ages, ranging from 6 weeks to 70 years.

Review

1. Provide a plausible model that shows three waves of infections for the outbreak from Disneyland in December 2014, including dates (or date ranges) to February 2015, using information from case studies 9.1.1 and 9.1.2.
2. Estimate the number of initial infectious individuals who may have caused the measles outbreak from Disneyland, assuming the reported R_0 of 15–16 by the CDC for measles.
3. Research the vaccination rate for measles in California and predict the spread of disease after 8 February.
4. Estimate the total number of exposed local individuals in Disneyland during 16–23 December, using the vaccination rate for measles in California.
5. Identify the limitations to estimating the number of individuals exposed in Question 4.

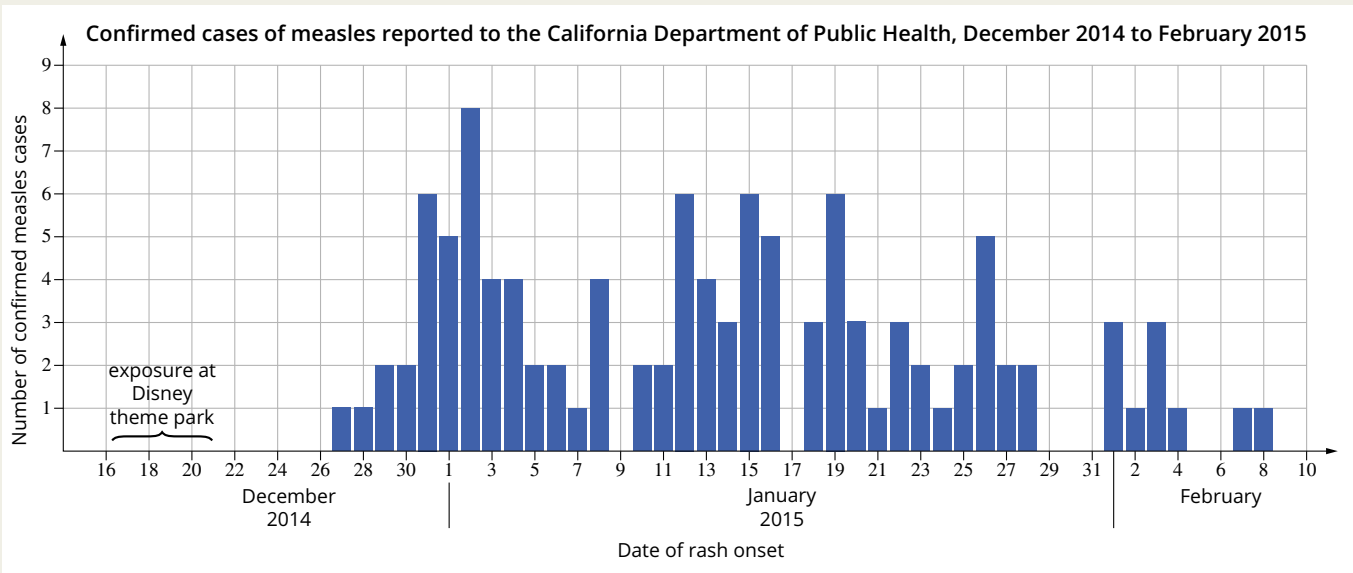


FIGURE 9.1.14 The confirmed cases of measles reported to the California Department of Public Health from December 2014 to February 2015

CASE STUDY 9.1.3

MERS outbreak in South Korea originating in Saudi Arabia, June 2015

MERS (Middle East respiratory syndrome) is a viral respiratory illness caused by the coronavirus (Figure 9.1.15). Coronaviruses are common throughout the human population and most people contract them at some point. However, usually only mild to moderate flu-like symtpoms develop (Figure 9.1.16). The MERS coronavirus is new to humans and was first discovered in 2012 in Saudi Arabia. Most people who contract the MERS coronavirus develop a severe respiratory disease. However, a small number have mild or no symptoms.

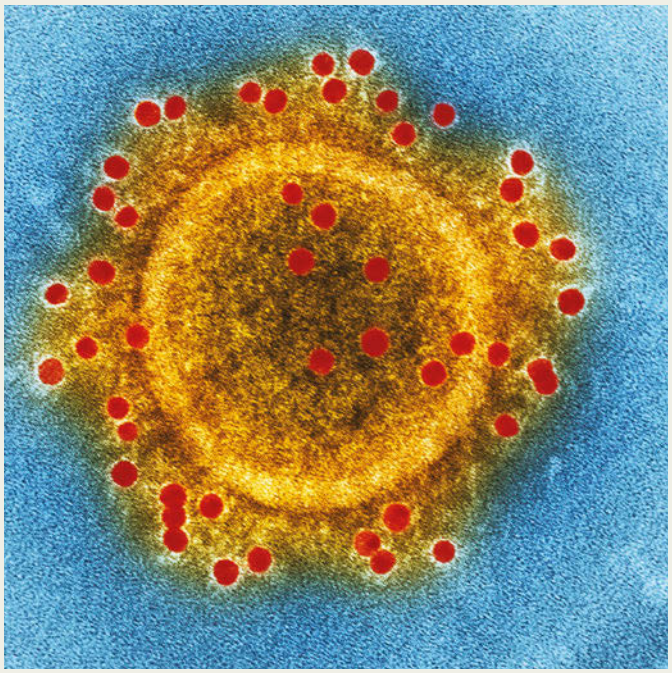


FIGURE 9.1.15 A coloured transmission electron micrograph of a MERS coronavirus (MERS-CoV) particle with antibodies (red spheres) attached to the viral envelope proteins

An infected case arrived in Seoul, South Korea, and visted three locations, St Mary's Hospital (Pyeongtaek), 365 Yeollin Clinic (Seoul) and Asan Seoul Clinic (also known as the Asan Medical Center, Seoul), shown in Figure 9.1.17. There was an outbreak of MERS at St Mary's Hospital (Pyeongtaek), including a total of 34 secondary and tertiary infections. An individual from St Mary's Hospital (Pyeongtaek) transmitted the infection to the Samsung Medical Center (Seoul) and the Goodmorning Hospital (Pyeongtaek). More than 60 infections were diagnosed at the Samsung Medical Center (Seoul). The first case of MERS was diagnosed in Seoul on 20 May, and the outbreak data was recorded on 12 June.

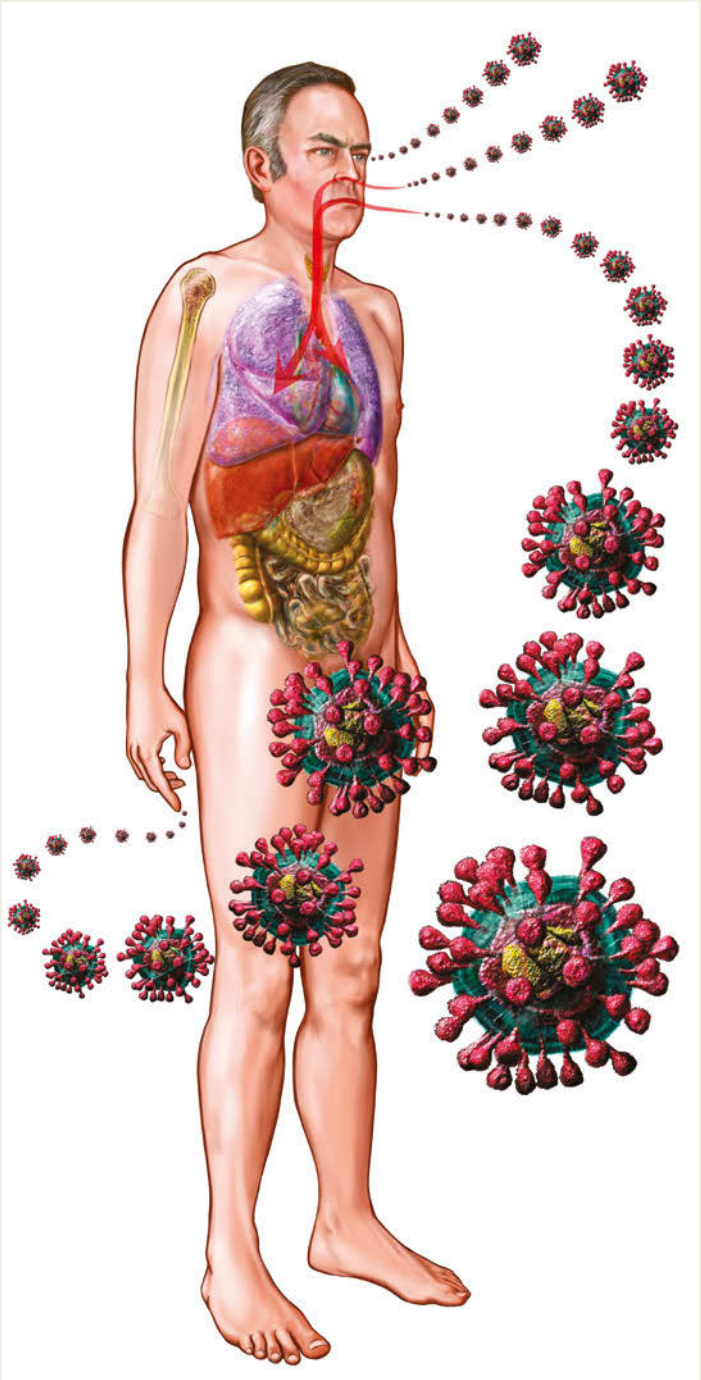


FIGURE 9.1.16 The MERS virus causes severe acute respiratory syndrome (SARS). It infects the lungs where it causes coughing, sneezing and watering eyes. This spreads the virus in liquid droplets through the air. It can also be contracted by touching contaminated surfaces or fluids.

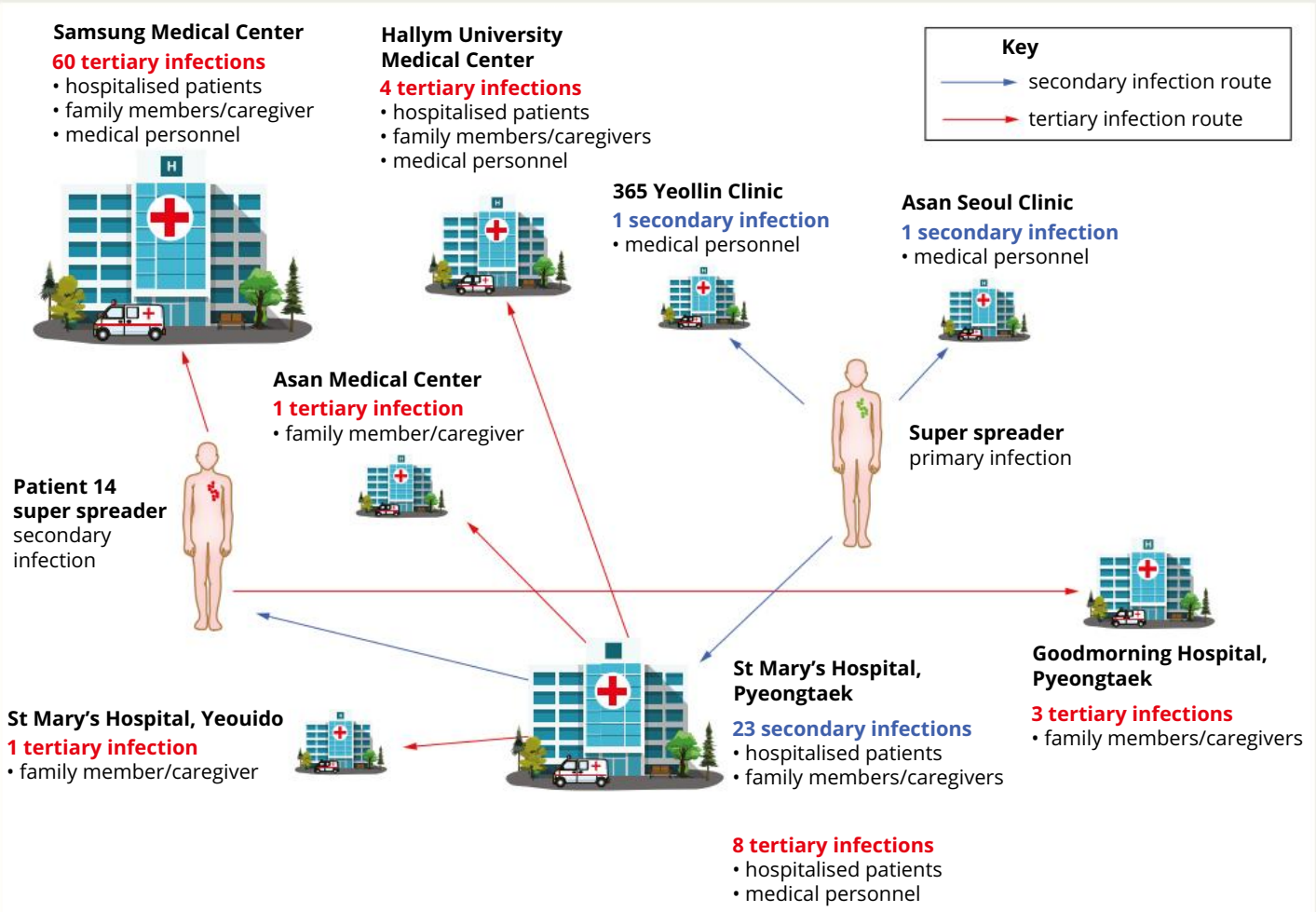


FIGURE 9.1.17 MERS outbreak in South Korea, June 2015. The data is represented as a schematic, showing the initial infectious individual (super spreader) in green, secondary infections in blue and tertiary infections in red.

Review

1 Specify the waves of infections from the evidence in Figure 9.1.17.

2 Provide a plausible reason, using your knowledge of adaptive immunity, for why the super spreader and patient 14 only caused one outbreak each.

3 Suggest a mechanism of transmission supported by:
- sufficient and relevant evidence
- relevant patterns (Question 1 or 2)
- a justified scientific argument using concepts of mechanisms of transmission.

4 According to WHO and the CDC, the transmission of MERS is not well understood. Current understandings of MERS transmission are that it is transmitted through direct contact, including droplets from coughing, although is not airborne. Health authorities and disease researchers in Seoul , South Korea, who studied MERS during the outbreak believe their data contradicts current understandings.
Identify the data the WHO and CDC would have observed to determine MERS is not airborne.

CASE STUDY 9.1.4

Influenza outbreak in Queensland, Australia, June 2017

In 2017, a new strain of the influenza virus spread across Australia, causing more hospitalisations and deaths than recorded previously. Figure 9.1.18 shows data from the Australian Government Health Department July report, which included data recorded up to 21 July. Before the next report was published, the Queensland Medical Association delivered updated data at a press conference on 11 August, stating that Queensland had recorded 14 455 cases since 1 January 2017 and in the past week more than 3500 new cases had been identified.

Review

1 Use Figure 9.1.18a,b to predict the number of influenza notifications in Queensland per week until week 52 of 2017.

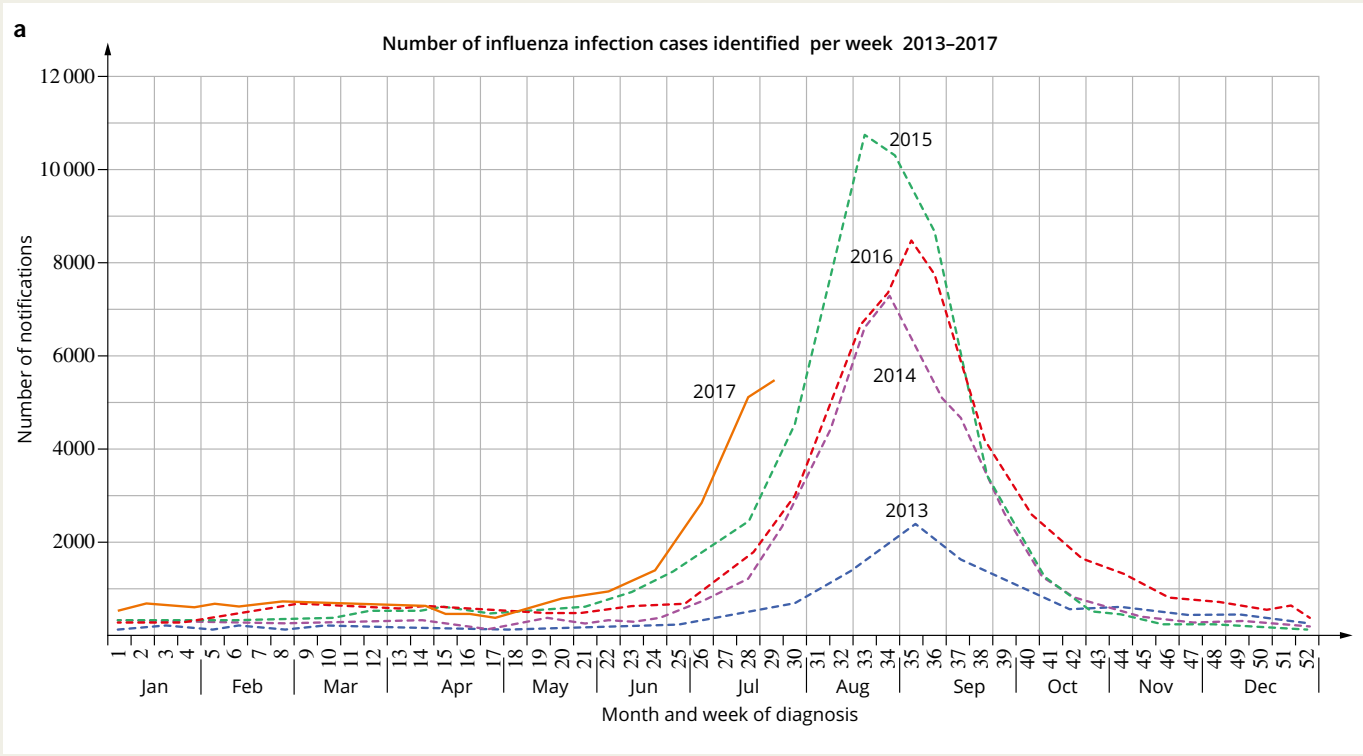
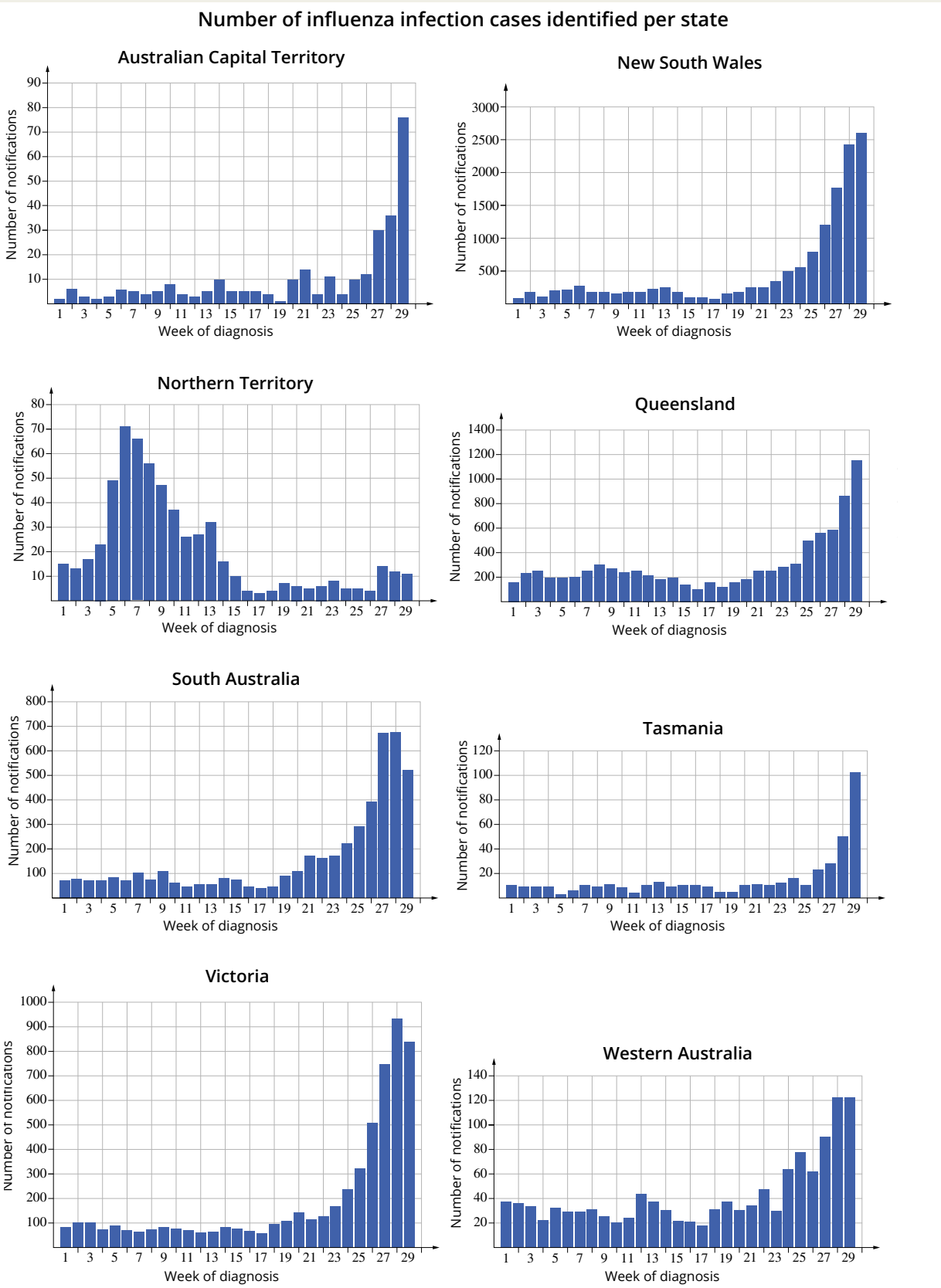


FIGURE 9.1.18 (a) Number of flu infection cases identified by health professionals from 2013 to 2017. (b) Number of flu infection cases identified per state by health professionals from 1 January to 21 July per week.

b


Number of influenza infection cases identified per state
Australian Capital Territory
Number of notifications
Week of diagnosis
New South Wales
Number of notifications
Week of diagnosis
Northern Territory
Number of notifications
Week of diagnosis
Queensland
Number of notifications
Week of diagnosis
South Australia
Number of notifications
Week of diagnosis
Tasmania
Number of notifications
Week of diagnosis
Victoria
Number of notifications
Week of diagnosis
Western Australia
Number of notifications
Week of diagnosis

CASE STUDY 9.1.5

Malaria epidemic in sub-Saharan Africa

Malaria is a disease caused by parasitic protozoans. It results in flu-like symptoms, fever, chills, headache and nausea. Left untreated, malaria can cause severe disease and death. WHO estimates that there were 188 million cases of infection in sub-Saharan Africa in 2015, 88% of the world's total malaria cases (214 million). WHO also estimates that malaria caused 394 000 deaths in sub-Saharan Africa. WHO stated that, at the time of their report, nine sub-Saharan African countries had reliable estimates of infections from medical clinics and regional programs.

The parasitic protozoan that causes malaria undergoes many stages in its life cycle, which requires at least two different organisms—humans and female *Anopheles* mosquitoes (Figure 9.1.19). In humans, the juvenile protozoans grow and multiply in the liver, where they mature. They can lie dormant in the liver for weeks or even up to 4 years before continuing their life cycle. Eventually, they multiply in the infected liver cells causing rupture, and the mature protozoans are released into the bloodstream. In the blood, they multiply asexually, eventually rupturing the red blood cells and releasing mature daughter protozoans.

The cycle continues, they invade other red blood cells and they increase in number. The mature protozoans also release male and female gametes into the blood.

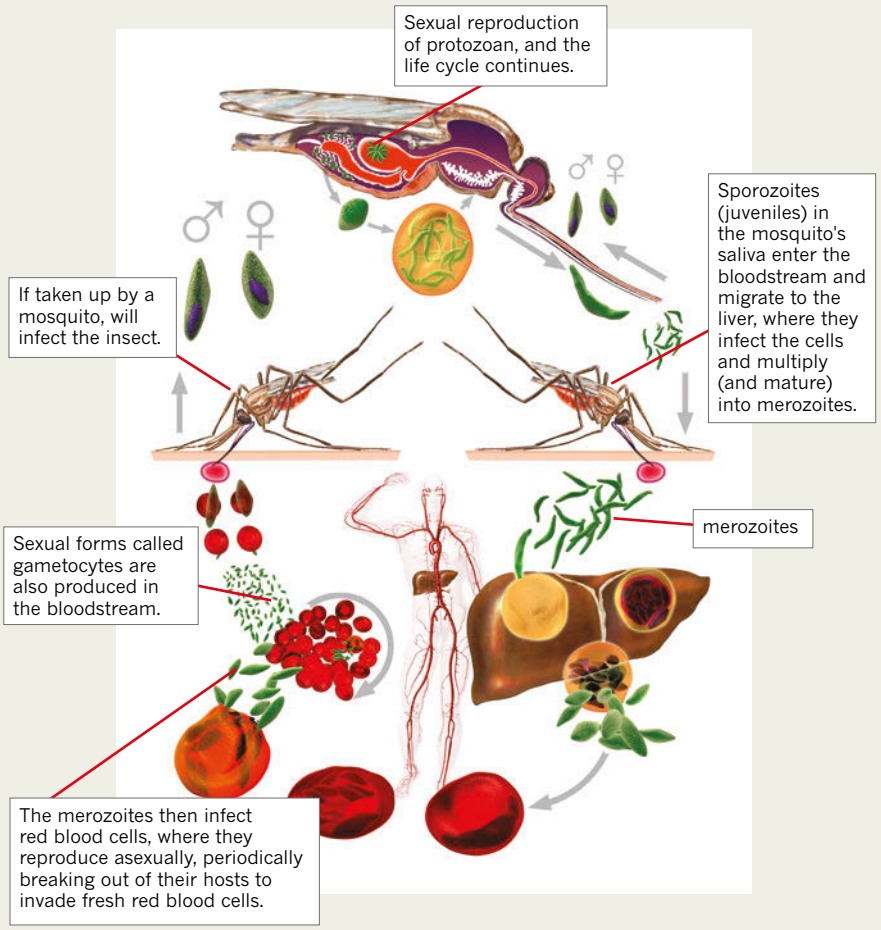


FIGURE 9.1.19 The protozoan life cycle is completed between mosquitoes and humans, which causes disease in humans.

While in the blood, the parasite causes symptoms such as anaemia, fever, chills, nausea, flu-like illness, coma and death. Also while in the blood, the female *Anopheles* mosquito (Figure 9.1.20) receives the protozoan gametes when feeding, and the cycle continues.

After 10–18 days, the parasites are found (as sporozoites) in the mosquito's salivary glands. When the *Anopheles* mosquito has a blood meal from another human, the sporozoites are injected with the mosquito's saliva and start another human infection when they parasitise the liver cells.

Thus, the mosquito carries the disease from one human to another (acting as a vector). Unlike the human host, the mosquito vector does not suffer from the presence of the parasite.

Malaria is treatable with medication, but the medication is costly and may have side effects after long-term use. A vaccine for malaria is not currently available although preliminary human trials are being conducted on a few potential vaccines. These are a couple complications related to dealing with the epidemic in sub-Saharan Africa.

FIGURE 9.1.20 A coloured scanning electron micrograph of *Anopheles gambiae*, female mosquito, the vector of malaria

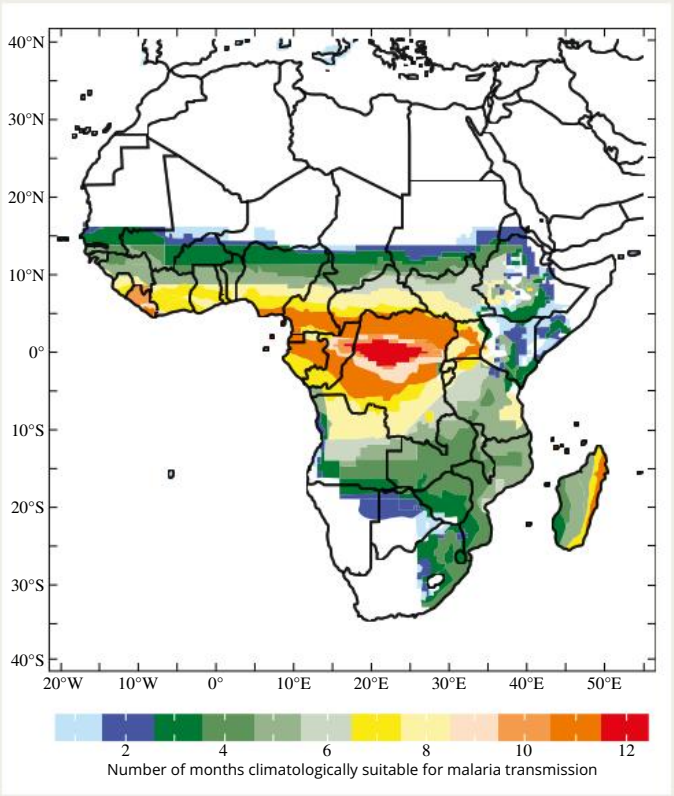


FIGURE 9.1.21 The sub-Saharan regions, showing the suitability to vector-borne malaria transmission due to climate. In general, the more central regions in the sub-Saharan region are more suitable to vector-borne malaria transmission.

Other complications include climate. The climate for approximately half the region is suitable for the mosquito vector to reproduce and grow, as illustrated in Figure 9.1.21. The female *Anopheles* mosquito requires water to lay her eggs. Conditions for mosquitoes to reproduce and grow can be temporarily suitable many times a year, depending on seasonal variations and rain. Other complications that hinder treatment include civil unrest, numerous governments, international borders and politics, as well as access to susceptible populations.

A recent strategy to decrease the number of infections (incidence) of malaria in the sub-Saharan region of Africa is an insecticide-treated mosquito net (ITN). In 2004, less than 4% of the sub-Saharan population slept under an ITN. This increased to approximately 50% in 2013, with 427 million nets delivered to the region since 2012.

