

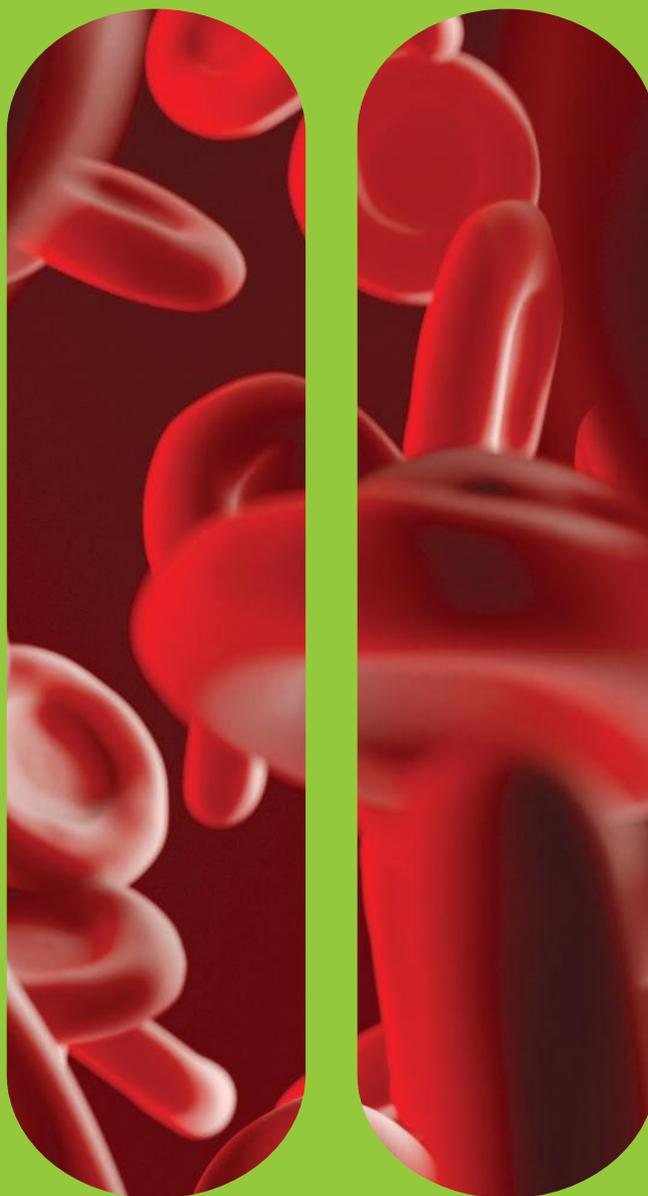
NELSON

QCE Biology

UNITS

1

2



Wendy Cook
Louise Munro





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NELSON

QCE Biology

UNITS

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LEARNING DISCOVERY RED BLOOD CELLS



In the symphony of cells that sustain our lives, red blood cells supply much needed oxygen to tissues and organs to support our function and survival.

Wendy Cook
Louise Munro

Nelson QCE Biology Units 1 & 2

1st Edition

Wendy Cook

Louise Munro

Product manager: Katherine Roan

Content developer: Dr Trisha Downing

Editor: Catherine Greenwood

Proofreader: Kelly Robinson

Series designer: Danielle Maccarone

Series cover design: Regine Abos (Studio Regina)

Series text design: Rina Gargano (Alba Design)

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Permissions researcher: Lumina Datamatics

Content manager: Alice Kane

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CONTENTS

Author and reviewer team	v
About this book	vi

DIGITAL CHAPTER

DC	SCIENCE RESEARCH	
	DC.1 Student experiment	DC-5
	DC.2 Research investigation	DC-33

Chapter summary	DC-37
Chapter exam	DC-43
Answers	DC-48

UNIT ONE CELLS AND MULTICELLULAR ORGANISMS 2

TOPIC 1: CELLS AS THE BASIS OF LIFE

1	CELLS AND CELL SPECIALISATION	4
	1.1 Prokaryotic cells	6
	1.2 Eukaryotic cells	7
	1.3 Comparing prokaryotic and eukaryotic cells	15
	1.4 Using a microscope	18
	1.5 Properties of stem cells	24
	1.6 Cell cycle and differentiation	27
	1.7 Specialised cells	30
Chapter summary	33	
Chapter exam	35	

2	CELL MEMBRANE	38
	2.1 Structure of the cell membrane	40
	2.2 Passive movement	43
	2.3 Active transport	48
	2.4 Surface area-to-volume ratio	53
	Chapter summary	59
Chapter exam	61	

SCIENCE AS A HUMAN ENDEAVOUR: STEM CELL RESEARCH	64
---	-----------

TOPIC 2: EXCHANGE OF NUTRIENTS AND WASTES

3	SYSTEM SPECIALISATION	66
	3.1 Hierarchy	68
	3.2 Circulatory system	70
	3.3 Respiratory system	72
	3.4 Digestive system	75
	3.5 Excretory system	76

Chapter review	81
Chapter exam	83

4	BIOMOLECULES AND ENZYMES	86
	4.1 Biomolecules	88
	4.2 Chemical digestion	94
	4.3 Enzymes	95
	4.4 Factors affecting enzyme function	98
	Chapter summary	105
Chapter exam	107	

SCIENCE AS A HUMAN ENDEAVOUR: KIDNEY DISEASE	110
---	------------

TOPIC 3: CELLULAR ENERGY, GAS EXCHANGE AND PLANT PHYSIOLOGY

5	CELLULAR ENERGY	112
	5.1 Metabolism	114
	5.2 Cellular respiration	117
	Chapter summary	122
Chapter exam	124	

6	PLANT PHYSIOLOGY	126
	6.1 Photosynthesis	128
	6.2 Gas exchange in the leaf	132
	6.3 Plant transport systems	136
	6.4 Transpiration	139
	Chapter summary	144
Chapter Exam	147	

SCIENCE AS A HUMAN ENDEAVOUR: SOLAR POWER FROM PLANTS	149
--	------------

UNIT TWO MAINTAINING THE INTERNAL ENVIRONMENT 150

TOPIC 1: HOMEOSTASIS – THERMOREGULATION AND OSMOREGULATION

7	NERVOUS SYSTEM	152
	7.1 Sensory receptors	154
	7.2 Cells that transport nerve impulses	156
	7.3 Different types of neurons	159
	7.4 Passage of a nerve impulse	162
	Chapter summary	167
	Chapter exam	169
8	ENDOCRINE SYSTEM	174
	8.1 Hormones as chemical messengers	176
	8.2 Receptor binding	179
	Chapter summary	182
	Chapter exam	184
9	HOMEOSTATIC REGULATION – SYSTEMS WORKING TOGETHER	188
	9.1 Stimulus–response model	190
	9.2 Feedback–control diagrams	194
	9.3 Thermoregulation	195
	9.4 Osmoregulation	202
	Chapter summary	205
	Chapter exam	207

SCIENCE AS A HUMAN ENDEAVOUR: WEARABLE CARBON NANOTUBES	210
--	------------

TOPIC 2: INFECTIOUS DISEASE AND EPIDEMIOLOGY

10	INFECTIOUS DISEASE	212
	10.1 What is disease?	214
	10.2 Pathogens	215
	10.3 Pathogenesis	223

Chapter summary	229
Chapter exam	230

11	IMMUNITY	234
	11.1 Stimulating an immune response	236
	11.2 Innate immune response in vertebrates	238
	11.3 Inflammatory response	241
	11.4 Adaptive immune response in vertebrates	245
	11.5 Active versus passive immunity	249
	11.6 Innate immune responses in plants	252
	Chapter summary	255
	Chapter exam	258
12	TRANSMISSION AND SPREAD OF DISEASE	264
	12.1 Modes of disease transmission	267
	12.2 Factors affecting the spread of disease	271
	12.3 Strategies to control the spread of disease	275
	12.4 Analysing disease data	276
	12.5 Interpreting long-term immune response data	281
	Chapter summary	286
	Chapter exam	288

SCIENCE AS A HUMAN ENDEAVOUR: FIRST NATIONS AUSTRALIANS TRADITIONAL MEDICINE	294
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Answers	298
Glossary	322
Index	332

AUTHOR AND REVIEWER TEAM

Nelson QCE Biology is adapted from *Nelson QScience Biology Units 1 & 2* and *Nelson QScience Biology Units 3 & 4*, by Pam Borger, Jane Wright, Kelli Grant, Louise Munro.

WENDY COOK

Wendy Cook has been teaching in Science for 24 years. She is currently the Head of Science at an independent school on the Sunshine Coast, where she has a focus on developing skills and scientific thinking in students. Wendy has taught in both the UK and Australia, including A Level, OP and ATAR Biology. She has written curriculum programs and internal assessment items.

LOUISE MUNRO

Louise is a highly experienced teacher of Senior Biology and Chemistry. Her areas of expertise include molecular biology and biochemistry.

REVIEWERS

The following people have contributed to the review of the Nelson QCE Biology series (in no particular order): Dr Amanda Strachan, Lucy Cardus, Debra Smith and Joe Sambono.

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SYLLABUS
DOT POINTS**SCIENCE INQUIRY SKILLS**

Throughout the course of the study, students will:

- identify, research and construct questions for investigation
- propose hypotheses and/or predict possible outcomes
- design investigations, including the procedure/s to be followed, the materials required, and the type and amount of primary and/or secondary data required to obtain valid and reliable evidence, e.g.
 - distinguish between different types of investigations: descriptive, comparative, correlational, experimental, case studies
 - consider replicates, sample size, number of data points and quality of sources
 - identify the types of errors, extraneous variables or confounding factors that are likely to influence results and implement strategies to minimise systematic and random error
- Identify and implement strategies to manage risks, ethics and environmental impact, e.g.
 - ethical guidelines
 - cultural guidelines, protocols for working with the knowledges of First Nations peoples

- material safety data sheets
- workplace health and safety guidelines
- appropriate disposal methods
- standard operating procedures
- acknowledgement of sources and referencing
- use appropriate equipment, techniques, procedures, and sources to systematically and safely collect primary and secondary data, e.g.
 - microscopy techniques: total magnification and field of view, scientific drawing
 - laboratory and field techniques: measurement, equipment calibration, species identification
 - sampling methods: random, systematic, stratified
 - sampling techniques: quadrats, line transect, belt-transect, capture-recapture
 - models and simulations
 - ICTs, scientific texts, databases, online sources
- use scientific language and representations to systematically record information, observations, data and measurement error, e.g.
 - symbols, units and prefixes
 - scale and magnification
 - indicators of measurement uncertainty
 - tables, graphs and diagrams
 - charts and maps
 - logbooks
- translate information between graphical, numerical, and/or algebraic forms, e.g.
 - units and measurement conversions
 - ratios and percentages
 - symbols and notation
 - charts and maps
- use mathematical techniques to summarise data in a way that allows for identification of relevant trends, patterns, relationships, limitations and uncertainty, e.g.
 - comparative investigations: mean, standard deviation, standard error, Student's t-test
 - correlational investigations: regression analysis, Pearson's correlation coefficient, Spearman's rank
- select and construct appropriate representations to present data and communicate findings, e.g.
 - summary tables
 - column graphs (with error bars)
 - scatterplots (with trendline and R^2)
 - profile diagrams
 - scientific drawings
 - charts and maps
 - indexes and summary statistics



- analyse data to identify trends, patterns and relationships; recognise error, uncertainty and limitations of evidence
- select, synthesise and use evidence to construct scientific arguments and draw conclusions
- extrapolate findings to determine unknown values, predict outcomes and evaluate claims
- use data and reasoning to discuss and evaluate the validity and reliability of evidence, e.g.
 - discuss ways in which measurement error, instrumental uncertainty, the nature of the procedure, sample size or other factors influence uncertainty and limitations in the data
 - evaluate information sources and compare ideas, information and opinions presented within and between texts, considering aspects such as acceptance, bias, status, appropriateness and reasonableness
 - compare findings to theoretical models or expected values
- suggest improvements and extensions to minimise uncertainty, address limitations and improve the overall quality of evidence
- communicate to specific audiences and for specific purposes using appropriate language, nomenclature, genres and modes
- acknowledge sources of information and use standard scientific referencing conventions
- appreciate the role of peer review in scientific research.

Biology 2025 v1.1 General Senior Syllabus © QCAA 2024

Introduction

Conducting structured experiments is an important part of science because it allows for the gathering of information to help develop a greater appreciation and understanding of the world.

Researching topics and the process of developing and implementing experimental methods form a large part of the scientific studies throughout this course. In fact, the Student Experiment (IA2) and Research Investigation (IA3) make up a significant portion of the internal assessments, incorporating both primary and secondary data. Furthermore, the scientific thinking acquired through these processes is regularly examined in the external assessment. As such, it is important to develop these skills not just for this course, but also to improve critical thinking.

ASSUMED KNOWLEDGE

- ✓ The purpose of experiments is to collect information about a key idea or to answer a question.
- ✓ Controlled experiments have a general structure.
- ✓ Variables are factors or conditions that can be changed, controlled or measured and which can influence the result of an investigation.
- ✓ The data collected from an experiment needs to be related to the question being investigated.
- ✓ Data collected from an experiment can be presented in different ways depending on the nature of the data.
- ✓ Data can be classified as primary or secondary.

LEARNING OUTCOMES

- ✓ Develop research questions for research.
- ✓ Identify the importance of peer review in scientific research and compare different ideas and information from scientific texts.
- ✓ Plan and modify investigations, including the materials and methods needed to collect valid and reliable data (both primary and secondary data).
- ✓ Consider safety, ethics and the environment when conducting scientific investigations.
- ✓ Determine the best method to present data; for example, tables and graphs.
- ✓ Use scientific language and visual representations to organise and present information accurately.
- ✓ Identify and minimise errors in measurements.
- ✓ Calculate uncertainties and other measures of data accuracy and describe their impact on data.
- ✓ Select and construct the most appropriate data presentation technique.
- ✓ Make predictions based on trends observed in the data.
- ✓ Use mathematical techniques to analyse data to find patterns, trends and relationships, taking into account any limitations or sources of error or uncertainty.
- ✓ Draw conclusions based on evidence, comparing findings to expected results.
- ✓ Communicate scientific information in a clear and appropriate manner for different audiences, while acknowledging sources and using proper referencing.
- ✓ Reflect on investigations and suggest ways to improve the quality and accuracy of data and findings.

DC.1 Student experiment

Forming

The research question

For your Student Experiment (IA2), you will be required to design an experiment to answer a **research question** related to a topic in the syllabus. In science, the design of experiments is guided by the scientific method (**Figure DC.1.1**) – a systematic and structured approach that ensures that the results are objective, accurate and reliable.

A research question is the question you are trying to answer with your research, and by doing so it helps to guide and refine the research and experimental method. For example, a research question could be ‘How does a fever of more than 38°C affect the function of enzymes

research question a question that directs the scientific inquiry activity; it focuses the research investigation or experiment, informing the direction of the research, and guiding all stages of inquiry, analysis, interpretation and evaluation

in the body?’ Remember to make the research question both specific and relevant. Including units for the independent and dependent variables will help with this.

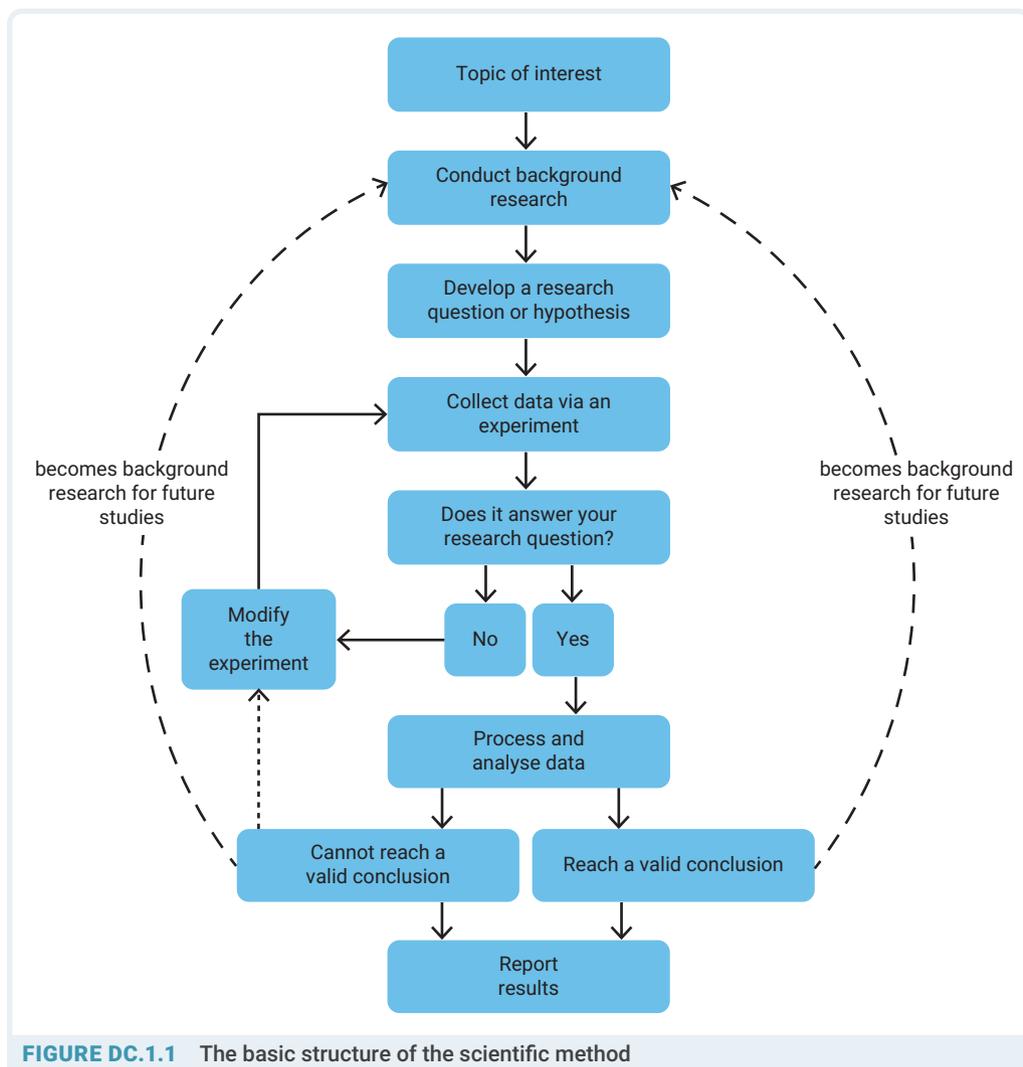


FIGURE DC.1.1 The basic structure of the scientific method

Rationale

When developing a research question, it is important to demonstrate an understanding of the underlying theory related to the topic. This is described in the rationale of your experiment and is also implied through your research question. In the example above, the research question explores the relationship between enzymes and temperature. Given that it is known that the function of enzymes can be affected by changes in temperature, exploring the impact of an increase in temperature (because of a fever) expands our understanding of enzymes.

With an understanding of the topic, it is likely that you have developed a possible answer to the research question. As you know, this is the hypothesis. The hypothesis highlights the relationship between the **independent** and **dependent variables**, showing the directional impact that one would have on the other. A possible hypothesis to the example above is ‘As the temperature of the fever increases, enzyme function would be reduced’. In this case, the independent variable is the change in temperature and the dependent variable is the level of enzyme function, which can be measured by the amount of product produced over time.

independent variable the variable that is changed or manipulated in an experiment

dependent variable the variable that changes because of changes to the independent variable

Methodology

For your experiment, you will need to modify an existing method from previous studies. During your research, you may have encountered various studies conducted by scientists who were interested in investigating a similar topic. These studies can serve as a valuable foundation for you to build on and refine your own approach. How and what you modify in the experiment will depend on:

- the variables you are testing
- sources of error and bias in the previous method
- the type of data being collected (**quantitative** or **qualitative**)
- how much data you will need to collect to ensure that there is sufficient data for analysis
- access to resources.

In Biology, scientists often use different types of investigations. These can be categorised into five main types:

- descriptive
- comparative
- correlational
- experimental
- case studies.

Table DC.1.1 summarises the five main types of investigations.

qualitative data
information that is not
numerical in nature

quantitative data
numerical information

TABLE DC.1.1 The five main types of investigation techniques used in Biology

Investigation type	Description	Example
Descriptive	Researchers collect data through surveys, interviews or observations to gain a better understanding of the subject being investigated.	Describing the distribution of a species in an ecosystem
Comparative	Two or more groups or variables are compared to identify similarities and differences between them. Researchers can use this information to investigate the impact of factors on the groups being investigated.	Comparing the growth of different plants under different environmental conditions
Correlational	These investigations focus on identifying the relationship between variables. Data collected in these investigations is used to determine whether changes in one variable are associated with a change in another variable. Note: correlation does not mean causation.	Identifying the relationship between temperature and plant growth
Experimental	Variables are manipulated to determine whether there is a cause-and-effect relationship between the variables.	Testing the effect of a fertiliser on plant growth
Case study	Analysis of a particular individual, group or situation	Studying the behaviour of a particular type of frog in a specific ecosystem

Once you have your base experiment (which could be one that you completed in class), you will be required to make some modifications to design your own student experiment. A modification may be one of three different types (see **Table DC.1.2**).

TABLE DC.1.2 Types of modifications that can be made to methodologies for the Student Experiment (IA2)

Type of modification	Explanation	Instruction	Example
Refine	To improve by making subtle changes to improve the accuracy or precision of the data	<ul style="list-style-type: none"> • Make improvements without changing the independent or dependent variables. 	<ul style="list-style-type: none"> • Use equipment with a higher level of precision. • Improve the methodology or way of measuring the independent variable. • Change the sample size.
Redirect	To gain further insight by changing the course or direction of the data	<ul style="list-style-type: none"> • Change the independent variable. 	<ul style="list-style-type: none"> • Measure pH instead of temperature. • Use a different species. • Use different chemicals.
Extend	To change or extend the scope of the current data range	<ul style="list-style-type: none"> • Change the range of the independent variable. • Extend the range of the independent variable. 	<ul style="list-style-type: none"> • Use more concentrations of solution. • Use more sample categories or data ranges.

Although you will not need to write your entire methodology in your experiment, it is important that you can justify the modifications that you made. For example, if you decided to refine an experiment by using a digital thermometer instead of an analogue alcohol thermometer, you could justify this by saying that your refinement will improve the accuracy of your data collection because the digital thermometer has a smaller uncertainty and removes human error.

Sampling techniques

In a biological experiment, it is often not feasible to collect information about a whole population or ecosystem. So, we need to select a subset or sample from the larger population that can be considered representative of the population. The way we select the sample is known as the sampling technique. The main sampling techniques are summarised in **Table DC.1.3**.

TABLE DC.1.3 A summary of different sampling techniques

Technique	Description	Example
Random sampling	Samples are selected randomly from the population. There is an equal chance of being selected. This helps minimise bias. It is generally used when there are time constraints and/or the samples appear relatively uniform in species composition.	Randomly selecting trees from a forest to study the biodiversity within the forest
Systematic sampling	Samples are selected at fixed intervals in a particular pattern.	Determining the species of fish in a river by collecting data at regular intervals at a point along the river
Stratified sampling	Groups in a population are divided into subgroups based on certain characteristics. Samples are randomly selected from each subgroup as a representative of their population. Samples are taken in proportion to the different strata present, i.e. if it is 30% field and 70% scrub, 30% of the quadrats are placed in the field and 70% in the scrub.	Studying the diversity of bird species across different forest canopy layers

Depending on the nature of the experiment, you need to be familiar with the techniques and measuring instruments involved. Surveying techniques are the methods used to gather

information and/or data for your investigation. **Table DC.1.4** summarises common surveying techniques often used to gather information for biological investigations.

TABLE DC.1.4 A summary of different types of surveying techniques

Surveying technique	Description	Example
Quadrats	Square or rectangular frames used to sample an area. Data is measured from within the frame.	Investigating the abundance of a particular species of weed in an area
Transects	A line is drawn through the area of interest from one point to another. Data is collected along this transect line at specific points or intervals.	Examining the changes in vegetation along a walking path of a mountain or in relation to an environmental gradient

Regardless of the type of sampling and surveying technique, misreading the instruments used to collect the data results in inaccurate results. For example, when reading the volume of a liquid in a measuring cylinder, the measurement must be taken at eye level and measured from the bottom of the meniscus (**Figure DC.1.2**).

When collecting and recording data, ensure that it is measured in the appropriate units. For example, the concentration of solutions can be measured using different units such as g L^{-1} , mol L^{-1} or ppm (parts per million). However, this will depend on the nature of the experiment. Since there are different units to express the same measurement, you will often need to convert between units, especially when analysing results. **Table DC.1.5** shows common unit conversions.

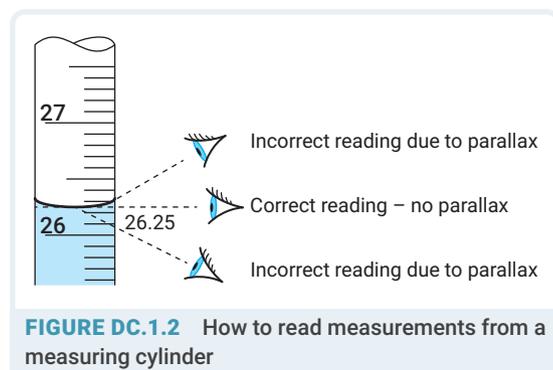


FIGURE DC.1.2 How to read measurements from a measuring cylinder

TABLE DC.1.5 Common unit conversions

Measurement	Common conversions
Distance	1 km = 1000 m = 100 000 cm = 1 000 000 mm
Mass	1 kg = 1000 g = 1 000 000 mg
Volume	1 L = 1000 mL = 1000 cm ³

Essentially, any modifications to the methodology are done to improve the reliability of data and validity of the experiment. Although you will not need to show your full methodology, you will need to explain and justify any modifications and refinements in your final presentation of your experiment (Table DC.1.2).

If the proposed experiment involves exploring knowledges of First Nations peoples, it is extremely important to understand all the cultural guidelines and protocols involved in conducting such research. For example, the *Traditional Knowledge Guidelines – Biodiscovery Act 2004* released by the Queensland Government helps to identify the measures that need to be taken for biodiscovery.



Weblinks
*Traditional Knowledge
 Guidelines – Biodiscovery
 Act 2004*

Guidelines for Ethical
 Research in Australian
 Indigenous Studies

Finding

Health and safety

Health and safety are important considerations for practical exercises in all sciences. When undertaking your own practical research investigations, you must consider any relevant

workplace health and safety guidelines. In Queensland, this includes the *Work Health and Safety Act 2011*. As the researcher, you must ensure safe laboratory practices when planning and conducting investigations by using risk assessments, supported by material safety data sheets (MSDSs), and accounting for risks. MSDSs are important when you are using chemicals as part of your investigation. This includes both the use and the disposal of any potentially harmful materials used and produced in your experiment. Even if your research does not use chemicals but requires participants to take some actions that may cause harm, you will still need to complete a risk assessment form (**Figure DC.1.3**). Your school is likely to have one of these documents for you to complete when you conduct your experiment. If you are unsure of either the ethical, environmental or the health and safety aspects of your experiment, check with your teacher.

Science investigation risk assessment for <i>Nelson Science 10</i>			Nelson MindTap
Chapter 2			
School			
Name of teacher/technician			
Date		Year level/class	
Name of investigation/activity	Modelling natural selection		
Book reference	<i>Nelson Science 10</i> , Chapter 2, Module 2.4, downloadable/PDF science investigation		
Activity type	Demonstration	Student activity	
Description of activity			
Equipment			
Equipment to be used	Potential hazards	Control measures/safe handling procedures	
	Electrical ⚡ Radiation ☢ Thermal Sharps Projectile Glass Gravity – Weights or magnets Other –	Safety glasses Sharps container Thermally insulated gloves Signage Safety shield Other –	
Chemicals			
Chemicals to be used	Potential hazards		Control measures/safe handling procedures
	Explosive ⚠ Flammable ⚠ Oxidising ⚠ Gases under pressure ⚠ Corrosive ⚠	Acute toxicity ⚠ Chronic health hazards ⚠ Health hazards ⚠ Environmental ⚠ Other –	Ventilation Fume cupboard Safety shield Safety glasses Lab coat Gloves Limit concentration/quantity Other –

FIGURE DC.1.3 A section of a risk assessment form

Any risks that you identify need to be highlighted in your experiment, including the steps to mitigate these risks.

1.4 Management of risks

The overall experiment was given a low–medium risk due to several safety hazards. An over-heating power supply may cause melting to outer-plastic and can shut down – affected connected outlets to the supply (Hill 2021). Consequently, the power supply was shut off every 2 minutes and was placed over a heat-resistant mat to eliminate heat-transfer and to allow a risk-free 8 V supply. Furthermore, many power cables were connected to walls, computers and other equipment throughout the procedure, hence a safety hazard for a potential ‘trips and falls’ in the laboratory-safety-procedure section (Safety 2013). Thereby, chairs were placed over all wires – to caution to anyone in near premises. Finally, gloves and sanitisation of equipment were also utilised for COVID-19 regulations to prevent cross-contamination.

FIGURE DC.1.4 An example of the inclusion of risks in an experiment

Apart from highlighting any potential dangers, another way to reduce the risk of injury and improve safety is to clearly outline the procedures in the experiment. This also includes the proper use of any materials involved in the experiment. This can be referred to as the standard operating procedures of an experiment.

Ethics

Ethics is a guiding framework that all research investigations must follow. Ethical concepts provide moral guidance for making decisions about the design and implementation of a research investigation. Examples of ethical concepts are shown in [Table DC.1.6](#).

TABLE DC.1.6 Descriptions of different ethical concepts

Concept	Description
Beneficence	Having a commitment to do good (and minimise risk and harm)
Integrity	Acting with honesty and transparency
Justice	Ensuring fair distribution of benefits, risks, costs and resources
Non-maleficence	Avoiding harm or ensuring that potential harm is outweighed by benefits
Respect	Respecting individual differences and ensuring the right to autonomy and choice

You must apply your ethical understanding throughout your study of science, particularly for your own research.

Analysing data

The **primary data** collected in the experiment should be first organised into a raw data table. When constructing these tables, the independent variable is usually expressed in the first column and the dependent variables from the trials in the experiment are placed in the subsequent columns. For example, when measuring the time taken for a current to pass through a solution of different concentrations, the different concentrations (the independent variable) are presented in the first column, and the time measurements (dependent variable) are presented in subsequent columns ([Table DC.1.7](#)). It is often suggested that you record everything in your **logbook**; however, this is not a mandatory component of your investigation.

primary data data collected directly by a person or group

logbook a complete, permanent record of how an experiment or research project was conducted; it shows what was done at every step along the way

TABLE DC.1.7 An example of a table of raw data from an experiment

Concentration (mol L ⁻¹)	Time (± 0.5 s)		
	Trial 1	Trial 2	Trial 3
0.2	359.5	368.5	364.5
0.4	360.0	345.5	327.5
0.6	325.5	339.5	333.5
0.8	343.5	307.0	327.5
1.0	307.0	339.5	326.5

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As shown in Table DC.1.7, the units for each measurement are included in the column headings.

Once the data has been collected, the next step is to analyse it. As part of this, we need to make a judgement on the quality of the data in terms of:

- accuracy
- precision
- reliability
- validity
- sources of error.

It is important to note that each senior subject will have different and specific forms of mathematical analysis. What is appropriate for one type of data in one subject may not be appropriate for another. For example, calculated means and uncertainties might be appropriate for a Chemistry or Physics experiment, but mean and standard deviations might be more appropriate for Psychology or Biology experimental data. The following information is a general overview of the types of analysis you could undertake, but it is best to check that the type of analysis you choose is appropriate for your data.

Accuracy and precision

In science, the **accuracy** of a measurement is how close it is to the true value of the quantity being measured. Even when the true value is unknown, scientists can rely on the best available **accepted value** to compare with the experimental measurement result to determine its accuracy. Often the accepted value is the theoretical value calculated for the measurement.

A way to help indicate the accuracy of a measurement is to calculate **percentage error**. Percentage error shows us how close the measured value is to the true or accepted value:

$$\text{Percentage error (\%)} = \left| \frac{\text{measured value} - \text{true value}}{\text{true value}} \right| \times \frac{100}{1}$$

KEY FORMULA

Percentage error

$$\text{Percentage error (\%)} = \left| \frac{\text{measured value} - \text{true value}}{\text{true value}} \right| \times \frac{100}{1}$$

accuracy the degree to which the result of a measurement, calculation or specification conforms to the correct value or a standard

accepted value the value of a substance or quantity that is universally agreed as being a best estimate due to multiple and highly accurate measurements

percentage error the difference between a measured result and an accepted value, expressed as a percentage of the accepted value

WORKED EXAMPLE DC.1.1

A student used a ruler to measure the height of a 100 mL beaker. These beakers are known to have a height of 7.2 cm. The measured value was 6.8 cm.

Calculate the percentage error of the measurement.

ANSWER

1 Determine the measured and true values.

Measured value: 6.8 cm

True value: 7.2 cm

2 Substitute and calculate the percentage error.

$$\begin{aligned}\text{Percentage error} &= \left| \frac{6.8 - 7.2}{7.2} \right| \times 100 \\ &= 5.6\%\end{aligned}$$

This suggests that the measurement is slightly lower than the true value.

A low percentage error indicates a high degree of accuracy, whereas a high percentage error indicates a low degree of accuracy.

In contrast, **precision** describes how close a set of measured values are to each other. For single measurements, precision is about the level of detail given by the measurement usually based on the instrument used to take the measurement. For example, 0.3 g is less precise than 0.312 g. Note that precision can apply to the type of instrument used to take the measurement (instrument precision) or as a measure of reliability of the data collected (data precision).

Measurements that are precise are not necessarily accurate (**Figure DC.1.5**).

precision the closeness of several independent measurements of the same quantity to each other

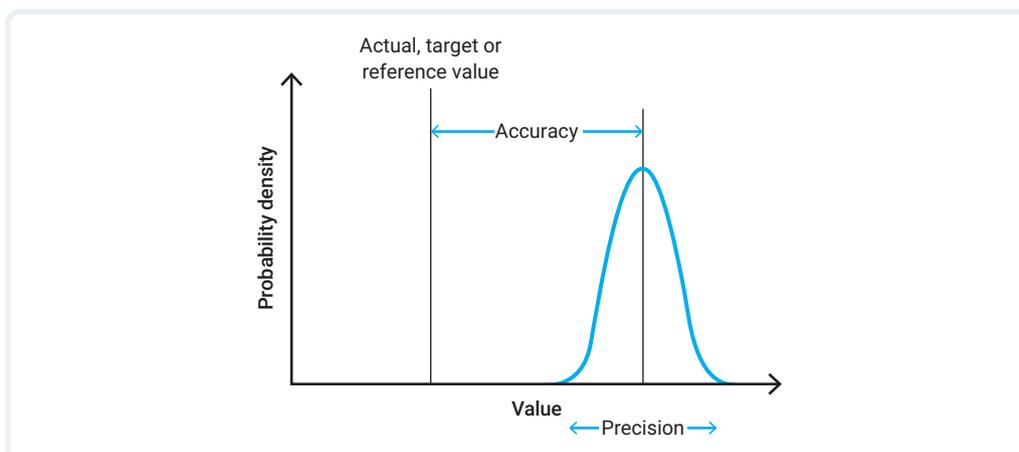


FIGURE DC.1.5 A graph showing the difference between accuracy and precision

Figure DC.1.6 helps further distinguish between accuracy and precision. In parts a and c, the individual indication values cluster closely around the mean; whereas parts b and d show imprecise measurement results as the individual measured values spread significantly around the mean.

For example, for an individual experiencing a fever, having precise measurements of body temperatures of 32.1°C, 33.2°C and 32.0°C does not mean that this is an accurate measure of their body temperature. We know this because humans have a core body temperature of approximately 37.0°C and fevers cause an increase, not a decrease, in body temperature.

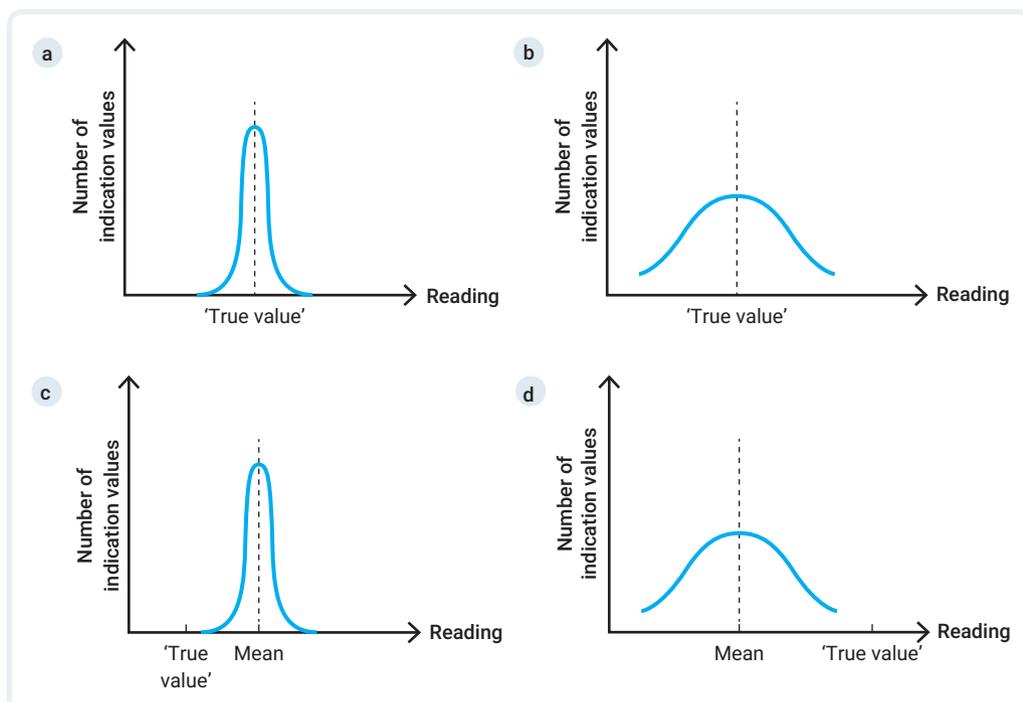


FIGURE DC.1.6 In a plot of measured values versus reading, results can be: (a) accurate and precise, (b) accurate and imprecise, (c) inaccurate and precise or (d) inaccurate and imprecise.

To improve the accuracy of measured values, you could:

- conduct multiple trials and average the results
- ensure that all variables except for the independent variable are controlled (also referred to as fair testing)
- ensure that the measuring tools used in the experiment are appropriate for what is being measured.

This helps to minimise the impact of any errors in the experiment that could affect the accuracy of the measured results. Errors will be discussed in more detail in a later section.

Reliability

If an experiment is repeated, you would expect to obtain very similar results. When this happens, we say that the experimental results are reliable. However, this is not always the case because errors can affect the data collected. **Reliability** can be measured with uncertainty and standard deviation; concepts that will be described in more detail in a later section. The reliability of results can be improved by carefully controlling all variables apart from the independent variable. We will discuss other factors affecting reliability later in this section.

Validity

The quality of the data affects the **validity** of an experiment. We describe data as being valid if the result is due to the independent variable only and can answer the research question. In the example of measuring the effect of temperature on enzyme function, if variabilities in pH in the environment are not properly controlled, they can also affect enzyme function. As a result, we cannot confidently conclude that the results measured from the experiment are due to the changes in temperature only. This type of variable is known as an **extraneous variable** and can affect the relationship between the dependent and independent variables. In this example, pH is a specific type of extraneous variable known as a **confounding variable** because it relates

reliability the extent to which the results of assessments are consistent, replicable and free from error

validity the extent to which the experiment measures what it is intended to measure

extraneous variable any variable that is not directly related to the experiment but could affect the results of the experiment

confounding variable a variable that is related to the independent and dependent variables

to both the independent and dependent variables. This is why it is important to ensure that all variables other than the independent variable are controlled.

Apart from extraneous variables, **errors** can also affect the results of an experiment. The two main types of errors are random and systematic errors.

error the difference between a measured value and the true value

Errors

Random errors are unpredictable variations that can occur during measurement. When taking multiple readings of the same thing, random measurement errors cause small variations so that you end up recording a spread of readings. These errors affect the precision of a measurement and can be caused by limitations of measuring instruments. You can reduce the effect of random errors by taking more or repeated measurements and calculating the **mean** (or average). To calculate the mean, divide the sum of the measured values by the total number of measurements:

random error a variation that affects a measurement in a random way so that successive measured values may show small changes from each other

$$\text{Mean} = \frac{\text{sum of measured values}}{\text{total number of measurements taken}}$$

mean the average value of a set of values

The mean value is then regarded as the most likely or best estimate of the true value. However, we cannot be certain that it is the true value.

While random errors affect the precision of data, **systematic errors** affect the accuracy of a measurement. These errors cause the readings to differ from the true value by a consistent amount in the same direction. This can occur when measuring instruments are not properly calibrated, so readings differ from the true value by the same amount. Systematic errors can also be caused by observational error if there is a consistent distortion in the way we view things that causes errors that are the same every time. For example, a tall person may read a thermometer from a higher viewpoint and record a lower measure than the true value every time. To minimise the impact of systematic errors, it is important to know how to use measuring tools properly and to calibrate them before use.

KEY FORMULA

Mean

$$\text{Mean} = \frac{\text{sum of measured values}}{\text{total number of measurements taken}}$$

Figure DC.1.7 highlights the differences between random and systematic errors.

systematic error a value that is either consistently above or consistently below an expected value; an error that acts in a predictable manner to give a consistent offset in data

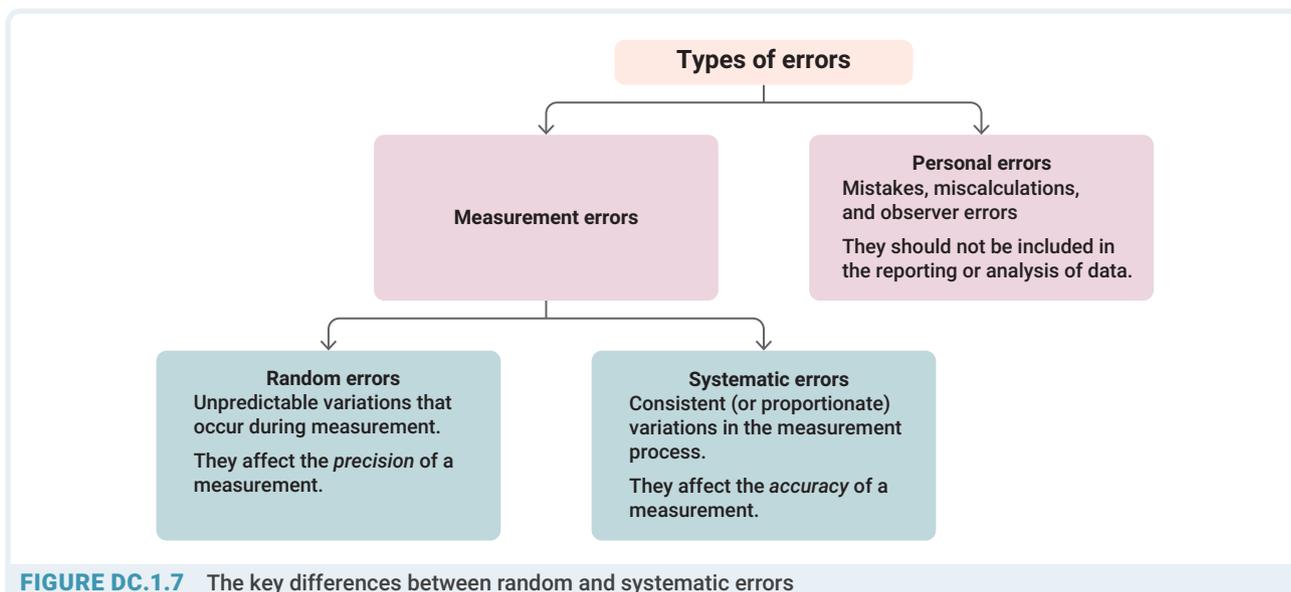


FIGURE DC.1.7 The key differences between random and systematic errors

Uncertainty

uncertainty the 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

instrumental uncertainty the inherent limitations and potential errors associated with the measuring instruments or tools used in scientific experiments or observations

absolute uncertainty the magnitude of the difference between the observed/measured value and the true value

range the difference between the maximum and minimum values of a measured confidence interval

While systematic errors can be accounted for by subtracting or adding the value of the error, random errors contribute to the **uncertainty** of a measurement. This reflects the lack of exact knowledge of the true value of the measurement. All measurements are subject to uncertainty because there are many sources of variation. For example, **instrumental uncertainty** in measuring tools can result in variability and imprecision of results due to factors such as sensitivity, calibration and resolution. To minimise the effect of instrumental uncertainty, it is important to calibrate tools, ensure that the appropriate tools and techniques are used and consider any limitations when designing the experiment. Uncertainty can also occur because of the way the person taking the reading interacts with the tool.

Uncertainties can sometimes be quantified. We can estimate the uncertainty of a measurement, which is usually expressed as \pm a certain value. This is known as **absolute uncertainty**.

Absolute uncertainty of repeated measurements

Most experiments require you to take multiple measurements. As mentioned above, doing so and averaging the results can help to reduce the effect of random errors. Imagine you take multiple measurements of your body temperature. The values are 35.6°C, 36.1°C, 35.9°C and 36.4°C. The difference between the maximum and minimum values is called the **range**. The absolute uncertainty of the mean is calculated as the halfway point between the maximum and minimum values, or half of the range:

$$\begin{aligned}\text{Absolute uncertainty} &= \pm \frac{\text{maximum} - \text{minimum}}{2} \\ &= \pm \frac{36.4 - 35.6}{2} \\ &= \pm 0.4^\circ\text{C}\end{aligned}$$

The measurement result would be the mean of the values:

$$\begin{aligned}\text{Mean} &= \frac{35.6 + 36.1 + 35.9 + 36.4}{4} \\ &= 36.0^\circ\text{C}\end{aligned}$$

The reported value includes both the mean and the absolute uncertainty. In this example, the reported value would be $36.0 \pm 0.4^\circ\text{C}$. In other words, the actual value could lie anywhere between 35.6°C and 36.4°C.

Absolute uncertainty of single measurements/device details

For analogue devices, the uncertainty is normally determined as half of the smallest division on the scale. For example, a glass thermometer with graduations of 1°C has an uncertainty of $\pm 0.5^\circ\text{C}$.