Figure 9.1.22 shows the percentage of the sub-Saharan African population sleeping under ITNs from 2005 to 2013. Sub-regions still have little to no population sleeping under an ITN, while both the number of regions and the number of people sleeping under an ITN within regions is increasing. Some have reached 100%. Data in some countries has been validated by authorities, while others are estimates related to roll-out programs. Figure 9.1.23 on page 422 shows the decrease of infections from 2005 to 2013 in general across the region.

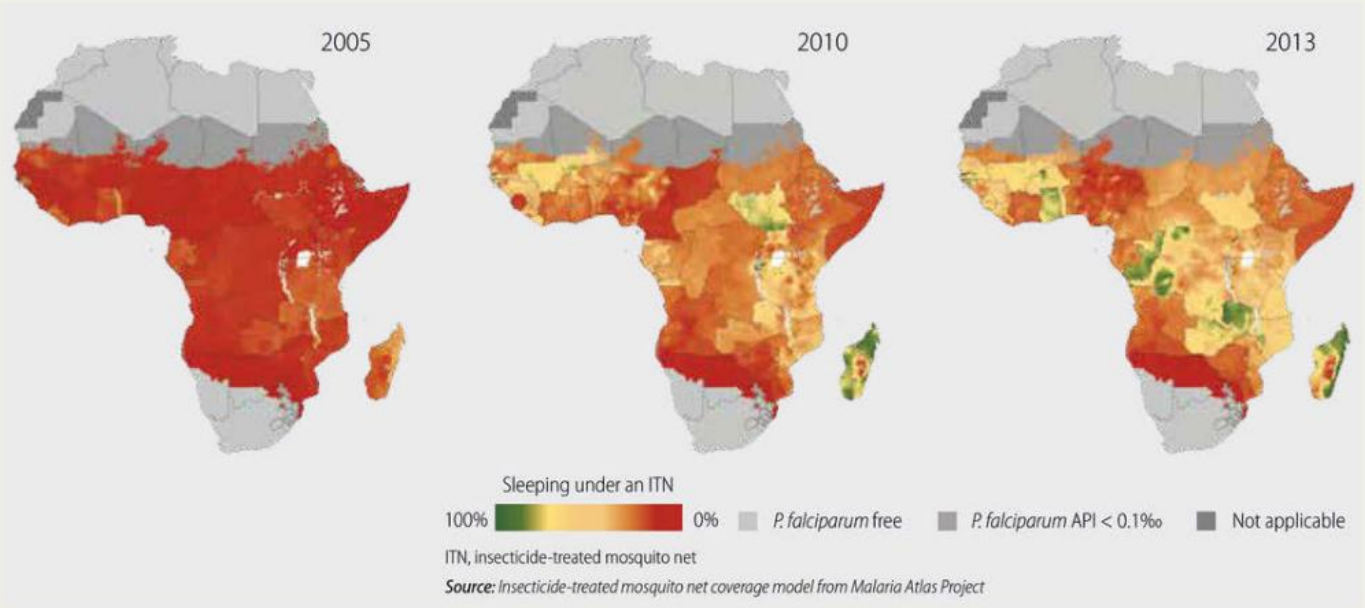


FIGURE 9.1.22 The percentage of the sub-Saharan African population sleeping under insect-treated bed nets has increased from 2005 to 2013.

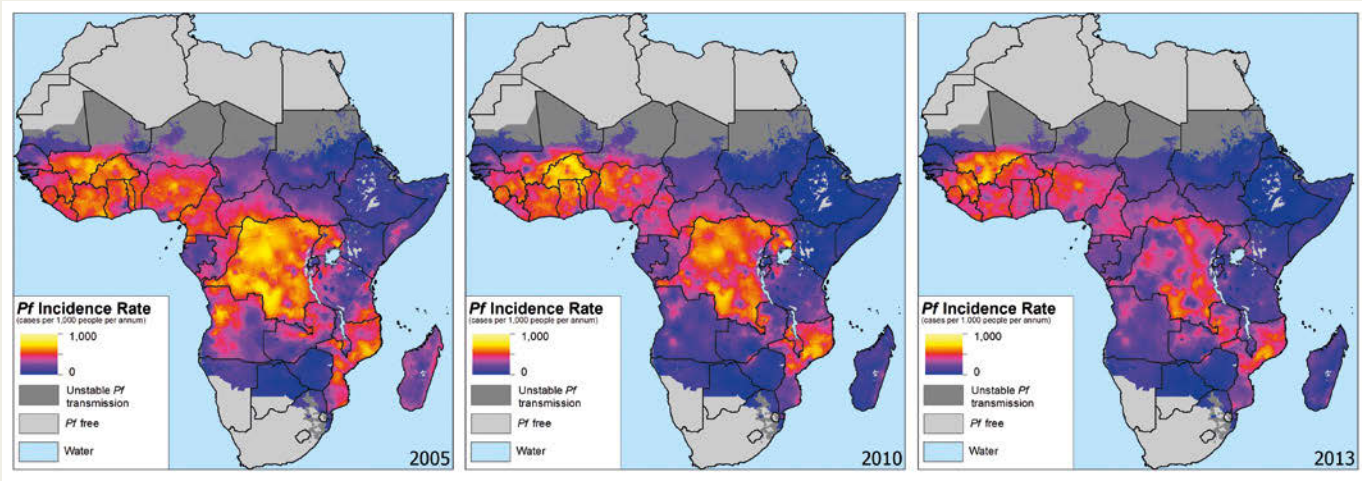


FIGURE 9.1.23 This incidence map has been developed from data estimating the incidence of vector-causing malaria across sub-Saharan Africa. It shows the decrease of infections from 2005 to 2013 in general across the region. Some areas still have exceptionally high numbers of infections.

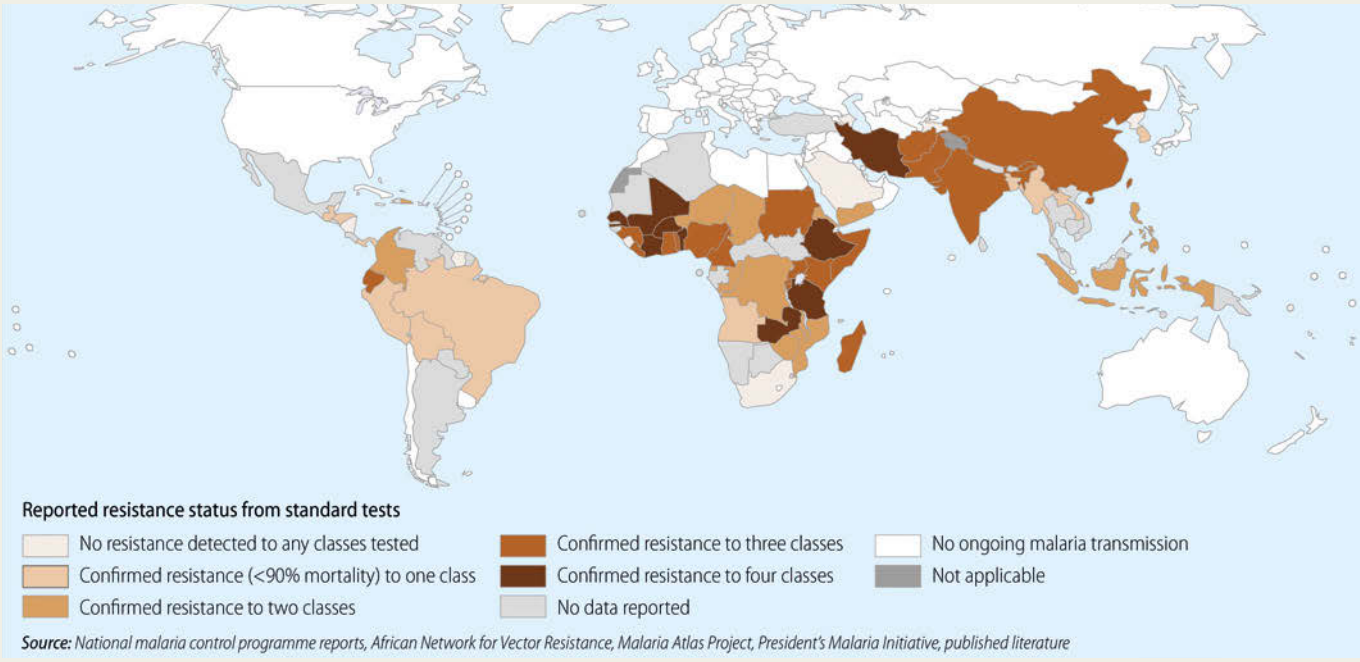


FIGURE 9.1.24 The world malaria report 2014 illustrates the location and countries reporting insecticide resistance of ingredients found in ITNs.

Since 2010, many countries have reported that mosquitoes are developing resistance to the four ingredients used in an ITN. In 2000–2004, the resistance for each insecticide ingredient—carbamate, organochlorine, pyrethroid and organophosphate—was reported in approximately 3%, 21%, 19% and 4% of all countries worldwide, respectively. From 2010 to 2013, resistance was reported in 23%, 30%, 34% and 16% of all countries worldwide, respectively (Figure 9.1.24).

Review

1. Determine whether or not the data supports a correlation between malaria and climate.
2. Identify the uncertainty for the data in Figure 9.1.21.
3. Explain the relationship between the use of ITNs across the sub-Saharan region and the incidence of malaria, specifying biological details that are relevant.
4. Identify limitations in the evidence regarding malarial infections and ITN use. Outline plausible effects of these limitations on the data in Figures 9.1.22 and 9.1.23.
5. Model the incidence of malaria for 2015–2025 in sub-Saharan Africa.

CASE STUDY 9.1.6

Communicable diseases

Communicable diseases are diseases that are infectious from person to person, either directly, indirectly or through a vector. Across the globe, they are major causes of death and socioeconomic disruption to businesses and governments. For some countries, communicable diseases can result in economic instablity. For other countries, communicable diseases can result in millions or billions of lost dollars for governments and major employers. It is almost inevitable that taxpayers will bear the cost of the financial impact of communicable diseaes, to varying levels.

The Australian Department of Health requires medical practitioners to enter data into the National Notifiable Diseases Surveillance System to record all cases of communicable diseases in Australia. This is extremely important because it provides real data to health organisations and medical practitioners about current disease trends and communicable issues that affect their patients. Each fortnight, the surveillance system produces the *National Communicable Diseases Surveillance Report*. A summary of the report is shown in Table 9.1.10. With this data, the government can make informed decisions about appropriate vaccines, medications, early warnings and possibly earlier treatment to improve the health of individuals and communities. Planning and evaluation of disease prevention and control programs can be developed and, ultimately, reduce the spread of disease and the number of infections.

The data published in the *National Communicable Diseases Surveillance Report* allows for large-scale data analysis and longitudinal studies. Longitudinal studies investigate the same sample (e.g. population) over a long period of time, such as years or decades. This helps authorities understand the effects over years, regardless of the number of events and how these may influence other factors. The government can use the information to develop educational campaigns, evaluate health systems, inform the public and distribute funds where appropriate to help minimise the spread of disease in Australia.

Limitations of the *National Communicable Diseases Surveillance Report* include that it only records infectious people who visit a medical practitioner, and the number of infections for only the diagnosed diseases. Other limitations are that some communicable diseases are, or can be, asymptomatic, some can be a '24-hour bug', where people recover from acute illness within a day or two and do not seek medical assistance, while others are misdiagnosed as stress, anxiety or something other than a communicable disease.

TABLE 9.1.10 A summary of the year to date (YTD) reported communicable disease data in Australian states and territories by the Australian Government Department of Health from the *National Communicable Disease Surveillance Report* (18 July 2017)

Disease	ACT	NSW	NT	Qld	SA	Tas	Vic	WA	2017 YTD
hepatitis B (unspecified)	0	61	0	44	3	0	56	31	3471
hepatitis C (unspecified)	4	147	5	102	1	3	70	54	5963
campylobacteriosis (gastrointestinal)	15	–	18	262	127	31	44	120	12928
cryptosporidiosis (gastrointestinal)	0	18	2	22	12	1	39	7	3795
salmonellosis	8	81	11	104	28	7	98	83	11200
chlamydial infection	45	882	53	938	177	27	0	348	48488
gonococcal infection	9	276	36	161	45	3	221	118	16896
influenza (laboratory confirmed)	174	7182	24	2973	1363	194	1959	283	42521
pertussis	9	221	3	77	34	1	53	60	7279
varicella zoster (unspecified)*	10	–	0	449	1032	19	2	97	10258
varicella zoster (shingles)*	10	–	11	0	54	0	7	57	4440
Ross River virus infection	0	14	4	71	2	2	5	11	6348

*South Australia (SA) notified a retrospective varicella dataset, including data with diagnosis dates from 2012 to 2017 this fortnight.

The flu, caused by the influenza virus, is an example of where the National Notifiable Diseases Surveillance System records only a fraction of the infections across Australia each year. It is well accepted that only a portion of influenza infections are recorded each year. However, the longitudinal data enables predictions and trends to be known even with a limited number of recorded cases.

Another example is chlamydia, a bacterial infection of the reproductive and urinary systems. The 2016 *National Blood-borne Viruses and Sexually Transmissible Infections Surveillance and Monitoring Report* published by the University of New South Wales Kirby Institute estimated that there were 257 545 chlamydia infections in 15–29 year olds in Australia in 2015. The Notificable Diseases Surveillance System only recorded 93 142 in total for Australia. The difference is attributed to 80% of people infected with chlamydia being asymptomatic.

Every year, there is a 'peak flu season' in which the number of infleunza infections dramatically increases and peaks before dramatically declining (see Case study 9.1.4). To combat the number of infections, illness, death and strain on the health system (e.g. use of beds, quarantine for the highly infectious, attention required by medical staff and governments' funds to nurse patients) due to influenza, one preventative action plan by the government is the annual flu vaccination. This vaccine is subsidised by the government every year for people in the high-risk category. Also, many workplaces offer the government flu shot (vaccine) free to their employees to minimise the number of days employees miss work due to influenza and thus minimise the loss of income to the business.

The difficulties and limitations for the influenza vaccine, and the preventative action plan, are that each year the peak flu season can be caused by a different viral strain. Health authorities state that international travel and antigenic drift and shift contribute to the annual changes in the strain. Often, Australians returning from international travel are the greatest source of the strains. Typically the trend is a 12-month lag from either the USA or Western Europe. Antigenic shift is another major influence on the peak flu season. However, it is often too complex to understand the source.

Review

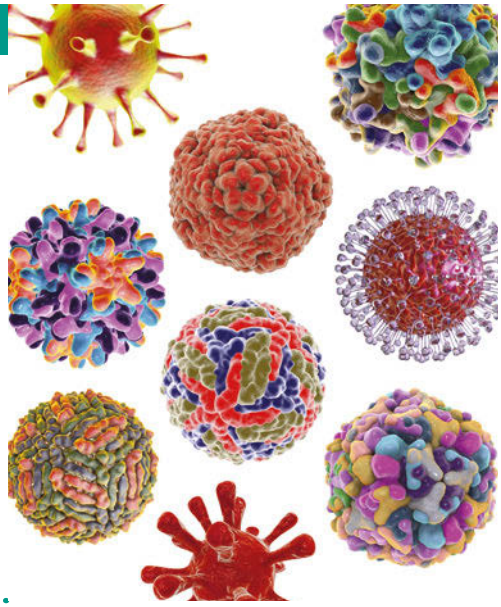
1. Use research to create a list of diseases from Table 9.1.10 that are treatable with medication.
2. Conduct an internet search for the Australian Government Health Department, National Notifiable Disease Surveillance System. Go to the reports section of the website and select 'Selected disease by month and year'. Using this page, determine a 10-year trend for the two most reported communicable diseases in Table 9.1.10 and one other.
3. Develop an action plan, Medicare rebate policy or educational program to reduce the number of infections for one of the diseases in your response to Question 2. Ensure your action plan, Medicare rebate policy or educational program is justified by a rationale.

SAT IA3

9.2 Epidemiology and the control of disease

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

- understand the importance of personal hygiene measures in controlling the spread of disease
- evaluate strategies to control the spread of disease at the community level, such as:
  - contact tracing and quarantine
  - school and workplace closures
  - reduction of mass gatherings
  - temperature screening
  - travel restrictions
- make and justify decisions in regard to best practice for the prevention of disease outbreaks based on the critical analysis of relevant and current information
- interpret data for the modelling of the spread of disease using secondary data.



In this module, you will learn measures and strategies of personal hygiene that minimise the spread of disease and transmission between individuals and throughout communities. You will learn about the effectiveness of hand washing, consider **hygiene etiquette** in disease transmission, and learn about the importance of hygiene and etiquette while travelling. Community measures to control the spread of disease will be covered that relate to mass gatherings, quarantine strategies and temperature screening. Combating outbreaks requires considerable effort from many organisations and personnel. Modelling and preparing for potential outbreaks, or monitoring for source (initial) infections, can enable responses that protect communities.

PERSONAL HYGIENE TO CONTROL SPREAD OF DISEASE

Hygiene refers to actions that lead to cleanliness and good health. The spread of disease can be minimised and controlled through appropriate personal hygiene. Personal hygiene involves practices that an individual performs on his or her own body to maintain cleanliness, health and wellbeing. Examples of personal hygiene practices include:

- washing hands, other body parts and hair with soap and clean water (Figure 9.2.1a on page 426)
- avoiding coughing and sneezing on others (Figure 9.2.1b on page 426)
- cleaning items that you come into contact with when you are ill (Figure 9.2.1c on page 426)
- appropriately disposing of tissues and other items that may contain germs
- using protective barriers, such as gloves and condoms (appropriately and consistently), when there is a risk of infection (Figure 9.2.1d on page 426).

Clean running water is not always available in some countries, communities or locations and so achieving personal hygiene can sometimes be difficult. This can be the case in remote locations, locations beyond urban development where infrastructure does not exist, in underdeveloped countries and communities where poverty and famine are common, war-torn regions and refugee camps. If personal hygiene is not maintained, many diseases can spread.

FIGURE 9.2.1 (a) Washing hands removes microbes from skin. (b) Sneezing into a tissue minimises the spread of disease. (c) Cleaning common use areas is important after they have been used by someone with an infection. (d) Gloves provide a protective barrier to minimise any possible transfer.

FIGURE 9.2.2 Hands can carry pathogens from one place to another, so they need to be washed thoroughly.

FIGURE 9.2.3 Various hand sanitisers

Hand washing

The transfer of pathogens by hands is the most common personal mechanism of pathogen transfer (as illustrated in Figure 9.2.2). Some estimates state that 80% of infectious diseases involve transmission via hands. Generally, hand washing is seen as the primary preventative measure in disease transmission. Thorough washing with adequate quantities of water and plain soap removes 90% of transient (superficial) **contaminants** on the skin, including pathogens. To prevent the transmission of pathogens by hands, it is recommended you wash your hands:

- before and after eating or handling food or drink
- before providing medication
- after hands become visibly soiled
- after visiting the toilet
- after using a computer keyboard
- after handling laundry
- after handling waste
- after blowing, wiping or touching your nose or mouth
- after sneezing or coughing
- after contact with an ill person
- after contact with animals.

Disinfectants and alcohol-based soaps and hand sanitisers (with at least 60% alcohol) are highly effective **antibacterials** and in general kill 99.99% of microbes. However, these should only be used if water and soap is unavailable. Non-alcohol hand sanitisers may not work equally well for all microbes (e.g. gram-negative compared to gram-positive bacteria), may develop resistance in the microbes, and may reduce microbe growth rather than kill them. Various hand sanitisers can be seen in Figure 9.2.3.

No single product will kill, remove or eliminate all microbes. It is important to use them appropriately. Alcohol-based sanitisers will not work effectively in too small volumes or if they are wiped off before they dry. They do not kill, eliminate or inactivate all microbes, and water and soap are more effective than sanitisers for some microbes. Research has also shown that alcohol-based sanitisers do not work well when hands are heavily soiled (visibly dirty) or greasy, such as after handling food, playing sports, working in the garden, camping or fishing.

CASE STUDY 9.2.1

Hand washing in schools, USA

Scientists in the USA investigated whether alcohol gel hand sanitiser could reduce the number of infections. The study sampled children from 16 schools in California, Delaware, Ohio and Tennessee. At each location, multiple districts were chosen and two schools in each district were selected as the sample population. Different locations and demographics were chosen, with schools being paired on the basis of similar population demographics and locations. Some information about the schools is listed in Table 9.2.1. Within each district, one of the paired schools was assigned as the control group (no alcohol gel hand sanitiser) and the other school was assigned as the test group or product group (alcohol gel hand sanitiser was used). A total of 6080 students were included in the study.

The study was conducted over a full academic year, of which the test groups were instructed to wash their hands with the alcohol gel hand sanitiser when entering and leaving the classroom (including first thing in the morning, before and after lunch, after recesses, after use of the toilet, and before going home), and after sneezing and coughing.

Absenteeism in the study was defined as the total number of school days not attended because of colds, flu and gastrointestinal disease. Common infectious illnesses such as conjunctivitis, abscesses and skin infections (though prevalent among the students in the study) were not included. All other types of absenteeism, such as doctors' appointments, family vacations and accident injuries, were excluded. Absenteeism records were kept by school staff, who identified the reason for the absence. The schools provided the study coordinators with the records on absenteeism due to illness.

TABLE 9.2.1 Geographic and demographic characteristics of US school districts chosen to test the effectiveness of alcohol gel hand sanitiser

Location	Population	Per capita income	Classification of area
Cuyahoga Falls, Ohio	49913	$40700	suburban
Hudson, Ohio	22287	$26545	suburban
Athens, Tennessee	13340	$17512	rural
Irvine, California	127220	$28037	urban
Wilmington, Delaware	71500	$18011	urban

Table 9.2.2 shows the results of the study. The results showed less absenteeism in the group using the hand wash compared to the control group that did not.

Review

1. Identify and explain the valid methodologies employed by the hand washing study in US schools.
2. Explain the limitations of the study design when considering the selection of schools.
3. Explain the limitations of the sampling methodologies.
4. Determine how the percentage difference over control is calculated and infer what may have affected the calculations slightly.
5. Interpret the percentage difference over control.
6. Consider the appropriateness of percentage difference over control for the different sample sizes between Wilmington, Delaware, and Cuyahoga Falls, Ohio.

TABLE 9.2.2 The results of a study on the effect of an alcohol gel hand sanitiser in schools

School district	Number of students	Grades	Students in product group	Students in control group	Days absent hand sanitiser group*	Days absent control group*	Days absent per student in hand sanitiser group	Days absent per student in control group	Per cent difference over control
Cuyahoga Falls, Ohio	2576	K–5	1440	1136	2327.5	2738	1.62	2.41	32.96†
Hudson, Ohio	818	2, 3	266	552	724	1697	2.72	3.07	11.49†
Wilmington, Delaware	223	3, 4	110	113	478	533	4.35	4.72	7.87
Athens, Tennessee	1272	K–6	680	592	1953	2102	2.87	3.55	19.07†
Irvine, California	1191	K–5	579	612	1959	1996	3.38	3.26	–3.75
Overall	6080	K–6	3075	3005	7441.5	9066	2.42	3.02	19.76†

* Numbers were normalised for equal populations before calculating percentage difference over control.
† Statistical significance ($P < 0.05$).

CASE STUDY 9.2.2

TABLE 9.2.3 Geographic and demographic characteristics of New Zealand school districts chosen to test the effectiveness of alcohol gel hand sanitiser

Category	Characteristic	Hand sanitiser group		Control group	
		Number or mean	Percentage or SD	Number or mean	Percentage or SD
Schools	Total schools	34		34	
	roll just prior to study (mean, SD)	228.8	115.8	209.6	102.2
	City				
	Christchurch	19	55.9%	18	52.9%
	Dunedin	11	32.4%	12	35.3%
	Invercargill	4	11.8%	4	11.8%
	School decile*				
	1–3 (least advantaged)	5	14.7%	11	32.4%
	4–7	9	26.5%	6	17.6%
	8–10	20	58.8*	17	50.0%
	Total follow-up children	1301		1142	
Follow-up children	follow-up children with a baseline questionnaire	1287		1132	
	Household income ($A)				
	not stated	101	7.9%	87	7.7%
	0–40 000	156	12.1%	163	14.4%
	40 001–80 000	525	40.8%	415	36.7%
	>80 000	505	39.2%	467	41.3%
	Ethnicity (prioritised)†				
	Maori	163	12.7%	132	11.7%
	Pacific	31	2.4%	35	3.1%
	Asian	41	3.2%	33	2.9%
	European	1019	79.2%	907	80.1%
	other	25	1.9%	21	1.9%
	not stated	8	0.6%	4	0.4%
	Education (highest qualification in household)				
	no qualifications stated	51	4.0%	61	5.4%
	some high school qualification	334	26.0%	309	27.3%
	university	632	49.1%	515	45.5%
	alternative qualification	270	21.0%	247	21.8%
	Self-reported overall family hand hygiene				
	not stated	82	6.4%	58	5.1%
	poor/fair	115	8.9%	88	7.8%
	good/very good/excellent	1090	84.7%	986	87.1%
	number of people in household	4.4	1.12	4.36	1.07
	number of children in household	2.42	0.96	2.43	0.93
	Children under 5 years in household				
	0	903	70.2%	807	71.3%
	1	322	25.0%	275	24.3%
	2	58	4.5%	48	4.2%
	3	4	0.3%	2	0.2%
	Caregivers in paid employment				
	both caregivers, at least 20 h/week	514	39.9%	455	40.2%
	at least one caregiver employed <20 h/week	289	22.5%	219	19.4%
	at least one caregiver not in paid employment	478	37.1%	446	39.4%
	missing	6	0.5%	12	1.1%

Hand washing in schools, New Zealand

A 2010 study in New Zealand investigated if the use of hand sanitiser of at least 60% alcohol in primary schools could reduce absenteeism due to illness. A total of 68 primary schools from the south island within the areas of Canterbury, Otago and Southland were selected. Each school had to have at least 100 children and have no previous use of hand sanitisers. The schools in each area were randomly chosen to be a hand sanitiser group or control group, with equal representation of each (one of the researchers randomly assigned schools to each group without knowing which would be the hand sanitiser group or control group). A total of 50 students per school were randomly chosen, with a total of 2443 students involved in the study.

Table 9.2.3 shows the characteristics of participant school's families and students.

All schools received a single health education session on hand hygiene during term 1 (March and April) 2009. The study began in term 2 and concluded in term 3 (being conducted during the winter season of 27 April to 25 September 2009), with the hand sanitiser group applying 60% alcohol-based hand sanitiser during this time. The health education session ensured both groups had equivalent knowledge of hand hygiene and cleaning. The students were able to use the sanitiser at any time, but teachers ensured that the students used the hand sanitiser after coughing, sneezing and blowing their nose, and when leaving the classroom for morning break and lunch break.

The study measured the number of absence episodes due to any illness excluding injuries and infestation (head lice and scabies). A new absence was defined as an absence after at least 3 days without absence. The study collected the absence information from each school weekly. Results can be seen in Table 9.2.4.

Review

1. Identify and explain the valid methodologies employed by the hand washing study in New Zealand schools. Consider the locations, random association of groups, number of schools and previous use of sanitisers.
2. Explain the limitations of the design of the study when considering the selection of schools.
3. Explain the appropriate methodologies employed to choose the population sample. Consider sample size and sample selection of students.
4. Compare and contrast the reported results of the US study (Case study 9.2.1) and the New Zealand study (Case study 9.2.2) of hand washing in schools.
5. Explain whether or not it is valid to compare the results between the studies in Case study 9.2.1 and Case study 9.2.2.

TABLE 9.2.4 Results from New Zealand hand sanitiser study

Outcome	Number of children (34 schools per group)		Control group		Hand sanitiser group		IRR, hand sanitiser vs control (95% CI)	*P* value	ICC* (95% CI)
	Control group	Hand sanitiser group	Number of events (child days of follow-up)	Rate (per 100 child days or %)	Number of events (child days of follow-up)	Rate (per 100 child days or %)			
Primary outcome									
number of absence episodes due to any illness	1142	1401	1291 (111 451)	1.16	1542 (127 471)	1.21	1.06 (0.94, 1.18)	0.346	0.018 (0.012, 0.043)

Table 9.2.3 footnote:
* School level deprivation uses the decile assigned to each school by the New Zealand Ministry of Education for funding purposes. It reflects the proportion of students who live in more or less advantaged communities, using information from the census on household income, occupation, household crowding, educational qualifications and income support. Decile 1 schools are in the least advantaged communities and decile 10 schools are in the most advantaged.

† Respondents were asked to tick all the ethnicities represented in their household. Prioritised ethnicity, in New Zealand, codes as Maori participants who report Maori as one of their ethnic groups, as Pacific those who do not report Maori but do report a Pacific ethnicity as one of their ethnic groups, as Asian those who do not report Maori or Pacific but report an Asian ethnicity, and the remainder as European (if New Zealand European or another European ethnicity reported) or other (if not).

Hygiene etiquette

FIGURE 9.2.4 Hygiene etiquette is extremely important in medical practices to minimise transmission to susceptible individuals.

Good hygiene etiquette can interrupt the spread of disease, especially when an individual is sick. It can be exceptionally helpful to exercise hygiene etiquette when coughing or sneezing symptoms exist with an illness. Hygiene etiquette can minimise the spread of respiratory diseases that are highly infectious and cause a high number of infections and severe disease, such as influenza, respiratory syncytial virus (RSV), whooping cough and severe acute respiratory syndrome (SARS).

Coughing or sneezing into your hands or having unclean hands and then touching your face or other objects spreads disease to yourself and others. In this case, hygiene etiquette includes:

- covering your mouth and nose with a tissue when coughing or sneezing
- placing your used tissue in a rubbish bin
- washing your hands after you have coughed or sneezed
- coughing or sneezing into your elbow or the upper sleeve of your shirt if you do not have a tissue.

Hygiene etiquette in medical practices is especially important, as seen in Figure 9.2.4. Patients are exposed during invasive medical procedures, so medical staff must practice hygiene etiquette to minimise transmission directly into the body of a patient. In such cases infection can take hold very quickly. Places of medical assistance and health services are where highly susceptible populations are located. Many people seeking assistance have compromised immune systems. Also, because ill and infected people congregate in these locations, there are high levels of infectious agents and pathogens. For these reasons, medical staff need to practice hygiene etiquette to minimise transmission of disease from one person to another.