With digital devices, the uncertainty is normally defined as the smallest division because we cannot see in between divisions as we can in an analogue device. For example, a digital thermometer that measures in 1°C has an uncertainty of $\pm 1^\circ\text{C}$. One limitation of this calculation is that it does not indicate the direction of the error; we do not know if we overestimated or underestimated.

KEY FORMULA

Absolute uncertainty

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

Percentage uncertainty

Absolute uncertainty can be used to calculate **percentage uncertainty**. Percentage uncertainty is calculated relative to the measured quantity, and is calculated by:

$$\text{Percentage uncertainty (\%)} = \frac{\text{absolute uncertainty}}{\text{measured value}} \times \frac{100}{1}$$

A low percentage uncertainty indicates a more precise measurement, whereas a high percentage uncertainty indicates a less precise measurement because of greater variability.

Once data has been processed in this way, a table can be presented that also includes these measurements of uncertainty (**Table DC.1.8**)

percentage uncertainty
a measure of the uncertainty of a measurement compared with the size of the measurement, given as a percentage

KEY FORMULA

Percentage uncertainty

$$\text{Percentage uncertainty (\%)} = \frac{\text{absolute uncertainty}}{\text{measured value}} \times \frac{100}{1}$$

TABLE DC.1.8 An example of a summary table showing measurements of uncertainty

Voltaic cell	Cathode metal	Potential difference (± 0.05 V)			Mean potential difference (V)	Absolute uncertainty of mean ($\pm V$)
		Trial 1	Trial 2	Trial 3		
1	B(s)	2.25	2.40	2.20	2.28	0.10
2	C(s)	1.30	1.28	1.37	1.32	0.45
3	D(s)	3.11	3.15	3.04	3.10	0.55

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Standard deviation

Standard deviation (SD) can give information about the spread of data points measured against the mean of the results. Consider using a mercury thermometer to measure the temperature of the same liquid four times. Given that the resolution of the thermometer is 1°C , the absolute uncertainty is $\pm 0.5^\circ\text{C}$. Suppose the measurements are 10°C , 9°C , 11°C and 9°C . The standard deviation will show us how much each individual measurement deviates from the mean of 9.75°C . Calculating the standard deviations of measurements involves a series of steps that can become time consuming if completed manually. Software such as Excel and other graphing tools have functions to calculate the standard deviation of given data.

A small standard deviation indicates that the data points are close to the mean, whereas a large standard deviation indicates that the data points are spread out over a larger range, which suggests a low level of precision.

Standard error

Where standard deviation measures the variability of data in a single sample, **standard error** shows the variability of the sample data compared to true population. In other words, it estimates how much the mean differs from the rest of the sample population. To calculate the standard error of the mean:

$$\text{Standard error} = \frac{\text{SD}}{\sqrt{n}}$$

where: SD = standard deviation

n = sample size.

Standard error can be considered a measure of accuracy.



Weblink

Calculating mean and standard deviation

standard deviation (SD)

a statistical measure that quantifies the variation in a set of data values

standard error

a statistical measure that describes the variability of sample mean data compared to the population mean

KEY FORMULA

Standard error

$$\text{Standard error} = \frac{\text{SD}}{\sqrt{n}}$$

where: SD = standard deviation
 n = sample size

WORKED EXAMPLE DC.1.2

A scientist was investigating the diameter of human red blood cells. They carefully measured 50 samples and the standard deviation is known to be $0.27 \mu\text{m}$. Determine the standard error for this sample.

ANSWER

- 1 Identify the values for each variable.

$$n = 50$$

$$\text{SD} = 0.27 \mu\text{m}$$

- 2 Use the formula to calculate the standard error.

$$\begin{aligned}\text{Standard error} &= \frac{0.27}{\sqrt{50}} \\ &= 0.038 \mu\text{m}\end{aligned}$$

Based on the samples, the average diameter is likely to be within $\pm 0.038 \mu\text{m}$ of the true value.

Graphs

Although tables can be an effective way to collect and record data, it is difficult to visualise any trends or relationships between the independent and dependent variables. Presenting data in graphical form makes it easier to identify if any trends exist between the variables.

Many different types of graphs can be used to represent data; for example, column graphs, pie charts, scatterplots and line graphs. Choosing the right graph depends on the nature of the data collected and what you are trying to show. For graphs that involve an x -axis and a y -axis, the independent variable is represented by the x -axis and the dependent variable is represented by the y -axis (**Figure DC.1.8**).

It is also important to choose an appropriate scale when drawing graphs because it represents the data in a way that can be easily interpreted. It also avoids misleading representations that imply inaccurate relationships between data. All graphs need to have a title that outlines the information being presented.

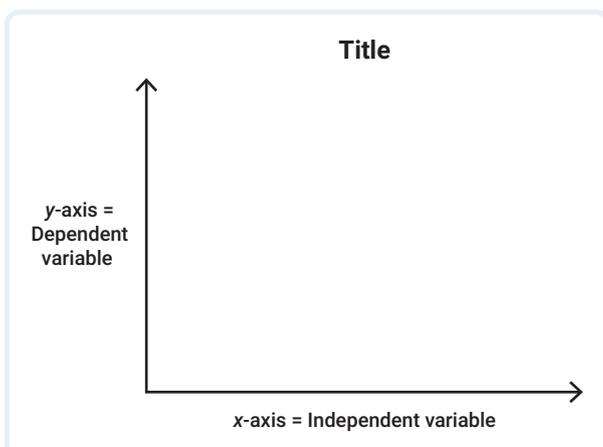


FIGURE DC.1.8 The positive quadrant of cartesian plane showing the variables represented on the x -axis and y -axis

Pie charts

Pie charts are best used to show parts of a whole and the percentage composition of each different category. For example, pie charts can be used to show the composition of a mixture of air – nitrogen, oxygen and other gases – and the percentage of each (Figure DC.1.9).

A limitation with pie charts is that they become visually cluttered when there are many different categories.

Column graphs

Column graphs are useful when comparing quantities or different categories of groups (Figure DC.1.10).

These types of graphs are preferred for comparing categories when order or time is important to show changes over time, or when comparing the differences between groups.

Line graphs

Line graphs are ideal for showing trends over time for continuous data, particularly when comparing multiple series over the same period. In line graphs, each data point is connected to the next and the relationship between the two variables can be represented as the equation:

$$y = mx + c$$

where: m = the gradient

c = the y intercept.

For example, the calibration curve measuring the absorbance of light based on concentration of a solution can be represented by a linear graph as shown in Figure DC.1.11.

If using Excel to draw these graphs, it is sometimes useful to use the x,y scatter plot.

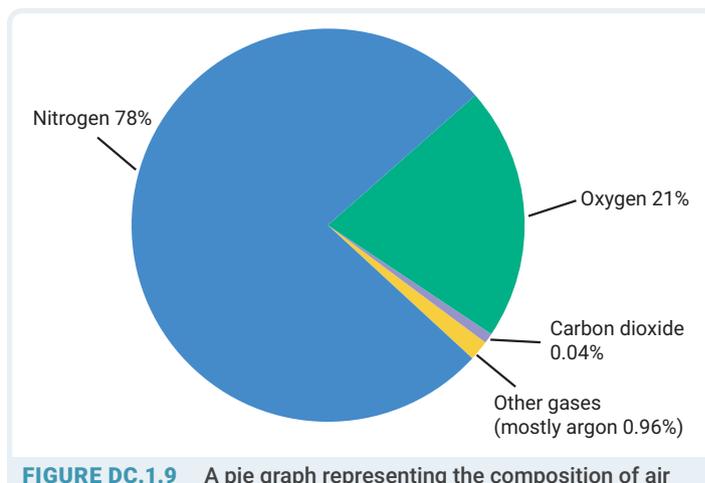


FIGURE DC.1.9 A pie graph representing the composition of air

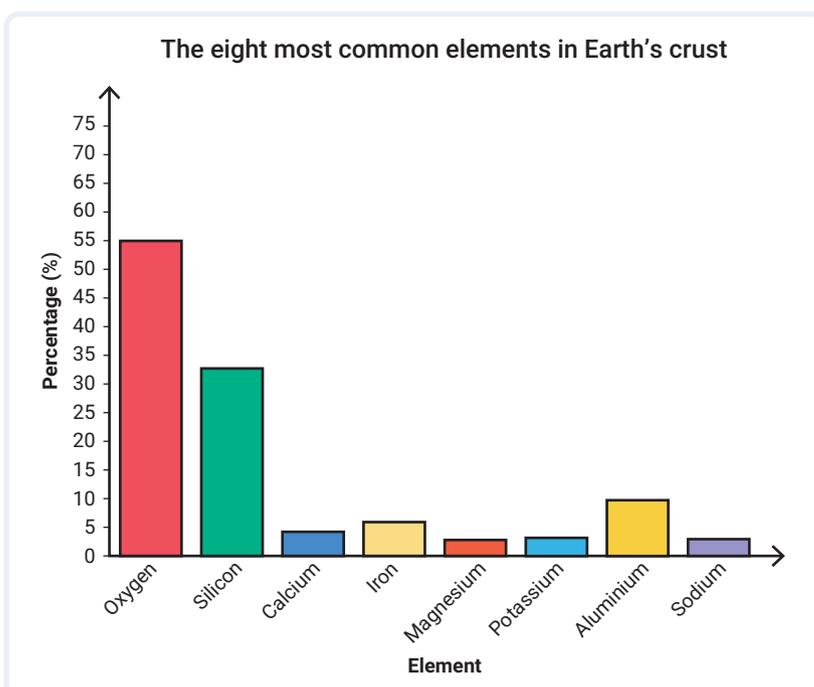


FIGURE DC.1.10 A column graph showing the differences in mineral composition of Earth's crust

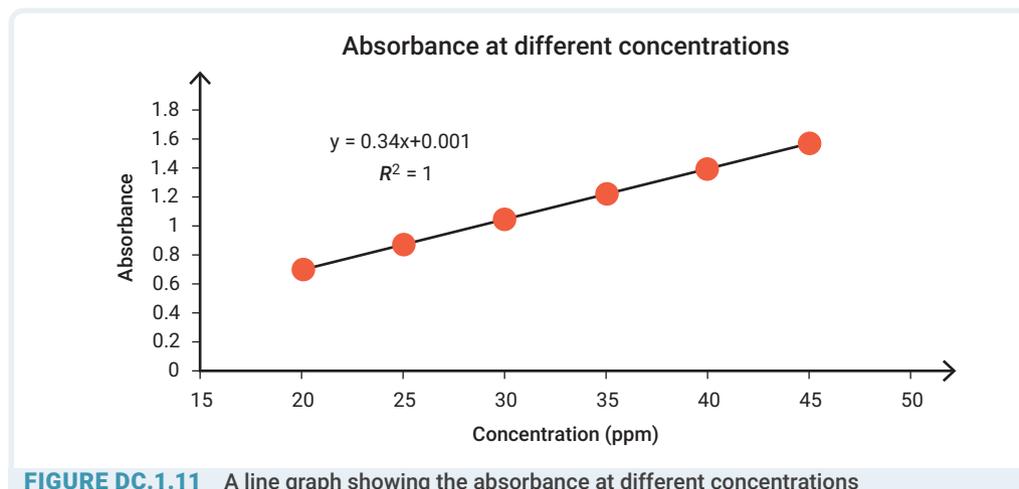


FIGURE DC.1.11 A line graph showing the absorbance at different concentrations

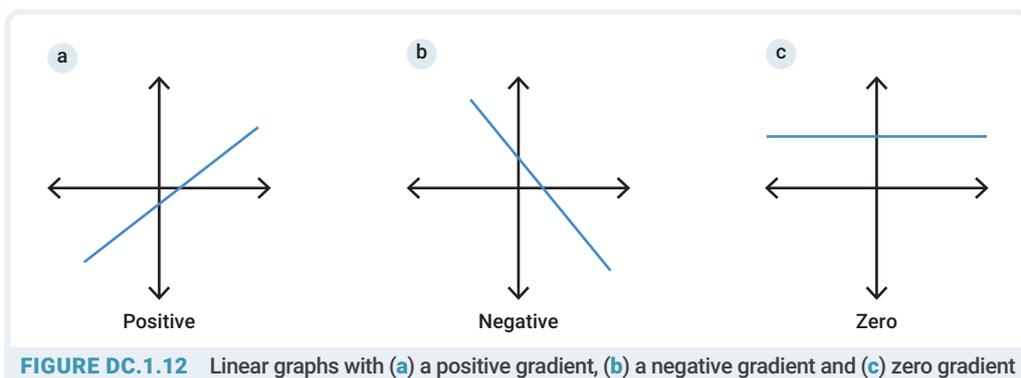
The gradient is a useful piece of information that helps to describe the relationship between the independent and dependent variables. For linear relationships, the gradient of the slope helps to identify the nature of the relationship between the independent and dependent variables. To calculate the gradient of a linear graph, m , where the equation is $y = mx + c$:

$$\text{Gradient } (m) = \frac{\Delta y}{\Delta x}$$

Determining the gradient in this way only requires two data points, where the difference in the y values is divided by the x values of the same two points. Depending on the value of the gradient, a:

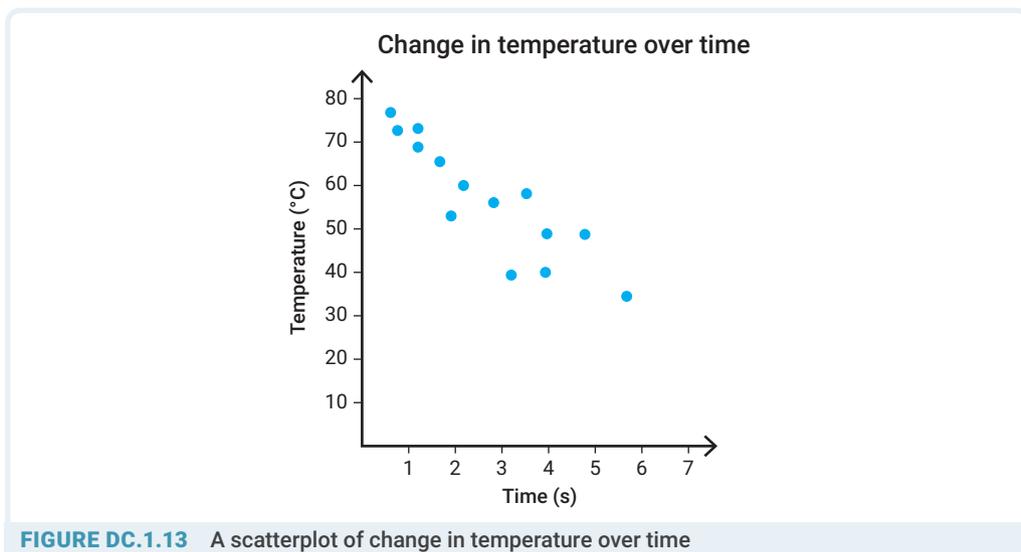
- positive gradient (**Figure DC.1.12a**) indicates that as the x value (independent variable) increases, so does the y value (dependent variable)
- negative gradient (**Figure DC.1.12b**) indicates that as the x value (independent variable) increases, the y value (dependent variable) decreases
- gradient of zero (**Figure DC.1.12c**) indicates that as the x value (independent variable) increases, there is no change in the y value (dependent variable). As such, there is a constant relationship between the two variables.

Analysing the gradient for non-linear relationships is a bit more complicated and requires us to calculate the gradient of different tangents at specific points along the graph and compare the changes.



Scatterplots

Scatterplots are similar to linear graphs in that they show individual data points, highlighting the relationship between the independent and dependent variables. However, unlike line graphs, the data points in scatterplots are not connected (**Figure DC.1.13**)



Although the points are not connected, organisation of the data points relative to each other in these graphs can identify a relationship between the variables. **Trendlines** can be drawn through or near the datapoints to help make the relationship between the independent and dependent variable more visible (**Figure DC.1.14**) while also showing the strength of this relationship.

Although it is possible to draw trendlines manually, it is more accurate to use software. When adding trendlines manually, the line should be drawn so that it minimises the distance between the line and the data points.

If a trend does exist, we can often easily identify whether it is positive (positive correlation) or negative (negative correlation). In a positive trend, the dependent variable increases as the independent variable increases, whereas in a negative trend, the dependent variable decreases as the independent variable increases (**Figure DC.1.15**).

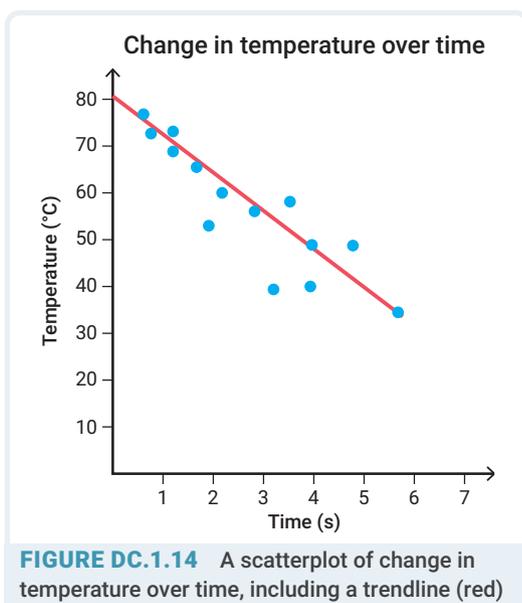


FIGURE DC.1.14 A scatterplot of change in temperature over time, including a trendline (red)

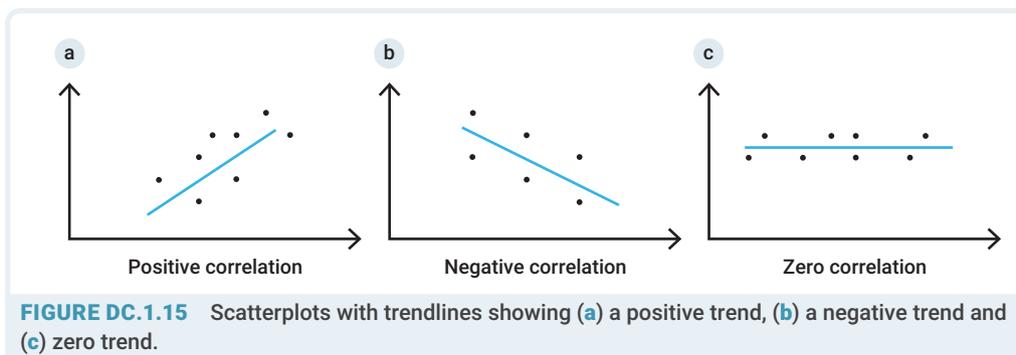


FIGURE DC.1.15 Scatterplots with trendlines showing (a) a positive trend, (b) a negative trend and (c) zero trend.

Maximum and **minimum trendlines** are visual representations of the strength of the relationship between the variables (**Figure DC.1.16**). A wider range between the two suggests a greater variability of uncertainty in the data, whereas a narrow range suggests a lower variability in the measured values.

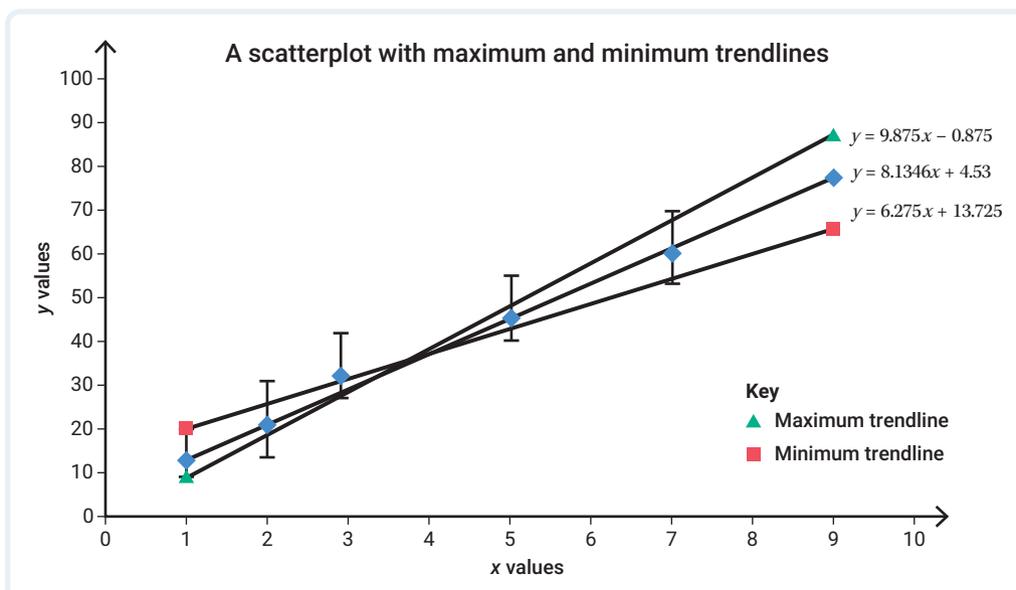


FIGURE DC.1.16 An example of a scatterplot that includes a maximum and minimum trendline

trendline a line that represents the general direction or pattern of data points

maximum trendline a trendline with the greatest gradient that fits within the data within the uncertainty values

minimum trendline a trendline with the smallest gradient that fits within the data within the uncertainty values

Analysing maximum and minimum trendlines together can help us predict the potential range of outcomes. For example, using trendlines to forecast temperature changes as a result of emissions can help us predict and prepare for worst-case scenarios. Maximum and minimum trendlines can also help identify potential errors in the experiment. Values that fall significantly outside the area between the maximum and minimum trendlines suggest an outlier that may have been due to a random error.

Greater variability in certain areas of the graph may also suggest error. For example, when measuring the rate of a reaction at different temperatures, it may be evident that there is a large variability in the rates at higher temperatures. This could imply an error in temperature control at higher temperatures.

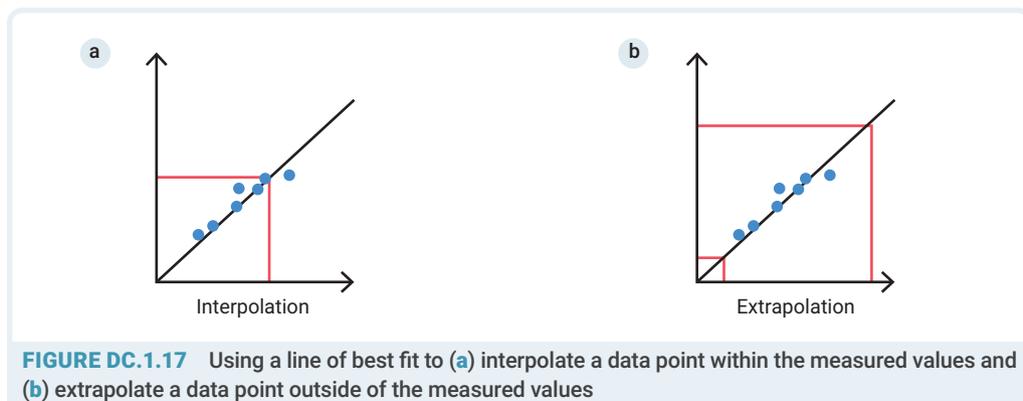
A common strategy used to draw a:

- maximum trendline involves drawing a line from the bottom of the error bar of the starting data point to the top of the error bar of the last data point
- minimum trendline involves drawing a line from the top of the error bar of the starting data point to the bottom of the error bar of the last data point.

Although trendlines are more general and can be used for different types of graphs with linear and non-linear data, the **line of best fit** is better suited for linear relationships. Since the line of best fit is used for linear relationships, the data points can be used to establish the relationship expressed as $y = mx + c$.