PA 2.2.2

Facemasks are most often used in Japan by people who have colds, so as not to infect others, or to avoid catching infections themselves (Figure 9.2.5).

FIGURE 9.2.5 In Japan, it is common to wear facemasks while commuting to work.

CASE STUDY 9.2.3

Coughing and sneezing etiquette

The Australian Government National Health and Medical Research Council has released the *Australian Guidelines for the Prevention and Control of Infection in Healthcare* (2010). Community groups and businesses can use this information to develop policies or inform the public. The 2010 report includes guideline B1.6 Respiratory Hygiene and Cough Etiquette, which outlines cough etiquette, as shown in Figure 9.2.6.

Steps in respiratory hygiene and cough etiquette

- Cover the nose or mouth with disposable single-use tissues when coughing, sneezing, wiping and blowing noses.
- Use tissues to contain respiratory secretions.
- Dispose of tissues in the nearest waste receptacle or bin after use.
- If no tissues are available, cough or sneeze into the inner elbow rather than the hand.
- Practice hand hygiene after contact with respiratory secretions and contaminated objects or materials.
- Keep contaminated hands away from the mucous membranes of the eyes and nose.

FIGURE 9.2.6 The recommended etiquette for coughing outlined by the Australian Government National Health and Medical Research Centre

The 2010 *Australian Guidelines for the Prevention and Control of Infection in Healthcare* have been adopted by many businesses. Businesses can buy posters that inform employees about infection control. An example of a poster is in Figure 9.2.7.

FIGURE 9.2.7 A workplace poster that details hygiene etiquette for coughing and sneezing

Review

1. Describe how the 2010 *Australian Guidelines for the Prevention and Control of Infection in Healthcare* would affect the transmission of influenza.
2. Compare the workplace poster in Figure 9.2.7 with the 2010 *Australian Guidelines for the Prevention and Control of Infection in Healthcare*.
3. Predict with justification which guidelines would most effectively decrease the spread of disease.

CASE STUDY 9.2.4

Travellers visiting Australia

Queensland Health, a department of the Queensland Government, reports approximately 3000 cases of Ross River fever annually with occasional peaks of 5000–6000. The annual cases are generally dispersed evenly across the Queensland coast where water environments are close to larger populations. Areas of higher prevalence of Ross River fever include Cairns, Townsville, Central Queensland, Wide Bay, Sunshine Coast, Brisbane and the Gold Coast (including the hinterlands associated with each region).

Cases in Australia are correlated to climate and seasons. Tropical and subtropical regions of Australia report cases all year round (mostly in Queensland and Northern Territory), while southern parts of Australia (i.e. New South Wales, Victoria, southern South Australia and Tasmania) report seasonal infections.

Cases of Ross River fever in Europe are very rare and are typically found in individuals who are returning from Australia or the Oceanic region.

The extract (right) is from an article written by a health service for travellers, which provides vaccinations and health advice. It is a paid service, in which all medical staff are stated to be experienced travel and health doctors. The doctors are part of the Travel Medical Alliance (TMA), an Australian alliance of independent travel medicine practitioners.

Review

A couple from the Netherlands are about to visit Australia and will spend 2 weeks in Queensland, 1 week in Cairns and 1 week on the Gold Coast. In Cairns they plan to snorkel, visit the forest in the hinterlands, and swim in local swimming holes (rivers and water falls). In both destinations, they will spend a few days walking along trails in the hinterlands, including a visit to the glow-worms. On the Gold Coast, they will also visit the Currumbin Wildlife Sanctuary.

1. Provide recommendations the couple should receive from a travel doctor regarding their health in Australia.
2. Explain how the couple can avoid Ross River fever while coming into contact with kangaroos, horses, sheep and koalas at the Currumbin Wildlife Sanctuary.
3. Predict the potential for outbreaks of Ross River fever in infected travellers returning to their home in the following scenarios:
   - one couple returning to their home on the Nieuwe Maas, Rotterdam, Netherlands, in January
   - another couple returning to their home in Alto da Boa Vista, Rio de Janeiro, Brazil, in January.

RECENT OUTBREAKS:

Gold Coast University Hospital infectious diseases director John Gerrard said he expected thousands more cases of Ross River fever to emerge in coming weeks. 'The majority of people will recover within six weeks but some people will have symptoms that will last up to a number of months', Gerrard said.

The virus that causes Ross River fever is not contagious and is spread only by mosquitoes (Figure 9.2.8). The main **reservoir** hosts are kangaroos and wallabies, although horses, possums and possibly birds and flying foxes play a role. Over 30 species of mosquitoes have been implicated as possible vectors, but the major species for Ross River fever are *Culex annulirostris* in inland areas, *Aedes vigilax* in northern coastal regions and *Aedes camptorhynchus* in southern coastal regions.

People who contract the virus from an infected mosquito will start to show symptoms 3–11 days later.

Symptoms of the disease may vary widely in severity, but major indicators are pain in joints, arthritis (inflammation and stiffness of the joints), fever and rash. The incubation period is 7–9 days. About a third of infections are asymptomatic, particularly in children.

ACUTE ILLNESS

About 95% of symptomatic cases report joint pain. This is typically symmetrical and with acute onset, affecting the fingers, toes, ankles, wrists, back, knees and elbows. Fatigue occurs in 90% of patients, while fever, pain in muscles and headache occur in 50–60%.

A rash occurs in 50% of patients and is widespread and maculo-papular (small, flat discoloured spots as well as raised bumps on the skin). Disease in the lymph nodes occurs commonly; [so do] sore throat and inflammation of the mucous membrane in the nose. Diarrhoea is rare.

ROSS RIVER FEVER IN QUEENSLAND

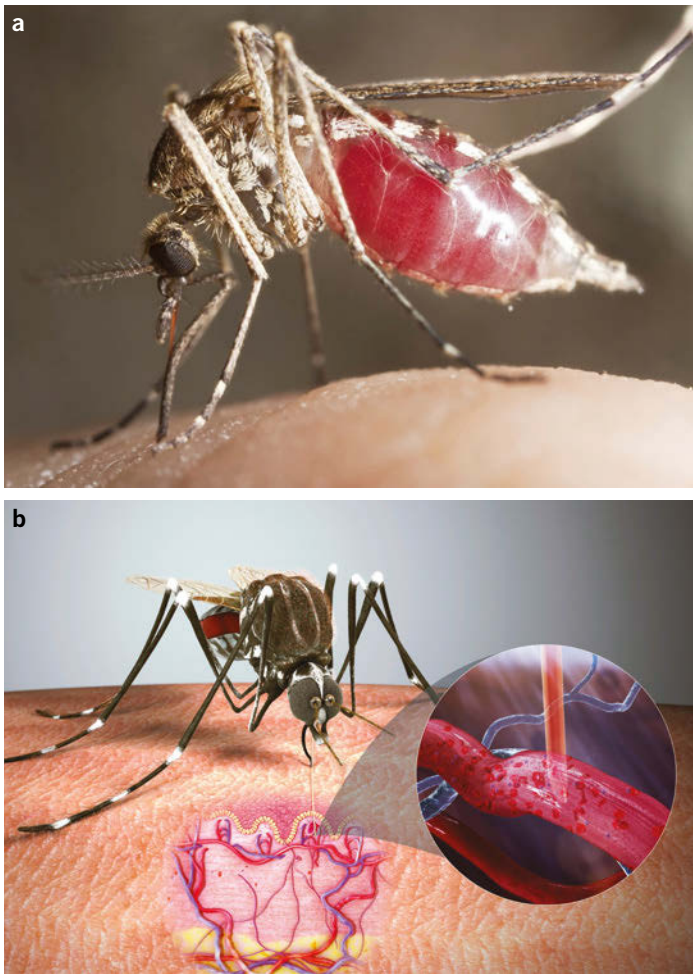


FIGURE 9.2.8 (a) This mosquito is a vector for Ross River fever. When it bites, it penetrates the skin and shares fluids with a susceptible person. (b) Fluids from a mosquito are transferred directly into the bloodstream of a person.

The virus remains in the host after infection has occurred, and secondary symptoms of joint and muscle inflammation, pain and stiffness can last for many years.

Headache, neck stiffness and photophobia may occur. There have been some case reports suggesting meningitis (inflammation of the meninges, a tissue that surrounds the brain) or encephalitis (inflammation of the brain).

CHRONIC ILLNESS

Reports from the 1980s and 1990s suggested Ross River fever infection was associated with **arthralgia**, fatigue and depression lasting for years. More recent prospective studies have reported a steady improvement in symptoms over the first few months, with 15–66% of patients having ongoing arthralgia at 3 months. Arthralgia has resolved in the majority by 5–7 months. The incidence of chronic fatigue is 12% at 6 months and 9% at 12 months, similar to Epstein-Barr virus and Q fever.

There is no known cure for the disease, which inflicts on its victims swollen, painful joints, rashes, fever, fatigue, headaches and muscle pain.

TRAVEL HYGIENE

Many factors can influence a traveller's health as well as whether or not they develop disease from infections. One factor is exposure to a species or strain of a microbe that an individual may not have been exposed to before. This makes them susceptible to disease. Also, in foreign locations it is possible that different vectors and fomites exist that can transmit pathogens without travellers being aware.

When travelling to a new destination, you may need a different hygiene etiquette to maintain health. Therefore, it is especially important to develop an understanding of common vectors and fomites at foreign destinations when travelling, and learn the local hygiene etiquette. The list of common recommendations below outlines typical hygiene etiquette when travelling to foreign destinations.

Developing the hygiene etiquette of local residents in a community is difficult. This is because local and expert knowledge is vast and sometimes not obvious. Also, expert knowledge continually develops, making local practices outdated. There may also be inconsistencies between traditional and up-to-date practices, making it difficult for a traveller to understand hygiene etiquette.

Before travelling, you should seek medical advice about diseases at your travel destinations. Health and disease organisations continually update their databases and information, improving understanding of disease transmission. This is valuable information for travellers. They can be informed about regions or areas to avoid, recommended vaccinations (Figure 9.2.9a) to receive prior to departing, or methods to minimise disease transmission (e.g. vector control using insecticides or repellents), as seen in Figure 9.2.9b. They can also learn about hygiene etiquette for common diseases, typical fomites and other mechanisms of transmission, all of which enable travellers to plan or develop strategies to maintain good health.

FIGURE 9.2.9 (a) Receiving vaccinations specific to the destinations of international travel. (b) Insect repellents are a valuable product to have when travelling. They minimise the incidence of infections that are transmitted by insect vectors.

Common recommendations to minimise infections and disease transmission while travelling include the following. Most relate to the individual or water.

- Drink only bottled water.
- Do not use tap water to clean your teeth.
- If no clean or other water source is available, boil water for 1 minute at a rolling boil before drinking it (Figure 9.2.10).
- When washing your hands, ensure they are totally dry before touching food.
- Do not wash fruit or vegetables in unsafe water.
- Ensure that dishes, cups or any other utensils are completely dry after they are washed.

FIGURE 9.2.10 The rapid bubbling of the water in a rolling boil, which is greater than when simmering.

COMMUNITY MEASURES TO CONTROL SPREAD OF DISEASE

Identifying infections and controlling the spread of disease at the community level is difficult. All the factors and variables related to controlling the spread of disease in individuals are compounded at the community level. The technology and strategies that can reveal disease or infections have been developed for individual detection. Currently, community detection does not exist. Therefore, the measures implemented to control the spread of disease through communities are based on modelling and predictions.

Contact tracing enables health authorities to monitor, provide and prioritise health care. This strategy uses the resources for disease detection and prevention at the source in the hope of eradicating transmission any further. Mass gatherings, which are unique, place immense strain on health authorities and resources. They require imperative planning and preparation. Temperature screening can test multiple individuals in a community or large samples of a population quickly. It is usually used at borders to respond rapidly and protect the larger population of cities and countries from new pathogens. Quarantine is the most effective strategy, and one of the oldest ways of combating the spread of disease. By isolating the ill and infected, disease cannot spread.

Contact tracing

Contact tracing is a strategy to identify and monitor infected individuals. Once an individual has been confirmed as infected, they are questioned about their activities as well as the activities, responsibilities and occupations of other individuals who have been around them since the onset of the illness. This includes identifying individuals through direct and indirect contact, and could include family members, work colleagues, friends, healthcare providers and service staff in the hospitality industry, for example.

The process of contact tracing lists all individuals considered to have had contact with the infected person. Then, attempts are made to identify every listed individual so that they can be informed of their contact status with the infected individual. They are monitored, their symptoms are surveyed and early care is provided if necessary. Contact tracing continues with a list of possible contacts for secondary infections. In some cases, high-risk contacts are quarantined or isolated, either at home or in hospital.

The process of contact tracing was employed for case studies 9.1.1, 9.1.2 and 9.1.3 in Module 9.1 and the value of tracing back to the origin of infection is evident. It can find individuals in the community who are possibly infected, provide early care and minimise the spread of disease as well as enabling the determination of R_0. It is a commonly used strategy in disease **epidemiology**. It is one of the only strategies that can provide information for diseases that are **asymptomatic**, lie dormant or have long incubation periods. Examples of diseases with long incubation periods are infectious mononucleosis (glandular fever) and hepatitis B. Chlamydia is most often asymptomatic and shingles (herpes zoster) can lie dormant for decades.

When outbreaks occur, contact tracing is one of the first strategies employed. Examples are the case studies in Module 9.1 as well as the Zika virus in South America, bird flu and swine flu in Asia, Ebola (Figure 9.2.11) and SARS across numerous continents in recent times. The difficulty with contact tracing is the quality of information received from surveyed individuals. Depending on the disease or infection, some individuals may be embarrassed or ashamed, others may lead a busy life and may not remember all the details, and others may not realise the importance of some details.

Typically, not all infections are found through contact tracing, and as R_0 increases, it is less likely that contact tracing will identify a larger proportion of the infected population.

FIGURE 9.2.11 The CDC contact tracing strategy for Ebola

Mass gatherings

WHO has defined a mass gathering, in the context of public health, as:

> … any occasion, either organised or spontaneous, that attracts sufficient numbers of people to strain the planning and response resources of the community, city or nation hosting the event.

Common mass gatherings include religious and sporting events, music concerts, festivals and political rallies (Figure 9.2.12). A major concern is that an infection acquired at a mass gathering will not only spread quickly among the attendees, but be transmitted back 'home'. This could easily be within 12 hours or possibly anywhere around the world in almost 24 hours.

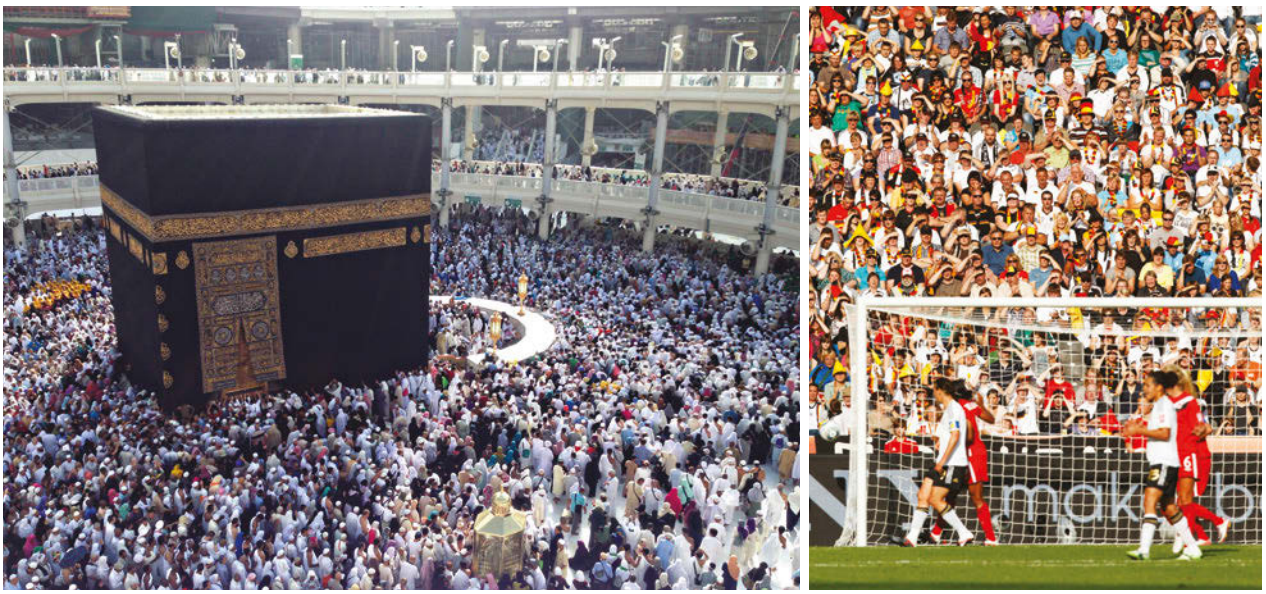


FIGURE 9.2.12 Mass gatherings occur for a variety of reasons, including religion, music concerts, festivals and sport.

Other than cancelling or postponing events, strategies to help manage events that involve mass gatherings include:

- political commitment
- effective planning
- surveillance systems
- documenting activities.

WHO suggests that political commitment is essential. It is highly valuable to have public health professionals involved in the highest level of organisation of events. This is an opportunity for competing agencies to work together for the benefit of the attendees of the mass gathering.

Mathematical modelling is a useful tool for planning and preparing for a mass gathering. Modelling helps organisers to predict potential communicable diseases, project outbreaks and implications for attendees and health service personnel and infrastructure. The predictions and projections can model both slow and rapid infection scenarios, and consider unanticipated incidents and quality of communication between health and emergency units.

Surveillance systems can be developed to consider infections and disease as well as chemical-related events and extreme heat and cold situations. They are recommended to be adaptable to a variety of different settings.

All personnel, organisers and authorities involved in planning mass gatherings are advised to document their efforts and activities as they proceed. Records should include personal accounts of experiences and formal records including details of planning, training and exercises. Official reports and public media releases are both valuable because incident-free mass gatherings should be acknowledged as well as the problems with mass gatherings, which are often exaggerated. It is important for the organisation and operation of future mass gatherings that information and reports are evaluated appropriately.

Temperature screening

Global travel has increased considerably in recent times, which has increased the spread of disease. Many international travellers are not aware that they have an infection because they may still be in the incubation period. Other travellers may not consider themselves ill enough to not travel. They may be unaware that the strain of disease they are infected with is foreign to their destination and so they are about to expose a susceptible population. In any instance, human travellers are the greatest contributor to epidemics and pandemics.

Recent cause for concern and risk of epidemics and/or pandemics include severe acute respiratory syndrome (SARS), MERS, swine flu and bird flu (avian influenza) strains as well as other influenza strains, yellow fever and cholera. The pandemic outbreaks of SARS in 2003 and influenza in 2009 prompted many international airport quarantine stations to develop non-invasive and indirect strategies to diagnose people with infections. Infrared thermal image scanners (ITIS) became common. They attempted to use the temperature of skin to detect infected individuals, as seen in Figure 9.2.13.

FIGURE 9.2.13 Thermal monitoring attempting to detect infectious travellers

Many infections, including recent pandemics and localised epidemics, cause the core body temperature to increase, which can be felt on the skin. One immune response to an infection is increased metabolism as the immune system synthesises antibodies and B and T cells to fight against the invasion of a pathogen. Therefore, fever is a symptom of illness and can be observed and measured by infrared thermal imaging.

The normal temperature of skin for a healthy individual is difficult to obtain. Some research has found mean skin temperatures ranging between 31°C and 37°C, while others have reported mean total skin temperature to be at 30–31°C. Skin temperature can change with environmental conditions, such as ambient temperature (e.g. in air-conditioning), humidity and wind. Also, different areas of the human body can have different skin temperatures (by up to 10–15°C); for example, skin on the foot can be a different temperature from skin on the chest.

Other factors affecting general body and skin temperature include clothing, both the number of layers as well as the type of material, the physical activity of an individual, whether they are exercising or resting, as well as whether they are carrying a load or not. The time of day is important, too, because skin temperature immediately after waking in the morning is different from 30 minutes after waking, at meal times or when digesting food and during an illness.

CASE STUDY 9.2.5

Infrared thermal image scanners at international airports

In 2009, border control at Narita International Airport, Japan, implemented screening of passengers arriving from destinations with H1N1 influenza infections. The screening included a health declaration completed by passengers and infrared **thermoscanning** in the cabin of the plane before disembarking. These strategies were implemented to detect **symptomatic** passengers with infections. A total of 129 546 passengers were screened upon entry (before leaving the cabin) and nine were detected with symptoms. One passenger had the H1N1 influenza strain.

Enhanced surveillance (a contact tracing method implemented separately to thermoscanning) that included mandatory reporting of individuals with infections in the community identified 141 individuals who had travelled internationally and were not detected by entry screening. Of these 141 people, 24 had symptoms on entry and were missed by the screening.

Review

1. Determine the success rate of both thermoscanning and enhanced surveillance per 1000 passengers.
2. Provide two plausible reasons why thermoscanning missed 24 individuals with symptoms on entry.

Quarantine

In most cases, placing an individual or group of people or animals into isolation from the rest of the population will stop disease transmission. **Quarantine** is isolation for a period of time in an appropriate location to stop transmission of disease. The more infectious a pathogen, meaning the higher the R_0, the more important it is to quarantine the individual or group. Again, this is due to humans being the most effective transmission pathway for pathogens and disease. With so many variables involved in disease transmission, it is best to tackle the spread of disease by enacting strategies that directly address the infected. This is also true for infected animals, especially livestock, because the economical impact can severely affect all levels of industry, from farmers to trade, producers to consumers. It is important that those providing health care to the quarantined do not transmit the pathogen from quarantine to the outside population.

Quarantine can be established for individuals in specially made facilities (e.g. hospital rooms or wards, or holding pens for pets or livestock) or it can be more generalised to international borders and entire countries. Most countries have guidelines and laws about what can be brought into the country. In Australia, the Department of Agriculture and Water Resources determines the restrictions for travelling to Australia from overseas, including returning residents. This enables Australia to be a quarantined zone from certain pathogens, vectors and fomites, protecting the residents and agricultural industry.

Quarantine facilities may have a variety of specialised procedures, guidelines, equipment and personnel to handle the isolation of infected individuals or groups. This includes a:

- separate room
- separate cleaning service for consumables (e.g. bedding)
- room with its own bathroom, toilet and sink
- room with its own ventilation and air filtration system separate from the rest of the hospital
- higher level of personal protective equipment for nurses and medical staff.

It may be necessary to quarantine someone in their home. This isolates infected individuals from the public and interrupts transmission. The quarantine at home may include:

- only one adult caring for the infected individual
- isolating the infected individual from other members of the household; for example, in their bedroom with the door closed
- a separate bathroom for the infected (if possible)
- isolating the infected individual's items from everyone else's. For example, don't share towels or eating utensils, or store toothbrushes in the same holder
- using disinfectant to clean items touched by the infected individual, including bedside tables and bathroom surfaces.

If isolation at home is not possible, all family members should try to keep at least 1 metre away from the infected person, and/or wear a facemask.

CASE STUDY 9.2.6

Influenza outbreak causes school closure, 2016

In August 2016, an influenza A outbreak caused the closure of a Toowoomba school. The school informed its community on a Friday that it would close for the following Monday and Tuesday.

The typical incubation period for influenza is 1–4 days with 2 days being the average. The mechanism of transmission is mostly droplets (direct contact) and also contaminated objects or fomites (indirect contact). Airborne transmission is possible but the data supporting this is very limited. Infection can be transmitted 1 day before symptoms become evident and up to 5–7 days after falling ill.

A newspaper article reported that students with clinical signs of flu were asked not to return on the Wednesday that the school re-opened. The article provided symptoms to be aware of, including:

- a temperature of 38°C or above
- chills and body aches
- vomiting and/or diarrhoea
- severe headaches
- upper respiratory tract infection with symptoms such as a sore throat, runny nose, cough and/or nasal congestion.

Students with these symptoms were instructed to remain at home.

Review

1. Predict the result of influenza A transmission in this case, assuming the entire school community remains isolated as recommended. Use evidence and conceptual understanding in your prediction.
2. In reality, complete isolation of the entire school community is unlikely. Propose two limitations with this action plan to control the spread of disease through the school community, detailing the effect of the proposed limitations.

CASE STUDY 9.2.7

Agricultural biosecurity against fruit fly

Agricutural biosecurity and quarantine guidelines at Australian borders (including air freight and shipments) is a strategy to combat **agricultural pests**. Pests mostly consist of insects, such as fruit flies, which can cause damage and rotting of crops in egg, larval or adult stages. Pests can also be vectors that cause infections of plant pathogens, resulting in disease.

About 7000 hectares of mangoes are grown in Queensland. Fruit flies are one of the major pests. The Queensland mango industry produces an average of 53 500 tonnes of fruit and $140 million per year in profit, with trays being sold for $40–50 each. The cost of managing all pests is approximately $350–450 per hectare.

The Department of Agriculture and Fisheries (Queensland Government) provides the following recommendation for the management of **endemic** fruit flies:

> To monitor fruit fly activity hang male lure traps under the shady canopy, where flies tend to rest. Check the number of flies trapped each week. A number of traps (one per hectare) should be hung in the middle of each large orchard block of 5.0 ha or more according to manufacturer's instructions. Control may be necessary as soon as two flies per trap per day are caught.

> Queensland fruit fly infests both indigenous and introduced fruits. Commercial varieties affected include abiu, apple, avocado, babaco, capsicum, carambola, casimiroa, cherry, citrus, custard apple, granadilla, grape, guava, kiwifruit, mango, nectarine, papaya, passionfruit, peach, pear, persimmon, plum, pomegranate, prune, quince, loquat, santol, sapodilla, tamarillo, tomato and wax jambu.

Scientific research was conducted to study the management of the Queensland fruit fly in Queensland in the mango industry. As the Queensland fruit fly is a major pest for many fruit and vegetable crops, it is hoped this research can inform the agricultural industry and community as a whole. The study was conducted from August 2013 to February 2014 and employed various strategies of baiting, luring and trapping flies to comprehensively evaluate the effectiveness of each.

Figure 9.2.14 shows the effect of treatments to the trunks of mango trees with fruit fly luring solutions. Bowen and Dimbulah sprayed with fruit fly lure, with Bowen spraying (treating) the trunks of every second tree in each row while Dimbulah sprayed (treated) only the perimeter trees. Mutchilba hung Cera Traps in perimeter trees. For perimeter studies, cue-lure traps were placed approximately 15 metres apart. For the study of cue-lure traps throughout a crop, there were 5–10 traps per hectare. All traps were hung within the outer canopy at approximately 1.8 metres high.

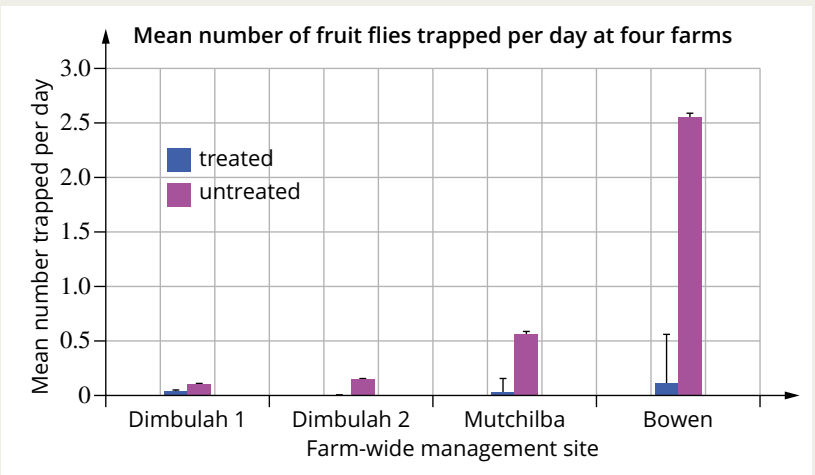


FIGURE 9.2.14 The mean number of fruit flies trapped per day at four different farms of treated and untreated crops. The Dimbulah results were affected by heavy rain, causing the spray treatment schedule to be severely altered.

Figure 9.2.15 shows the results of specific bait height testing conducted at Cleveland. Two plant species were studied, cassava and forage sorghum, which can provide resting sites for fruit flies. Trials were performed in four 3 × 3 × 2.5 metre gauze-sided cages within a shade house at the Department of Agriculture and Fisheries Redlands Research Facility (Cleveland). In each cage, three plants were placed in each corner with only one plant type in each cage. Baits were placed at different heights in each corner. A total of 300 fruit flies, male and females were released into each cage.

Another scientific research studied fruit fly behaviour by placing a crop adjacent to forage sorghum at the Maroochy Research Facility (Nambour) (Figure 9.2.16). A row of forage sorghum was planted at one end of the crop, and was 2.3 metres in height at the time of the study. Zucchini was planted in rows parallel to the sorghum in a netted area. Rows 7, 22 and 52 metres from the sorghum were used for the trial. Both male and female fruit flies were released into the sorghum. Sample zucchini fruit were collected 1, 4, 7 and 24 hours later, and held under controlled conditions (26°C, 70% relative humidity) on drip trays in ventilated containers for a minimum of 11 days to allow eggs to develop to the pupal stage.

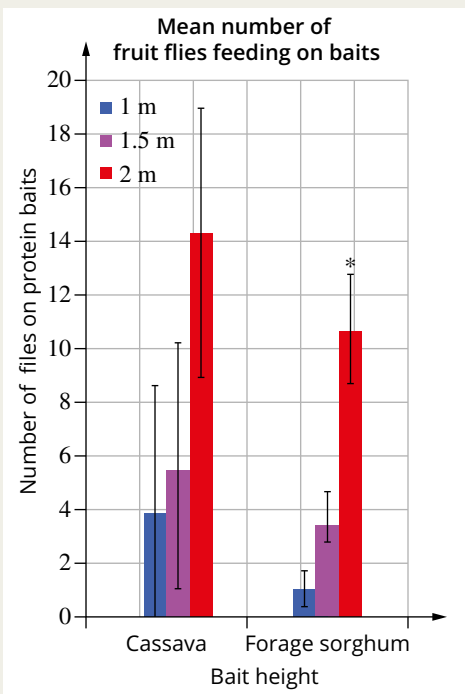


FIGURE 9.2.15 Mean number of fruit flies feeding on baits per 30 min at different heights (1 m, 1.5 m and 2 m) on cassava and forage sorghum plants. * is a statistically significant result.