Although this can be done manually, the calculations can become complex and therefore it is often easier (and more accurate) to use software such as Excel, which can both draw the graph and establish the corresponding equation for the line of best fit. Lines of best fit can be used to predict values not measured in the experiment (extrapolation) or estimate values within the range of data collected (interpolation) that were not directly measured (**Figure DC.1.17**)

line of best fit a straight line through data points in a graph that best expresses the relationship shown in a scatterplot



Drawing the line of best fit involves specific statistical models such as linear regression and is often accompanied by a quantifiable level of certainty, known as the R -squared value (R^2) (also referred to as the coefficient of determination). Regression analysis provides an equation for a graph so that predictions can be made about the data.

Linear regression is a basic and commonly used type of predictive analysis. The overall idea of regression is to examine two things:

1. Does a set of predictor variables do a good job at predicting an outcome (dependent) variable?
2. Which variables in particular are significant predictors of the outcome variable?

These regression estimates are used to explain the relationship between one dependent variable and one or more independent variables.

This can be calculated in Excel.

Before discussing R^2 values, we must first understand the significance of R values.



Weblink

Linear regression and Excel

A method that can be used to quantitatively describe the direction and strength of a linear relationship between the independent and dependent variables is the **Pearson correlation coefficient (R)**, which measures the correlation between two sets of data. R values can be between -1 and 1 , where:

- $R = 0$ suggests no correlation
- $R = 1$ suggests a strong positive correlation
- $R = -1$ suggests a strong negative correlation

The formula to calculate the R value is complicated and therefore it is much easier to use software to help with this calculation. Programs such as Excel have options for calculating R when plotting a graph.

Squaring the R gives us the R^2 value. This value indicates the strength of the correlation of the linear relationship between two sets of data. In simple terms, it answers the question, 'Can I draw a line graph to represent the data?' Calculating this coefficient does not allow you to fit a line to your data (use a regression analysis for this). The value is also not able to tell the difference between the independent and dependent variables; for example, investigating a high-calorie diet causing diabetes might give a correlation of 0.8 . However, you could also get the same result with the variables switched around – diabetes causes a high-calorie diet. Therefore, as a researcher you must be aware of the data you are putting in and note the difference between correlation and causation:

- $R > 0.8 = \text{strong correlation}$.
- $R < 0.5 = \text{weak correlation}$.

Non-linear graphs

Not all trends show a linear pattern. For example, a graph showing the solubility of substances at different temperatures shows a non-linear relationship (**Figure DC.1.18**).

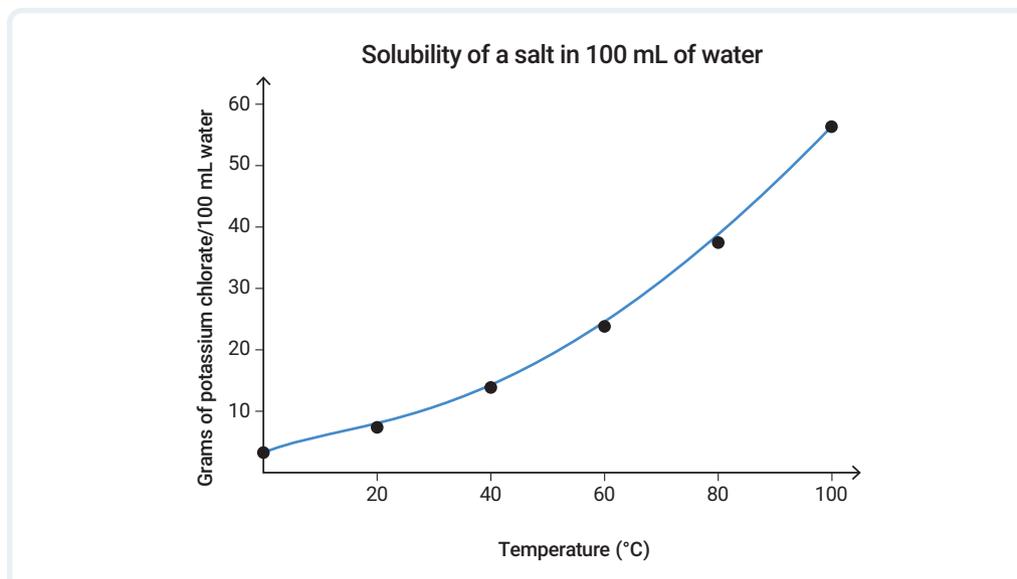
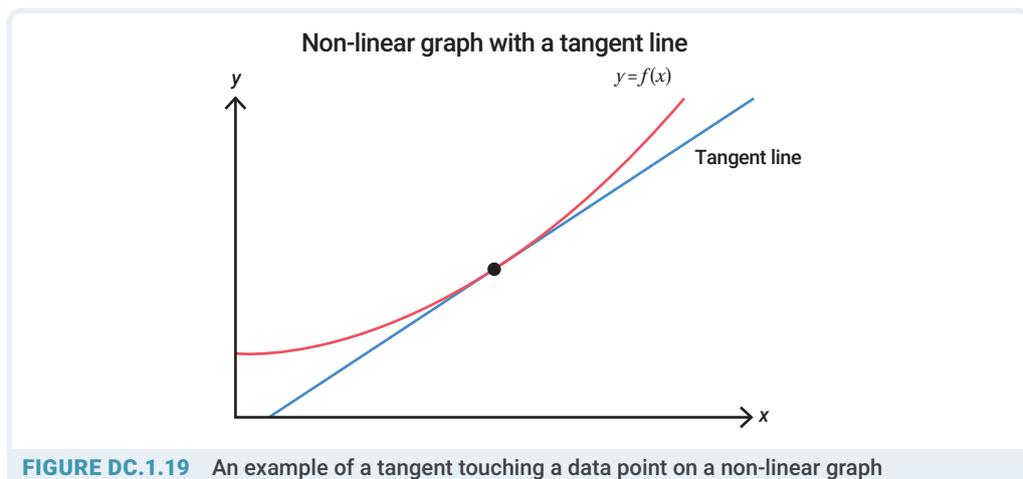


FIGURE DC.1.18 The solubility of a particular salt in 100 mL of water at different temperatures shows a non-linear relationship.

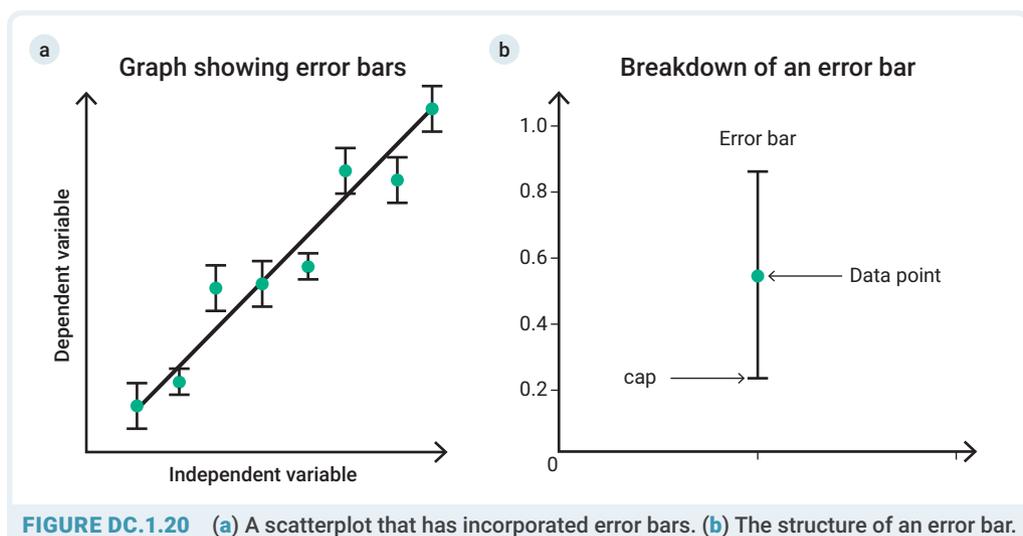
The simplest way to identify whether a relationship between two variables is linear or non-linear is to plot the data points on a graph to identify the overall trend. Gradient analysis can be conducted on non-linear graphs by calculating the instantaneous gradient of the tangent line at each data point and comparing the extent of the changes between each point. The tangent line is a straight line that 'touches' the data point and has the same gradient as the curve at the given data point (**Figure DC.1.19**).

Pearson correlation coefficient (R) a statistical measure that quantifies the direction and strength of a relationship between two variables



Error bars

To illustrate uncertainty, your graphs should incorporate error bars. These extend from data points to demonstrate the uncertainty the measurement (**Figure DC.1.20**).



Weblinks
Error bars

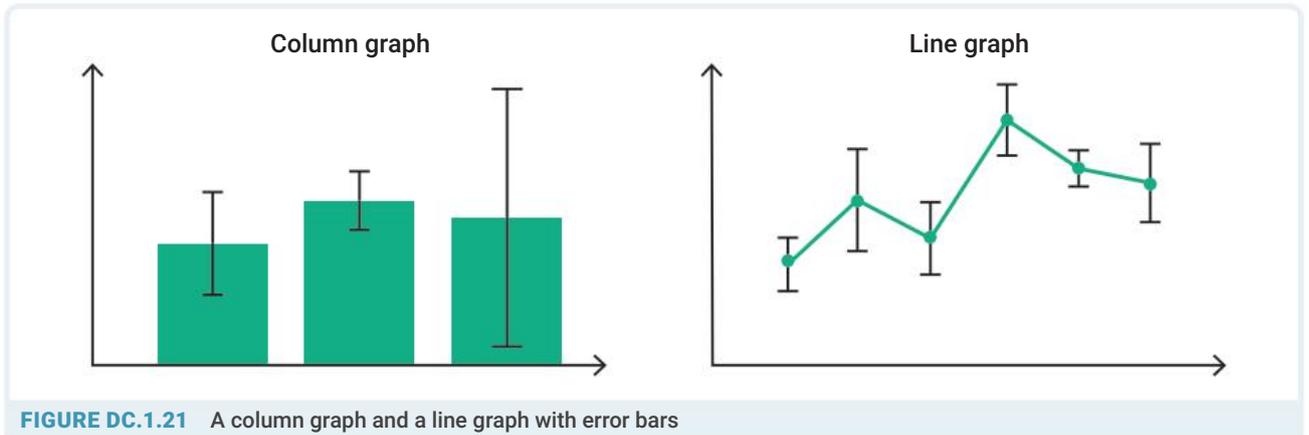
Drawing graphs with error bars

The upper and lower limits of the error bars can be determined by using descriptive statistics such as standard deviation or absolute uncertainty. (Note: There are different types error bars, e.g. standard deviation, confidence intervals, absolute uncertainty, percentage uncertainty.) To draw error bars on graphs:

1. Identify the data point.
2. Calculate the uncertainty of the mean or standard deviation for the data point. This determines the upper and lower limits of the error bar.
3. Use the values from step 2 to identify the maximum and minimum value for the data point. Use this to draw the error bar.

Graphing applications such as Excel have an option to include error bars in graphs. This is a faster and often more accurate method for generating graphs with error bars. Note that Excel usually puts on average error bars. If the error for each independent variable value is different, you will need to manually adjust the error bars in Excel.

A larger error bar indicates that the values are spread out and suggests greater uncertainty than a smaller error bar, which signals that the measurements are clustered around the data point. Error bars can be drawn for different types of graphs (Figure DC.1.21).

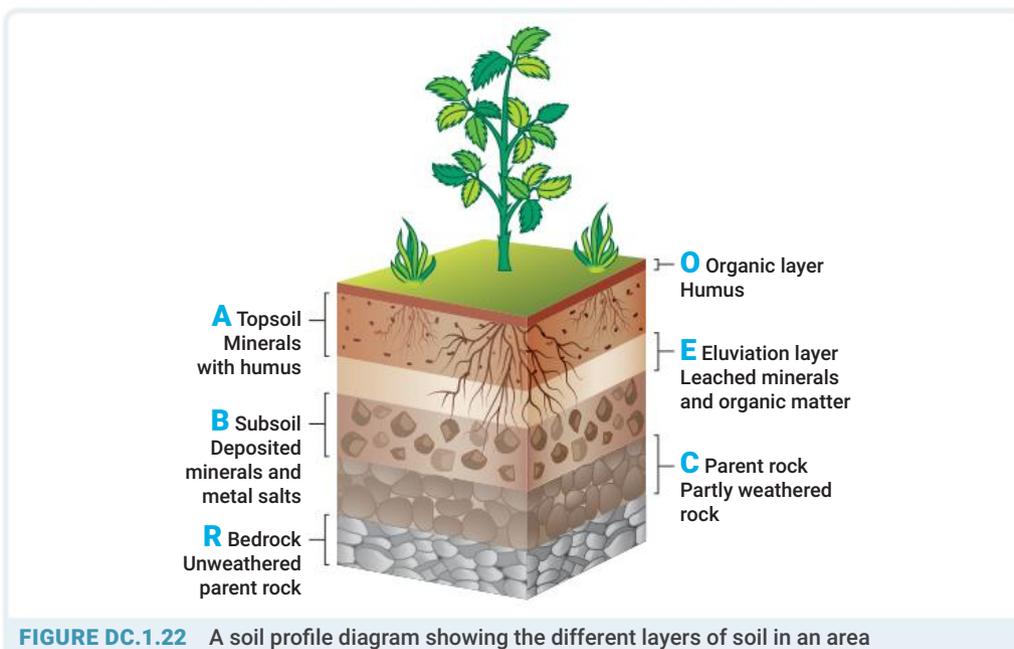


Other representations of data

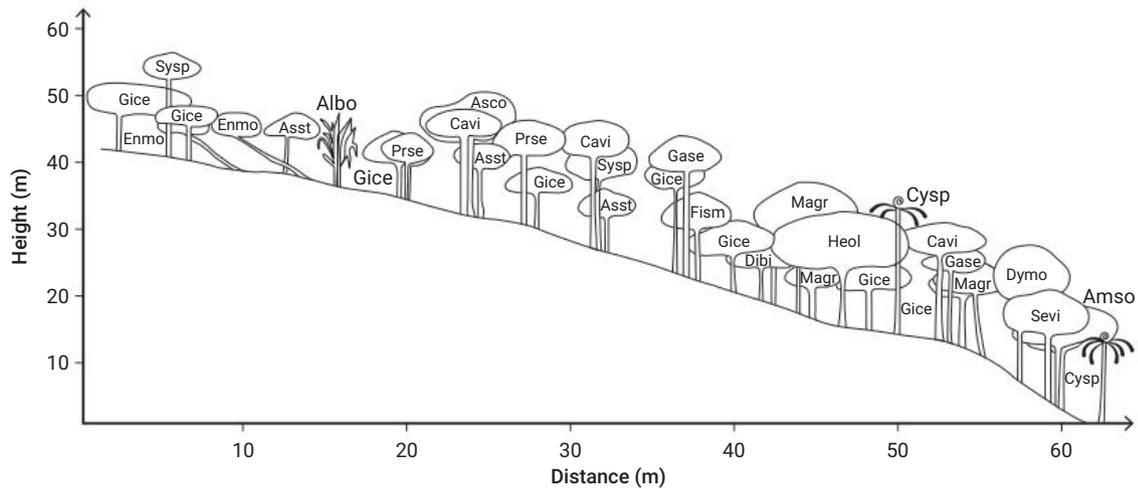
Profile diagrams

Profile diagrams help to visually show the different layers or sections of an ecosystem and how they vary from one another. These diagrams help us understand how things such as plant and animal species, as well as their heights or population sizes, change as we move along a specific line or area. For example, soil profile diagrams are side-view cross-sections that show the different layers of soil in an area (Figure DC.1.22).

profile diagram a visual representation that shows a cross-sectional view or side view of a specific aspect of an ecosystem or organism



Forest profile diagrams are effective for visually representing the distribution of plant and tree species, as well as their varying heights, along a transect line (Figure DC.1.23). By examining profile diagrams, we can get a better understanding of how the ecosystem has changed and the factors influencing these changes.



Source: Tuiwawa, Marika & Pene, Sarah & Winder, Linton. (2021). Vegetation Patterns in Waisol Primary Rainforest, Southeast Viti Levu, Fiji. Pacific Science. 74. 10.2984/74.3.2.

FIGURE DC.1.23 A forest profile diagram of a slope rain forest in Viti Levu, Fiji

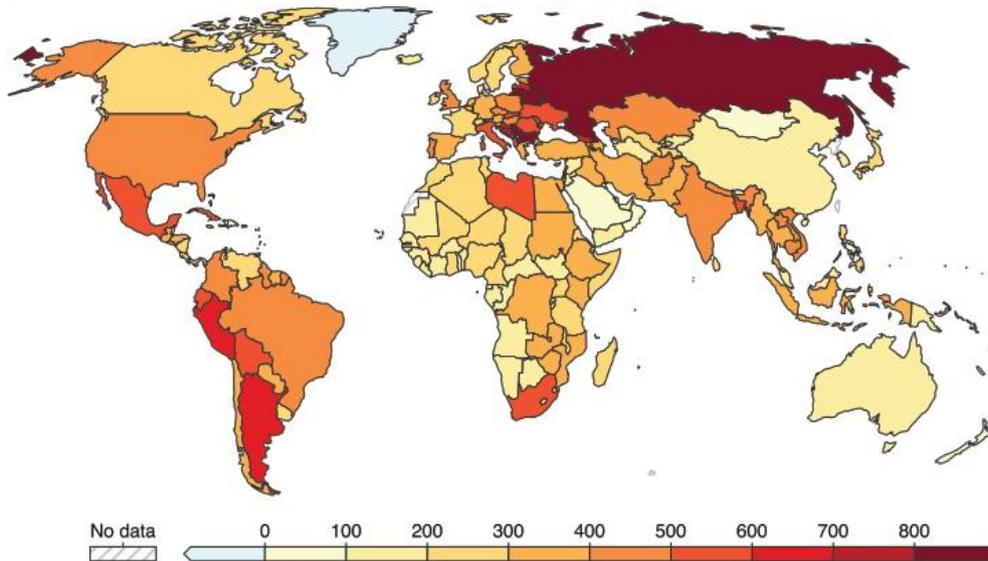
Maps

Like profile diagrams, maps are visual representations of data. Maps can represent complex data in a way that is easy to understand and identify trends and relationships. For example, governments often use maps to track the causalities of COVID-19 across the world (**Figure DC.1.24**).

Estimated cumulative excess deaths per 100,000 people during COVID-19, Jun 17, 2024

Our World in Data

For countries that have not reported all-cause mortality data for a given week, an estimate is shown, with uncertainty interval. If reported data is available, that value only is shown. On the map, only the central estimate is shown.



Data source: The Economist (2022); WHO COVID-19 Dashboard

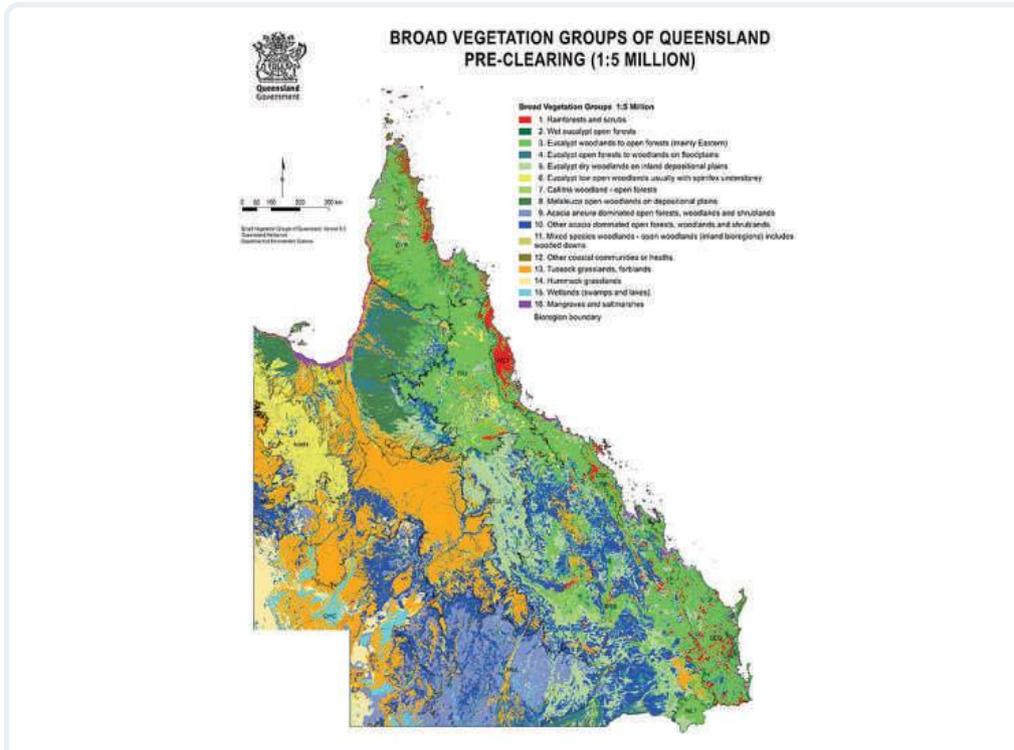
CC BY

Note: For some countries, all-cause deaths and COVID-19 deaths use different date schemes, in which one refers to when the death occurred and the other to when it was reported. This difference could produce an artificial lag between the two time series.

FIGURE DC.1.24 A map showing the worldwide cumulative deaths due to COVID-19

Our World In Data. CC BY. <https://ourworldindata.org/coronavirus/country/australia>

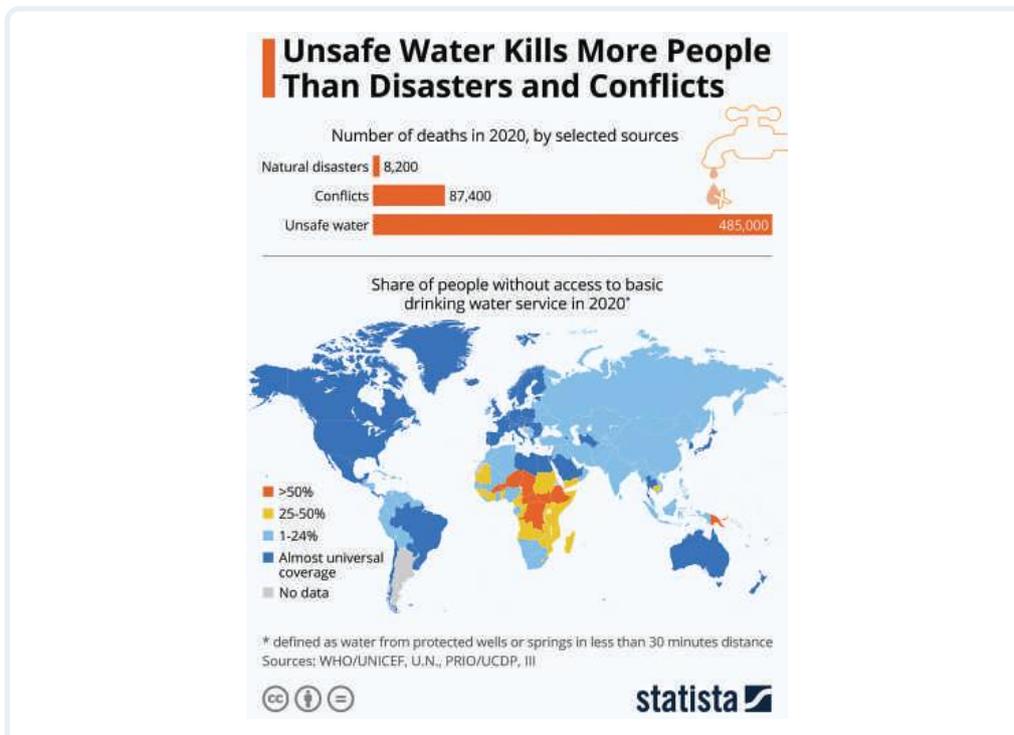
The Queensland Government uses maps to monitor the state's vegetation and regional ecosystems (Figure DC.1.25)



The State of Queensland

FIGURE DC.1.25 A map of Queensland's regional ecosystems and vegetation

Sometimes, especially in infographics, maps and charts can be used together to illustrate trends and relationships about a topic (Figure DC.1.26).