Review

1. Interpret the error bars for the data in Figure 9.2.14, assuming they are standard deviation.
2. Interpret the error bars for the data in Figure 9.2.15, assuming they are standard deviation.
3. Interpret the error bars for the data in Figure 9.2.16, assuming they are standard deviation.
4. Interpret the forage sorghum results in Figure 9.2.15 assuming the student *t*-test was applied, using the 2-metre-high baits as the independent variable in the null hypothesis.
5. Interpret the cassava results in Figure 9.2.15, assuming the student *t*-test was applied, using the 2-metre-high baits as the independent variable in the null hypothesis.
6. From the data presented in Figures 9.2.14–9.2.16, suggest a model for farmers to use that would minimise disease and rotting for mangoes from fruit flies.
7. Calculate the cost of managing pests at a higher level of control for the model developed for Question 6, if the typical cost of managing pests is $350–$450 per hectare.

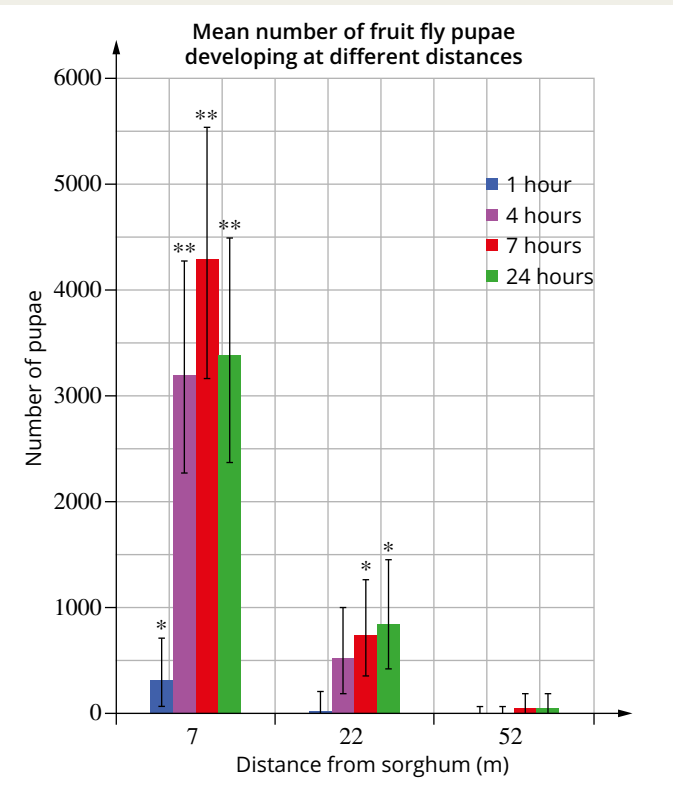


FIGURE 9.2.16 Mean number of fruit fly pupae developing in zucchinis at different distances from sorghum. The closer the zucchinis to sorghum, the greater number of pupae developing. ** is a statistically significant difference from both other distances, * is statistically significantly different from 52 m.

The costs involved in managing fruit fly pests and eradicating exotic fruit fly incursions (the importation of foreign fruit flies which are found in Australia) have been estimated and reported in the Australian Bureau of Agricultural and Resource Economics and Sciences report *Benefit–Cost Analysis of the National Fruit Fly Strategy Action Plan*. The cost to eradicate an **exotic incursion** fruit fly is $13.3 million per year across Australia for each exotic incursion. Table 9.2.5 shows the distribution of this cost across Australia, excluding Queensland, though the total of $13.3 million includes Queensland.

TABLE 9.2.5 Cost of eradicating an exotic fruit fly incursion into Australia, across all states excluding Queensland

State	Average annual cost ($ millions)
Western Australia	0
South Australia	1.7
Victoria	5.5
New South Wales	1.4
Tasmania	0.4
Total	8.64

Source: Plant Health Australia 2009, updated with data from state governments, where available.

The report estimated that production costs of fruit and vegetables grown in fruit fly endemic areas (Queensland, New South Wales and Victoria) was $2.6 billion with 0.5–3% damaged by fruit flies. The production costs include pest management. It also reported that the value of fruit and vegetables grown in fruit fly endemic areas Australia wide is $5.3 billion, shown in Figure 9.2.17.

8 If Australia's quarantine strategy of border biosecurity did not stop an exotic Asian fruit fly incursion into Queensland, estimate the total cost over 10 years and report per year. Assume:

- eradication strategies were undertaken for 10 years without success
- the exotic fruit fly becomes a common pest like the Queensland fruit fly in 10 years, with consistent growth over the 10 years.

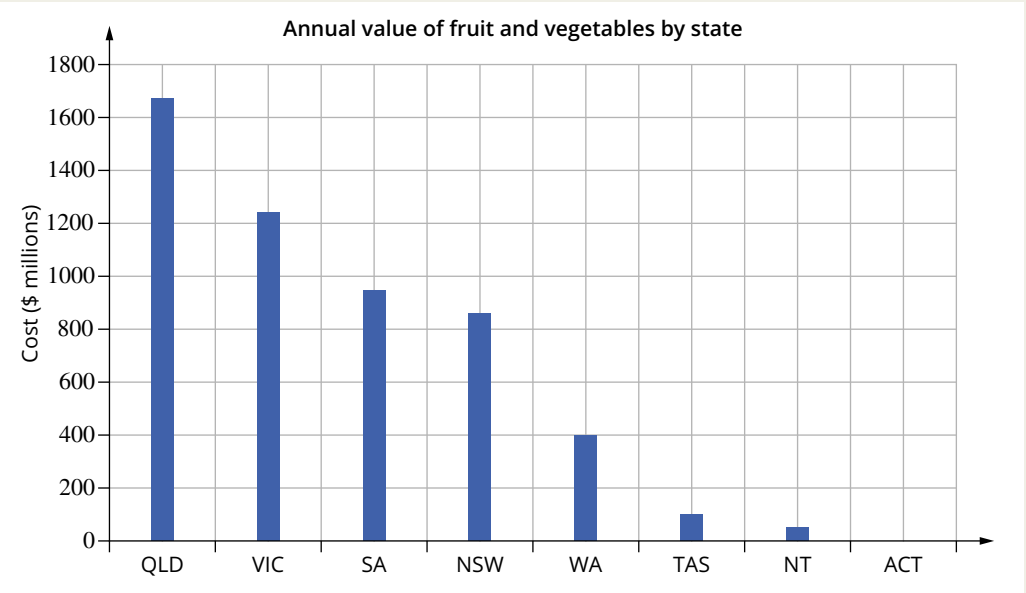


FIGURE 9.2.17 The annual value of fruit and vegetable produce in Australia by state

Review

SUMMARY

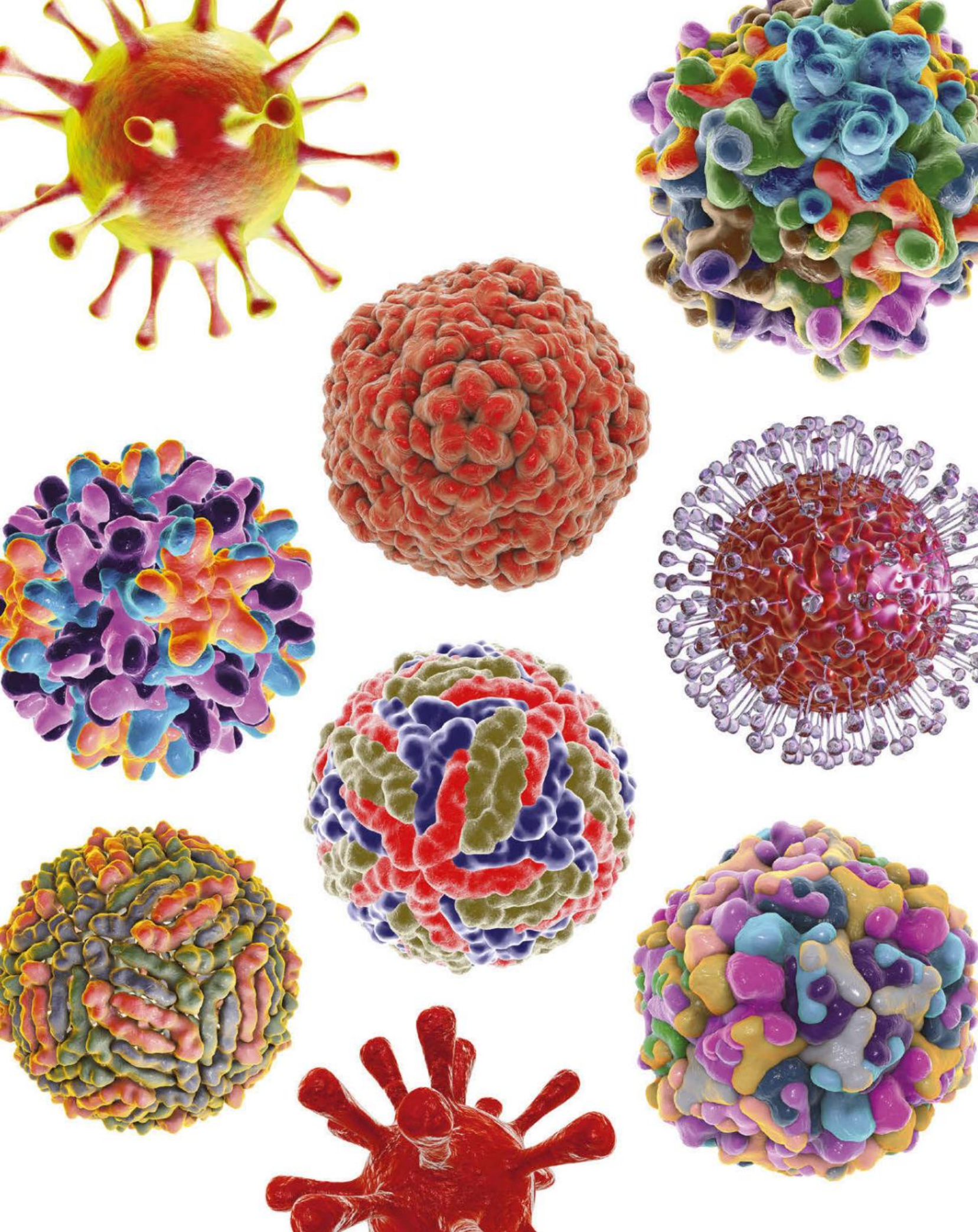
- Epidemiology is the study of diseases, how they are transmitted, and how they might be controlled.
- Various related variables must be considered, for example:
  - mechanism of transmission (direct versus indirect)
  - rate of transmission (R_0)
  - contact tracing
  - infrastructure
  - travel (regional and global)
  - herd immunity
  - hygiene
  - quarantine
  - mass gatherings.
- Epidemiology enables some prediction and control of the spread of disease using models (e.g. mathematical models).
- Developing models of disease transmission requires:
  - the understanding of transmission and methods of prevention.
  - retrieving and comprehending knowledge (including immunity, pathogens and cellular biology)
  - analysing and interpreting evidence
  - applying knowledge to infer, conclude, predict, and also to utilise knowledge to create and develop preventative plans
- Scientific skills applicable to the data test, student experiment and research investigation were utilised to complete case studies

WS 2.2.8 WS 2.2.9

09

KEY TERMS

agricultural pest
antibacterial
arthralgia
asymptomatic
cluster
communicable disease
community immunity
contact tracing
contaminant
direct contact transmission
droplet
exotic incursion
fomite
herd immunity thresholds
hygiene
hygiene etiquette
immunisation coverage
immunosuppressed
indirect contact transmission
mathematical modelling
simulate
morbidity
mucous membrane
quarantine
reproduction number (R_0)
reservoir
sanitation
secondary infection
susceptible
symptomatic
thermoscanning
virulence



TR 2.1 TR 2.2

REVIEW QUESTIONS

Topic 1 Homeostasis

Multiple-choice questions

1 Select the correct statement about signalling molecules called steroid hormones.

A They are secreted by the adrenal cortex, testes and ovaries, and have their effects on target cells some distance away.
B They are hydrophilic and so cannot penetrate the plasma membrane.
C They always bind to cell surface receptors to trigger chemical cascades.
D They never enter the blood of humans.

2 Identify the reason(s) most extracellular signalling molecules act on cell-surface receptors rather than intracellular receptors.

I The signalling molecules are too large to pass directly across the plasma membrane.
II The signalling molecules are too hydrophilic to pass directly across the plasma membrane.
III The signalling molecules are too hydrophobic to pass directly across the plasma membrane.

A I only
B II only
C I and II only
D I and III only

3 Identify the best representation of the stimulus–response pathway.

A receptor → stimulus → control centre → response → effector
B stimulus → receptor → control centre → effector → response
C control centre → stimulus → receptor → effector → response
D effector → control centre → receptor → stimulus → response

4 A person is placed in water at 15°C. Assess the situation and decide how the person's body will react in order to maintain thermoregulation.

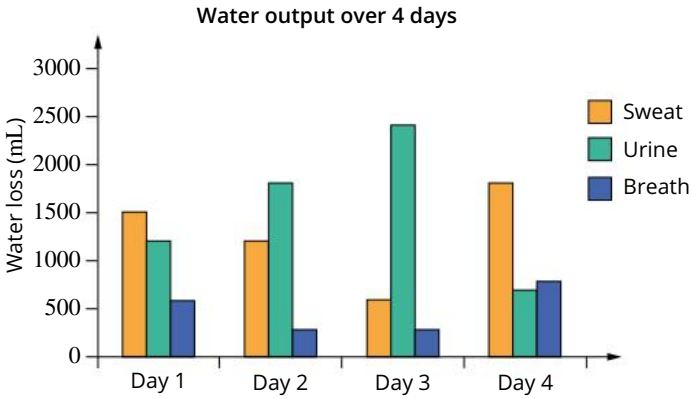
	Circulation to the skin surface	Activity of sweat glands	Skeletal muscle contractions
A	increases	increases	decreases
B	decreases	decreases	decreases
C	increases	increases	increases
D	decreases	decreases	increases

5 An athlete who has just completed a 20 km run will have lost an excessive volume of water through sweating. Demonstrate your understanding of water and salt regulation by selecting the statement that most accurately describes what will happen.

A Dilute urine will be produced.
B An increased volume of urine will be produced.
C ADH will be released into the bloodstream, increasing the reabsorption of water from the collecting ducts in the kidney.
D Vasopressin will be released into the bloodstream, decreasing the reabsorption of water from the collecting ducts in the kidney.

6 A scientist was studying how water balance and environment interacted in maintaining a stable core temperature. The scientist hypothesised that environmental temperature and humidity would cause variations in how water was lost from the body.

A subject was provided with the same amount of food and drink for four days and their water output was measured. The results of the experiment were graphed as shown below.



Environmental conditions varied over the four days. Analyse the data and select the situation that would disprove the scientist's hypothesis.

A Day 4 was hot and dry.
B Day 2 was cold and wet.
C Day 1 was cool and dry.
D Day 3 was cool and humid.

7 State where neurotransmitters are released into the synapse.

A cell body
B Golgi apparatus
C presynaptic membrane
D postsynaptic membrane

8 Salmon lay their eggs in freshwater streams, where they are fertilised. Soon after hatching, the young salmon (smolts) swim downstream and out to sea. Once in the ocean, the smolts grow into fully developed adult salmon. These adults then make their way back to their original freshwater stream to lay eggs.

Identify the best description of what would happen when the smolts move from a freshwater to a marine environment.

A The concentration of water in the blood plasma would decrease.

B A smaller volume of more concentrated urine would be produced.

C A larger volume of more dilute urine would be produced.

D Less solutes, including urea, would be filtered out of the blood.

9 After exercising in extremely hot conditions, a decrease in the concentration of sodium ions in the blood will occur. Identify which of the following will return the sodium ion concentration to its normal level.

	Aldosterone secretion	Reabsorption of sodium ions	Blood pressure
A	increased	increased	increased
B	decreased	increased	increased
C	increased	decreased	decreased
D	decreased	decreased	increased

10 Select the alternative that best depicts the correct feedback process in an endotherm.

A increase in temperature → thermoreceptor → vasodilation → hypothalamus → heat loss

B decrease in temperature → hypothalamus → vasodilation → heat gain → thermoreceptor

C increase in temperature → hypothalamus → thermoreceptor → vasodilation → hypothalamus → heat loss

D increase in temperature → thermoreceptor → hypothalamus → vasodilation → heat loss

11 After emerging from hibernation, some male red-sided garter snakes (*Thamnophis sirtalis infernalis*) can produce pheromones that mimic those produced by female snakes. This attracts other males to attempt to mate with them and, in doing so, transfer heat to them.

Identify the term given to this mode of heat transfer.

A aestivation

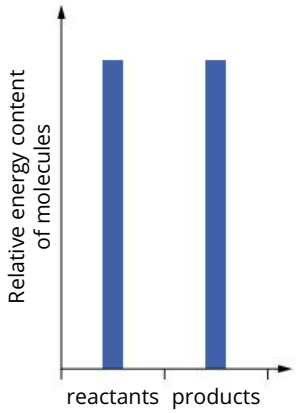
B thermogenesis

C kleptothermy

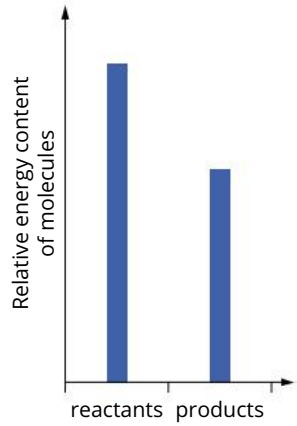
D endothermy

12 Select the graph that best represents a catabolic chemical reaction.

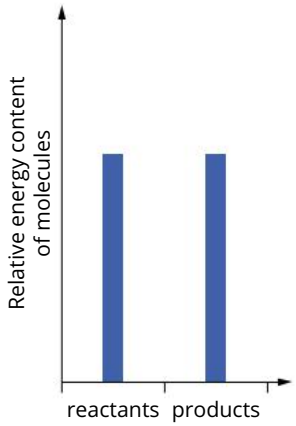
A



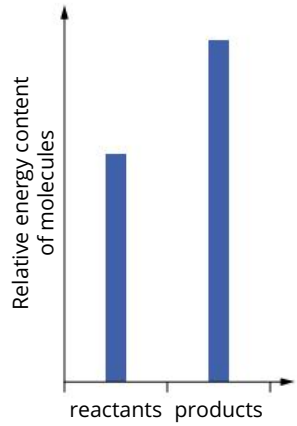
B



C



D



Short-answer questions

13 Define:

a metabolism

b osmoconformer

c thermogenesis

d osmoregulator

e aestivation

f anabolic.

14 Plants produce signalling molecules called phytohormones. Auxins are one group of phytohormones and are responsible for phototropism.

a Explain the term 'positive phototropism'.

b **i** Name two sites of auxin production.

ii Describe how auxins travel to the site where they are active.

c One mechanism by which auxin causes its action is shown in the flow diagram. In the case of phototropism, the kinases at step 7 activate enzymes that soften the cell wall, making it more flexible. Identify the three stages of signal transduction in the action of auxin.

Step 1
Auxin joins with a receptor on the plant cell membrane.

↓

Step 2
An enzyme attached to the cytoplasmic side of the receptor is activated.

↓

Step 3
The enzyme catalyses the change of a lipid, PIP_2, in the membrane of the cell into chemicals called IP_3 and DAG.

↓

Step 4
IP_3 then moves to the vacuole of the cell where it joins to a receptor in the vacuole membrane.

↓

Step 5
The recognition of IP_3 by the vacuolar receptor triggers the pumping of Ca^{2+} ions out of the vacuole into the cytosol.

↓

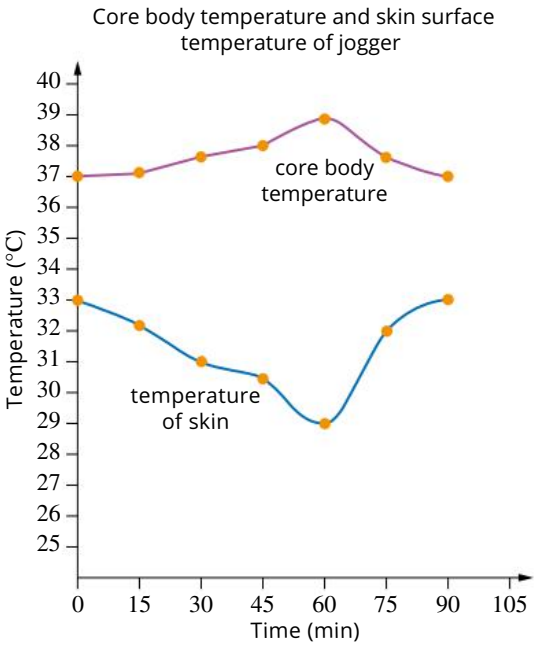
Step 6
The presence of Ca^{2+} ions in the cytosol activates enzymes called kinases.

↓

Step 7
The kinases result in changes in cell activity.

d Identify the stimulus and the response of the plant at a:
- **i** cellular level
- **ii** whole organism level.

15 The diagram shows the changes in the core body temperature and skin surface temperature of a jogger. He jogged from $t = 0$ to $t = 60$ minutes. From $t = 60$ to $t = 90$ minutes, the jogger stopped and sat on a chair.



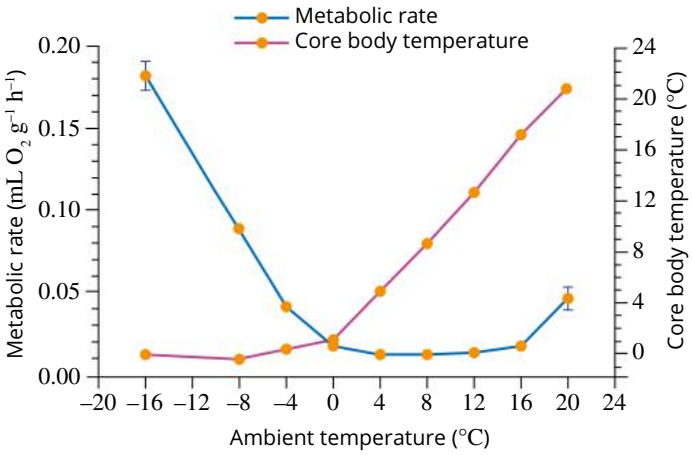
a Describe the changes in core body temperature and temperature of the skin from $t = 0$ to $t = 60$ minutes.

b Explain the homeostatic cause of the patterns described in part **a**.

c Propose why the temperature of the jogger's skin started to rise after $t = 60$ minutes.

d A phenomenon experienced by some joggers is heat stroke. In this case core body temperature rises, sometimes as high as 40°C. Heat stroke can be fatal. Hypothesise a reason why, that is related to enzymes.

16 Scientists investigated the effect of ambient (surrounding) temperature on metabolic rate and core body temperature of Arctic ground squirrels (*Spermophilus parryii*). The scientists placed the squirrels in a cool environment and then slowly increased the temperature of the environment. At the same time, they measured changes to core body temperature and respiratory quotient (ratio of carbon dioxide produced to oxygen consumed) of the small mammal. Results of the experiment are shown in the following diagram.



a In order to estimate the metabolic rate of the squirrels, the scientists measured their rate of oxygen consumption. Propose why.

b Outline the effects of ambient temperature on core body temperature.

c Propose why when core body temperature is low, the metabolic rate of the squirrel is high.

17 Draw a labelled diagram of a:

a motor neuron

b sensory neuron.

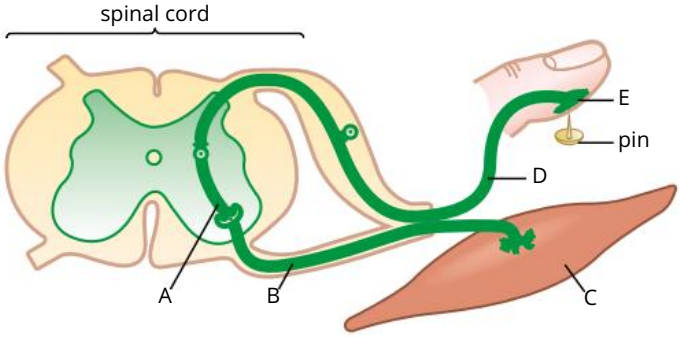
18 **a** Name the group of chemicals to which acetylcholine belongs.

b Acetylcholinesterase is an enzyme that breaks down acetylcholine. Propose where you would expect to find this enzyme. Justify your proposition.

c Redback spiders (*Latrodectus hasselti*) are found throughout Australia. They have a highly venomous bite that can result in paralysis. The situation following a bite becomes serious when the muscles of the chest are affected, causing difficulty breathing. Studies have shown that the venom causes a slow leak of acetylcholine from the presynaptic membrane of motor neurones.

Explain how redback spider venom causes paralysis.

19 Carefully examine the diagram.



a Identify the structures A–E.

b Name the neural pathway shown in the diagram.

c Identify the stimulus and response shown in this situation.

d When you prick your finger with a pin, you immediately move your hand, but then you feel the pain afterwards. Explain why the two experiences are not simultaneous.

20 In a cold acclimitisation experiment, scientists noted that over a 10-day period there was increased activity in brown adipose tissue (brown fat). Explain how this could result in a reported higher level of climate comfort by the subjects of the experiment.

21 Name the specific group of receptors responsible for passing information about the position of arms and legs to the brain.

22 **a** The distribution of stomata across the upper and lower epidermis of four different plants was tabulated and the results are shown in the table.

Plant	Number of stomata per cm^2 on the upper epidermis	Number of stomata per cm^2 on the lower epidermis
J	0	22 500
K	46 000	0
L	1190	28 000
M	0	0

The plants investigated were those living:

- in a forest (*Eucalyptus pilularis*)
- floating on the surface of lakes (*Nymphaea alba*)
- in deserts (*Pistacia mexicana*)
- totally submerged (*Elodea canadensis*).

Match each of the plants J–M with the environment in which it grows and in each case explain why you made your choice.

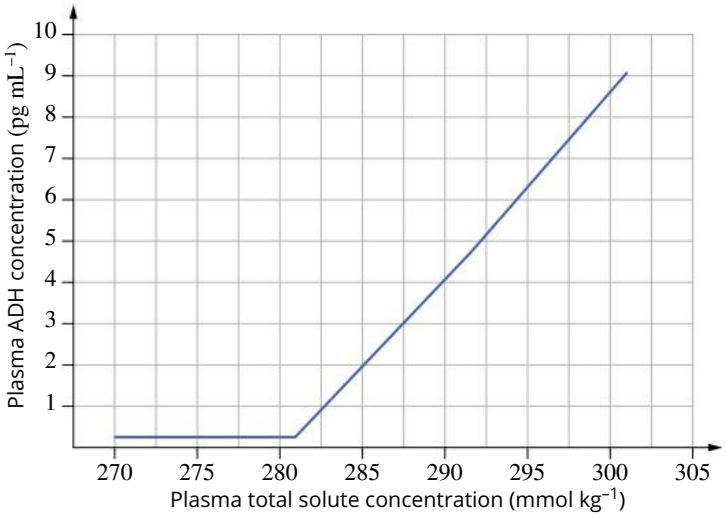
b Identify three other mechanisms that can be found in plants such as *Pistacia mexicana* that assist in maintaining water balance.

23 Antidiuretic hormone (ADH) is a signalling molecule produced in the hypothalamus and released by the pituitary gland.

a Name the cells in the body that respond to the presence of ADH.

b The graph shows the change in ADH as the concentration of solutes in the blood increases.

Blood ADH concentration as plasma concentration varies



i State the expected total plasma solute concentration when plasma ADH concentration is 2 pg mL^{-1}.

ii Explain how an increase in ADH concentration results in a return to a blood plasma concentration within the ideal range.

c The release of ADH is triggered when baroreceptors identify a reduction in the stretch of blood vessels and/or when osmoreceptors (which measure solute concentration in the hypothalamus) register increased concentration. Classify these two examples of receptors.

d Alcohol inhibits the production of ADH. Explain how this results in dehydration after excessive consumption.

e The spinifex hopping mouse (*Notomys alexis*) is well adapted to the desert environment where it lives. Its nephrons have very long loops of Henle. Propose how this assists the mouse to maintain water balance and live in a desert.

f When examining the concentration of ADH in the blood of hopping mice, it has been shown not to increase during periods of water deprivation. When the blood of the common house mice (*Mus musculus domesticus*) is examined under similar circumstances, they are found to have significantly higher ADH levels.

Hypothesise how hopping mice can increase their uptake of water without increasing levels of ADH while common house mice cannot.

24 The thyroid gland produces the hormone thyroxine, which stimulates cell metabolism. It increases the rate of cellular respiration and so increases the production of both ATP and heat. The thyroid produces thyroxine when it is signalled by a hormone produced by the pituitary gland. This hormone, thyroid stimulating hormone (or TSH), is hydrophilic. The pathway to an increase in cell metabolism is shown below.

pituitary produces TSH
↓
receptors accept TSH
↓
thyroid produces and releases thyroxine
↓
body cell thyroxine receptors accept thyroxine
↓
body cells increase metabolism

a **i** Name the group of hormones to which TSH belongs.

ii State where the cellular receptors for TSH are. Explain your reasoning.

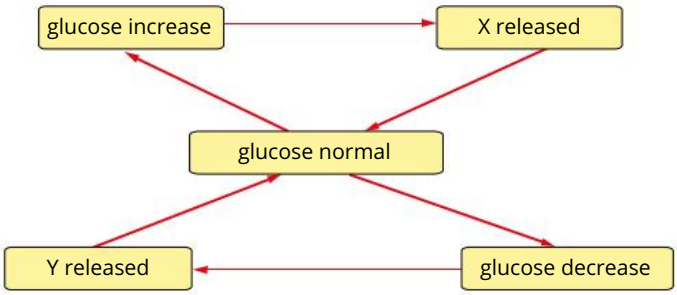
b One disease associated with the thyroid gland is Hashimoto's thyroiditis. In this disease, antibodies block the TSH receptors. Hypothesise how this affects cellular functioning throughout the body. Justify your proposition.

c In Graves' disease, antibodies attach to the TSH receptors and cause continuous stimulation.

i Explain how thyroid cells would respond to this.

ii Explain what effects you would expect in the body.

25 The following diagram shows how the body regulates the glucose concentration in blood.

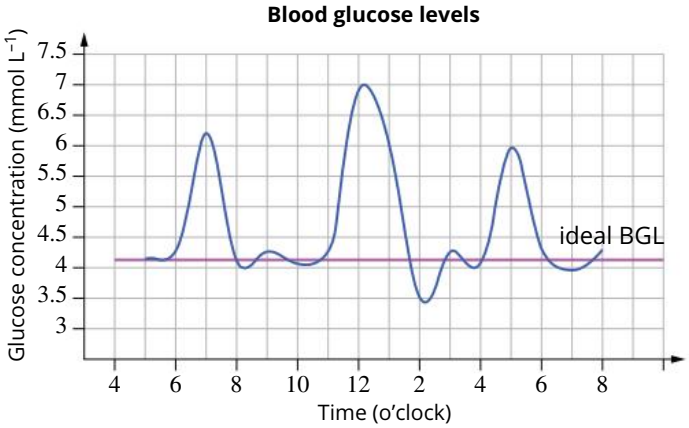


a Identify X and Y.

b **i** Explain how the body regulates the glucose concentration in blood.

ii Name the tissues that are the effectors in reducing blood glucose levels.

c The graph below shows the blood glucose levels (BGL) of a person throughout the day.

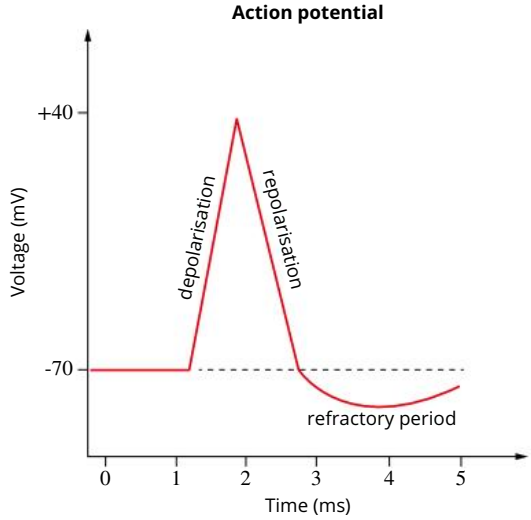


i Explain at what time the person ate breakfast.

ii Explain why the BGL dips so significantly below the ideal at 2.00 pm.

ii This graph shows a normal homeostatic response. Propose what differences would you expect to see if a person had type II diabetes.

26 **a** Explain, using the graph, what is happening within both the neuron's membrane and cytoplasm during depolarisation and repolarisation.



b Explain why not all stimuli generate an action potential.

27 **a** Design an experiment to determine the effects of air humidity on the rate of photosynthesis in geranium plants in a hot climate. Identify your controlled, dependent and independent variables.

b Explain why humidity can effect of the rate of photosynthesis.

c Explain why temperature must be controlled for all of the plants.

Topic 2 Infectious disease

Multiple-choice questions

1 Identify which of the following lists contains only diseases caused by a nutritional deficiency.

A melanoma, scurvy, bulimia, anaemia
B Down syndrome, anorexia, beri beri, tetanus
C anaemia, scurvy, beri beri, anorexia
D colour blindness, rickets, anorexia, anaemia

2 Malaria is an infectious disease, with the *Anopheles* mosquito as its vector. Identify the role played by the vector.

a disease-causing organism
B blood-sucking parasite
C disease-carrying organism
D the host organism

3 Define 'pathogen'.

A a cell that destroys bacteria by injecting toxin into it
B an organism that transfers disease from one host to another
C an organism that can live in or on the host
D an organism or infectious agent that causes disease in the host

4 Identify the incorrect statement.

A Complement proteins are part of the innate immune response.
B Complement proteins attract phagocytes to the site of the infection.
C Complement proteins include antibodies.
D Complement proteins can be activated in the absence of antibody–antigen reactions.

5 Identify which of the following statements correctly states how natural active immunity is achieved.

A exposure to live or attenuated vaccines
B infection by particular bacteria or virus
C the administration of antibodies or antitoxin specific to a particular microorganism
D adequate breastfeeding in newborn infants

6 Identify the best protection for newborn babies from pertussis until week 8.

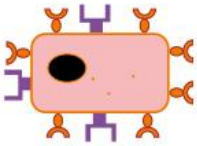
A active immunity
B herd immunity
C passive immunity
D specific immunity

7 Identify which of the following represents the correct sequence of events when the body is responding to a bacterial infection.

I antigen presentation by macrophages
II activation of B cells
III activation of helper T cells

A I, II, III
B I, III, II
C III, II, I
D II, III, I

8 The pathogen shown below enters a human body and antibodies are produced against it.



Select the antibody that would be made in response to the pathogen.

A


B


C


D


9 Identify how skin and mucous membranes act as barriers to infection.

	Skin	Mucous membranes
A	Skin is tough and forms an effective physical barrier.	Mucous membranes are thick and elastic, so pathogens are repelled.
B	Phagocytes on the skin surface trap pathogens.	Mucus is moved out of the body by the beating of hair-like cilia.
C	Skin is tough and forms an effective physical barrier.	Pathogens are trapped by sticky mucus.
D	Phagocytes on the skin surface trap pathogens.	The acidity of mucus kills harmful bacteria.

10 Select a correct explanation for why are there many different types of B lymphocytes in the body.

A Each type can recognise one specific antibody and produces a specific antigen against it.
B Each type can recognise one specific antigen and produces a specific antibody against it.
C Each type can recognise one antigen and engulf it by phagocytosis.
D Each type can recognise one antibody and engulf it by phagocytosis.

11 Plants have defences against invading pathogens. Select the alternative that is not a plant defence against pathogens.

A chitinases, which disrupt the cell membranes of fungi
B perforins, which rupture the cell membranes of bacteria
C tannins, which are toxic to insects
D defensins, which are toxic to microbes

12 Identify the alternative that correctly describes rejection by the immune system to an organ transplantation.

A The transplanted organ contains white blood cells, destroying the recipient's immune system.
B Blood from the transplanted organ will cause a deterioration of the recipient's tissues.
C Antibodies from the donor will react with the antibodies from the recipient.
D The donor organ carries markers on the cell surface that are recognised as foreign by the recipient's T cells.

13 Identify which of the following types of data it would be necessary to collect for an epidemiological study.

A gender
B age
C date of diagnosis of disease
D all of the above

14 Identify which of the following methods would be ineffective at preventing the spread of an airborne contagious disease.

A washing hands after using the bathroom
B wearing a mask in public places and on public transport
C coughing into a tissue and disposing of it
D staying at home until no longer infectious

15 A baby was born severely jaundiced and anaemic. The baby recovered after a blood transfusion, but concerned doctors tested the blood of both the baby and her mother. It was discovered that the baby and her older brother were positive to the Rhesus factor, while their mother was Rhesus-negative.

Deduce the reason why the baby's haemolytic disease of the newborn occurred.

A The mother's antigens recognised the baby's antibodies as foreign and attacked them.
B The mother had an adaptive immune response to the Rhesus factor in the blood of her first child, and memory cells triggered an immune response to the Rhesus factor in the blood of her second child.
C The baby developed antibodies in response to her mother's Rhesus-negative blood and caused an immune response.
D The Rhesus antigen present on the mother's red blood cells caused an immune response to the baby's blood, which was free of the antigen.

Short-answer questions

16 Describe the difference between an infectious disease and a non-infectious disease.

17 Identify the type of pathogen that causes the disease and list the features of that type of pathogen in order to complete the table.

Disease	Type of pathogen	Characteristics of the pathogen
tetanus		
malaria		
thrush		
leaf gall		
trichinosis		
mad cow disease		
common cold		

18 Describe how each of the following factors contributes to the virulence of a disease caused by a pathogen.

a adhesin factors
b invasion factors
c capsules
d toxins

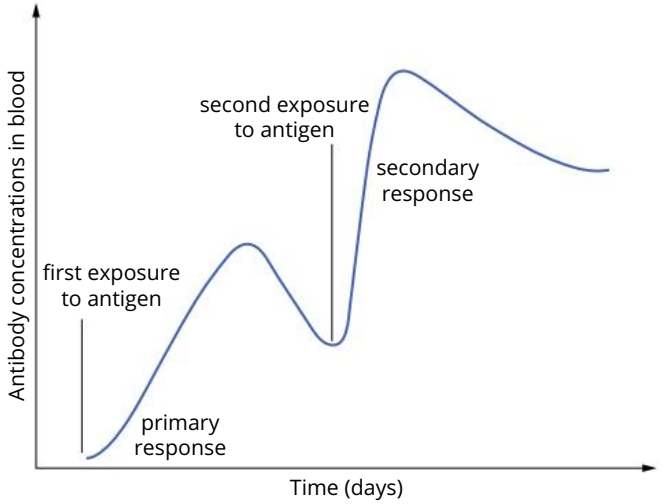
19 **a** Define 'inflammation'.
b Outline the steps involved in initiating an inflammatory response.

20 **a** Define 'chemical barrier' and provide an example for both plants and animals.
b Explain why taking a course of antibiotics can disrupt microbiological barriers in animals.

21 **a** Distinguish between complement proteins and cytokines.
b Identify the type of defensive molecule that includes interferons.

22 **a** Distinguish between bacteria and viruses.
b Briefly outline why antibiotics are effective against bacteria but not viruses.

23 Most people in Australia are vaccinated against measles in childhood. The vaccination schedule requires children to be given one injection at 12 months and a second injection at 18 months. The antibody response to the vaccinations is shown in the graph below.



a Explain why the secondary response is so much greater than the primary response.

b T lymphocytes play a significant role in the adaptive immune response of the body against viruses such as the one that causes measles. Describe the role of T cells in immunity.

c In February 2016, Department of Health statistics showed that 93.58% of 5-year-old children in Victoria were fully immunised against measles. In some areas the immunisation rate is as low as 73%. Explain why this statistic would be concerning to epidemiologists.

---

24 The calculation of R_0 needed to predict the spread of disease is given by the formula:

$$R_0 = r \times c \times d$$

where r is the transmissibility of the pathogen, c is the average rate of contact between susceptible and infected individuals and d is the duration of infectiousness of the disease.

Consider the information given in the table for some hypothetical emerging diseases.

a Calculate the value of R_0 for each of the diseases by using the formula given.

b Identify which disease(s) is diminishing in the population.

c Identify which of the diseases most probably is demonstrating the effects of herd immunity. Explain your reasoning.

d **i** Propose which of the diseases would be of most concern to health authorities. Justify your proposal.

ii Explain three public health initiatives which could be introduced to reduce the spread of this disease.

iii List at least one initiative that is unlikely to have much effect.

Disease	Probability of infection given contact between an infected person and a susceptible person (transmissibility)	Rate of contact (probability) between an infected and a susceptible person	Duration of infectiousness (days)	Mortality (%)	Pathway of spread	Type of pathogen
A	0.9	0.95	7	4	foodborne	bacterium
B	0.2	0.05	14	30	airborne droplets	virus
C	0.35	0.4	20	0.2	insect vector	protozoan
D	0.8	0.6	11	12	contaminated water	bacterium
E	0.1	0.9	6	0.2	direct contact	virus

---

25 Explain the cause and method of transmission of HIV.

26 Evaluate the ability of quarantine to prevent the entry and spread of disease into Australia, using examples to illustrate your answer.

27 Many natural therapies websites describe eucalyptus oil as an excellent antiseptic.

a Distinguish between antiseptics, disinfectants and antibiotics.

b Design an experiment, using paper discs, to test whether the claim that eucalyptus oil is an effective antiseptic is valid.

c Predict the outcome if the claim that eucalyptus oil is an effective antiseptic is valid.

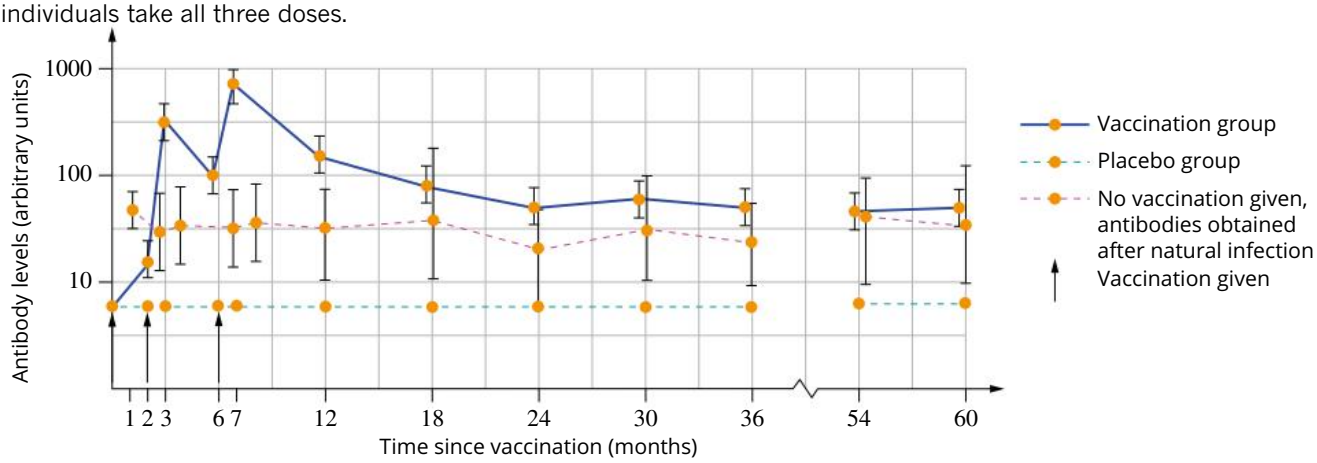
d Explain why it is necessary to include a paper disc without eucalyptus oil.

28 The graph below shows the antibody levels for human papilloma virus (HPV) 18 in women aged between 15 and 26 years. The level of antibodies in the blood was measured for three different groups of women: the first group were given the vaccination against HPV (Gardasil®), the second group were given a placebo, and the third group consisted of individuals who had obtained antibodies after natural infection.

a State when the vaccination group had the highest levels of antibodies for HPV 18.

b Contrast the levels of antibodies for HPV 18 between the three groups.

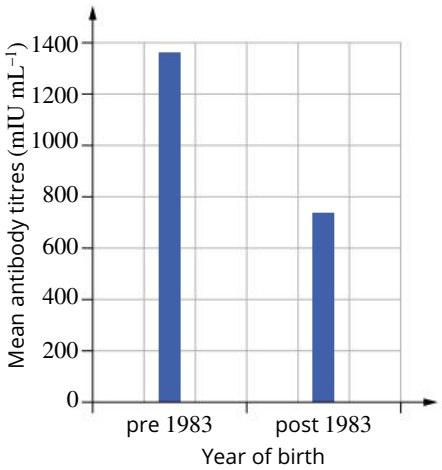
c HPV vaccination is often given as three injections over 6 months: the second dose is 1–2 months after the first dose, and the third dose is 6 months after the first dose. Based on the results of the study, explain why it is essential that individuals take all three doses.



29 Routine measles vaccinations began in France in 1983. In 2005 a study was undertaken to examine the concentration of measles antibodies in French women of childbearing age. The aim was to discover the effect of immunisation on maternal antibody levels. Antibody levels must exceed 200 mIU mL^{-1} for protection to be maintained.

The results of this study are shown in the graph.

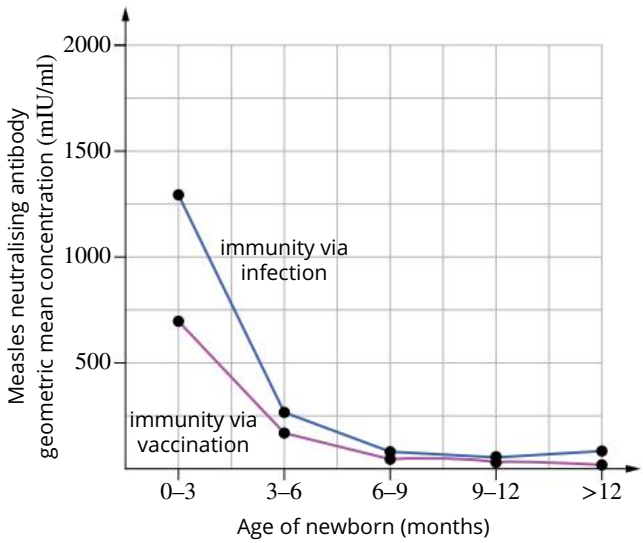
Blood antibody concentration of women born before or after 1983



a Determine the effect of vaccination on long-term antibody levels. Explain your findings.

Following the examination of the adult women, a further study to examine the effects on newborn babies and their antibody levels of the vaccination program was undertaken. The results are shown in the graph.

Newborn measles immunity according to maternal acquisition



b Evaluate how the vaccination program affected maternal antibody presence in newborns.

c The first dose of MMR vaccine is routinely given in Australia at 12 months of age. Predict the possible consequences of this in light of the data collected in France and the decline in childhood vaccination rates in Australia.

30 In 2004, a new influenza strain in the H5N1 family of viruses arose in birds in Asia. 'Bird flu' caused worldwide concern, as it became clear that the virus could move from birds to humans. Strict quarantine of anyone showing symptoms contained the disease, but there were still significant numbers of fatalities. Many of the fatalities occurred as a result of acute respiratory distress syndrome (ARDS). ARDS is severe damage to the lungs caused by excessive release of cytokines, which causes many lung cells to undergo apoptosis.

a The stimulation of large numbers of cytokine receptors in lung cells results in the triggering of apoptosis in otherwise healthy cells, by the extrinsic pathway. Explain why lung cells are exposed to many cytokines during an influenza infection.

b The table shows the incidence of bird flu in humans and the number of fatalities up to December 2006.

Country	Time frame	Number of cases	Number of fatalities
Azerbaijan	Feb 06 – Mar 06	8	5
Cambodia	Jan 05 – Mar 06	6	6
China	Oct 05 – Apr 06	18	12
Egypt	Mar 06 – Apr 06	12	4
Indonesia	Jul 05 – Mar 06	32	24
Iraq	Jan 06 – Jan 06	2	2
Thailand	Jan 04 – Nov 05	22	14
Turkey	Dec 05 – Jan 06	12	4
Vietnam	Dec 03 – Nov 05	91	42

i Hypothesise with justification where bird flu might have originated.

ii In all major airports, anyone coming from a country where bird flu had occurred was screened for a raised temperature and, if the result was positive, the person was immediately quarantined.

For typical strains of influenza, 9–13% of infected people die. Using the data in the table, explain why such stringent precautions against the spread of bird flu were implemented.

iii Following the outbreak, there was a large research effort to create a successful vaccine, and people in affected areas were encouraged to be vaccinated.

Explain how a large-scale vaccination program reduces the risk of a major outbreak of a communicable disease.

c The table shows the distribution of deaths due to bird flu, by age and sex.

Age group (years)	Deaths	
	Male	Female
<5	13	8
5–9	19	13
10–19	18	31
20–29	18	27
30–39	17	16
40–49	5	6
>50	6	5

i Draw a graph using the data in the table.

ii Explain limitations in the data displayed that may result in it being misleading.

iii Explain whether the data suggests that either sex is more susceptible to bird flu.

iv The data given is from a WHO (World Health Organization) report. WHO does not collect its own data. It relies on self-reporting from affected countries. Comment on the reliability of the data presented.

31 Rabies is a serious disease caused by a virus. It infects many animals, including dogs but does not occur in Australia. After infection, the reproduction of the virus is very slow and the disease is also slow to become symptomatic. Australia's quarantine laws restrict the movement of dogs into the country. These laws were contravened in 2015 when US actor Johnny Depp brought two dogs into Australia.

a Predict the effects of the entry of rabies into the Australian native animal population. Justify your prediction.

b When individuals are bitten by a potentially rabid animal overseas, a treatment regime is initiated. This regime begins with an initial injection of immunoglobulins followed by a vaccination series.

i Explain how the first injection differs from the later series of vaccinations.

ii State the type of immunity provided by each injection.

iii Suggest why the first injection is given.

iv Propose why the later vaccinations are also required.

Glossary

RED ENTRIES Biology 2019 v1.2 General Senior Syllabus © Queensland Curriculum & Assessment Authority.

A

abscisic acid A growth-inhibiting plant hormone associated with leaf and fruit fall, as well as bud and seed dormancy.

absolute uncertainty The uncertainty of a measurement that results from the smallest available increment on an instrument.

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.

action potential A reversal of the normal potential difference across a cell membrane, or between the inside and outside of a nerve fibre.

activation energy The energy that is required to start a biochemical reaction.

active immunity Immunity that involves an individual's own adaptive immune response, through B and T lymphocytes.

active site The specific site of an enzyme that binds the substrate and where catalysis occurs.

active transport The movement of substances across membranes that requires the expenditure of energy; occurs through selective protein channels.

adaptive immune response An immune response that is modified on each subsequent infection to become more effective and to provide long-term immunity to pathogens.

adaptive immunity An immune response that is specific to a specific antigen; thought to be present only in vertebrates.

adenosine triphosphate (ATP) A molecule that provides energy for immediate use by a cell; produced during glycolysis and cellular respiration.

adhesion A structure or molecule on the surface of bacteria, which allows them to attach to their prospective host cell.

adjuvant A chemical added to a vaccine that enhances the ability of the vaccine to induce an immune response.

adrenaline A hormone released by the adrenal gland.

adult stem cell A stem cell that is present in some adult tissues. Adult stem cells can give rise to only a limited range of cells.

aeciospore A small, usually single-celled, asexual body generally containing two nuclei.

aerobic Requiring oxygen.

aerobic respiration Cellular respiration being undertaken in the presence of oxygen.

aestivation A period of prolonged torpor or dormancy of an insect, fish or amphibian during a hot or dry period.

afferent (sensory) neuron A neuron that communicates information from tissues and organs to the central nervous system.

agglutination The process in which antibodies bind to antigens on the surface of cells and form antigen–antibody complexes that clump together and activate phagocytes and the complement cascade.

agricultural pest An organism that is detrimental or a nuisance to agriculture, often causing disease.

air sac A lung compartment containing air.

aldosterone A hormone released from adrenal glands that simultaneously regulates sodium and potassium levels by increasing potassium excretion into the urine and causing sodium reabsorption into the blood.

alkaloid An often toxic chemical produced by plants, including caffeine and nicotine, and which helps protect the plant from pathogens.

allele An alternative form of a gene.

allergen An antigen that elicits an allergic response.

alveolus A small air sac in the lungs of mammals, located at the ends of the bronchioles. Alveoli have very thin cell membranes surrounded by a network of capillaries, which enables efficient gas exchange across their surface.

amino acid An organic compound containing an amino group ($-NH_2$) and a carboxyl group ($-COOH$) at opposite ends of the molecule. Linked amino acids form the peptide chains in protein molecules.

ammonia A compound (NH_3) that is the first nitrogenous waste to be formed from the breakdown of proteins. Ammonia is highly toxic and is excreted mainly by aquatic animals.

amylase An enzyme that breaks down starch molecules.

amyloplast An organelle in plant cells where starch is made and stored.

anaerobic respiration Cellular respiration being undertaken in the absence of oxygen.

animal Any live non-human vertebrate (i.e. fish, amphibians, reptiles, birds and mammals, encompassing domestic animals, purpose-bred animals, livestock, wildlife) and cephalopods.

anomaly Something that deviates from what is standard, normal, or expected (Taylor 1982).

antibacterial An agent or substance that works against bacteria.

antibiotic A substance, produced by a microorganism or synthesised, that inhibits the growth of a type of bacteria.

antibody A blood protein secreted by plasma cells that binds to a particular antigen and marks it for elimination; also known as immunoglobulin.

antidiuretic hormone (ADH) A hormone secreted by the pituitary gland that increases the permeability of the collecting tubule of the mammalian kidney to water. ADH increases the amount of water absorbed and so causes a smaller volume of more concentrated urine to be formed.

antigen A substance capable of stimulating an immune response.

antigen–antibody complex A specific chemical interaction between an antibody (immunoglobulin) molecule and an antigen molecule.

antigen-presenting cell (APC) A cell that uses MHC-II on its surface to present foreign antigens to helper T lymphocytes to elicit an adaptive immune response.

antigenic drift A slow change in the antigens on the surface of a pathogenic organism due to random mutations.

antigenic shift An abrupt change in the genetic code of a virus due to re-assortment of genes from different viral strains, resulting in significantly different antigens on the coat of the virus.

antiserum An aliquot (measured volume) of blood serum that contains specific antibodies against a specific antigen; is used to induce artificial passive immunity.

aorta The large artery that carries blood from the left ventricle of the heart to the body.

arteriole A small blood vessel that stems from an artery and leads to capillaries.

artery A blood vessel with thick, elastic walls, through which blood flows from the heart to the rest of the body.

arthralgia A condition with pain in the joints.

artificial active immunity The immunity induced by injection of antibodies produced by another organism.

artificial passive immunity The immunity induced by administration of a serum containing antibodies made in another organism.

asymptomatic To be without symptoms, or not showing symptoms while infected and/or diseased.

atrium A chamber of the heart that receives blood returning from the body or the lungs, before passing the blood into a ventricle. The left atrium receives oxygenated blood from the lungs, and the right ventricle receives deoxygenated blood from the rest of the body.

autonomic nervous system A subdivision of the nervous system that regulates the internal environment.

autotroph An organism that can produce its own food from inorganic materials, using light or chemical energy. Plants that photosynthesise are the most common autotrophs. All autotrophs are producers.

auxin A plant hormone that promotes the growth of new shoots, phototropic responses and the development of leaves and fruit.

axon The part of a nerve cell that conducts an action potential away from the cell body towards the next nerve cell.

B

B lymphocyte (or B cell) A white blood cell that when stimulated produces large quantities of antibodies specific to a particular antigen. They are responsible for the humoral immune response.

bacteriophage A virus that infects bacteria.

bar graph A graph that shows the measured value (or value of central tendency) of the dependent variable by the length of the horizontal bar.

baroreceptor A receptor that detects changes in blood pressure, which is an indication of the volume of blood.

basal metabolic rate The rate at which energy is used by an animal at rest.

basidiospore A haploid reproductive cell produced by meiosis that can divide and develop into a haploid fungus.

bias An inclination or prejudice towards something.

bile A secretion produced by the liver and stored in the gall bladder, from where it is released into the small intestine. Bile acts as an emulsifying agent, physically breaking up large fat droplets into smaller droplets to increase the surface area of food being digested.

biogenesis The hypothesis that living matter arises only from other living matter.

bladder A muscular organ that receives urine from the kidneys and holds it before it is excreted through the urethra.

blastocyst The blastula stage in the development of a mammalian embryo; consists of an outer layer of cells that develop into the placenta, an inner mass of cells that develop into the embryo, and a fluid-filled cavity.

Bowman's capsule The region of a nephron into which filtered plasma flows from the glomerulus.

bronchus An airway in the respiratory tract that conducts air into the lungs.

brumation A state or condition of sluggishness, inactivity or torpor exhibited by reptiles (such as snakes or lizards) during winter or extended periods of low temperature.

C

caecum An intestinal pouch at the junction of the small and large intestine. In some herbivores, such as koalas, it is very enlarged and acts as a fermentation chamber for the digestion of cellulose.

calibration The adjustment of an instrument with a standard scale of readings.

capillary A tiny blood vessel with a wall only one cell thick, across which exchange occurs between blood and tissues.

capsid The protein coat of a virus.

capsule A polysaccharide layer that coats the outside of the cell wall of some species of bacteria.

carbohydrate An organic compound consisting only of carbon, hydrogen and oxygen atoms, with the hydrogen and oxygen atoms in the same proportion as in water (2:1). Carbohydrates include sugars, starches and cellulose.

carnivore An organism that feeds only on other animals.

carotid rete system A configuration of blood vessels from the carotid artery in the sinus cavity that cools the brain.

carrier (1) An organism infected by a pathogen, usually without being affected by the pathogen, which can transmit the pathogen to another organism. (2) An organism with an allele for a genetic disease, who does not show the disease because they are heterozygous and the other allele is expressed.

carrier protein A protein that transports a specific substance across the cell membrane.