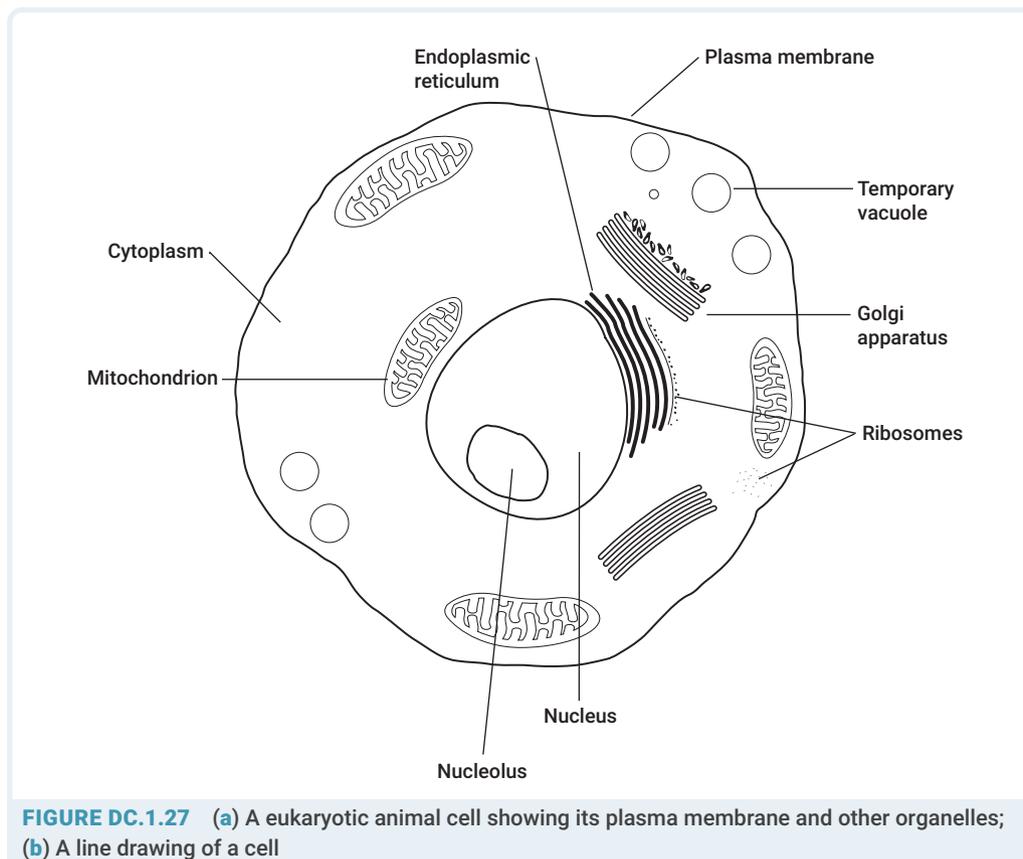


Statista

FIGURE DC.1.26 An infographic combining a chart and map to show the impact of unsafe water

Scientific drawings

Textbooks are full of scientific drawings that represent structures, organisms and processes. These drawings are highly detailed, accurate and clear. For example, examine the detailed drawing of an animal cell in **Figure DC.1.27**.



Scientific drawings include labels and annotations and are drawn to scale to show the relative proportions of the elements involved.

Identifying trends, relationships and patterns

The purpose of an experiment is to collect relevant data that can be analysed and used to understand the relationship between the independent and dependent variables.

Analysing graphs

When analysing graphs, it is important to consider all aspects presented in the graph. Consider the graph shown in **Figure DC.1.28**. What we tend to notice first is the overall trend in the data. The graph shows a negative trend where the cell potential decreases as the concentration of Zn^{2+} increases. We determine this visually based on the shape of the line; however, it is possible to also measure the negative gradient for the line. The large R^2 value of 0.9723 (very close to 1) suggests high correlation between both variables.

The graph in **Figure DC.1.28** also contains error bars showing the overlap of all data points. When this happens, it suggests that the differences between the overlapping data points are statistically insignificant and are due to random errors. As such, the trend shown may not reflect the true relationship between the concentration and cell potential.

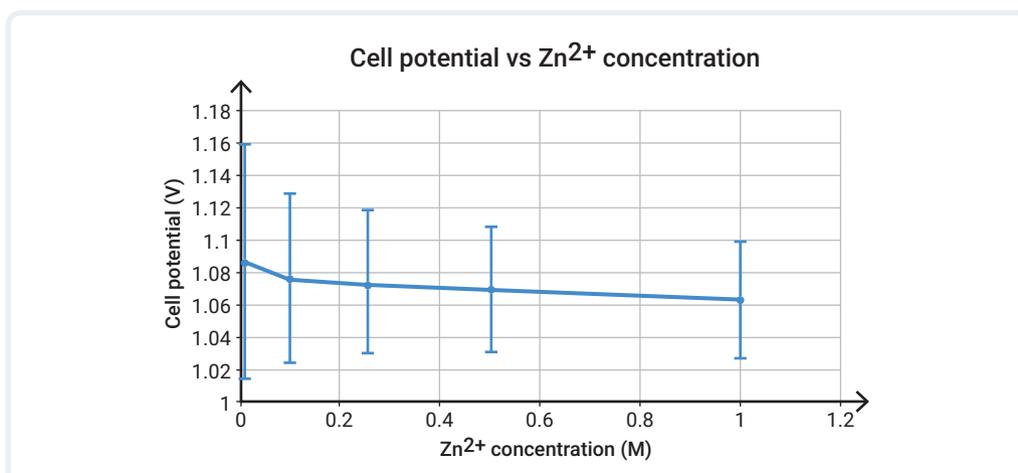


FIGURE DC.1.28 A graph showing the effect of the concentration of Zn^{2+} on cell voltage

Although not as easy to visually identify as graphs are, raw data tables can also be interpreted to identify the relationship between two variables. Consider the raw data table for the graph above (**Table DC.1.9**).

TABLE DC.1.9 A data table for the experiment testing the effect of the concentration of Zn^{2+} on cell voltage

ZnSO_4 conc. (M)	Mean cell potential (V)	Absolute uncertainty (V)	Percentage uncertainty (%)	Theoretical E_{cell} (V)	Percentage error (%)
0.01	1.087	± 0.005	± 0.460	1.159	± 6.249
0.10	1.077	± 0.005	± 0.464	1.129	± 4.681
0.25	1.073	± 0.005	± 0.465	1.117	± 3.977
0.50	1.070	± 0	± 0	1.108	± 3.506
1.00	1.063	± 0.005	± 0.470	1.100	± 3.333

All results have an overall low percentage error, suggesting that the experiment has high validity.

Spearman's rank

Data that is ranked – there is an order or sequence – is often analysed using **Spearman's rank correlation coefficient** (ρ). The value calculated lies between -1 and $+1$, which indicates the strength of the relationship between two sets of ranked data. Values that are closer to $+1$ show a strong positive correlation between the variables, whereas values closer to -1 indicate a strong negative correlation between the variables. Similar to some of the tests already mentioned, calculating ρ can be complicated and is best done using software such as Excel or Spearman's rank calculators (see weblink).

Student's *t*-test

The student's *t*-test, often shortened to *t*-test, is used to compare the means of different groups of samples. The value generated from the test, also known as the *p*-value, measures the probability

Spearman's rank a statistical measure that quantifies how closely two data sets (ranked data) are related



Weblinks

Spearman's rank calculator
P-value | Hypothesis testing

of the results being due to chance. We measure p -values between 0 and 1.0. A value of 0.05 or less is considered statistically significant and the observed data is considered to have a low probability of occurring due to chance. Again, software such as Excel can be used to calculate the p -value from t -tests.

Interpreting and evaluating evidence

To demonstrate that you have a robust understanding of the results of the experiment, it is important to identify the trend, pattern or relationship between the variables and comment on the reliability and validity of the relationships using your calculations of errors and uncertainty. Although it sounds counterintuitive, highlighting sources of error in your experiment and describing its effect on your results strengthens your argument. It also allows you to identify any limitations and offer suggestions for improvements and/or extensions to your experiment. By doing so, you are demonstrating an ability to critically analyse data, which helps to develop well-informed arguments.

You need to scientifically justify the argument. This is done by referencing theory and previous studies to explain the phenomena being shown through the data. For example, in an experiment measuring the effect of temperature on enzyme function, we would want to refer to the theory relating to the current understanding of enzyme function and use that to justify the arguments made from the trends identified in the data.

The culmination of this allows us to draw well-informed conclusions that help to answer the research question.

LEARNING CHECK DC.1

DESCRIBING

- 1 Describe the difference between:
 - a accuracy and precision
 - b reliability and validity.
- 2 Identify two strategies to improve the accuracy of data.
- 3 Identify the type of data most suited to:
 - a pie charts
 - b line graphs
 - c column graphs.
- 4 Describe the importance of:
 - a a logbook
 - b MSDS
 - c ethics in experiments.
- 5 Sequence the following sections of the scientific method in the correct order:
methods, materials, discussion, research question.

APPLYING

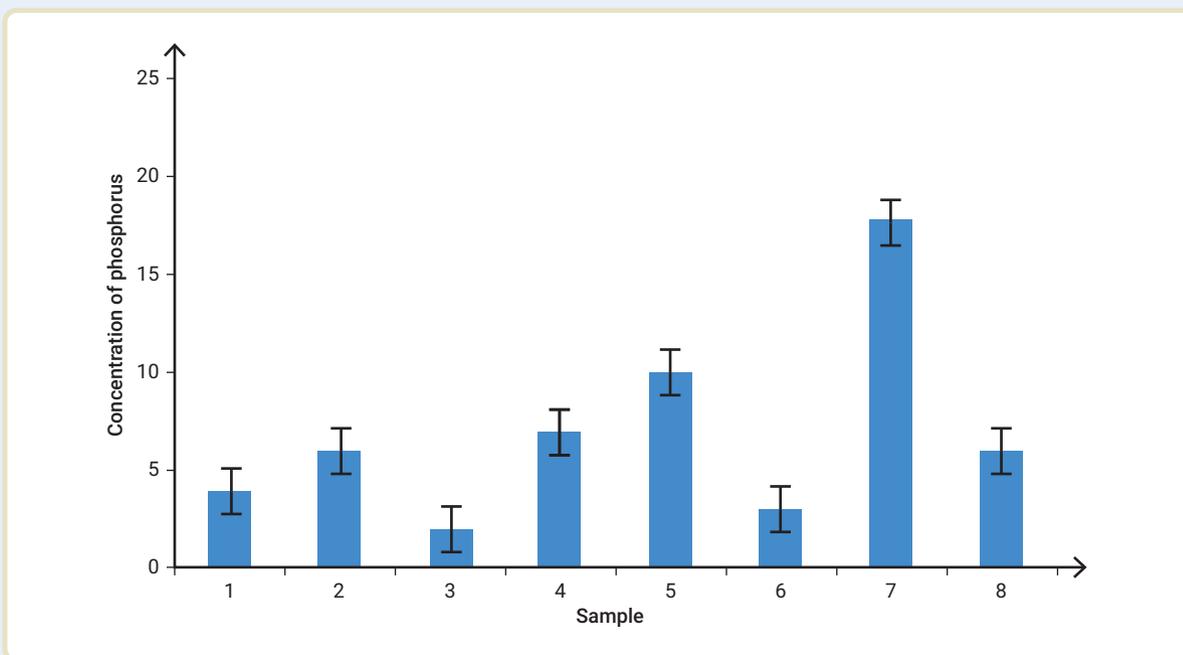
- 6 Consider the following research question.
'How does increasing light exposure (hrs per day) affect the rate of plant growth (cm/day)?'
Identify the:
- dependent variable
 - independent variable.
- 7 A student wanted to conduct an experiment to see whether eating food before running had any effect on how far she could run. Write a research question for this experiment.
- 8 A student is conducting an experiment involving the use of a glass measuring cylinder to measure and pour a sample of acid into a 100 mL glass beaker. **Identify** one safety concern associated with the experiment and how the risk can be minimised.
- 9 In a medical experiment, a participant was asked to undergo a series of additional tests that could reveal sensitive information about their health situation. The participant refused to give consent to the tests. However, the experimenter ignored this and requested for the tests to be conducted anyway. Which ethical concept has the experimenter breached? **Explain** your answer.
- 10 A student measured a value of 20 cm in their experiment with an absolute uncertainty of 1 cm.
- Calculate** the percentage uncertainty.
 - What does this value suggest about the precision of the measurement?
- 11 A group of students designed an experiment to measure the effect of water on plant growth. The plants were kept in the same room and the growth of the plants was measured daily.
- Identify** an extraneous variable for this experiment.
 - Each student took turns measuring the growth of the plant. Students used their own rulers to measure the growth, and it was noticed that all rulers had different resolutions (graduations). **Identify** the type of error that occurred as a result of this.
- 12 In a particular set of measurements, a student recorded the following measurements: 14.2, 14.1 and 14.3 cm. **Calculate** the absolute uncertainty.
- 13 The results from a student's experiment are shown below.

Concentration of nutrient solution (%)	Plant height (cm)		
	Day 10	Day 20	Day 30
0	5	8	10
5	7	10	12
10	9	13	15
15	12	16	20
20	15	19	25
25	17	22	28
30	18	24	30

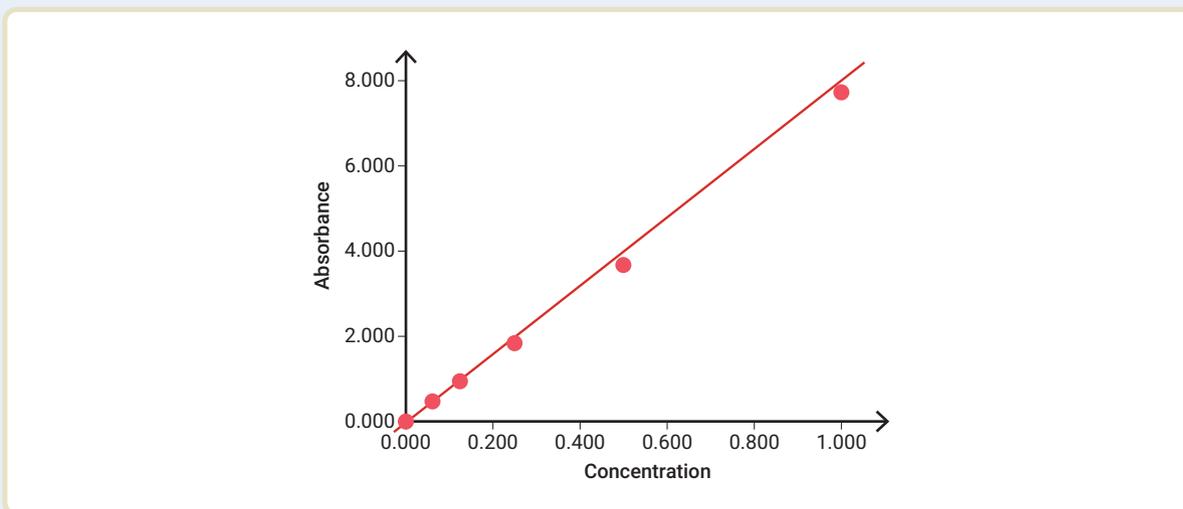
- Identify** the dependent and independent variables for this experiment.
- Calculate** the mean value for each concentration.
- Use the values to draw a graph to represent this data.
- Determine** the correlation (if any) between the independent and dependent variables.

ANALYSING

14 Consider the following graph.



- Determine the dependent variable.
 - Determine which sample shows the greatest variability.
- 15 The following graph was drawn for an experiment measuring the change of absorbance as a result of a change of concentration.



- Identify the name of the type of graph drawn.
- Identify the name given to the line drawn in the graph.
- Calculate the gradient (m) of the line.
- Determine the approximate absorbance at a concentration of 0.200.
- On the basis of the graph, would you expect the R value to be closer to 1 or to 0? Explain your response.

DC.2 Research investigation

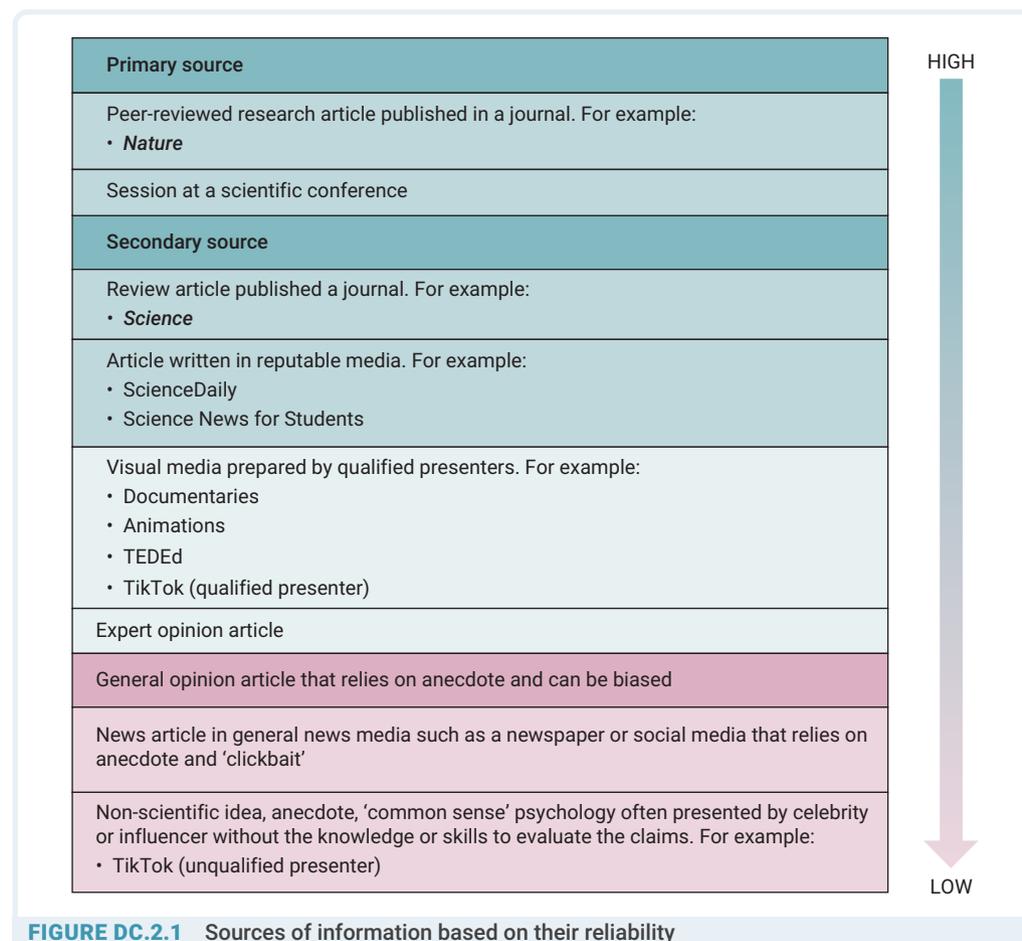
To help prompt your Research Investigation (IA3) assessment, your teacher will provide a list of claims that you can investigate. These claims will be related to particular topics outlined in the syllabus. After selecting a claim, you will be required to choose a research question to investigate. Unlike the Student experiment, the Research investigation requires you to collect and analyse **secondary data** about your topic and particular research question.

secondary data data that is collected by someone else

Forming and finding

Researching

As with the Student experiment, you will need to conduct research before developing a research question. This involves reading scientific articles and books and investigating other resources to develop a solid understanding of the topic. From blogs to scientific journals, there are many resources available to help develop your understanding. These sources may be available through open access (e.g. Google Scholar) or through organisations such as government websites and local or national libraries. For scientific research, it is important to use a variety of credible resources. Therefore, you will need to be able to assess the reliability of the sources you are using. For example, blogs that can be written by anyone are not as reliable as a scientific article from a peer-reviewed journal (**Figure DC.2.1**).



This is why the peer review process in scientific research is so important (**Figure DC.2.2**). For an article to be published in a journal, it must be reviewed by multiple experts, who evaluate it and make suggestions for further improvement. Before it can be resubmitted, the author must review and respond to the suggestions. This process can take months. Only once this process has been completed is the article accepted by the journal.

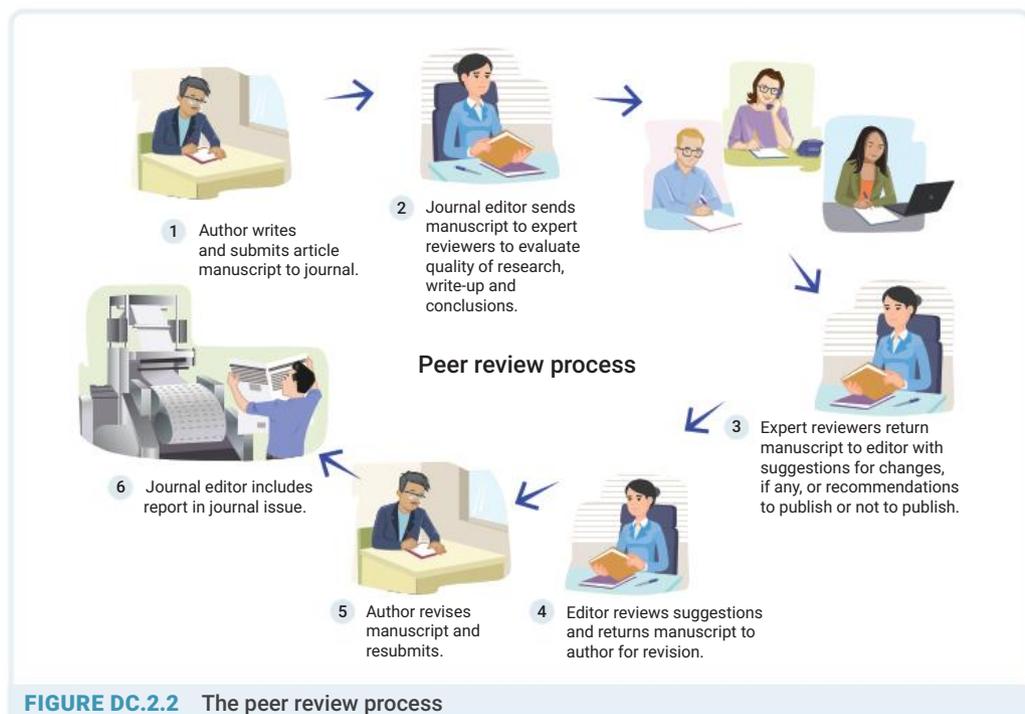


FIGURE DC.2.2 The peer review process



Weblink
Evaluating the information
you find

When using sources that are not from peer-reviewed journals, it is important to assess the reliability and validity of the information. It is helpful to ask yourself question such as:

- Is the author(s) an expert in this domain?
- Does the author use evidence to support their claims?
- Is the methodology valid?
- If evidence is used, where does the data come from?
- Is this publication trustworthy?
- Is there any bias; for example, is there a conflict of interest among the researchers?