Casparian strip A water-resistant strip in the endodermis of roots that regulates the entry of water and solutes.

catalyst A substance that accelerates the rate of a chemical reaction by lowering the activation energy, without being used up in the reaction.

catecholamine An amine derivative of catechol that acts as a neurotransmitter or hormone (e.g. adrenaline and dopamine).

cell The smallest structural and organisational unit of which all living things are built.

cell compartmentalisation The characteristic of eukaryotic cells where the cell is divided into functional membrane-enclosed regions (organelles) with particular specialised functions.

cell differentiation The process by which a cell changes from one type to another. This is usually an unspecialised cell becoming a specialised cell.

cell membrane The plasma membrane at the boundary of every cell that acts as a selective barrier, thereby regulating the chemical composition of the cell.

cell-mediated immunity An immune response that is mediated by T lymphocytes.

cellular respiration The energy-releasing processes that occur in cells. In particular, the aerobic stage in the complete breakdown of glucose to produce ATP, which occurs in mitochondria and produces 30–38 molecules of ATP per molecule of glucose.

cellulose A complex carbohydrate molecule consisting of a chain of many glucose molecules. It is the main component of plant cell walls. Its formula is $(C_6H_{10}O_5)_n$.

central nervous system (CNS) The brain and spinal cord in vertebrates.

channel protein A specialised protein that allows the transport of specific substances across a cell membrane.

chemical (HAZCHEM) code A system of codes and images that provides warnings of hazards about items to users.

chemical digestion The action of enzymes in breaking down complex compounds into simple compounds that can be used for metabolism.

chemoautotroph An organism that is able to produce its own food from inorganic materials, using chemical energy.

chemokine A cytokine that attracts leukocytes to the site of an infection.

chemoreceptor A sensory receptor that detects and responds to specific chemical substances.

chlamydospore A resting spore with a thick cell wall that is produced asexually.

chloroplast A membrane-bound organelle involved in photosynthesis.

cholesterol A steroid found in cell membranes of animal tissues.

chromosome A structure made of DNA that encodes all of the information needed to make and operate a cell.

cilium A hair-like structure on the surface of some eukaryotic cells, consisting of a '9 + 2' arrangement of microtubules enclosed by an extension of the cell membrane. Cilia move with an oar-like motion and are usually shorter and more numerous than flagella.

claim An assertion made without any accompanying evidence to support it.

clonal deletion The process of identifying and destroying lymphocytes that have receptors that would respond to self-cells.

clonal expansion The process of a particular B lymphocyte dividing rapidly to form many plasma cells that will produce specific antibodies.

clonal selection The theory that in a group of lymphocytes, a specific antigen will activate only the lymphocyte that has a receptor that specifically recognises it. This lymphocyte will then undergo clonal expansion.

closed circulatory system A circulatory system in which the fluid (blood) is confined to vessels and is kept separate from the interstitial fluid.

cluster A larger than expected number of cases of disease occurring in a particular locality, group of people, or period of time.

coefficient of determination A calculated value that indicates the ability to predict the dependent variable value from the independent value.

coenzyme A small organic molecule that combines with an enzyme and is necessary for its activity.

cofactor A metal ion or an organic molecule that is required for enzyme activity.

cohesive bond A bond between molecules of a substance resulting from the shape and structure of the molecules.

colony A group of organisms of the same species that live together.

column graph A graph that shows the measured value (or value of central tendency) of the dependent variable by the height of the column.

communicable disease An infectious disease that can be transmitted from person to person within a community.

community immunity The phenomenon in which indirect protection from a pathogen is achieved through the immunity of a large proportion of the population, providing protection to non-immune or non-vaccinated individuals. Often achieved through vaccination and is also known as herd immunity.

competitive inhibition When an inhibitor has the same binding site as a substrate, they will compete for access to the enzyme.

complement protein A protein that can kill foreign cells by lysis. There are more than 30 different complement proteins, which are activated in response to antigen–antibody complexes, antigens and carbohydrates on the surface of some bacteria and parasites.

complement system A component of the innate immune response which complements, or enhances, the activity of antibodies and phagocytes, activates inflammation and immune clearance, and the rupture of membranes of foreign cells.

concentration gradient The difference in concentration between two solutions.

confidence interval A calculated range in values that estimates where the true value is likely to be, according to a pre-determined level of confidence.

connective tissue A type of tissue that connects, separates or supports tissues or organs in the body.

constant region The region of antibody molecules that remains the same and interacts with receptors on the body's cells.

contact tracing The identification of possible contact with individuals from a source of an infection, determining the number infections, providing care and surveillance of further transmission.

contagious An ability to be spread from one organism to another, generally by direct contact.

contaminant Something that causes an impurity, pollution or a substance to become poisonous.

continuous variable A numerical variable that is based on a continuum in which infinite fractional values exist.

control group The selected test group (sample group) in which no change to the independent variable exists and represents the typical natural conditions.

controlled variable A variable that is controlled during an experiment so that it does not change and does not influence the measured results or dependent variable.

cord blood Blood taken from the umbilical cord after the birth of a baby.

coronary circulation The movement of blood through the heart muscles. Blood is supplied through arteries from the base of the aorta, and returns to the lungs through veins from the right atrium.

cortisol A steroid secreted in small amounts as hydrocortisone from the human adrenal cortex of the adrenal gland.

countercurrent exchange The flow of oxygenated water across the gills in the opposite direction in relation to blood flow.

countercurrent blood flow A system of heat exchange where blood is warmed or cooled by blood in an adjacent blood vessel flowing in the opposite direction.

Creutzfeldt–Jakob disease (CJD) An infectious disease caused by a misfolded PrP protein.

cyanogenic glycoside A compound produced by plants that breaks down to form hydrogen cyanide, a compound extremely toxic to eukaryotic cells. These compounds assist the plant to resist infection by pathogens and damage by herbivores.

cytokine A chemical used for cell communication, especially between cells of the immune system. Cytokines are peptides or proteins.

cytokinin A plant hormone that, in the presence of auxin, stimulates the division of plant cells.

cytology The study of the structure and function of cells.

cytoplasm The fluid content of a cell, made up mostly of water; includes ions, enzymes, food molecules and organelles other than the nucleus.

cytosol The fluid component of cytoplasm in which organelles are located.

cytotoxic T lymphocyte (T_C) A T lymphocyte that is stimulated by cytokines to bind to antigen MHC-I complexes on the surface of infected host cells and release cytotoxic compounds that destroy the infected cells.

D

DALY (disability adjusted life years) A measure of overall burden of disease. It is a measure of the shortening of life span, which the disease burden causes.

data In science, measurements of an attribute or attributes; data may be quantitative or qualitative and be from primary or secondary sources (ACARA, 2015c)

data logger A portable tablet that records and logs data acquired or measured by using probes, sensors and instruments.

defensin A protein produced by plants that disrupts the activity of digestive enzymes and which is also thought to damage the cell membranes of microbes. Defensins help to protect plants from infection and production of them increases when the plant is under threat.

denature (or denaturation) An irreversible change in the tertiary structure of a protein (e.g. as a result of heating the protein above a critical temperature).

dendrite A long extension of the cell body that increases the surface area for receiving inputs from other neurons or sensory receptors.

dependent variable The variable that is measured or observed during an experiment; is assumed to change due to changes in the independent variable.

diffusion The passive movement of a solute from a region of high concentration to a region of lower concentration.

digestion The breakdown of food into a form that can be used by an organism for metabolism; involves mechanical digestion and chemical digestion.

digestive enzyme An enzyme that assists in the breakdown of otherwise indigestible matter.

digestive enzyme inhibitor An enzyme or lectin that blocks normal digestion of starch by insects.

direct contact transmission The transmission (transference) of a pathogen from one individual to another through physical contact.

discrete variable A numerical variable that is based on defined integer values; fractions between integers do not exist.

disease Any condition that impairs the normal functioning of an organism.

DNA (deoxyribonucleic acid) A double-stranded nucleic acid made up of a sequence of deoxyribose sugars and bases (adenine, cytosine, guanine and thymine) linked by phosphate bonds. It is the carrier of genetic information in all cellular organisms and most viruses; found in chromosomes (and mitochondria and chloroplasts).

dopamine A catecholamine that acts as a neurotransmitter in the central nervous system.

droplet A form of direct contact transmission through a drop of saliva larger than 5 µm ejected by coughing, sneezing, laughing or talking.

Duffy An antigen found on the surface of red blood cells used by the malarial parasite to gain entry to the cell.

E

ectoparasite A parasite that lives on the outside of its host, usually on the skin or surface.

effectors A muscle or gland that responds to a stimulus.

efferent (motor) neuron A neuron that transmits information from the central nervous system to the tissues and organs (effector cells).

egestion The elimination of food that has not been absorbed by the gut.

eicosanoid A compound derived from the fatty acid arachidonic acid and can act as an intracellular messenger.

electron transfer chain A chain or interconnected series of enzymes and cytochromes embedded in the inner mitochondrial membrane.

ELISA (enzyme-linked immunosorbent assay) A method to detect the presence and concentration of a particular antigen or antibody in a sample solution or serum.

embryo The stage in the development of a vertebrate, between the fertilisation of the ovum and the development of adult characteristics (the fetus).

embryonic stem cell A stem cell that can be obtained from blastocysts. Embryonic stem cells are pluripotent and can differentiate into any of the three germ layers (ectoderm, endoderm and mesoderm).

endemic A regularly found or prevalent distribution in a population or area.

endocrine system A system of endocrine glands secreting a variety of hormones.

endocytosis The movement of substances into the cell from the extracellular fluid to the cytoplasm.

endoparasite A parasite that lives within its host.

endosymbiotic theory The theory that proposes that eukaryotic organelles such as mitochondria and chloroplasts were once prokaryotic cells that were engulfed by another cell and lived in symbiosis inside the cell, and eventually evolved into a unified cell.

endotherm A warm-blooded vertebrate.

endotoxin A lipopolysaccharide that is part of the cell wall of gram-positive bacteria.

enteric nervous system A system of nerves around the alimentary canal.

enzyme A protein molecule that acts as a biological catalyst. Enzymes speed up rates of reactions that would otherwise take place much more slowly. Their action is often specific to only one type of reaction.

enzyme–substrate complex The temporary complex that forms when an enzyme binds to a substrate.

epidemic The sudden increase in incidence of a disease in an area above what is normally expected.

epidemiology The study of the incidence and prevalence of disease and the methods of disease control.

epidermis The outermost layer of cells of a multicellular organism.

epiglottis A thin flap of cartilage that covers the entrance to the larynx, preventing food from entering the trachea while eating.

epithelium A thin layer of tissue covering the external surfaces of a multicellular organism, and also lining the inner surfaces of internal structures such as intestines and lungs.

epitope The part of an antigen that binds to the antigen-binding site of a specific antibody.

ergotism A disease caused by consumption of ergot alkaloids produced by the fungus *Claviceps purpurea,* infecting grains, usually wheat or rye.

error A measure of the estimated difference between the observed or calculated value of a quantity and its true value.

ethics The moral principles that govern a person's behaviour or how an activity is conducted.

ethylene A plant hormone associated with fruit development and ripening; also known as ethene.

eukaryote An organism composed of one or more cells that contain distinct membrane-bound nuclei and many organelles; eukaryotes include protists, fungi, plants and animals.

excretion The removal of waste substances from the body of an organism.

exhalation Expiration of air from the lungs.

exocytosis The movement of substances out of the cell from the cytoplasm to the extracellular fluid.

exotic incursion The sudden invasion of foreign material or organisms.

exotoxin An extremely poisonous toxin released by bacteria into their surroundings, either directly or during lysis by immune system cells.

experimental group The selected test group (sample group) in which the independent variable has changed to elicit a change in the measured results.

extend In science, to extend an experiment is to modify the methodology to overcome limitations of the scope or applicability of the data.

external environment The environment immediately surrounding an organism.

exteroreceptor A neurological receptor that receives information from the environment external to the organism.

extracellular digestion Chemical digestion in which the enzymes are secreted into a cavity where digestion takes place.

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

extremophile An organism that can live in a physically or geochemically extreme environment that most organisms are not able to adapt to.

F

facilitated diffusion The passive diffusion through selective protein channels in membranes.

fact A known and witnessed entity that is distinguishable from transient theories; it is definite, permanent and independent of any subjective interpretation.

$FADH_2$ (flavin adenine dinucleotide) a redox coenzyme that is formed during the Krebs cycle and utilised during the last part of aerobic respiration, the electron transfer chain.

fermentation The stage in the breakdown of glucose that follows glycolysis when there is no oxygen present; produces either lactic acid (in most animals) or alcohol (in most plants and microorganisms).

fever An increase in body temperature that results from the set body temperature point being raised by the hypothalamus in response to the presence of inflammatory cytokines. Fever increases the activity of some leukocytes and decreases the activity of some bacteria.

filariform The thin hair-like larvae of nematode worms.

filtration In the kidney, the process by which the primary kidney filtrate is formed, from fluid passing from Bowman's capsule into the nephron.

fetus The stage in the development of a mammal, following the embryonic stage. The fetus has all of the major structures of the adult mammal. In humans, this stage lasts from the eighth week of gestation until birth.

fomite An object or material that can carry a pathogen.

fungus A non-photosynthetic eukaryote that has a rigid cell wall made of chitin; fungi include moulds, yeasts, mushrooms and toadstools.

G

gall An abnormal growth of plants, similar to a tumour, which is caused by pathogens or insects.

gastrula An early stage in the development of an embryo, consisting of three layers of cell—ectoderm (outer layer), mesoderm (middle layer) and endoderm (inner layer).

gastrulation A series of cell and tissue movements at the blastocyst stage of animal development, during which the embryo is reorganised to form a gastrula.

gene The region/s of DNA that are made up of nucleotides; the molecular unit of heredity.

gene regulation The processes that control gene expression such as turning a gene on or off.

genophore A circular DNA chromosome found in prokaryotic cells.

germ layer The primary layer of cells that are formed during embryogenesis. Animals with bilateral symmetry have three layers—endoderm, mesoderm and ectoderm. Animals with radial symmetry have two layers—endoderm and ectoderm.

gibberellin A naturally occurring hormone that accelerates plant growth by increasing stem elongation. Gibberellins are present at active growth sites such as apical buds and root tips.

gill The organ through which fish and other aquatic organisms exchange gases.

glomerulus A clump of looping capillaries in the kidney embedded in the Bowman's capsule.

glucose A monosaccharide ($C_6H_{12}O_6$) that is the most common compound from which energy is released in respiration.

glycogen A complex carbohydrate molecule consisting of glucose subunits; the main carbohydrate storage molecule in animals.

glycolipid A carbohydrate molecule linked to lipids; for example, on the outer surface of a cell membrane.

glycolysis The first stage in the breakdown of glucose to produce ATP; occurs in the cytoplasm and produces a net of two molecules of ATP for each glucose molecule.

glycoprotein A carbohydrate molecule linked to proteins; for example, on the outer surface of a cell membrane.

Golgi apparatus A stack of flattened, smooth membrane sacs, which form vesicles to process and transport the proteins from the cell.

gram stain A stain applied to bacteria that separates bacteria into two groups according to their cell wall chemistry. Cells can either stain gram positive (violet) or gram negative (pink).

granzyme A protein that is released by natural killer cells and cytotoxic T lymphocytes, which stimulates body cells to undergo rapid cell death/apoptosis.

gravitropism The orientation of plant parts growth in response to gravity.

guard cell The cells that form a pair of curved cells that surround a stoma, becoming larger or smaller according to the pressure within the cells.

H

haemagglutinin A glycoprotein found on the surface of viruses that assists the virus to attach to the prospective host cell.

haemoglobin A protein molecule in red blood cells that carries oxygen from the lungs, and returns carbon dioxide from the tissues to the lungs; occurs in mammals and many other animals, and gives red blood cells their characteristic colour.

haemolytic disease of the newborn A disease of newborn babies in which their red blood cells are attacked by antibodies that have crossed the placenta from their mother. Caused by Rh incompatibility.

heat exchange The movement of heat between the body of an organism and the surrounding medium, usually air or water.

heavy chain The polypeptide chain that forms the stem of a Y-shaped antibody.

helminth A member of the worm-like phyla; includes nematodes and platyhelminths.

helper T lymphocyte (T_H) A lymphocyte that binds to antigen MHC-II complexes on antigen-presenting cells and then activate B lymphocytes to secrete antibodies, macrophages to phagocytose pathogens and cytotoxic T lymphocytes to kill infected cells.

herbivore An animal that feeds only on producers, such as plants or algae.

herd immunity The phenomenon in which the immunity of a large proportion of a population provides protection from a pathogen to non-immune or non-vaccinated individuals. Often achieved through vaccination and also known as community immunity.

herd immunity threshold The percentage of the population required to have immunity to a pathogen that is estimated to achieve herd immunity.

heterotroph An organism that must obtain nutrients from other organisms.

heterozygote advantage The increase in chances of survival resulting from having a heterozygous genotype.

heterozygous Having two different alleles at the same gene locus on each member of a homologous pair.

hibernation A controlled lowering of the body temperature of an endotherm as a means of reducing energy expenditure. Hibernation reduces the amount of energy required at a time when little food is available.

histamine An organic compound involved in the inflammatory response and allergic reactions. Histamines cause blood vessels to dilate and become more permeable. They also promote fever.

homeostasis The maintenance of a relatively stable internal environment in the face of changes in the internal or external conditions.

homozygous The presence of identical alleles at the same gene locus on each member of a homologous pair.

hormone A substance that is produced by one tissue and transported to another tissue, where it induces a specific physiological response.

human leukocyte antigen An alternative name for the major histocompatibility complex in humans.

humoral immunity An immune response involving B lymphocytes that produces specific antibodies against specific antigens.

hydrolysis A chemical reaction involving the splitting of a molecule by the addition of a water molecule at a particular point.

hydrolytic enzyme An enzyme, found in plants, that breaks down the cell walls of fungi, oomycetes and bacteria and the exoskeletons of insects. They are produced in greater quantities when the plant is under attack.

hydrophobic The property of an aversion to water, tending to coalesce and form droplets in water.

hydrophyte A plant that lives in, on or under water.

hygiene The actions that lead to cleanliness and result in good health.

hygiene etiquette The practice, activities, customary code or behaviour of cleanliness, interrupting pathogen transmission and encouraging health.

hypha A long, branching filamentous structure that makes up the bodies of many fungi and oomycetes.

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 (ACARA 2015c).

I

immunisation The process of artificially inducing immunity to a particular antigen, usually by administering a vaccine.

immunisation coverage The proportion or percentage of the population that has immunity to a pathogen, achieved through vaccination.

immunogen An antigen that elicits an immune response.

immunoglobulin (Ig) A type of protein, produced by B lymphocytes in an immune response to a specific antigen; also called an antibody.

immunosuppressed The suppressed state of an individual's immune system, resulting in slowed adaptive immune responses to pathogens. Immunosuppressed individuals are at higher risk of disease due to the slow immune system response.

inactivated vaccine A vaccine made from inactivated (often killed) forms of a pathogen. Inactivation destroys the pathogen's ability to replicate and cause disease but its antigens are preserved so that they can be recognised by the immune system.

incubation period The period of time from infection until symptoms appear.

independent variable The variable during an experiment that is deliberately altered, or selected to be tested, which is assumed to cause a change in the dependent variable.

indirect contact transmission The transmission (transference) of a pathogen from an infected individual to another through non-physical contact.

infectious A pathogenic molecule or organism that can be spread from one organism to another organism.

inference A conclusion derived from evidence and reasoning without witnessing every explicit detail; made by listening or reading beyond what has been literally expressed; an implication.

inflammation A protective response triggered by damaged tissues or invading pathogens, which leads to increased blood flow to the area of damage/infection, along with migration of leukocytes to those tissues. It results in heat, pain, swelling, redness and loss of function.

inhalation The physical action of inhaling or breathing in.

innate immunity Immunity that non-specifically protects against a wide variety of pathogens. It consists of physical, chemical and microbiological barriers that provide resistance to infection, and an innate response to infection that involves leukocytes such as phagocytes and defensive molecules such as complement proteins.

inorganic compound A compound that lacks a carbon atom.

insulin A hormone in vertebrates secreted by the beta cells of the pancreas, controlling the concentration of glucose in the blood.

integral protein A protein molecule that is a permanent part of the cell.

interferon A cytokine that is a signalling molecule important in animal immunity. Interferons are produced by virus-infected cells to inhibit viral replication and strengthen the barriers of surrounding cells. They interfere with the transcription of viral genes and also regulate the immune response by enhancing the activity of T lymphocytes.

interleukin A type of cytokine produced by leukocytes for regulating immune responses.

intermediate host The host in the life cycle of a parasite in which larval forms grow and develop.

internal environment The environment within an organism.

interneuron A neuron that connects neurons within the nervous system.

interoreceptor A neurological receptor that receives information from the internal environment of the organism.

intracellular digestion The breakdown of particles that takes place in the cytoplasm of a cell.

intracellular fluid The fluid contained within the cell membrane; the fluid of cytoplasm.

K

karyotype A picture of an organism's full set of chromosomes, arranged in homologous pairs.

killed vaccine A particular type of inactivated vaccine where the pathogen, such as a bacterium, used in the vaccine has been killed.

kleptothermy A form of thermoregulation in which animals (either voluntarily or involuntarily) share body heat.

Krebs cycle The second stage of aerobic cellular respiration, the oxidative metabolism of acetyl units to produce high-energy compounds such as ATP. From each turn of the Krebs cycle, one molecule of acetyl CoA is metabolised into two molecules of carbon dioxide, three molecules of NADH, one molecule of $FADH_2$ and one molecule of GTP (used to make one ATP).

L

lacteal The vessels of the lymphatic system close to the small intestine. Lacteal capillaries absorb digested fats from the small intestine, giving the lacteals a milky appearance.

lamella A thin layer, membrane, or plate of tissue, especially in bone.

larynx The organ in the upper trachea that contains vocal cords and is responsible for speech in humans. It is also involved in breathing and in preventing the aspiration of food or other large particles into the lungs.

law A causal relationship that describes or predicts phenomena under known conditions; the known cause of any effect in a system where the variables and conditions are known.

lenticel A porous group of cells that allows gas exchange across the otherwise airtight and waterproof cork layer covering the stems and roots of woody plants.

leukocyte A white blood cell; including phagocytes and all lymphocytes.

light chain The short polypeptide chain that forms the arms of the 'Y' shape.

lignin A complex organic polymer deposited in the cell walls of many plants, making them rigid and woody.

line graph A graph that displays continuous data by a line from one point of measurement to the next.

linear relationship A direct relationship between two variables in which a change in one is proportional to the change in the other.

lipase An enzyme that hydrolyses lipids.

lipid An organic compound that is insoluble in water but soluble in alcohol, ether or chloroform. Lipids include fats, oils, sterols, some hormones, fat-soluble vitamins, glycerides and phospholipids.

literature review An evaluative report that critically analyses the current body of knowledge.

live attenuated vaccine A vaccine that uses a living but weakened form of a pathogen in order to stimulate an immune response. The weakening of the pathogen ensures that it cannot cause disease.

liver A large organ in vertebrates that is involved in many important metabolic processes, including protein manufacturing, fat storage and processing, bile secretion and metabolism of toxins.

loop of Henle A U-shaped loop in a mammalian kidney between the proximal and distal convoluted tubules, dipping into the medulla. Its main function is to recover water and sodium chloride from urine, thus making the urine more concentrated and reducing the amount of water that needs to be taken in.

lumen (1) The region enclosed by the cell membrane of a cell. (2) The inside of a tubular structure such as a blood vessel or xylem tube.

lymph The fluid that circulates in the lymph system. It consists mainly of interstitial fluid (fluid forced from capillaries by blood pressure into the spaces between tissues) and contains lymphocytes, macrophages, proteins and fats. It has an important role in defending the body against harmful bacteria and other particles, and also in the absorption and transport of fatty acids.

lymphocyte A white blood cell formed or matured in lymphatic tissue such as B cells, T cells and natural killer cells. B cells and T cells are fundamental to the adaptive immune response.

lyse A method of cell destruction, usually by the rupture of the cell membrane.

lysosome A specialised vesicle that digests unwanted matter.

lysozyme An antibacterial enzyme present in body secretions such as tears and saliva. It disrupts bacterial cell walls.

M

macrophage A type of leukocyte that can engulf non-self material by phagocytosis.

major histocompatibility complex (MHC) A group of major histocompatibility proteins found on the surfaces of cells, which are involved in antigen presentation. MHC proteins are also known as human leukocyte antigens.

maltose A sugar formed by the digestion of starch. It is a disaccharide consisting of two glucose molecules.

mast cell An immune cell found embedded in many tissues, especially connective tissues, which releases histamine to induce inflammation when activated or damaged. Mast cells are strongly involved in allergic reactions such as hayfever and anaphylaxis.

mathematical modelling The development of a model that describes a system, concept or idea using mathematical language.

mean A calculated value that represents the centre of a set of numbers that have been averaged.

measure of central tendency A value that estimates the central position in a set of data.

measured variable A variable that is measured during an experiment because it cannot be controlled, and must be known so that any influence on the measured results or dependent variable can be determined.

mechanoreceptor A sensory receptor that detects and responds to a change in shape.

median The value in the middle of an ordered list of values.

megakaryocyte A large cell in the bone marrow that forms platelets.

memory T lymphocyte A type of T lymphocyte which remains in the body, usually in lymphoid tissues, after an infection. They can be activated upon subsequent infections with the same pathogen to provide a faster and larger response than the first infection.

merozoite An amoeba-like spore produced by certain protozoan parasites; including the parasite that causes malaria.

mesophyte A terrestrial plant living under moist conditions with well-aerated soils.

metabolic rate The rate at which energy is required by an organism to maintain homeostasis.

metabolism The total of the physical and chemical processes by which energy and matter are made available by an organism for its own use; is controlled by enzymes.

methodology A systematic, ordered approach to gathering data in a scientific experiment or investigation.

microbe-associated molecular pattern (MAMP) A specific molecule typical of certain pathogens found on the surface of their cell wall or cell membrane that can be recognised by receptors found in plant cells and which cause an immune response in the plant. Each subsequent infection by the same pathogen elicits the same response.

microflora Microorganisms that colonise particular sites of the body. They usually do not cause disease and may offer benefits to the host.

mitochondrion An organelle responsible for energy transformation within the cell.

mitosis A division of a nucleus that results in two cells that are genetically identical to the parent cell. Asexual reproduction and cell replication for growth occur by mitosis.

mode The value that occurs most often in a list of values.

model In science, a representation that describes, simplifies, clarifies or provides an explanation of the workings, structure or relationships within an object, system or idea (ACARA 2015c).

modify Change the form or qualities of; make partial or minor changes to something.

morbidity The physical state or condition of being diseased.

morula An embryo consisting of an unorganised mass of 16 cells, resulting from a series of divisions of the zygote.

mRNA (messenger RNA) An RNA molecule transcribed from DNA in the nucleus, which passes into the cytoplasm and binds to a ribosome, where it is translated into an amino acid sequence (polypeptide).

mucous membrane A lining or thin tissue of the body that separates the internal environment from the external and secretes a protective mucus. Mucous membranes line many body cavities and tubular organs, including the gut and respiratory passages, as well as the eyes and nose.

multipotent (cell) A cell that can develop only into cells of a similar type. For example, stem cells in bone marrow are multipotent because they can develop into different blood cells but not into other types of cells.

murein A polymer consisting of sugar and amino acids, forming the cell wall of most bacteria.

mutation A permanent change in the genetic sequences of an organism, including changes in the nucleotide sequences or chromosomal arrangements.

myelin sheath The fatty sheath surrounding nerves.

myoglobin A red respiratory pigment that occurs in muscles; carries oxygen that can be used when other oxygen reserves are depleted.

N

NADH (nicotinamide adenine dinucleotide) A similar compound to $FADH_2$ but delivers more H^+ and electrons to the electron transfer chain as well.

naive A type of lymphocyte that is fully mature but which has not yet encountered the antigen specific to its receptor.

natural active immunity The active immunity formed as a result of survival from a natural infection with a particular pathogen.

natural passive immunity The transfer of antibodies from one individual to another by natural means; the transfer of antibodies from mother to fetus via the placenta during fetal development and from mother to baby in breast milk.

negative feedback loop A mechanism in homeostasis whereby a change in the physiological condition triggers a response that re-establishes homeostasis.

nematode A worm of the phylum Nematoda, including hookworms, roundworms and threadworms. Many nematodes are parasitic.

nephron The functional unit of the kidney; consisting of a Bowman's capsule surrounding a glomerulus and a tubular region leading into a collecting duct. About one million nephrons are found in each human kidney.

neuraminidase An enzyme produced by viruses, especially those that escape by budding, which facilitates its release from the host cell.

neuron A nerve cell, including its body, dendrites and axon, forming the fundamental unit of the nervous system in animals.

neurotransmitter A chemical released from a neuron ending in response to a nerve impulse that interacts specifically with receptors on a responding cell.

nitrogenous waste The waste products from the breakdown of proteins, including ammonia, urea and uric acid.

nociception A sensing of painful or injurious stimuli.

nociceptor A receptor sensitive to painful or injurious stimuli.

node of Ranvier A constriction of the myelin sheath occurring at intervals along myelinated nerve fibres, and at which the axon membrane is exposed.

nominal variable A categorical variable based on a nominated category that is not dependent on order.

non-shivering thermogenesis The increased production of metabolic heat by oxidation of fat.

nucleoid An irregular-shaped region of a prokaryotic cell containing the genophore.

nucleolus A dark-staining body in the nucleus; site of synthesis of ribosomal RNA.

O

observation Witnessing an event or phenomenon.

omnivore An organism that feeds on both plants and animals.

oomycete A fungus-like pathogen with branching hyphae, called haustoria, that penetrate living tissue and absorb nutrients, or release enzymes that digest cytoplasm into molecules that can be absorbed.

open circulatory system A system for fluid circulation in animals in which there is no clear distinction between circulatory and interstitial fluids, so that fluids flow more or less freely between the cells of the tissues.

ordinal variable Categorical variables in which the order of the nominated category is important.

organ A structure, consisting of different tissues, that carries out one or more specific functions.

organelle A structure in eukaryotic cells that is surrounded by, or consists of, membranes (e.g. nucleus and mitochondria).

organic compound A complex molecule containing carbon, which occurs in living organisms (e.g. proteins, carbohydrates and lipids).

organism A living system that functions as an individual, whether unicellular or multicellular.

osmoconformer An animal that changes the internal osmotic concentration of its body fluids to maintain the same osmotic concentration of the external environment (it remains in an isotonic state with its surroundings).

osmolality A measure of the concentration of particles (e.g. sodium and chloride ions) that affect osmosis.

osmoreceptor A receptor that is sensitive to blood solute concentrations.

osmoregulator An animal that maintains the internal osmotic concentration of its body fluids regardless of changes in the external concentration.

osmosis The passive diffusion of free water molecules across a selectively permeable membrane from a solution in which there are more free water molecules (a dilute solution) to a solution in which there are fewer free water molecules (a concentrated solution).

osmotic gradient The difference in the concentration between two solutions on either side of a semipermeable membrane.

osmotic pressure The pressure causing water to move along a concentration gradient.

outlier A value that 'lies outside' (is much smaller or larger than) most of the other values in a set of data.

oxygen-carrying capacity The amount of oxygen that can be carried by a particular medium, such as blood.

oxyhaemoglobin A bright red substance formed by the combination of haemoglobin with oxygen, present in oxygenated blood.

oxytocin A hormone secreted by the posterior pituitary gland, which causes the uterine wall to contract during birth and releases milk from the mammary glands within the breast.

P

pandemic An epidemic that has spread over a large geographical area. It usually affects large numbers of people and may be worldwide.

parasite An organism that lives in or on another organism, called the host, and derives its nutrients from the host to the detriment of the host.

parasympathetic division The division of the autonomic nervous system that generally enhances body activities that gain and conserve energy.

partial pressure The pressure a particular gas contributes to the total pressure of a gas mixture. The partial pressure of gas X is written as P_X.

passive immunity The temporary acquisition of immunity to a particular pathogen through the transfer of antibodies from one organism to another. This may be artificial through injection of antibodies or natural as in the transfer from mother to child.

passive transport The diffusion of molecules across the cell membrane without the expenditure of energy.

pathogen An organism or infectious molecule that can induce disease in another organism; includes many microorganisms and parasites.

pathogen-associated molecular pattern (PAMP) A specific molecule typical of certain pathogens found on the surface of their cell wall or cell membrane, which can be recognised by receptors found in animal cells and which cause an immune response in the animal. Each subsequent infection by the same pathogen elicits the same response.

pathogenic molecule A prion or virus, which is non-living, but is infectious and causes disease.

pattern recognition receptor (PRR) A receptor on the surface of cells that recognises typical pathogen-associated molecules; MAMPs or PAMPs.

Pearson correlation coefficient A calculated estimate of the strength between variables for a relationship of linear regression, producing a line of best fit.

perforin A chemical produced by certain cells, such as natural killer cells, which causes perforations in the cell membrane of cells infected by viruses or which are abnormal, thereby killing the cell.

peripheral nervous system (PNS) The nerves outside of the brain and spinal cord.

peripheral protein A protein that binds to integral proteins or penetrates only one surface of the cell membrane.

peristalsis The coordinated muscular contractions and relaxations of the wall of the digestive tract that move a bolus of food from the oesophagus to the intestines.

personal protective equipment (PPE) The equipment specifically designed and used during activities to protect the user from hazards.

phagocyte Any cell capable of engulfing or phagocytosing pathogens or foreign particles.

phagocytosis The entry of large particles such as bacteria and cell debris into the cell.

phagolysosome A structure formed when a lysosome fuses with a phagosome so that the pathogen or foreign particle can be digested.

phagosome A vesicle formed around a pathogen or foreign particle in order to phagocytose it.

pharynx The tube or cavity, with its surrounding membrane and muscles, that connects the mouth and nasal passages with the oesophagus.

phenolic A protective chemical found in plants, which includes tannins and phytoalexins. Phenolics bind to salivary proteins and enzymes thereby de-activating them. They cause the death of the pathogen through inadequate energy intake.

phenomena Events that are not artificial and can be observed through the senses or can be scientifically described or explained.

phloem The plant tissue through which sugars and other organic compounds are distributed to different parts of a plant. In flowering plants, phloem consists of sieve tubes, companion cells and fibres.

phospholipid A fat-like substance, usually based on glycerol, that is an essential component of cells and is involved in the uptake of fats and fatty acids from the products of digestion.

photoreceptor A sensory receptor that detects and responds to light.

photosynthesis The process by which plants and other photosynthetic organisms convert energy from sunlight into chemical energy for biological function. It occurs in plastids

phytochrome A light-sensitive protein pigment in plants.

phytohormone A plant hormone, including auxins, gibberellins, cytokinins and abscisic acid.

pie chart A spherical display of either qualitative or quantitative data showing the proportion of each data set (measurement, independent variable, observation) as a part of the whole.

pili A hair-like structure found on the surface of bacteria that they often use to adhere to a host tissue or cell.

piloerection The innervation of muscles to hair follicles, causing them to rise (goose pimples).

pinocytosis The entry into cells of extracellular fluid and substances such as proteins and sugars that are dissolved in the fluid.

plaque A protein aggregation caused by prions.

plasma cell An activated B lymphocyte that produces large numbers of the same type of antibody.

plasma membrane See *cell membrane*

plasmid A small ring of double-stranded DNA.

plasmodesmata A microscopic channel that connects the cytoplasm of adjacent cells in plants and some algae.

plasmodium A member of a genus of parasitic protozoans; includes the parasites that cause malaria.

platelet A cell fragment, lacking nuclei, found in the blood in large numbers; assist with blood clotting.

platyhelminth A worm that includes flatworms, like tapeworms, and flukes such as the liver fluke.

pluripotent (cell) A cell that can develop into several different cell types. An example is a human embryonic stem cell, which can form all adult cell types.

polarised (1) The property of having a charge across a surface. (2) Restricting light to a single plane.

positive feedback loop A type of control mechanism in which the end-product of a particular pathway or process activates the first step in the pathway or in other pathways that contribute to the overall process.

precipitation The formation of a solid substance when two solutions are combined.

precision Accuracy; exactness; exact observance of forms in conduct or actions. In science, exactness; how close two or more measurements of the same object or phenomena are to each other.

primary data Data collected directly by a person or group (ACARA 2015c).

primary host The host in the life cycle of a parasite in which adult forms produce gametes that fuse to form the larval forms.

primary immune response The immune response to an antigen when it is being encountered for the first time.

primary source The original source from which information was created or data was measured.

principle The known cause of any effect, in a system where the variables and conditions are known.

prion A small protein particle that, when its shape is altered by mutation, causes protein aggregation and is toxic to neurons.

processed data Data that has been manipulated to produce meaningful information; a set of displayed data in an appropriate form such as tables or graphs; required information that has been extracted from a set.

prokaryote An organism composed of cells lacking a membrane-enclosed nucleus and membrane-enclosed organelles.

prostaglandin A hormone-like signalling molecule used by the body. Prostaglandins are involved in muscle contractions during birth, control of blood pressure, and mediating fever and inflammation.

protease An enzyme that digests proteins.

protease inhibitor A chemical produced by plants to protect against pathogens and herbivores which blocks the activity of proteases used for digestion by the invader.

protein An organic compound composed of long chains of amino acids; also called a polypeptide. These compounds perform structural, contractile, transport, catalytic, nutritional, structural, some hormonal and other functions.

psyllid A lice-type insect that feeds on plant tissue and vascular fluids and which may stimulate the formation of galls.

pulmonary vein A blood vessel that in humans carries oxygen-rich blood from the lungs to the left atrium of the heart.

pyruvate A three-carbon molecule formed by splitting a glucose molecule during glycolysis. In aerobic respiration, pyruvate is transported into the mitochondria by active transport where it is oxidised to a two-carbon acetyl group that becomes part of the Kreb's cycle.

Q

qualitative data Information that is not numerical in nature.

quantitative data Numerical information (Taylor 1982).

quarantine The isolation of an infected person or animal in a place, state and/or time to prevent transmission of disease.

R

random error An error that affects the measurement in an unpredictable way, resulting in an even variation (fluctuation) in measurements above and below the expected true value.

random selection The process of using a selection process that is not controlled by the experimenter.

range The variation in values between upper and lower limits on a particular scale or the largest and smallest measurements.

raw data Unprocessed and/or unanalysed data; data that has been collected without any additional processing (Taylor 1982).

reabsorption A process in the kidney, in which the non-waste substances in the primary kidney filtrate are taken back into the tissues via nephrons.

receptor A specialised structure that can detect a specific stimulus and initiate an action potential.

recombinant DNA technology A technique that combines DNA from two or more sources in cell cultures to create a new DNA molecule or genetic sequence.

redirect In science, to redirect an experiment is to modify the methodology to gain further insight into the phenomena observed in the original experiment.

reference list A list of resources that are cited or referred to in the document.

refine In science, to refine an experiment is to modify the methodology to obtain more accurate data or precise data.

reflex A rapid, unconscious response.

regression The calculated estimate of the strength of a relationship between variables.

regulatory T lymphocyte A T lymphocyte that down-regulates the immune response after an infection has been resolved.

relative uncertainty The measured uncertainty displayed as a percentage of the measurement.

reliability In science, the likelihood that another experimenter will obtain the same results (or very similar results) if they perform exactly the same experiment under the same conditions (ACARA 2015c, Taylor 1982)

renin An enzyme released from kidneys in response to changes in blood osmolality or pressure responses.

repeat trial The process of repeatedly conducting a process, activity or trial in an attempt to replicate the results.

replication The process of repeatedly conducting or choosing a process, activity or sample in an attempt to replicate the results, event or set-up.

reproduction number (R_0) The number of infections transmitted from a single case of infection; the number of secondary infections.

research question A question that directs the scientific inquiry activity; it focuses the research investigation or student experiment, informing the direction of the research, and guiding all stages of inquiry, analysis, interpretation and evaluation.

reservoir A biological entity that allows infestation of a pathogen through reproduction or multiplication, becoming a source of further infections.

retrovirus A type of virus that uses RNA as its nucleic acid. It uses the enzyme reverse transcriptase to copy its RNA into DNA as one of the first steps in infecting a host cell.

reverse transcriptase A type of polymerase enzyme, used by retroviruses to copy their RNA into DNA as part of the processes of viral infection of a host cell.

rhabditiform The first larval stage of *Strongyloides*, which can develop either into a free-living sexually reproducing adult or into infective filarial form larvae.

ribosome A tiny organelle often attached to the endoplasmic reticulum; composed of protein and RNA; the site of protein synthesis.

ribozyme An enzyme composed of a section of RNA that catalyses certain biochemical reactions, such as the cleaving or bonding of RNA strands.

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 (ACARA 2015c).

RNA (ribonucleic acid) A nucleic acid made up of a sequence of ribose sugars and bases (adenine, cytosine, guanine and uracil) linked by phosphate bonds.

root hair A very thin extension of an epidermal cell of a root. Root hairs increase the root's surface area, making the absorption of water and minerals from soil more efficient.

rough endoplasmic reticulum The endoplasmic reticulum with many ribosomes in association with it.

rRNA (ribosomal RNA) An RNA molecule synthesised in the nucleolus; it forms part of ribosomes.

rumen A large fermentation chamber for the digestion of cellulose, located before the stomach in many herbivorous animals, such as cattle and sheep.

S

safety data sheet (SDS) A document that outlines specific details about items that are required to be considered when handling the item for experimentation.

sample size The number of individual measurements or observations undertaken for each tested variable.

sanitation The provision and conditions, facilities and infrastructure resulting in cleanliness and health.

saponin A soap-like compound present in plants that breaks down lipids and that disrupts the cell membranes of potential pathogens.

scatterplot A graph that displays the measured values for two variables plotted along two axes.

scientific journal A book containing the entire collection of work related to an experiment or investigation.

scientific method An orderly process of determining the relatedness between phenomena that were originally witnessed and caused a query to develop.

scientific notation A measured value written as a mathematical expression, between 1 and 10 including decimals, displaying all significant figures, multiplied by ten raised to a specific power.

scientific report A document that follows the report genre, systemically organising the main information and findings of scientific research or work.

second messenger An intermediate signalling molecule that relays signals.

secondary data Data collected by a person or group other than the person or group using the data (ACARA 2015c).

secondary immune response The immune response to an antigen that was previously encountered and which provoked an immune response. The process activates memory cells and so is faster and stronger than the primary response.

secondary infection The infection that occurs after the initial infection or case. May be due to the primary or initial infection.

secondary source A source of information or data that was not created or measured by its author, but which cites another source.

secretion (1) The release of specific substances from a cell or group of cells. (2) In kidneys, the active excretion of particular substances by the cells of the duct walls.

selection bias An inclination or prejudice towards something during the process of selecting samples.

self-tolerance The inability of the immune system to respond to self-antigens.

semipermeable A barrier that allows solvent molecules to pass through, but preventing at least some of the solute molecules from doing so.

serum The fluid portion of the blood that remains once the blood cells and clotting factors have been removed.

shivering thermogenesis The increased production of metabolic heat through shivering.

signal transduction The passage of signals along nerve axons.

significant figures The digits recorded according to the precision of an instrument; the digits in a calculation that represent the precision of an instrument.

sink A site where something is stored or consumed.

solute A substance that is dissolved in a solution.

solvent The dissolving agent of a solution, usually water.

soma The animal or plant body as a whole with the exception of sex cells.

source (1) A site where something is produced. (2) Any piece of scientific literature or text from which scientific evidence is drawn.

Spearman rank correlation A calculated estimate of the strength between variables for a non-linear relationship, producing a line of best fit.

specialised cell A cell that has a specific function (e.g. a red blood cell).

spectrophotometer A piece of equipment used to measure the intensity of light at a specific wavelength emitted or passing through a particular substance.

standard deviation A calculated spread of data that estimates the quartile boundaries from the mean, assuming a normalised (bell) curve.

starch A complex carbohydrate consisting of glucose subunits; the main form of energy storage in plants.

stem cell A cell that can differentiate into a specialised cell.

steroid A polycyclic lipid with a hydrocarbon nucleus; steroids include bile acids, sterols and various hormones.

stimulus An agent that causes a reaction or change in an organism or in any of its parts.

stoma A pore in the leaf epidermis, bounded by specialised guard cells that open and close the pore. Stomata are the main routes through which gas exchange occurs in plants, and through which water loss is regulated.

student *t*-test A calculation that produces a value that estimates the likelihood that two variables are not related.

substrate A molecule that is acted on by an enzyme.

subunit vaccine A vaccine that contains only antigens from a pathogen. One or more antigens may be included to stimulate an immune response.

susceptible The state of being subject or open to influence or an agent of influence; likely to be influenced by a particular agent.

symbiosis A close association between two different organisms, in which at least one of the organisms benefits from the association. Symbiosis includes mutualism, commensalism and parasitism.

sympathetic division The division of the autonomic nervous system that generally increases energy expenditure and prepares the body for action.

symptomatic An organism that displays symptoms while infected and/or diseased.

synaptic terminal The point of communication between one nerve cell and another, or a nerve cell and a target cell such as a muscle or gland.

system A group of interacting objects, materials or processes that form an integrated whole; can be open or closed (ACARA 2015c).

systematic error An error in measurements caused by the design of a system (e.g. methodology) or instrument (without calibration) that results in the measurements shifting in a systemic direction.

T

T cell receptor (TCR) A receptor on the surface of T lymphocytes that binds to antigens displayed by antigen-presenting cells attached to MHC-II proteins. This binding activates the T lymphocyte and provides the link between the innate and adaptive immune responses. It is made up of two polypeptide chains that have a variable and a constant region and only one antigen-binding site.

T lymphocyte (or T cell) A type of lymphocyte that originates in the bone marrow and matures in the thymus gland. It is responsible for cell-mediated immunity. T lymphocytes include cytotoxic T lymphocytes, helper T lymphocytes, regulatory T lymphocytes and memory T lymphocytes.

taxonomy The system of naming groups recognised in a classification of organisms.

terpene A chemical produced by plants that is highly toxic to fungi and which is also toxic to many insects. In insects, terpenes mimic certain hormones, causing disruptions to their life cycle. Pyrethrins and phytoectysones are included in this group.

theory In science, a set of concepts, claims and/or laws that can be used to explain and predict a wide range of related observed or observable phenomena; theories are typically founded on clearly identified assumptions, are testable, produce reproducible results and have explanatory power (ACARA 2015c).

thermoreceptor A sensory receptor that responds to heat or cold.

thermoscanning Using a device to produce a thermal image by detecting infrared radiation, showing the temperature of the surface of an object and the variations in the surface temperature.

thigmonasty A change in the direction of plant growth in response to contact with a surface.

thyroid hormone A hormone secreted from the thyroid glands.

tidal volume The volume of air moved into and out of lungs during breathing.

tissue A group of similar cells functioning together.

tolerance range The range of environmental conditions under which an organism can survive.

tonoplast A large permanent vacuole surrounded by a membrane in plant cells

torpor A state of dormancy for a brief or long period, during which the metabolic rate is slowed and the animal becomes unresponsive to external touch or noise.

totipotent (cell) A cell that can give rise to any cell type and potentially a complete new organism.

toxoid vaccine A type of subunit vaccine that uses toxins, inactivated by the chemical formalin, to elicit an adaptive immune response.

trachea The tube in humans and other air breathing vertebrates extending from the larynx to the bronchi, serving as the principal passage for conveying air to and from the lungs; the windpipe.

tracheid A long, hollow cell with a thickened wall and tapering ends, found in the xylem of vascular plants. Tracheids transport water and nutrients to the living cells of the plant.

tracheole A fine respiratory tube of the trachea of an insect or a spider, part of the respiratory system.

transcription factor Any protein involved in the initiation or regulation of transcription process (e.g. copying mRNA from a DNA strand).

transduction cascade A series of events in which a change in one molecule causes a change in another and so on.

translocation The transport of organic substances in the phloem of a vascular plant.

transmembrane protein A type of membrane protein that spans the entire width of the membrane; it is often involved in transport of substances across the membrane.

transpiration The loss of water from the leaves of plants through stomata. Transpiration causes suction, which draws water up xylem vessels from the roots.

transpiration stream The flow of water within a plant, from the uptake by the roots to the loss of water to the environment via the leaves.

trend line A line drawn onto a graph to accurately display a relationship between the variables.

TRH (thyrotropin releasing hormone) A hormone secreted by the hypothalamus, which acts on the anterior pituitary to secrete TSH (thyroid stimulating hormone).

trichinosis A disease caused by the ingestion of the parasite *Trichinella spirali*, usually in raw or under-cooked meat.

true value An ideal measurement of a phenomenon without error.

turgor A state of high internal fluid pressure that is the result of the osmotic intake of water into plant cells whose volume is limited by the rigid cell wall.

U

uncertainty Range of values for a measurement result, taking account of the likely values that could be attributed to the measurement result given the measurement equipment, procedure and environment (ACARA 2015c); indicators of uncertainty may include percentage and/or absolute measurement uncertainty, confidence intervals, inferential statistics, statistical measures of spread, e.g. range, standard deviation.

unicellular An organism consisting of a single cell.

unipotent (cell) A stem cell that can differentiate only into one cell type.

urea A water-soluble diamide molecule (CH_4N_2O) that is a major product of protein breakdown. It is excreted by many vertebrates, including mammals.

ureter The tube that carries urine from a kidney to the bladder for storage, before release of urine via the urethra.

urethra The tube that carries urine from the bladder to the exterior for excretion.

uric acid A complex nitrogenous compound ($C_5H_4N_4O_3$) that is produced and excreted by birds and most land reptiles.

V

vaccination The process of introducing a vaccine into the body in order to elicit an adaptive immune response and create memory cells so future responses will be quicker and stronger if the antigen is encountered in the future. The process of creating artificial active immunity.

vaccine A preparation of altered, weakened or killed microorganisms, or inactivated forms of toxins or antigens introduced into the body (usually by injection) in order to elicit an adaptive immune response.

validity In science, the extent to which tests measure what was intended; the extent to which data, inferences and actions produced from tests and other processes are accurate (ACARA 2015c).

valve A specialised structure in circulatory systems that allows movement in one direction only. In humans, valves occur in the heart, veins and lymph vessels.

variable Adjective: apt or liable to vary or change; changeable; inconsistent; (readily) susceptible or capable of variation; fluctuating, uncertain; noun: in mathematics, a symbol, or the quantity it signifies, that may represent any one of a given set of number and other objects. In science, a factor that can be changed, kept the same or measured in an investigation (e.g. time, distance, light, temperature).

variable region The region of an antibody that varies between different antibodies and allows them to interact with different antigens.

vascular bundle A grouping of vascular tissues in vascular plants, containing both xylem and phloem. Vascular bundles are continuous, from the roots into the stem, branches and leaves.

vascular plant A plant that has vascular tissues (xylem and phloem) in which the cell walls contain lignin. All living plants, except bryophytes, are vascular plants.

vascular tissue The tissue that conducts water and nutrients around vascular plants. It consists of two types of tissue—xylem and phloem. Vascular tissue also provides structural support to a plant.

vascularised tissue The tissue that contains many blood vessels.

vasoconstriction The constriction of a blood vessel with a reduction of the lumen as a result of contraction of the smooth muscle in the blood vessel wall.

vasodilation The enlargement of the calibre of blood vessel by relaxation of smooth muscle in the blood vessel walls.

vector (1) An infectious disease. (2) An object or organism that transfers a parasite from one organism to another.

vein A blood vessel that carries blood towards the heart. All veins except the pulmonary veins carry deoxygenated blood.

ventilation The active movement of air or water past gas exchange surfaces in animals. In land animals, it is called breathing.

ventricle A muscular chamber of the heart that pumps blood out of the heart. In a four-chambered heart (as in humans) the right ventricle pumps deoxygenated blood to the lungs, and the left ventricle pumps oxygenated blood to other body tissues.

venule A small vessel that connects capillaries to a vein.

vertebrate An animal belonging to the phylum Vertebrata. Vertebrates have a brain enclosed in a skull, and a segmented spinal column consisting of vertebrae. They include fish, amphibians, reptiles, birds and mammals.

vesicle A membrane-bound organelle often involved in transport within the cell.

virion A single virus particle.

virulence A measure of the degree of pathogenicity of a particular pathogen (i.e. the degree to which it causes disease).

virus An infectious agent composed of genetic material (either DNA or RNA) enclosed in a protein coat, and sometimes also a lipoprotein envelope, which is only able to multiply in a host cell.

vital capacity The maximum volume of air that can be moved into and out of the lungs in one breath.

X

xerophyte A plant that has adaptations that conserve moisture and prevent the leaf temperature from rising too much.

xylem The tissue in vascular plants that transports water and nutrients upwards from the roots; it consists of hollow chains of dead cells.

xylem vessel A long tube consisting of cells joined end to end, through which water and nutrients are transported from the roots to the leaves in a vascular plant.

Z

zoonose An infectious disease that passes from a non-human animal to humans.

zoospore An asexually reproduced reproductive cell of fungi, oomycetes, protozoans or algae that possesses flagella and is thus motile.

Index

Attributions

Cover: Kenneth Bart/Visuals Unlimited, Inc./Science photo Library

Queensland Curriculum & Assessment Authority (QCAA): Biology 2019 v1.1 General Senior Syllabus © Queensland Curriculum & Assessment Authority. 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.

We thank the following for their contributions to our text book:

123RF: pp. 227, 261b, 311tr, 374; alila, pp. 285, 328cr, 328tr; Roberto Biasini, pp. 33t, 165tl; blueringmedia, p. 303b; Hans Christiansson, p. 104t; Andrea Danti, p. 64; delcreations, p. 275; designua, p. 361; Juan Gartner, p. 361tr; lculig, p. 72b; Sebastian Kaulitzki, p. 377; Andrey Khrobostov, p. 248br; Brian Lasenby, p. 30b; Anton Lebedev, pp. 73bc, 73bl, 73br, 74cl, 74tl; logos2012, p. 97c; Tatiana Makotra, p. 232c; my123rf88, p. 270br; Duncan Noakes, p. 263b; Rido, p. 265t; Andrei Samkov, p. 176t; seanjoh, p. 229br; subbotina, p. 132bl; Jacoba Susanna Maria Swanepoel, p. 264tl.

Australian Bureau of Statistics: © Commonwealth of Australia, based on ABS data, Australian Health Survey 2014/15 (4364.0), pp. 290br, 291, 297.

Australian Bureau of Agricultural and Resource Economics and Sciences: © Commonwealth of Australia 2012, *Benefit–cost analysis of the National Fruit Fly Strategy Action Plan*, licenced under CC BY 3.0 AU, p. 443.

Australian Institute of Health and Welfare: Based on Australian Institute of Health and Welfare, licenced under CC BY 3.0, pp 292, 296r.

Alamy Stock Photo: Prisma Archivo, p. 10b; BSIP SA, pp. 118–119, 354bl, 416l; Nigel Cattlin, pp. 136l, 305tr, 312t; Denis Crawford, p. 318c; Barry Diomede, p. 430t; The Granger Collection, p. 19c; Granger Historical Picture Archive, p. 19tl; *ibreakmedia;* Sebastian Kaulitzki, p. 354tla; Jonathan Larsen/Diadem Images, p. 437r; Emmanuel Lattes, p. 121tr; Mediscan, pp. 147tl, 290t; National Geographic Creative, p. 179b; Phanie, p. 434l; Amalia Sari, p. 437l; Science History Images, pp. 57c, 57tc, 57tr, 325bl, 404t.

American Chemical Society: Reprinted with permission from *Chemical Engineering News.* Copyright 2014 American Chemical Society, p. 295.

Auscape International Photo Library: Steve Downer/Ardea, p. 160; Nick Rains, p. 282c.

Australian Government Department of Agriculture and Water Resources: Nematode (*Xiphinema brevicolle*), Zhao, Zeng Qi & Crosby, T.K. (2012), p. 318t.

Australian Government Department of Health: Table 8.3.3 p. 378, Table 8.3.4 p. 383 Australian Government Department of Health's National Immunisation Program (NIP) Schedule. Provided as an example only. Access the on-line version on the Department's website for the most up-to date versions https://beta.health.gov.au/health-topics/immunisation/immunisation-throughout-life/national-immunisation-program-schedule; p. 418;
Australian Influenza Surveillance Report 2017 #06. Available at: http://www.health.gov.au/internet/main/publishing.nsf/Content/FD6A56E754EB4DE0CA25816E008027EB/$File/ozflu-surveil-no05-2017.pdf, p. 419.

Bayer Australia Ltd: Bayer Australia Limited (Animal Health), p. 316c.

BioMed Central Ltd: Bagaitkar J., Demuth D.R., & Scott D.A. (2008). 'Tobacco use increases susceptibility to bacterial infection, *Tobacco Induced Diseases*, *4(12)*. Licenced under CC BY 2.0, pp. 304, 308b, 308t;

Pullan, R.L., Smith, J.L., Jasrasari, R., & Brooker, S.J. (2014) 'Global numbers of infection and disease burden of soil transmitted helminth infections in 2010'. *Parasites & Vectors, 7(37)*, licenced under CC BY 2.0, p. 315t;

Prescott, S.L., Pawanka, R., Allen, K.J., Campbell, D.E., Sinn, J.K.H., Fiocchi, A., Ebisawa, M., Sampson, H.A., Beyer K., & Lee B.-W. (2013). A global survey of changing patterns of food allergy burden in children. *World Allergy Organization Journal, 6(18)*, licenced under CC BY 2.0, p. 340c.

Cambridge University Press: Noakes, T.D., Borresen, J., Hew-Butler, T., Lambert, M.I., & Jordann, E. (2008). Semmelweis and the aetiology of puerperal sepsis 160 years on: an historical. *Epidemiology and Infection, 136(1)*, 1–9, p. 319b.

Centers for Disease Control and Prevention: pp. 317b, 333b, 341, 343b, 343t, 380b, 381b, 389, 397b, 415, 436.

Department of Agriculture and Fisheries Queensland/Horticulture Innovation Australia: pp. 441–443.

Department of Health New South Wales: © Commonwealth of Australia. Adapted from Gidding, H.F., Burgess, M.A., & Gilbert, G.L. (2000). Diphtheria in Australia, recent trends and future prevention strategies. *Communicable Diseases Intelligence, 24(6)*, p. 394r. The time line of all locations visited by latest infected case of measles in Western Sydney © State of New South Wales NSW Ministry of Health. For current information go to www.health.nsw.gov.au, p. 414. Licenced under CC BY 4.0, p. 414.

Dreamstime: Caan2gobelow, p. 190tr.

Elsevier: Based on Liew, W.K. et al. (2009). *J Allergy and Clinical Immunology,* p. 396

Hammond, B., Ali, Y., Fendler, E., Dolan, M., & Donovan, S. (2000). Effect of hand sanitizer use on elementary school absenteeism. *American Journal of Infection Control, 28(5)*, pp. 340–346, © 2000. Reprinted with permission from Elsevier, p. 427b.

Environmental Health Perspectives: Reproduced with permission from Environmental Health Perspectives, p. 294.

European Centre for Disease Prevention and Control: Graph showing mumps notification from Gee, S., O'Flanagan, D., Fitzgerald, M., & Cotter, S. (2008). Mumps in Ireland, 2004–2008. *Eurosurveillance*, *13(18)*, licenced under CC BY 4.0, p. 342. Column graph of human influenza A (H5N1) by age and outcome from Dudley, J.P. (2009). Age-specifc infection and death rates for human A(H5N1) avian influenca in Egypt. *Eurosurveillance, 14(18)*, released under CC BY 4.0 licence, p. 332. Data collected by the WHO of H5N1 (bird flu) infection in wild and domestic birds and humans from Tarantola, A., Barboza, P., Gauthier, V., Loos, S., El Omeiri, N., Gastellu-Etchegorry, M. (2010). The influenza A(H5N1) epidemic at six and a half years: 500 notified human cases and more to come. *Eurosurveillance, 15(29)*, released under CC BY 4.0 license, pp. 94c, 342.

Sam Fesuk: p. 229br.

Fotolia: borisoff, p. 121tl; stockshoppe, p. 152; szymanskim, p. 449r; Vovan, p. 85t; san724, p. 91tr; evgenia sh, p. 97b.

Fresh and Clean/Alsco PL: Courtesy of Fresh & Clean, p. 431.

Getty Images: A. Martin UW Photography, p. 168tl; Michael Abbey, p. 258bl; Charles V. Angelo, pp. 127tl, 146r; Bettmann, p. 320b;

Wally Eberhart, p. 76bc; Jason Edwards, pp. 262tl, 262cl; Encyclopaedia Britannica, pp. 25b, 25br; Dr Stanley Flegler/Visuals Unlimited, p. 67tl; Juan Gaertner, p. 360t; Steve Gschmeissner, pp. 120cr, 354cl;
Neil Harding, p. 138b; Cathlyn Melioan, p. 248cr; Nancy Nehring, pp. 209b, 209cl, 209tl, 209tr; Michael Peuckert, p. 129t; Photo researchers, p. 381t; Pixologicstudio, p. 154t; QAI Publishing, p. 158t; Ed Reschke, pp. 131, 136c, 155c, 258br; J. C. Revy, ISM, p. 210c; Science Artwork/Science Photo Library, p. 405tr; Science Source, pp. 57bl, 228b; Sciepro, p. 206; Victor Shupletsov, p. 197b; Brian J. Skerry, p. 168bl; Jason Todd, p. 190c; Javier Torrent/VWPics, pp. 131bl, 131br; Universal Images Group, p. 74cr; Dr Gladden Willis, p. 354cl.

Dr. David Jolly: p. 310bl.

Michele Kohout: p. 309.

Malaria Atlas Project: Released under CC BY 3.0 agreement., p. 322.

McGraw-Hill Australia Pty Ltd: © McGraw-Hill Education, Australia, p. 366b.

Medical Images.com: Yoav Levy, p. 156b.

National Geographic Society: Michael Nichols, pp. 146l, 190b.

National Heart, Lung, and Blood Institute, National Institutes of Health: p. 286b.

National Oceanic & Atmospheric Administration: Kyle Carothers, p. 114bl.

National Health and Medical Research Council: Based on material provided by NHMC. Licensed under CC BY 4.0, p. 431.

North American Veterinary Community: p. 331.