It is also a good idea to cross-reference the information presented by these resources with other sources such as primary sources and textbooks. This initial research helps you to develop a rationale for your investigation, and as a result helps to craft a research question that is relevant to the claim. As with the student experiment, the research question needs to be able to be tested.

To help the reader have the necessary context for the research investigation, you need to provide a level of background. The background needs to include enough of a foundation that the reader can understand the theoretical underpinnings of the research while also showing that you have used scientific evidence to develop a research question that aligns with the claim.

Scientific conventions

The ability to communicate scientific understanding to an audience is often an overlooked skill. How we present the information depends on what we are sharing and the audience we are sharing with. For example, when communicating to a younger audience who are unfamiliar with many scientific concepts, it is important to use accessible language and visuals to help



Weblinks
Referencing style guides
Referencing sources

foster a foundational understanding of the topic. When communicating findings to those in the scientific community, we need to make sure to use scientific language, including correct nomenclature, units and symbols specific to the scientific theory.

Since experiments and scientific research draw on the knowledge, thoughts and ideas developed by others, we need to appropriately acknowledge sources of information. The referencing format that is required depends on the discipline; however, in most cases, science uses the APA (American Psychological Association) referencing style.

Analysing evidence

As part of your assessment, you will need to find scientific evidence from previous research related to your research question. The data derived from these studies is used in the same way as the data collected from your student experiment; to identify trends, patterns and relationships between variables to answer the research question.

Because there are multiple data points, it is important to re-organise the data and present it in a way that can be analysed. For example, **Table DC.2.1** shows data collected from two different scientific experiments that measured the prevalence of lactase persistence-associated alleles of populations in Finland.

TABLE DC.2.1 Comparison of results between different studies

Population	Long.	Lat.	N	-14010 G>C	-13915 T>G	-13907 C>G	-13910 C>T	Sum of all LP associated alleles	Predicted lactase persistence frequency
Finns	28.00	65.00	1876	0.00	0.00	0.00	0.58	0.58	0.82
Saami	39.00	69.00	60	–	–	–	0.17	0.17	0.31

Enattah, N.S., et al. (2008) *American Journal of Human Genetics*, 82(1): 57–72. doi: 10.1016/j.ajhg.2007.09.012.
(via Global Lactase persistence association database)

Additionally, the data can be used to construct graphs. Organising data in this way makes it easier to identify any trends, patterns or relationships that exist between the variables being tested. As in your student experiment, you would also need to identify any sources of error and levels of uncertainty that can affect the results.

Interpreting evidence

As you now know, presenting data and describing trends and relationships on their own is not sufficient. We need to be able use the evidence and scientific theory to justify the argument being made and to draw a conclusion.

When developing your conclusion, ensure that it directly answers the research question. Sometimes when assessing studies at an individual level, the data may point towards a particular conclusion. However, when studies in the same area are evaluated together, an overall analysis may suggest a different conclusion. If your investigation shows a different conclusion from the studies used, that in itself is an important conclusion. It highlights that further investigation is required to develop a deeper understanding of the area.

Evaluating evidence

The quality of the evidence can impact the reproducibility of the research and strength of the conclusions drawn. We can assess the quality of the evidence by identifying any limitations caused by errors and/or uncertainty (**Figure DC.2.3**). This may include assessing the:

- appropriateness of the method (where possible)
- sample size

- sources of error
- degree of uncertainty of the data.

It's also important to consider any bias (e.g. is the funding from a particular company?), recency of data as well as qualifications of the author(s). Identifying limitations also helps you to make interpolations or extrapolations of the findings, to further analyse the research claim.

However, there are issues associated with the evidence presented. Haglin was the only source for information about the lactose percentages in reindeer's milk. It could be assumed that this is because it is very cold in Finland and it takes two people to milk a reindeer to get 2 cups of milk. Maybe scientists are not interested in these conditions and don't really want to find out more about reindeer. Consequently, only one source of evidence limits the reliability of this information.

FIGURE DC.2.3 An excerpt evaluating the evidence provided by previous scientific studies

It is also important to suggest any further improvements for future studies related to this area. For example, you could identify any changes that you would make to the methodology to improve the validity or reliability of the data from the experiment. Suggestions for improvement should also address any limitations present in the experiment, including any:

- experimental limitations; for example, time available to conduct the experiment, errors
- methodological limitations; for example, accuracy and reliability of measurement techniques, ethical constraints
- external limitations; for example, environmental factors that can introduce variability, access to proper equipment.

As you can appreciate, being able to interpret and evaluate data is crucial for reaching informed conclusions about your research.



Weblink
Sample research
investigation

LEARNING CHECK DC.2

DESCRIBING

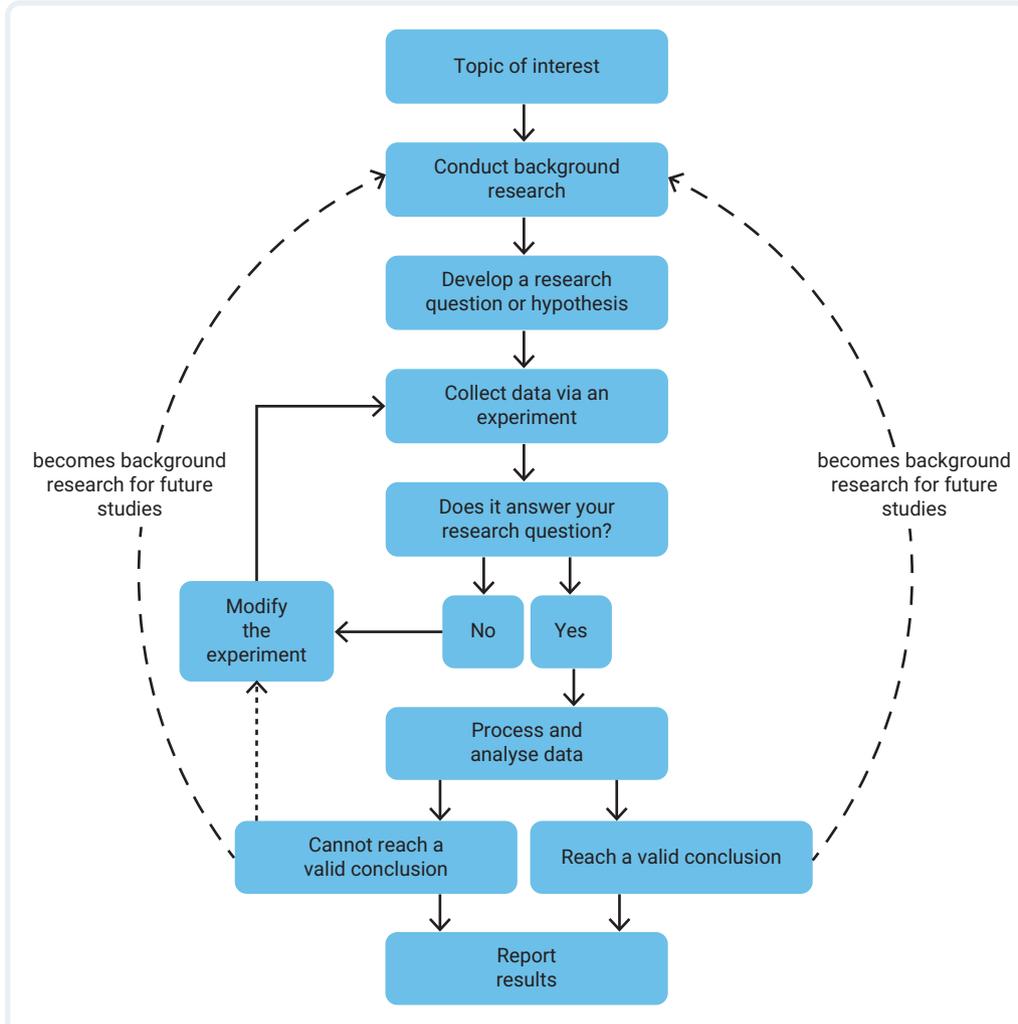
- 1 Identify the difference between primary and secondary data.
- 2 Describe the role of the peer review process in scientific research.

APPLYING

- 3 A student conducted an experiment to investigate the effect of different fertilisers on the growth of tomato plants. The student divided the tomato plants into four groups and assigned each group a different type of fertiliser: A, B, C and D. The plants were placed under identical conditions, receiving the same amount of water and sunlight. The student measured the height of the plants every week for 4 weeks.
Identify one possible experimental and one methodological limitation of this experiment.
- 4 **Consider** the following passage.
The rate of reaction is a fundamental concept in science. Enzymes function to increase the rate of reaction by providing an alternative pathway for a reaction to occur.
Rewrite the passage so that it can be read and understood by a primary school student who is studying science.
- 5 A student used the following source for their research investigation.
Cruzan, J. (2012). 'The most important solvent'. Retrieved from <http://www.drcruzan.com/Water.html>.
Use information from the 'Referencing sources' weblink to show how this resource would be referenced in the text.

Conducting research

- The scientific method follows a particular process aimed to maximise accuracy, reliability and objectivity while minimising uncertainty and error.



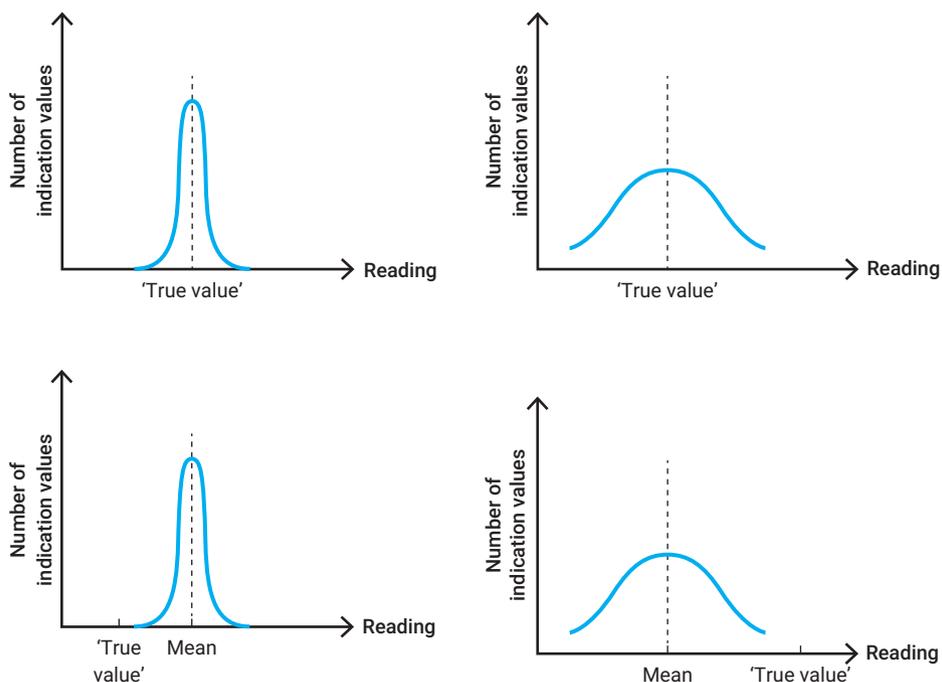
- There are five main types of investigations:
 - descriptive
 - comparative
 - correlational
 - experimental
 - case study.

Investigation type	Description	Example
Descriptive	Researchers collect data through surveys, interviews or observations to gain a better understanding of the subject being investigated.	Describing the distribution of a species in an ecosystem
Comparative	Two or more groups or variables are compared to identify similarities and differences between them. Researchers can use this information to investigate the impact of factors on the groups being investigated.	Comparing the growth of different plants under different environmental conditions
Correlational	These investigations focus on identifying the relationship between variables. Data collected in these investigations is used to determine whether changes in one variable are associated with a change in another variable. Note: correlation does not mean causation.	Identifying the relationship between temperature and plant growth
Experimental	Variables are manipulated to determine whether there is a cause-and-effect relationship between the variables.	Testing the effect of a fertiliser on plant growth
Case study	Analysis of a particular individual, group or situation	Studying the behaviour of a particular type of frog in a specific ecosystem

- Different sampling techniques are better suited to certain types of investigation.

Analysing data

- Precision describes the closeness of data, whereas accuracy describes how close the measured value is to the true value.
- The quality of data affects the validity of the experiment.



- Percentage error helps to indicate the accuracy of a measurement

$$\text{Percentage error (\%)} = \left| \frac{\text{measured value} - \text{true value}}{\text{true value}} \right| \times \frac{100}{1}$$

- Errors affect the accuracy and precision of data. These can be categorised into:
 - random errors
 - systematic errors.
- Uncertainty describes the variability in the measured results:

$$\text{Absolute uncertainty} = \frac{\text{maximum} - \text{minimum}}{2}$$

$$\text{Percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{measured value}} \times 100$$

- Standard deviation and standard error can be used to quantify variability of data. This is best calculated using software such as Excel:

$$\text{Standard error} = \frac{\text{SD}}{\sqrt{n}}$$

where: SD is the standard deviation and n is the sample size.

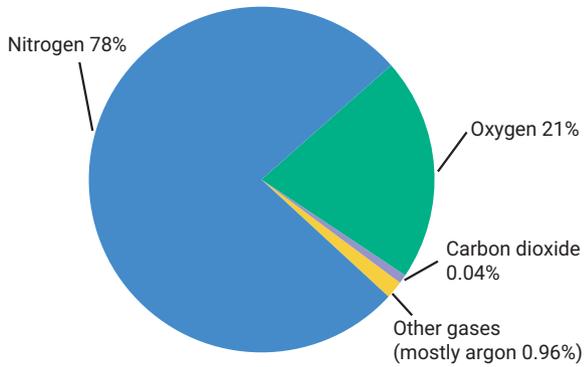
- The student's t -test measures the probability of results occurring due to probability. A $p < 0.05$ is considered statistically significant
- Pearson's correlation (R) coefficient helps quantify the direction and strength of the relationships between the measured variables.
 - $R = 0$ suggests no correlation.
 - $R = 1$ suggests a strong positive correlation.
 - $R = -1$ suggests a strong negative correlation.

- Spearman's rank (ρ) quantifies how closely data (ranked data) are related.
 - Values that are closer to +1 indicate a strong positive correlation between the variables
 - Values closer to -1 indicate a strong negative correlation between the variables.

Graphs

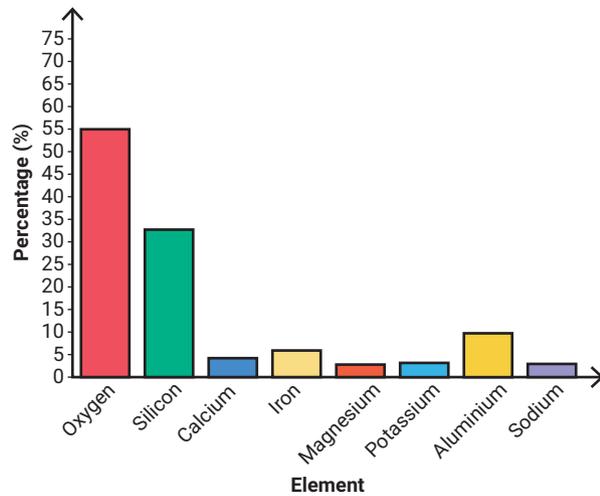
- There are many different graphical representations of data, including:
 - linear graphs
 - column graphs
 - pie charts
 - scatterplots.

Pie charts

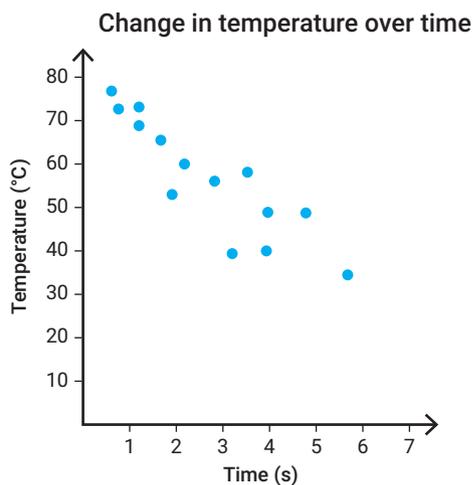


Column graphs

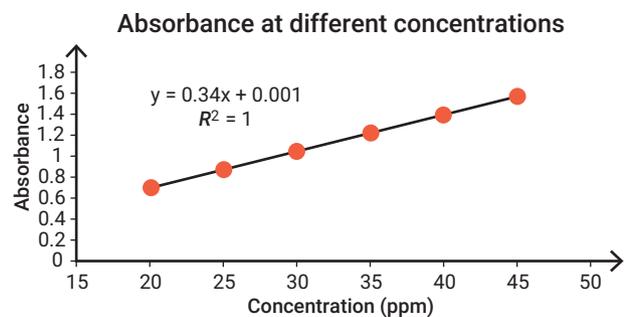
The eight most common elements in Earth's crust



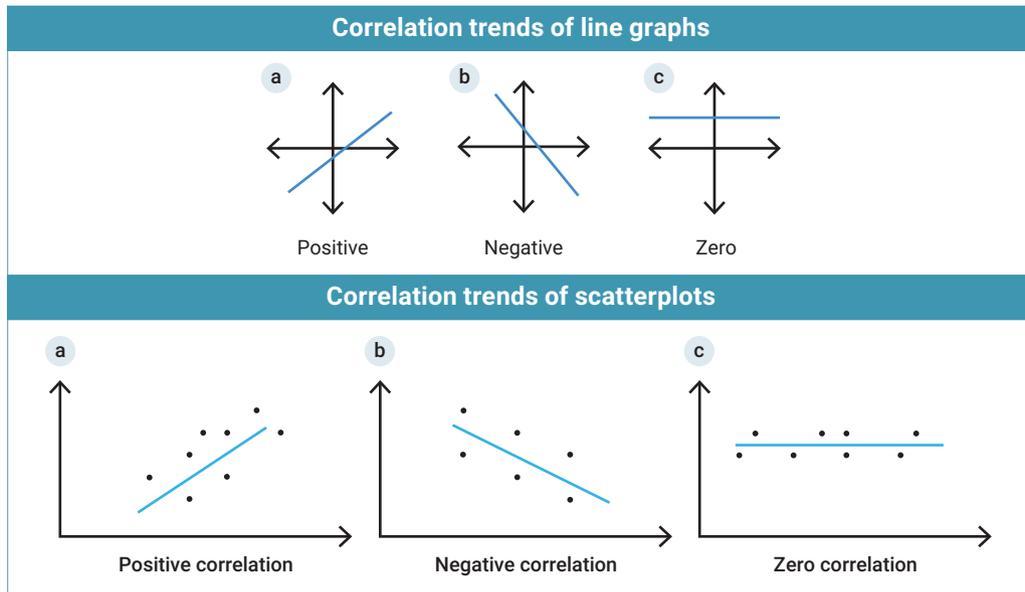
Scatterplots



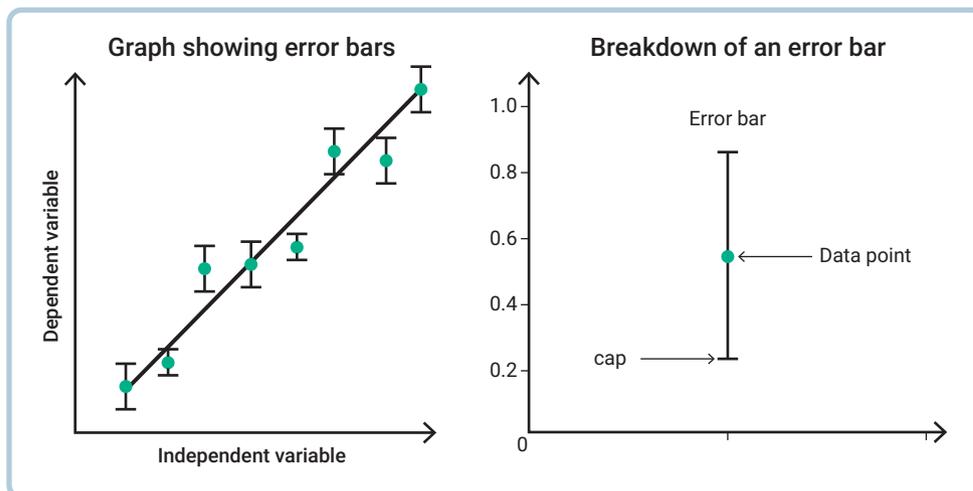
Line graphs



- Graphs help to show the relationship between variables. Although they can show correlation, this does not mean causation.

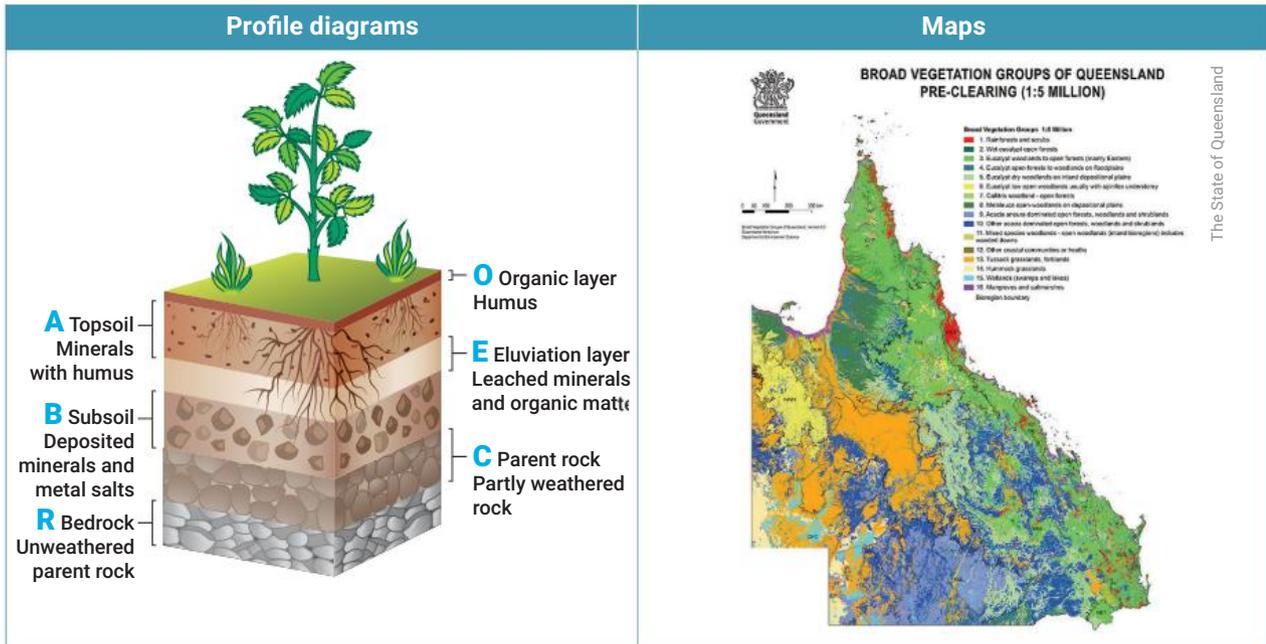


- Error bars on graph help to visualise variability of measurements around the mean.
 - The central point shows the data point.
 - The upper and lower limits show the variability of the measured values.

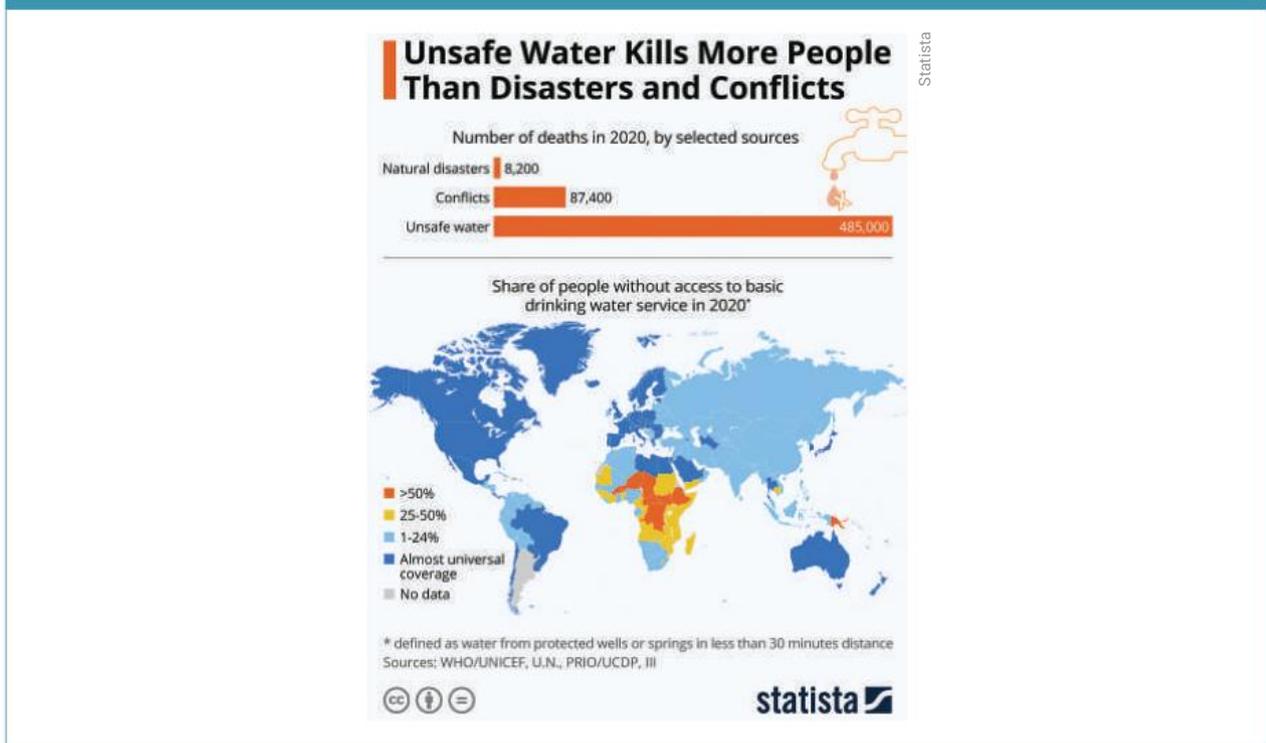


Other visual data representations

- Data can also be represented using profile diagrams, maps, or a combination of maps and charts.

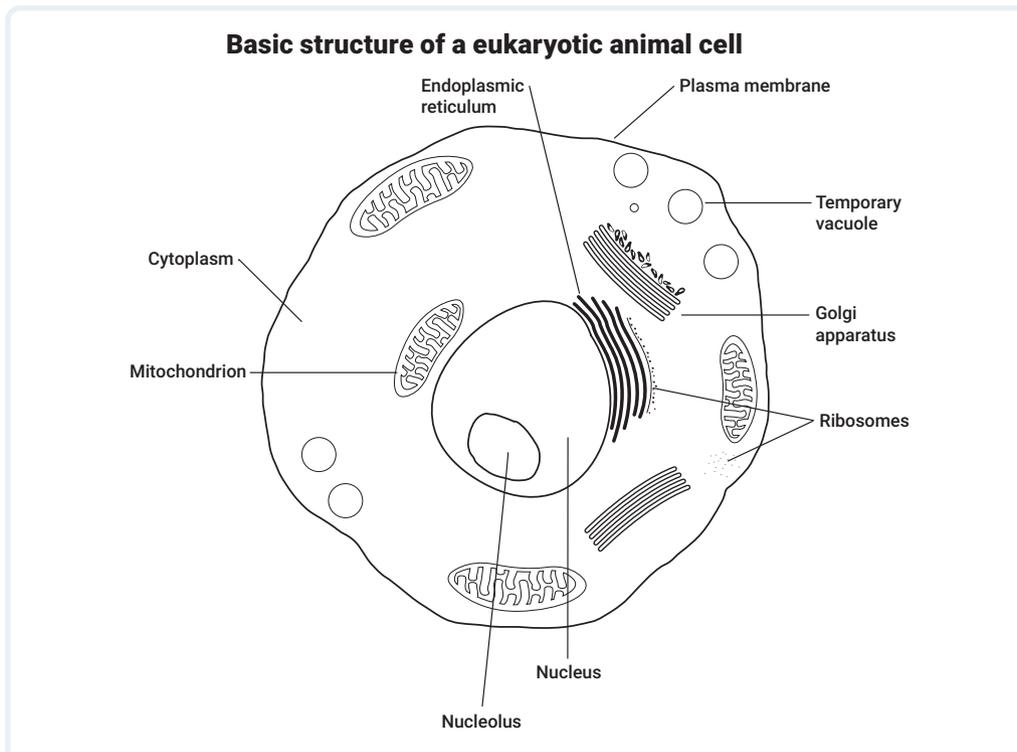


Combination of maps and charts



Scientific drawings

- Scientific drawings are representations of scientific concepts.



Interpreting, analysing evaluating evidence

- Apart from speaking to the trends shown in the data, when analysing data it is also important to assess the:
 - appropriateness of the method
 - sample size
 - sources of error
 - degree of uncertainty of the data.
- When evaluating evidence, make sure to also address any limitations present in the experiment, including:
 - experimental limitations; for example, time available to conduct the experiment, errors
 - methodological limitations; for example, accuracy and reliability of measurement techniques, ethical constraints
 - external limitations; for example, environmental factors that can introduce variability, access to proper equipment.

Communicating findings

- When communicating findings, make sure to:
 - use appropriate conventions and nomenclature
 - use language appropriate to the audience
 - reference appropriately using the relevant referencing system.

CHAPTER EXAM

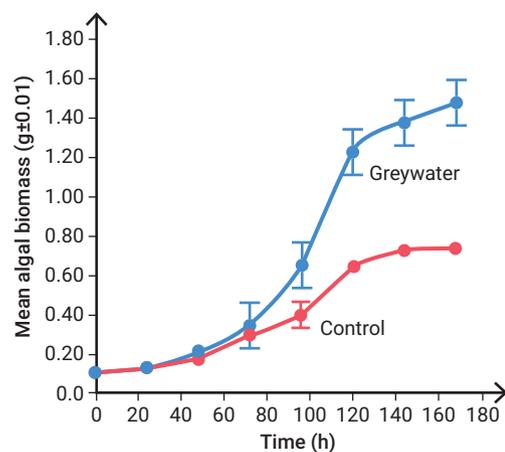
MULTIPLE CHOICE

- Which measure provides information about the spread or variability of data points in a data set?
 - Mean
 - Mode
 - Outlier
 - Standard error
- Which of the following data sets would be considered precise but not accurate?
 - Measuring a flower's height with a ruler missing the mm markings (Readings: 22, 21, 23 cm)
 - Measuring water temperature that is constantly 3° higher than the actual temperature (Readings 15°C, 15°C, 16°C)
 - Measurements made by different students of the width of leaves (Readings: 11.4, 15.8, 13.2 cm)
 - Measuring how long it takes a ball to roll down a hill (Readings: 11.14, 10.59, 10.77 s)
- A student measures the length of a plant stem to be 12.5 cm, using a ruler. The actual length of the stem, as determined by a more precise instrument, is 12.9 cm. The percentage error in the student's measurement is:
 - 1.5%
 - 2.4%
 - 2.6%
 - 3.1%
- Which of the following would not be considered a type of investigation?
 - Comparative
 - Correlational
 - Descriptive
 - Relative
- In a Biology experiment, students investigated the effect of light intensity on plant growth. Which of the following can be considered an extraneous variable?
 - Type of plant species
 - Soil moisture
 - Light intensity
 - Temperature

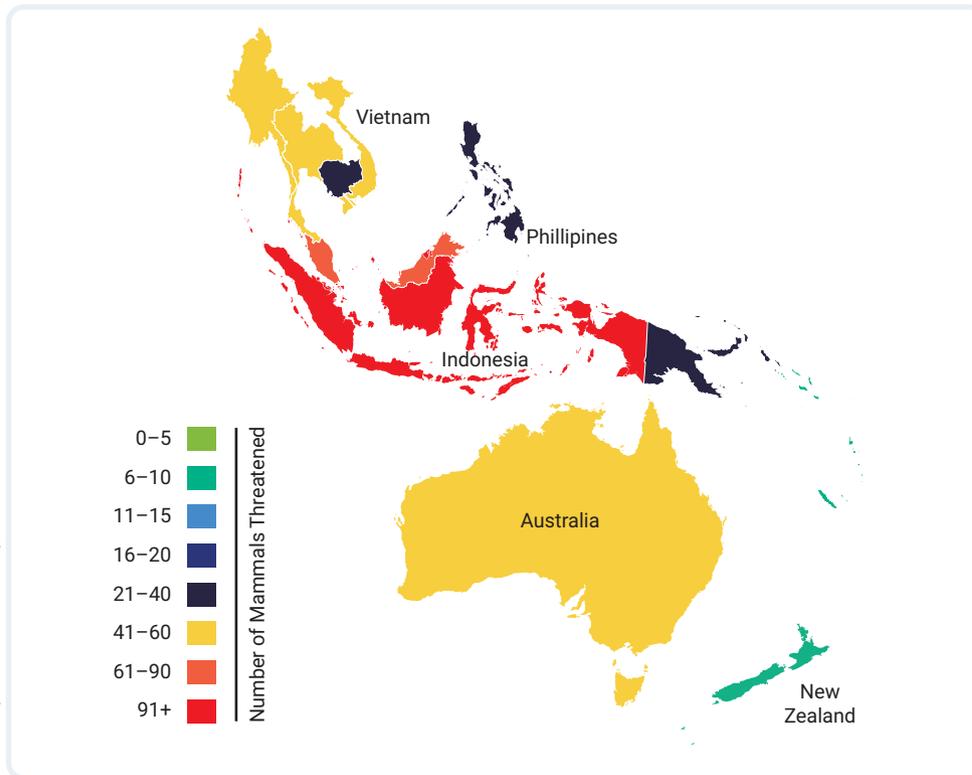
Questions 6–8 relate to the following information.

A student conducted an experiment to measure the change in mean algal mass over a 168-hour period, as shown in the graph.

- The independent variable for this experiment is:
 - control.
 - greywater.
 - mean biomass.
 - time (h).



7. Comparing the algal biomass growth, the algal biomass in:
- A the control experiences the greatest overall change.
 - B greywater grows faster than in the control throughout the experiment.
 - C greywater grows slower than in the control throughout the experiment.
 - D greywater and the control show similar growth rates initially, but the greywater condition eventually surpasses the control.
8. The data point showing the greatest variability is:
- A control at 66 hours.
 - B control at 142 hours.
 - C greywater at 88 hours.
 - D greywater at 120 hours.
9. Based on the map below, the area with the least number of mammals threatened is:
- A Australia.
 - B New Zealand.
 - C Philippines.
 - D Vietnam.



10. Which of the following cannot improve the reliability of results in an experiment measuring soil acidity levels in different areas?
- A Increasing the replicates in each area
 - B Use various measurement techniques
 - C Calibrating the pH meters before taking measurements
 - D Reducing the number of data points collected in each area

SHORT ANSWER

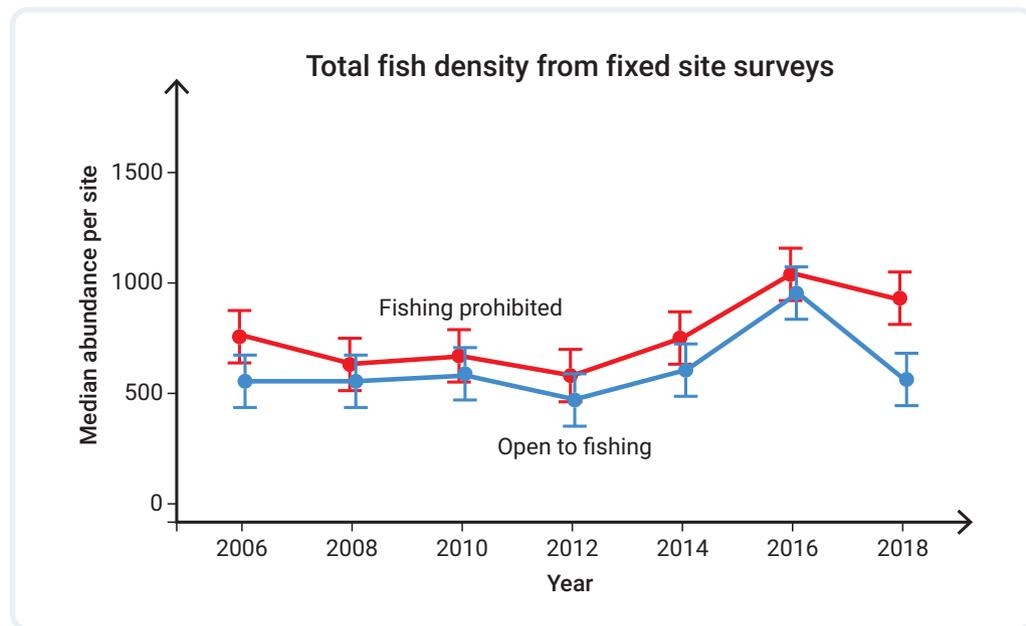
11. The following is a description of an experiment.

For this experiment, students are given sets of bean plants to investigate how different light conditions affect plant growth. In the experiment, the plants are exposed to three conditions: full sunlight, partial shade and artificial light.

All plants are given sufficient water and growth is measured weekly.

Write an appropriate research question for this experiment.

12. The graph below shows the impact of marine park zoning in reefs close to Townsville.

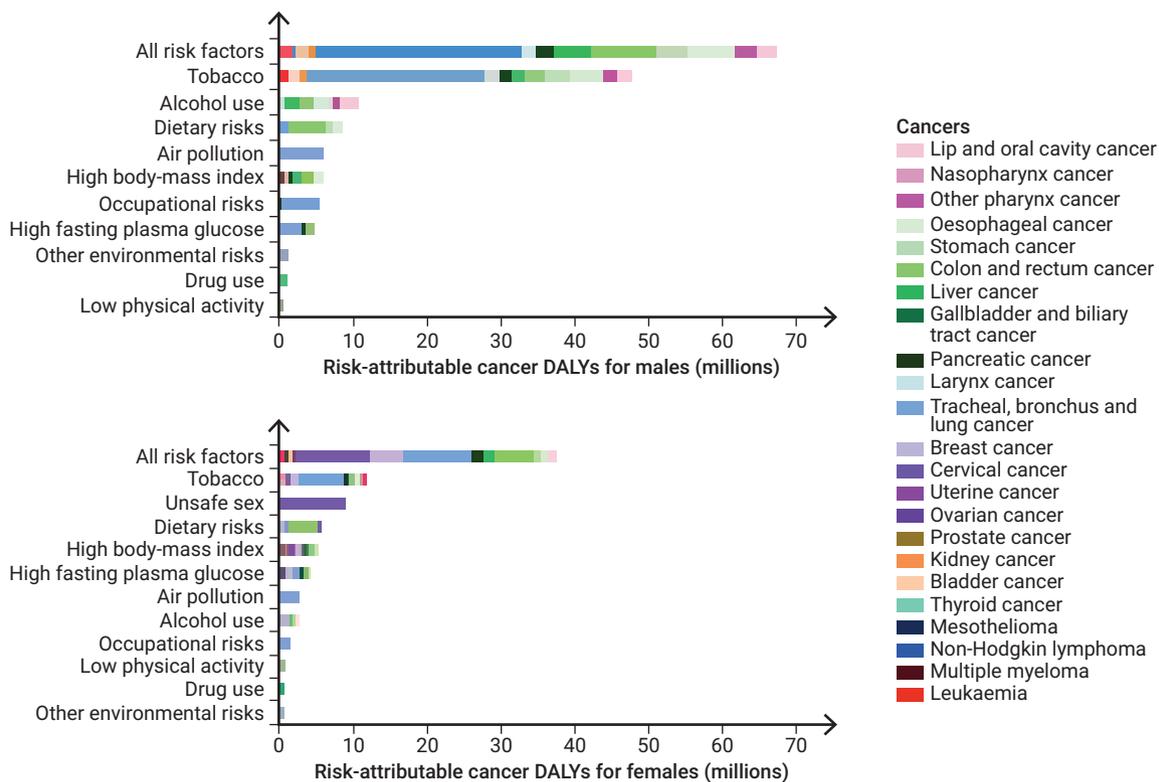


- a **Identify** the independent variable in the experiment.
b **Compare** the effect of the two conditions on the density of fish.
c **Comment** on the reliability of the results.
13. The Global Burden of Disease Study in 2019 set out to understand the magnitude of cancer burden attributed to different risk factors. The goal was to use this information to develop effective prevention and mitigation strategies. Selected graphs from the study are shown below.

On analysing these graphs, a student made the following statement.

‘For both sexes, occupational risks were the highest leading factor causing tracheal, bronchus and lung cancer.’

Assess the accuracy of this statement.



*DALY = the sum of years of life lost as a result of premature deaths and years lived with disability. One DALY represents the loss of one year of health.

14. The following data was collected from an experiment testing the effect of light intensities on plant growth over a 4-week period.

Week	Low intensity light		Medium intensity light		High intensity light	
	Mean height (cm)	Error (%)	Mean height (cm)	Error (%)	Mean height (cm)	Error (%)
1	2.0	5	3.0	5	4.5	5
2	3.8	5	5.7	5	8.0	5
3	6.0	5	8.5	5	12.0	5
4	7.5	5	11.0	5	15.5	5

Sketch an appropriate graph to represent this data.

ANSWERS

CHAPTER DC SCIENCE RESEARCH

LEARNING CHECK DC.1

DESCRIBING

- Accuracy refers to how close a value is to the true value, whereas precision describes how close a set of measurements are to each other.
 - Reliability refers to the consistency of measurements upon repeat experiments, whereas validity describes the extent to which the experiment measures what it is intended to measure.
- Calibrate measuring instruments. Take multiple measurements and take an average.
- Data that is in categories
 - Continuous data or measurements taken over time
 - Data that is in categories or discrete data
- A logbook contains detailed notes relating to the experiment, including observations, results and methodology. This information is important during the analysis of the results of the experiment.
 - MSDS contain information about the safe handling of any chemicals or substances used in an experiment. This ensures the safety of the researchers.
 - Ethics help to ensure the safety of participants in the experiment, the integrity of the experiment and the proper use of the experimental results.
- Research question, materials, methods, discussion

APPLYING

- Rate of plant growth
 - Light exposure
- Does the consumption of food (g) before running affect the total distance(km) a person can run?
- Potential risk: The student could drop the measuring cylinder, causing it to break and shatter. The pieces of glass could damage the skin.
Risk minimisation: Wear gloves and closed toe shoes to protect against pieces of broken glass.
- The experimenter breached informed consent. The experimenter ignored the participant's refusal to be tested and performed the procedure anyway. Participants need to give formal consent to participate in experiments and the experimenter must respect their wishes, not go against them.
- Percentage uncertainty = $\frac{1}{20} \times 100$
= 5%
 - This suggests that the measurements are relatively imprecise.

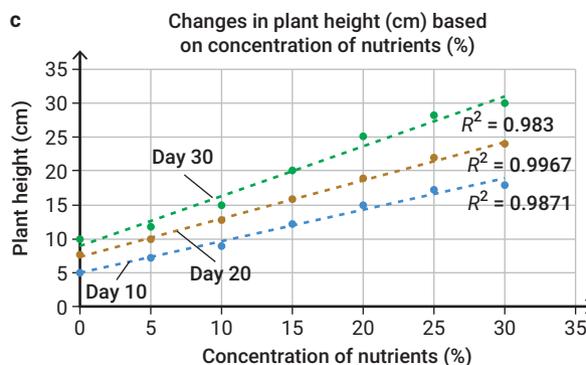
- Where the plant is placed and therefore the amount of sunlight exposure
 - Random error

$$\begin{aligned} 12 \text{ Absolute uncertainty} &= \frac{14.3 - 14.1}{2} \\ &= \pm 0.1 \text{ cm} \end{aligned}$$

- Independent: concentration of nutrients (%); dependent: plant height

b

Concentration of nutrient solution (%)	Mean height (cm)
0	7.7
5	9.7
10	12.3
15	16.0
20	19.7
25	22.3
30	24.0



- There is a positive correlation between the concentration of nutrients in the solution and the plant height. It is >0.98 on each measurement day.

ANALYSING

- Concentration of phosphorus
 - Sample 3
- Scatterplot
 - Line of best fit
- $$\begin{aligned} \text{Gradient} &= \frac{\Delta y}{\Delta x} \\ &= \frac{4 - 2}{0.480 - 0.250} \\ &= 8.70 \text{ (approximately)} \end{aligned}$$
- Approximately 1.500
- Since there is a strong positive correlation between the two variables, the R value is likely to be closer to 1 than to 0.

LEARNING CHECK DC.2

DESCRIBING

- 1 Primary data is firsthand data collected by the researcher, whereas secondary data refers to information collected from an experiment conducted by someone else.
- 2 The peer review process helps to ensure the quality of the research and the results. It also helps to add credibility to the research investigation.
- 3 Experimental: How different tomato plant types respond to the particular fertiliser used
Methodological: The consistent timing of when the plant heights are measured
- 4 How quickly a reaction occurs is important in science. Enzymes can make reactions occur in less time by providing a different pathway for the reaction to take place.
- 5 (Cruzan, 2012)

CHAPTER EXAM

MULTIPLE CHOICE

- 1 D 3 D 5 B 7 D 9 B
2 B 4 D 6 D 8 C 10 D

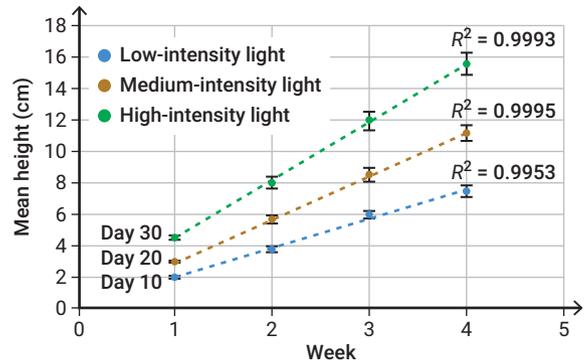
SHORT RESPONSE

- 11 How does exposure to light (hr) affect the growth of bean plants (cm)?

12 a Year

- b In general, in areas where fishing is prohibited, there is a larger density of fish than in areas that are open to fishing. However, both conditions have similar fluctuations, with a peak in 2016.
- c The graph shows relatively large error bars for both conditions and, at times, the error bars overlap for both the fishing prohibited as well as open to fishing conditions. As such, it's not certain that there was a difference in fish density between both conditions.
- 13 The statement is not accurate. According to the graph, tobacco was the leading risk for tracheal, bronchus and lung cancer for both male and females.