Oxford Designers & Illustrators Ltd: pp. 30c, 204b, 285, 312c, 366c.

Pearson Education, Inc: Figure from Marieb. E., & Hoen, K. (2013). *Human anatomy and physiology* (9th ed.). fig. 21.15. Reprinted and electronically reproduced by permission of Pearson Education, Inc., New York, NY., pp. 233t, 362. Figure from Freeman, S. (2008). *Biological Science* (3rd ed.). fig. 37.20. Reprinted and electronically reproduced by permission of Pearson Education, Inc., New York, New York, p. 197t.

Public Library of Science: Graph of population, age groups and whooping cough from Wanlapakorn, N., Ngaovithunvong, V., Thongmee, T., Vichaiwattana, P., Vongpunsawad, S., & Poovorawan, Y. (2016). Seroprevalence of antibodies to pertussis toxin among different age groups in Thailand after 37 years of universal whole-cell pertussis vaccination. *PLoS ONE, 11(2)*, p. 379; Analysis of participants in the study including demographics, socio-economic status, ethnicity and education from Priest, P., McKenzie J., Audas, R., Poore, M., Brunton, C., & Reeves, L. (2014). Hand sanitiser provision for reducing illness absences in primary school children: a cluster randomised trial. *PLOS Medicine, 11(8)*. Licenced under CC BY 3.0, pp. 428, 429.

Science Photo Library SPL: pp. 85br, 101t, 103b, 230t, 311bl, 325c, 400, 404b, 426b; AMI Images, pp. 23br, 301br, 347; Sally Bensusen, p. 169b; R. Bick, B. Poindextre, UT Medical School, p. 9c; Dr Jack Bostrack, p. 23c; Robert Brook, p. 407br; BSIP, Beranger, p. 372t; BSIP, VEM, p. 140bl; Dr Jeremy Burgess, pp. 16b, 18t, 67bl, 194; Callista Images/Cultura, p. 325br; Leonello Calvetti, p. 242tr; Jose Calvo, p. 8bc; Carolina Biological Supply Co/Visuals Unlimited, Inc., p. 147; David Cavagnaro, p. 199lt; Centre for Infections/Public Health England, p. 120tl; Martyn F. Chillmaid, p. 173t; Mark Clarke, p. 405tl; Clouds Hill Imaging Ltd, p. 310br; CNRI, pp. 184b, 210b; Herve Conge/ISM, pp. 147lb, 204c; Ashley Cooper, p. 71c; Dennis Kunkell Microscopy, pp. 3, 23bl, 135br, 303tr; Reinhard Dirscherl, p. 229c; Martin Dohrn, pp. 266, 435; Doncaster and Bassetlaw Hospitals, p. 373t; Edelmann, p. 11c; Wim Van Egmond, pp. 23bc, 87, 120bl; 174br, Emilio Segre Visual Archives/American Institute of Physics, p. 81bl; Eye of Science, pp. 25c, 55bc, 103tr, 129b, 140tl, 162t, 196t, 24l, 271t, 286t; Mauro Fermariello, p. 290bl; Simon Fraser, p. 403bl; Thomas Fredberg, p. 261tl; Dr David Furness p. 49; Dr Gary Gaugler, p. 301cr; Pascal Goetgheluck, p. 54c; Steve Gschmeissner, pp. 8br, 65, 125, 135cr, 141bl, 180, 189t, 267b, 304t, 349b, 353t, 354cr, 357c, 471c; Eric Grave, p. 157c; Eddy Gray, p. 55br; Klaus Guldbrandsen, p. 141bc; Roger Harris, p. 345; P. Hawtin/University of South Hampton, p. 300; Chris Hellier, p. 270c; Louise Hughes, pp. 11b, 55tl, 167br; ISM, pp. 98b, 124br; Jacopin, p. 267t; Mikkel Juul Jensen, p. 17; Manfred Kage, pp. 135bl, 146ct; Kallista Images/Custom Medical Stock Photo, p. 77bl; Nancy Kedersha, p. 354br; Russell Kightley, pp. 6c, 6l, 6r, 54t, 57cr, 69–70, 224, 416r; James King-Holmes, p. 324b; Ton Koene/Visuals Unlimited, Inc, p. 403tr; Dennis Kunkel Microscopy, pp. 27l, 27r, 420br; Laguna Design, pp. 72c, 79c; Francis Leroy, p. 127br; Dr Kari Lounatmaa, pp. 25b, 53b, 109r; Claus Lunau, p. 147br; Dr P. Marazzi, p. 405bl, 405br; Medi-Mation, p. 252t; Astrid & Hanns-Frieder Michler, p. 137b; Professors P. Motta/T. Naguro, pp. 50t, 51b, 51c, 52b, 53c; Dr Gopal Murti, pp. 57lb, 57br; National Cancer Institute, p. 157c; Niaid/National Institutes of Health, p. 353b; Susumu Nishinaga, p. 231tl; NSIL/Dick Roberts, Visuals Unlimited, p. 77tr; Claude Nuridsany & Marie Perennou, p. 169t; Matthew Oldfield, p. 143tr; Overseas/Collection CNRI, p. 177r; Alfred Pasieka, pp. 32t, 210tl; Gerard Peaucellier/ISM, pp. 148tc, 148tl, 148tr; Jose Antonio Penas, p. 406b; Power and Syred, pp. 27c, 76bl, 270t; Ramon Andrade 3DCiencia, p. 249c; Antonia Reeve, p. 141tr; Marilyn Schaller, p. 10c; Dr Lothar Schermelleh, p. 19tr; Stephanie Schuller, p. 303tl; Sci-Comm Studios, pp. 21l, 21r; Scientificanimations.com, p. 433b; Daniel Schroen/Cell Applications Inc., p. 20r; Alexander Semenov, p. 127bl; Seymour, p. 9br; John Sibbick, p. 122bl; Harvinder Singh, p. 249tl; Marty Snyderman, p. 86cl; Sputnik, p. 438; Sinclair Stammers, p. 122br; Tek Image, p. 141br; Dr Alvin Telser, p. 354cr; Sherman Thomson, p. 86bl; UCL, Grant Museum of Zoology, p. 176c; US Department of Agriculture, p. 434r; Van Egmond, Visuals Unlimited, p. 146cb; Bo Veisland, p. 420bl; Richard Wehr, p. 76t; Carol & Mike Werner, p. 22b; Dirk Wiersma, p. 273t; Dr Keith Wheeler, pp. 54b, 190tl; Dr Torsten Wittmann, pp. 8bl, 55tr; Andrzej Wojcicki, pp. 1–2; David Wrobel, Visuals Unlimited, p. 174c.

Science Source: Igor Siwanowicz, p. 10t.

Shutterstock: pp. 261c, 271br; Alila Medical Media, pp. 184t, 300b, 357tl; AlexeyVeselykh, p. 407bl; Andrey862, p. 128t; Leonid Andronov, p. 79b; anyaivanova, p. 9bl; Bignai, p. 426tc; BioMedical, p. 284; Greg Brave, p. 89c; Jan Bruder, p. 144; Jose Luis Calvo, p. 153t; CCat82, p. 274; Barnaby Chambers, p. 430b; danylyukk1, p. 174bl; Designua, pp. 89b, 231tr, 249br, 251, 367b; Nikolay Dimitrov, p. 167tr; Margoe Edwards, p. 426tl; ellepigrafica, p. 359br; EpicStockMedia, p. 124bl; eveleen, p. 363t; extender_01, p. 238; Susan Flashman, p. 182b, 261c; Bill Frische, p. 271t; Juan Gaertner, p. 363b; Gentoo Multimedia Limited, p. 260l; Pawel Graczyk, p. 218tl; Jubal Harshaw, p. 192t; Fon Hodes, p. 95c; Stephen van Horn, p. 93c; Alena Hovorkova, p. 186t; Eric Isselee, p. 281l; Natalie Jean, p. 94br; Sebastian Kaulitzki, pp. 105, 380t; Kateryna Kon, pp. 305bl, 305br, 346b, 398–399; Miro Kovacevic, p. 147r; Anya Ku, p. 452t; Dr Kucharski K. Kucharska, p. 317t; Lebendkulturen.de, p. 16c; Paul Looyen, p. 262cl; Meletios, p. 240; Michael Felix Photography, p. 24r; mihalec, p. 248cr; Monkey Business Images, pp. 403br, 403c; ngaga, p. 216b; Dmitry Naumov, p. 371t; Kathie Nichols, p. 75c; nokkaew, p. 406tl; optimarc, p. 75b; PeJo, p. 452b; petarg, p. 80tl; Catalin Petolea, p. 351c; photoinnovation, p. 86tl; Provasilich, p. 312b; Leigh Prather, p. 224; Dr Morley Read, p. 128b; Stephanie Rousseau, p. 230b; SAPhotog, p. 199b; sasimoto, p. 84r; sciencepics, pp. 82bl, 305bc; sevenke, p. 248cr; Sozaijiten,

p. 94bl; shunfa Teh, p. 311c; toeytoey, p. 354tr; Tomatito, p. 132t; Triff, pp. 9tc, 149–150; Marco Uliana, p. 232tl; Martin Valigursky, p. 124tl; Dmytro Vietrov, p. 426tr; Bogdan Wankowicz, p. 248br; wavebreakmedia, p. 426tc; zimowa, p. 77br; Zuzanae, p. 296l.

Sozaijiten: p. 95b.

US National Library of Medicine National Institutes of Health: Table showing growth of ducks exposed to increasing levels of ergot in their food from Dänicke, S. (2015). Ergot alkaloids in feed for Pekin ducks: toxic effects, metabolism and carry over into edible tissues. *Toxins, 7(6)*, 2006–2023, p. 322; Table showing worm infections of children from Koukounari, A., Estambale, B., Njagi, J., Cundill, B., Ajanga, A., Crudder, C., Otido, J., Jukes, M., Clarke, S., & Brooker, S. (2008). Relationships between anaemia and parasitic infections in Kenyan schoolchildren: a Bayesian hierarchical modelling approach. *International Journal for Parasitology*, *38*, 1663–1671, p. 323.

W. W. Norton & Company, Inc: Graph of adult level of serum immunoglobulins, from Janeway, C., Travers, P., Walport, M., & Shlomchik, M. (2002). *Immunobiology* (6th ed.), p. 379; phospholipid molecule from Alberts, B., Johnson, A., & Lewis, J. (2002) *Molecular Biology of the Cell* (4th ed.), Garland Science, p. 73t.

World Health Organisation: World Malaria report 2014, © pp. 421b, 422b.

Pearson Australia
(a division of Pearson Australia Group Pty Ltd)
707 Collins Street, Melbourne, Victoria 3008
PO Box 23360, Melbourne, Victoria 8012
www.pearson.com.au

First published 2019 by Pearson Australia

eBook credits
Resource author: Martin Hall et al.
Publisher: Alicia Brown
Project Manager: Michelle Thomas
Production Editor: Virginia O'Brien
Development editor: Zoe Hamilton
Editor: Catherine Greenwood, iEnergizer Aptara Ltd
Copyright & Pictures Editor: Lisa Woodland
Illustrator: DiacriTech
eBook Production Coordinator: Louise Grundy
Digital Administrator: Jenny Smirnov

ISBN 978 1 4886 1959 5

Pearson Australia Group Pty Ltd ABN 40 004 245 943

eBook acknowledgements
We would like to thank the following for permission to reproduce copyright material.

The following abbreviations are used in this list: t = top, b = bottom, l = left, r = right, c = centre.

Cover: Kenneth Bart/Visuals Unlimited, Inc./Science photo Library
Queensland Curriculum & Assessment Authority (QCAA): Biology 2019 v1.1 General Senior Syllabus © Queensland Curriculum & Assessment Authority. 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
123RF: pp. 227, 261b, 311tr, 374; alila, pp. 285, 328cr, 328tr; Roberto Biasini, pp. 33t, 165tl; blueringmedia, p. 303b; Hans Christiansson, p. 104t; Andrea Danti, p. 64; delcreations, p. 275; designua, p. 361; Juan Gartner, p. 361tr; Iculig, p. 72b; Sebastian Kaulitzki, p. 377; Andrey Khrobostov, p. 248br; Brian Lasenby, p. 30b; Anton Lebedev, pp. 73bc, 73bl, 73br, 74cl, 74tl; logos2012, p. 97c; Tatiana Makotra, p. 232c; Ivan Mikhaylov, p. e20l; my123rf88, p. 270br; Duncan Noakes, p. 263b; Rido, p. 265t; Andrei Samkov, p. 176t; seanjoh, p. 229br; subbotina, p. 132bl; Jacoba Susanna Maria Swanepoel, p. 264tl; Wong Sze Yuen, p. e25tr.
Australian Bureau of Statistics: © Commonwealth of Australia, based on ABS data, Australian Health Survey 2014/15 (4364.0), pp. 290br, 291, 297.
Australian Bureau of Agricultural and Resource Economics and Sciences: © Commonwealth of Australia 2012, *Benefit–cost analysis of the National Fruit Fly Strategy Action Plan*, licenced under a CC BY 3.0 AU, p. 443.
Australian Institute of Health and Welfare: Based on Australian Institute of Health and Welfare, licenced under a CC BY 3.0, pp 292, 296r.
Alamy Stock Photo: Prisma Archivo, p. 10b; BSIP SA, pp. e61c, 118-119, 354bl, 416l; Nigel Cattlin, pp. 136l, 305tr, 312t; Denis Crawford, p. 318c; Barry Diomede, p. 430t; Ray Evans, p. e62t, The Granger Collection, p. 19c; Granger Historical Picture Archive, p. 19tl; ibreakmedia; Sebastian Kaulitzki, p. 354tla; Jonathan Larsen/Diadem Images, p. 437r; Emmanuel Lattes, p. 121tr; Mediscan, pp. 147tl, 290t; National Geographic Creative, p. 179b; Phanie, p. 434l; Amalia Sari, p. 437l; Science History Images, pp. 57c, 57tc, 57tr, 325bl, 404t; Universal Images Group North America LLC, p. e101b.
American Chemical Society: Reprinted with permission from Chemical Engineering News. Copyright 2014 American Chemical Society, p. 295.
Auscape International Photo Library: Steve Downer/ardea.com, p. 160; Nick Rains, p. 282c.
Australian Government Department of Agriculture and Water Resources: Nematode (Xiphinema brevicolle), Zhao, Zeng Qi & Crosby, T.K. (2012) p. 318t.
Australian Government Department of Health: p. 378; https://www.myhealthycommunities.gov.au/interactive/immunisation, Australian Institute of Health and Welfare 2018, p. 383; p. 418;
Australian Influenza Surveillance Report 2017 #06. Available at: http://www.health.gov.au/internet/main/publishing.nsf/Content/FD6A56E754EB4DE0CA25816E008027EB/$File/ozflu-surveil-no05-2017.pdf. p. 419.
Bayer Australia Ltd: Bayer Australia Limited (Animal Health), p. 316c.
BioMed Central Ltd: 'Tobacco use increases susceptibility to bacterial infection', by J. Bagaitkar, Dr. Scott Demuth, *Tobacco Induced Diseases*, 4(1):12, 2008. Licenced under a CC BY 2.0, pp. 304, 308b, 308t;
'Global numbers of infection and disease burden of soil transmitted helminth infections in 2010', by Rachel L. Pullan, Jennifer L. Smith, Rashmi Jasrasaria and Simon J. Brooker, *Parasites & Vectors*, 7:37, January 2014, licenced under a CC BY 2.0, p. 315t;
'A global survey of changing patterns of food allergy burden in children' by Susan L. Prescott, Ruby Pawanka, Katrina J. Allen, Dianne E. Campbell, John KH Sinn, Alessandro Fiocchi, Motohiro Ebisawa, Hugh A. Sampson, Kirsten Beyer and Bee-Wah Lee, *World Allergy Organization Journal*, 6:18, 2013, licenced under a CC BY 2.0, p. 340c.
Cambridge University Press: 'Semmelweis and the aetiology of puerperal sepsis 160 years on: an historical review', by T. D. Noakes, J. Borresen, T. Hew-Butler, M. I. Lambert and E. Jordann, *Epidemiology and infection*, 2008 Jan, 136(1): 1-9., p. 319b.
Center for Disease Control and Prevention: pp. 317b, 333b, 341, 343b, 343t, 380b, 381b, 389, 397b, 415, 436.
Department of Health New South Wales: © Commonwealth of Australia. Adapted from "Diphtheria in Australia, recent trends and future prevention strategies" by H. Gidding et. al., *Communicable Diseases Intelligence*, 24(6), 2000, p. 394r. The time line of all locations visited by latest infected case of measles in Western Sydney © State of New South Wales NSW Ministry of Health. For current information go to www.health.nsw.gov.au., p. 414. Licenced under CC BY 4.0, p. 414.
Dreamstime: Caan2gobelow, p. 190tr.
Elsevier: Based on WK Liew et al. J Allergy Clin Immunol 2009, p. 396.
'Effect of hand sanitizer use on elementary school absenteeism,' by Brian Hammond, Yusuf Ali, Eleanor Fendler, Michael Dolan, Sandra Donovan. *American Journal of Infection Control*, Vol 28/Issue 5, pp. 340-346, © 2000. Reprinted with permission from Elsevier, p. 427b.
Environmental Health Perspectives: Reproduced with permission from Environmental Health Perspectives, pp. 294.
European Centre for Disease Prevention and Control: Graph showing mumps notification from 'Mumps in Ireland, 2004-2008' by S. Gee, D. O'Flanagan,

M. Fitzgerald, S. Cotter, *Eurosurveillance*, 13(18), 2008, licenced under a CC BY 4.0, p. 342. Column graph of human influenza A (H5N1) by age and outcome from 'Age-specifc infection and death rates for human A(H5N1) avian influenca in Egypt', by J P Dudley, *Eurosurveillance*, 14(18), 2009, released under a CC BY 4.0 licence, p. 332. Data collected by the WHO of H5N1 (Bird Flu) infection in wild and domestic birds and humans from 'The influenza A(H5N1) epidemic at six and a half years: 500 notified human cases and more to come' by A. Tarantola, P. Barboza, V. Gauthier, S. Loos, N. El Omeiri, M. Gastellu-Etchegorry, *Eurosurveillance*, 15(29), 2010. Released under a CC BY 4.0 License, pp. 94c, 342.
Sam Fesuk: p. 229br.
Fotolia: borisoff, p. 121tl; stockshoppe, p. 152; szymanskim, p. 449r; Vovan, p. 85t; san724, p. 91tr; evgenia sh, p. 97b; Heinz Walkudat, p. e25tl; Christian Pedant, p. e59tl; KAR, p. e60.
Fresh and Clean/Alsco PL: Courtesy of Freash & Clean, p. 431.
Getty Images: A. Martin UW Photography, p. 168tl; Michael Abbey, p. 258bl; Andrew Lambert Photography, p. e62c; Charles V. Angelo, pp. 127tl, 146r; Bettmann, p. 320b; Biology Media, p. 209cr; Biophoto Associates, pp 57, 171, 189b, 326tl; Dr. Jeremy Burgess p. 93t; Leonello Calvetti, p. 196b; CNRI, p. 99b; Martin Cohen, p. 262bl; Dr. John D. Cunningham, p. 12l; Wally Eberhart, p. 76bc; Jason Edwards, p. 262tl; Encyclopaedia Britannica, pp. 25b, 25br; Dr. Stanley Flegler/Visuals Unlimited, p. 67tl; Juan Gaertner, p. 360t; Steve Gschmeissner, pp. 120cr, 354cl; Neil Harding, p. 138b; Mint Frans Lanting, p. 262cl, Cathlyn Melioan, p. 248cr; Nancy Nehring, pp. 209b, 209cl, 209tl, 209tr; Michael Peuckert, p. 129t; Photo researchers, p. 381t; Pixologicstudio, p. 154t; QAI Publishing, p. 158t; Ed Reschke, pp. 131, 136c, 155c, 258br; J. C. Revy, ISM, p. 210c; Science Artwork/Science Photo Library, p. 405tr; Science Source, pp. 57bl, 228b; Sciepro, p. 206; Victor Shupletsov, p. 197b; Brian J. Skerry, p. 168bl; Jason Todd, p. 190c; Javier Torrent/VWPics, pp. 131bl, 131br; Universal Images Group, p. 74cr; Dr. Gladden Willis, p. 354cl;
Dr. David Jolly: p. 310bl.
Michele Kohout: p. 309.
Dr. Adam Laerd: Laerd Statistics, p. e36.
Malaria Atlas Project: Released under a CC BY 3.0 agreement., p. 322.
McGraw-Hill Australia Pty Ltd: © McGraw-Hill Education, Australia, p. 366b.
Medical Images.com : Yoav Levy, p. 156b.
National Geographic Society: Michael Nichols, pp. 146l, 190b.
National Heart, Lung, and Blood Institute, National Institutes of Health: p. 286b.
National Oceanic & Atmospheric Administration: Kyle Carothers, p. 114bl.
National Health and Medical Research Council: Based on material provided by NHMC. Licensed under a CC BY 4.0, p. 431.
North American Veterinary Community: p. 331.
Oxford Designers & Illustrators Ltd:. pp. 30c, 204b, 285, 312c, 366c;
PASCO Scientific: pp. e61bl, e61br, e61btl, e61btr, e68cb.
Pearson Education, Inc: Figure from *Human anatomy & physiology*, 9th ed., by E. Marieb, K. Hoen, fig 21.15 © 2013. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., New York, NY., pp. 233t, 362. Figure from *Biological Science*, 3rd ed. by S. Freeman, fig. 37.20, © 2008. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., New York, New York, p. 197t.
Public Library of Science: p. e93; Graph of population, age groups and whooping cough from 'Seroprevalence of Antibodies to Pertussis Toxin among Different Age Groups in Thailand after 37 Years of Universal Whole-Cell Pertussis Vaccination' by N. Wanlapakorn, V. Ngaovithunvong, T. Thongmee, P. Vichaiwattana, S. Vongpunsawad, Y. Poovorawan, *PLoS ONE*, 11(2)., p. 379; Analysis of participants in the study including demographics, socio-economic status, ethnicity and education from 'Hand Sanitiser Provision for Reducing Illness Absences in Primary School Children: A Cluster Randomised Trial' by P. Priest, J. McKenzie, R. Audas, M. Poore, C. Brunton and L. Reeves, *PLOS Medicine*, 11(8), 2014. Licenced under a CC BY 3.0, pp. 428, 429.
Science Photo Library SPL: pp. e24, e72, 85br, 101t, 103b, 230t, 311bl, 325c, 400, 404b, 426b; AMI Images, pp. 23br, 301br, 347; Sally Bensusen, p. 169b; R. Bick, B. Poindextre, UT Medical School, p. 9c; Dr. Jack Bostrack, p. 23c; Robert Brook, p. 407br; BSIP, Beranger, p. 372t; BSIP, VEM, p. 140bl; Dr. Jeremy Burgess, pp. 16b, 18t, 67bl, 194; Callista Images/Cultura, p. 325br; Leonello Calvetti, p. 242tr; Jose Calvo, p. 8bc; Carolina Biological Supply Co/Visuals Unlimited, Inc., p. 147; David Cavagnaro, p. 199lt; Centre for Infections/Public Health England, p. 120tl; Martyn F. Chillmaid, pp. e25br, e26r, 173t; Mark Clarke, p. 405tl; Clouds Hill Imaging Ltd, p. 310br; CNRI, pp. 184b, 210b; Herve Conge/ISM, pp. 147lb, 204c; Ashley Cooper, p. 71c; Dennis Kunkell Microscopy, pp. 3, 23bl, 135br, 303tr; Reinhard Dirscherl, p. 229c; Martin Dohrn, pp. 266, 435; Doncaster and Bassetlaw Hospitals, p. 373t; Edelmann, p. 11c; Wim Van Egmond, pp. 23bc, 87, 174br, 120bl; Emilio Segre Visual Archives/American Institute of Physics, p. 81bl; Eye of Science, pp. 271t, 25c, 55bc, 103tr, 129b, 140tl, 162t, 196t, 24l, 286t; Mauro Fermariello, p. 290bl; Simon Fraser, p. 403bl; Thomas Fredberg, p. 261tl; Dr. David Furness p. 49; Dr. Gary Gaugler, p. 301cr; Pascal Goetgheluck, p. 54c; Steve Gschmeissner, pp. 8br, 65, 125, 135cr, 141bl, 180, 189t, 267b, 304t, 349b, 353t, 354cr, 357c, 471c; Eric Grave, p. 157c; Eddy Gray, p. 55br; Klaus Guldbrandsen, p. 141bc; Roger Harris, p. 345; P. Hawtin/University of South Hampton, p. 300; Chris Hellier, p. 270c; Louise Hughes pp. 11b, 55tl, 167br; ISM, pp. 98b, 124br; Jacopin, p. 267t; Mikkel Juul Jensen, p. 17; Manfred Kage, pp. 135bl, 146ct; Kallista Images/Custom Medical Stock Photo, p. 77bl; Nancy Kedersha, p. 354br; Russell Kightley, pp. 6c, 6l, 6r, 54t, 57cr, 69-70, 224, 416r; James King-Holmes, p. 324b; Ton Koene/Visuals Unlimited, Inc, p. 403tr; Dennis Kunkel Microscopy, pp. e16t, 27l, 27r, 420br; Laguna Design, pp. 72c, 79c; Francis Leroy, p. 127br; Dr. Kari Lounatmaa, pp. 25b, 53b, 109r; Claus Lunau, p. 147br ?; Dr. P. Marazzi, p. 405bl, 405br; Medi-Mation, p. 252t; Astrid & Hanns-Frieder Michler, p. 137b; Professors P. Motta/T. Naguro, pp. 50t, 51b, 51c, 52b, 53c; Dr. Gopal Murti, pp 57lb;, 57br; National Cancer Institute, p. 157c; Niaid/National Institutes of Health, p. 353b; Susumu Nishinaga, p. 231tl; NSIL/Dick Roberts, Visuals Unlimited, p. 77tr; Claude Nuridsany & Marie Perennou, p. 169t; Matthew Oldfield, p. 143tr; Overseas/Collection CNRI, p. 177r; Alfred Pasieka, pp. 32t, 210tl; Gerard Peaucellier/ISM, pp. 148tc, 148tl, 148tr; Jose Antonio Penas, p. 406b; Power and Syred, pp. 27c, 76bl, 270t; Ramon Andrade 3DCiencia, p. 249c; Antonia Reeve, p. 141tr; Marilyn Schaller, p. 10c; Dr. Lothar Schermelleh, p. 19tr; Stephanie Schuller, p. 303tl; Science Stock Photography, p. e26bl; Sci-Comm Studios, pp. 21l, 21r; Scientificanimations.com, p. 433b; Daniel Schroen/Cell Applications Inc., p. 20r; Alexander Semenov, p. 127bl; Seymour, p. 9br; John Sibbick, p. 122bl; Harvinder Singh, p. 249tl; Marty Snyderman, p. 86cl; Sputnik, p. 438; Sinclair Stammers, p. 122br; Tek Image, p. 141br; Dr. Alvin Telser, p. 354cr; Sherman Thomson, p. 86bl; UCL, Grant Museum of Zoology, p. 176c; US Department of Agriculture, p. 434r; Van Egmond, Visuals Unlimited, p. 146cb; Bo Veisland, p. 420bl; Richard Wehr, p. 76t; Carol & Mike Werner, p. 22b; Dirk Wiersma, p. 273t; Dr. Keith Wheeler, pp. 54b, 190tl; Dr. Torsten Wittmann, pp. 8bl, 55tr; Andrzej Wojcicki, pp. 1-2; David Wrobel, Visuals Unlimited, p. 174c.
Science Source: Igor Siwanowicz, p. 10t.
Shutterstock: pp. 261c, 271br; Stanislav Akimkin, p. e69ct; Alila Medical Media, pp. 184t, 300b, 357tl; AlexeyVeselykh, p. 407bl; Andrey862, p. 128t; Leonid Andronov, p. 79b; anyaivanova, p. 9bl; Robin Atzeni, p. e59cr; Bignai, p. 426tc; BioMedical, p. 284; Bonchan, p. e68tl; Greg Brave, p. 89c; Breaking The Walls, p. e68ct; Bro Studio, pp. e101cl, e101cr, e102r, e106c, e106l, e106r; Jan Bruder, p. 144; Rob Byron, p. e63t; Jose Luis Calvo, p. 153t; CCat82, p. 274; Barnaby Chambers, p. 430b; danylyukk1, p. 174bl; Designua, pp. 89b, 231tr, 249br, 251, 367b; Nikolay Dimitrov, p. 167tr; Divgradcurl, p. e69tl; Sergei Drozd, p. e1; Margoe Edwards, p. 426tl; ellepigrafica, p. 359br; EpicStockMedia, p. 124bl; eveleen, p. 363t; extender_01, p. 238; T. Fabian, p. e59tr; Susan Flashman, p. 182b, 261c; Bill Frische, p. 271t; Juan Gaertner, p. 363b; Gentoo Multimedia Limited, p. 260l; Pawel Graczyk, p. 218tl; HamsterMan, p. e69bl; Jubal Harshaw, p. 192t; Fon Hodes, p. 95c; Stephen van Horn, p. 93c; Alena Hovorkova, p. 186t; Eric Isselee, p. 281l; Natalie Jean, p. 94br; Juliet Photography, p. e25bl; Sebastian Kaulitzki, pp. 105, 380t; Kateryna Kon, pp. 305bl, 305br, 346b, 398-399; Miro Kovacevic, p. 147r; KPG_Jsco, p. e26br; Anya Ku, p. 452t; Dr. Kucharski K. Kucharska, p. 317t; Iamnee, pp. e34, e68bl; Lebendkulturen.de, p. 16c; Rainer Lesniewski, p. e63; Bobo Ling, p. e59cl; Paul Looyen, p. 262cl; Lukasz Pawel Szczepanski, p. e69br; Meletios, p. 240; Michael Felix Photography, p. 24r; mihalec, p. 248cr; Monkey Business Images, pp. 403br, 403c; ngaga, p. 216b; Dmitry Naumov,

Disclaimer
Some of the images used in *Pearson Biology 11 Queensland* might have associations with deceased Indigenous Australians. Please be aware that these images might cause sadness or distress in Aboriginal or Torres Strait Islander communities.