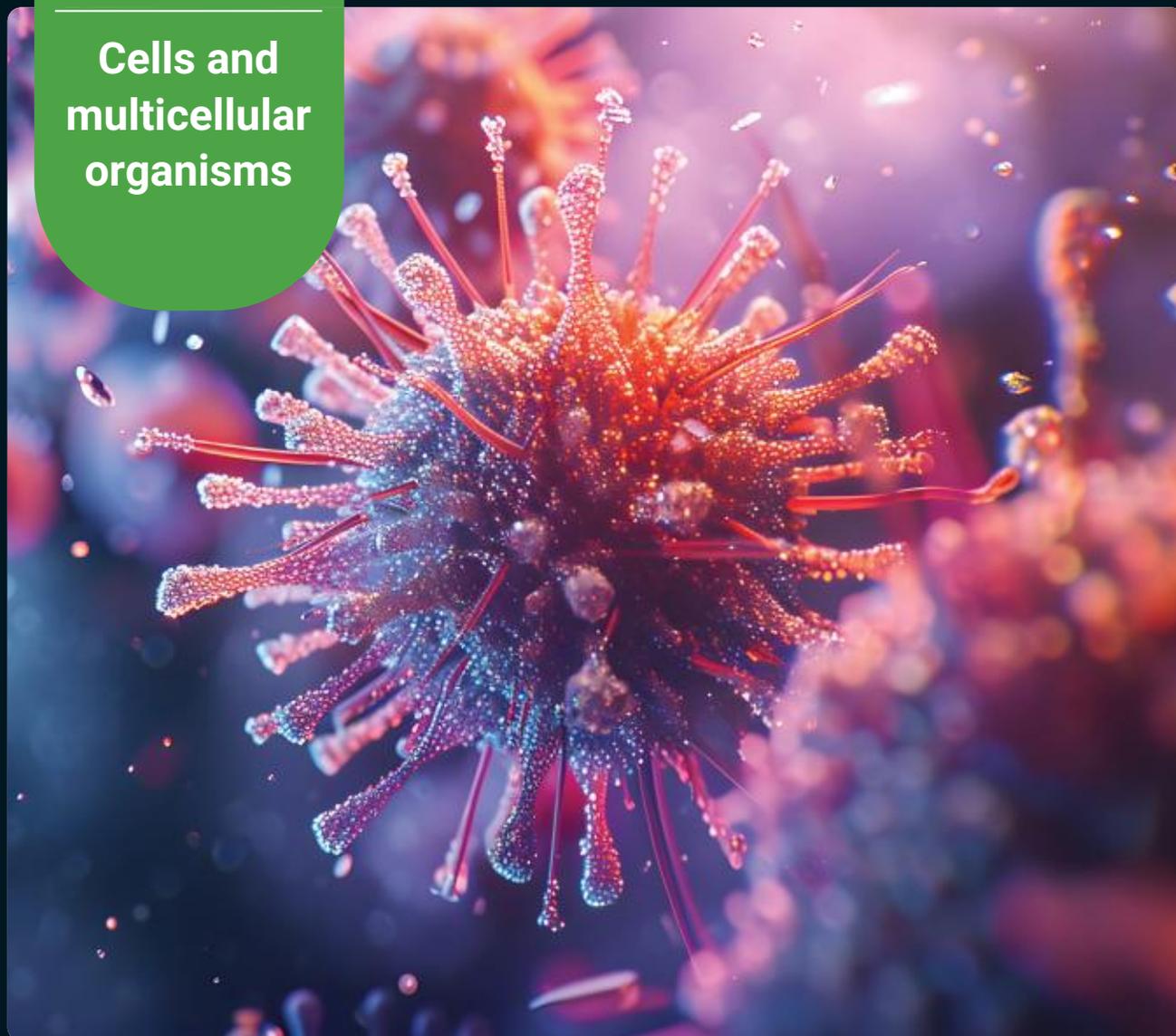
14 Changes in mean heights of plants (cm) at varying light intensities over a 4-week period



UNIT

1

Cells and multicellular organisms



BeautyStock/Adobe Stock Photos

Topic 1: Cells as the basis of life

CHAPTERS RELATED TO THIS TOPIC AREA: 1, 2 and 3

Topic 2: Exchange of nutrients and wastes

CHAPTERS RELATED TO THIS TOPIC AREA: 3 and 4

Topic 3: Cellular energy, gas exchange and plant physiology

CHAPTERS RELATED TO THIS TOPIC AREA: 3, 5 and 6

All organisms, no matter how simple in arrangement, are made up of structurally similar units, called cells. All cells have many similar features. Reasons for differences in some features are so that organisms can function more effectively. Single-celled organisms carry out all of the functions related to the need to exchange matter and energy with their immediate environment. Multicellular organisms are made up of more than one cell and are more structurally complex. These organisms are made up of specialised cells, which are organised to carry out specific functions vital for survival.

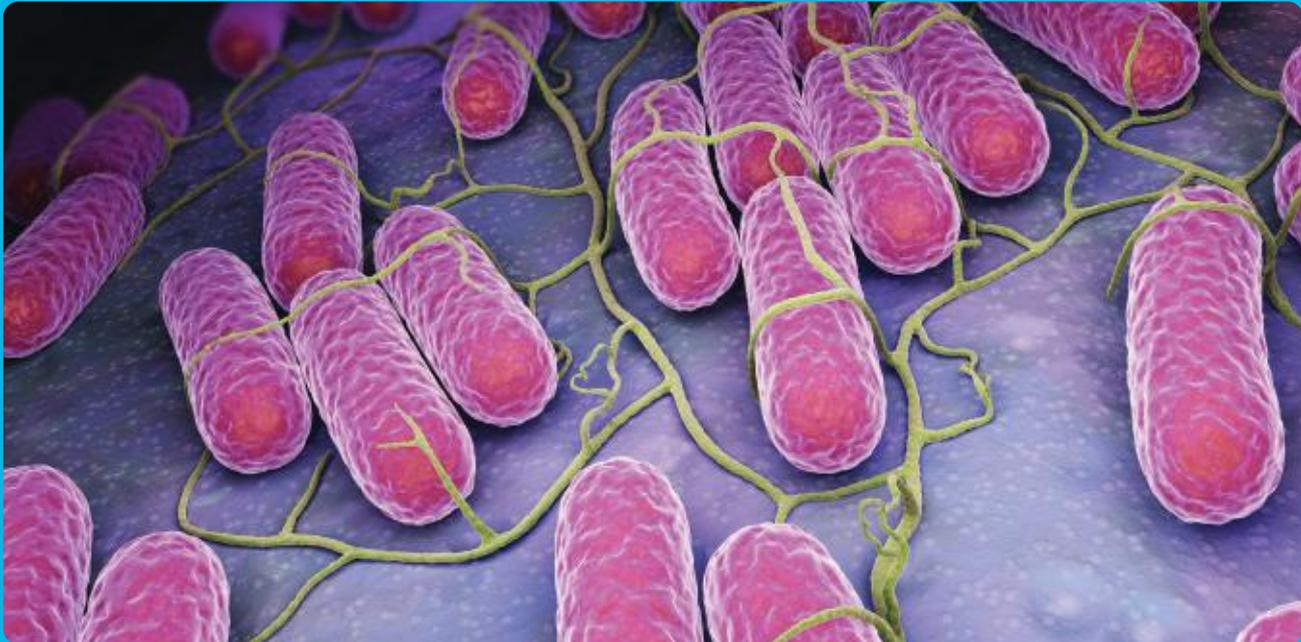
UNIT OBJECTIVES

By the end of this unit, students should be able to:

1. describe ideas and findings about cells as the basis of life; exchange of nutrients and wastes; and cellular energy, gas exchange and plant physiology
2. apply understanding of cells as the basis of life; exchange of nutrients and wastes; and cellular energy, gas exchange and plant physiology
3. analyse data about cells as the basis of life; exchange of nutrients and wastes; and cellular energy, gas exchange and plant physiology
4. interpret evidence about cells as the basis of life; exchange of nutrients and wastes; and cellular energy, gas exchange and plant physiology
5. evaluate processes, claims and conclusions about cells as the basis of life; exchange of nutrients and wastes; and cellular energy, gas exchange and plant physiology
6. investigate phenomena associated with cells as the basis of life; exchange of nutrients and wastes; and cellular energy, gas exchange and plant physiology.

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Cells and cell specialisation



iStockphoto/iLexx

SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- Compare prokaryotic and eukaryotic cells.
- Identify key organelles and their functions, including the nucleus, mitochondria, rough ER, ribosomes, smooth ER, Golgi apparatus, lysosomes, vacuoles and chloroplasts.
- Describe how stem cells originate through the process of mitosis and differentiate into specialised cells to form tissues.
- Distinguish between unipotent, multipotent, pluripotent and totipotent stem cells.
- Explain that each body system contains specialised cells and tissues that are structurally suited to function, including
 - size and shape (SA:V ratio)
 - organelle composition.





SCIENCE INQUIRY

- Use a light microscope or photographs to:
 - view tissues from the respiratory, circulatory, excretory, digestive and/or plant systems
 - calculate total magnification and field of view.
- Compare organelle composition of different cell types using electron micrographs.

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Introduction

Living things have many levels of organisation. Molecules are organised into cells, the smallest unit of living matter. All cells contain genetic material, fluid cytosol and cell structures (the cytoplasm) surrounded by a plasma membrane. As well as being made of one or more cells, living things have certain characteristics in common, including movement, respiration, sensitivity to changes, growth and the ability to replicate or reproduce themselves, excretion (removal of wastes) and nutrition.

There is an amazing diversity of cell shape and structure among all the living things that currently inhabit Earth. In multicellular organisms, these differences in cell structure relate to the specific function of the cells. This specialisation of cells allows the whole organism to function more efficiently in its environment, and thus survive to reproduce and ensure the continuation of the species.

Practicals

- Calculating field of view and magnification
- Investigating cells

Worksheets

- Cell structure
- Comparing types of cells
- Prokaryotic and eukaryotic cells
- Stem cell research



 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap

ASSUMED KNOWLEDGE

- ✓ Living things are made from cells.
- ✓ MRS GREEN – movement, reproduction, sensitivity, growth, respiration, excretion, nutrition.
- ✓ Use a light microscope.
- ✓ Make a wet mount slide of a plant cell.
- ✓ Eukaryotic cells contain organelles of different types and proportions.
- ✓ Cells can reproduce themselves.
- ✓ Cells can work together in systems to achieve outcomes required for an organism's survival.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ recognise each organelle listed when presented as a diagram or an electron micrograph
- ✓ state the clear facts or features about the function of each organelle
- ✓ identify and state similarities and differences between prokaryotic and eukaryotic cells
- ✓ make clear why the similarities and differences identified are important
- ✓ assemble a wet mount slide to observe cells under a light microscope
- ✓ describe what happens to the DNA in each step of mitosis and cytokinesis, including the name of each stage and arrangement of chromosomes
- ✓ state what type of cell can be developed from totipotent, pluripotent, multipotent and unipotent cells
- ✓ describe how changing the shape of a cell can increase its surface area to improve the surface area-to-volume ratio
- ✓ describe and explain how changing the proportion and distribution of organelles can ensure a cell completes a specific function.

1.1 Prokaryotic cells

prokaryotic cell a simple type of cell that lacks a nucleus and membrane-bound organelles; a member of domain Archaea or Bacteria

plasmid a small ring of DNA that is not a chromosome, most often found in prokaryotes

organelle a specialised structure or compartment within a cell that has a specific function

ribosome a small structure in all cells that builds amino acids into complex proteins; is not bound by a membrane

Prokaryotic cells exist as single cells and are grouped within two major classification domains: Bacteria and Archaea. They are very small, typically 1–10 µm in length and 0.2–2.0 µm in diameter. This is significantly smaller than eukaryotes, which range in size from 10 to 100 µm. Prokaryotic cells are the simplest type of cell (**Figure 1.1.1**). They contain a granular cytoplasm where the chemical reactions of life are carried out.

The genetic material in prokaryotes is contained in a single, circular chromosome of DNA. It lies in direct contact with the cytoplasm, rather than inside a nucleus. Numerous small rings of DNA, called **plasmids**, may also be present in the cytoplasm. These can reproduce independently of the main chromosome.

The lack of membrane-bound **organelles** limits the ability of prokaryotes to complete multiple cell processes simultaneously as all metabolic activity occurs in the cytoplasm. This is one reason why prokaryotic cells are typically smaller than eukaryotic cells.

Ribosomes are another clearly distinguishable structure in prokaryotic cells. Although ribosomes are too small to be seen with a light microscope, under an electron microscope they are clearly visible, scattered throughout the cytoplasm. Both prokaryotic and eukaryotic cells contain ribosomes, which synthesise proteins using instructions from DNA.

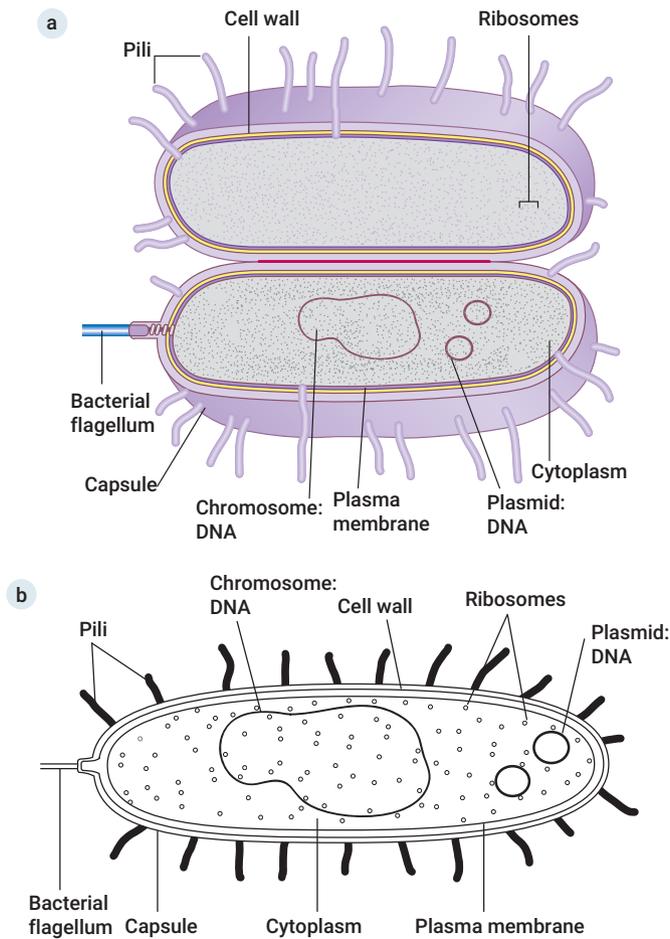


FIGURE 1.1.1 (a) A generalised diagram of a prokaryotic cell; (b) a line drawing of the cell



Weblink
Prokaryotic cell
interactive diagram

LEARNING CHECK 1.1

DESCRIBING

- 1 **Describe** the nature and location of genetic material in prokaryotic cells.
- 2 **Identify** one structure in a prokaryotic cell.
- 3 **Describe** what plasmids are.

APPLYING

- 4 **Explain** the main limitation of not having membrane-bound organelles.

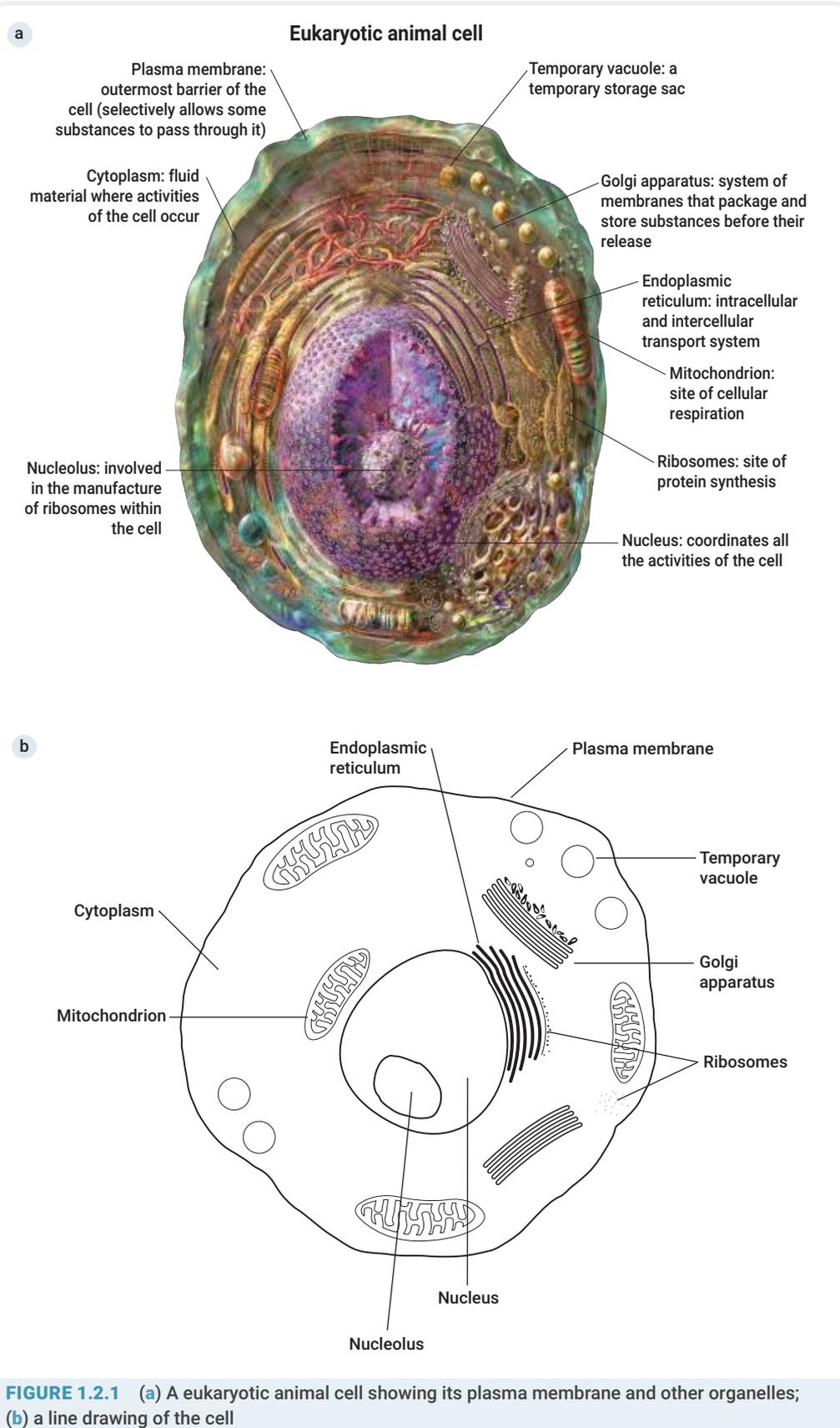
1.2 Eukaryotic cells

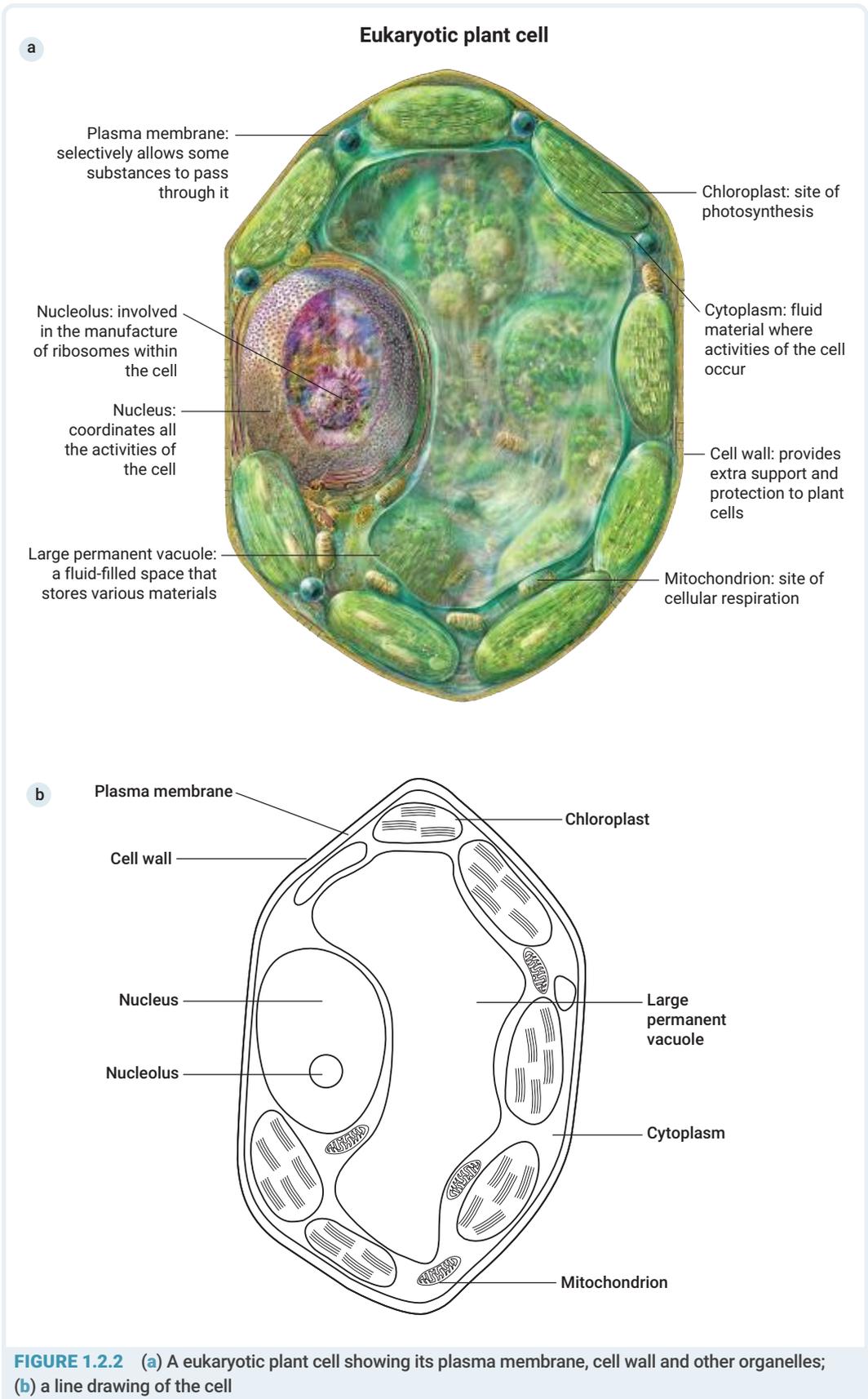
Unlike prokaryotes, **eukaryotic cells** have a number of membrane-bound organelles. The organelles provide distinct compartments for specific reactions, allowing the reactions to occur simultaneously without interfering with each other (**Figures 1.2.1 and 1.2.2**).

eukaryotic cell a complex type of cell with a nucleus and membrane-bound organelles; a member of domain Eukarya



Weblink
Eukaryotic cell interactive
diagram





Nucleus – the control centre

nucleus the organelle in a eukaryotic cell containing most of the DNA; its function is to coordinate cell activities

The **nucleus** consists of a nuclear membrane (envelope) that has inner and outer layers (**Figure 1.2.3**). Within the nuclear membrane is the chromatin (DNA and proteins generally organised as chromosomes), the nucleolus (where ribosomes are made) and the nucleoplasm (the fluid that fills the nucleus).

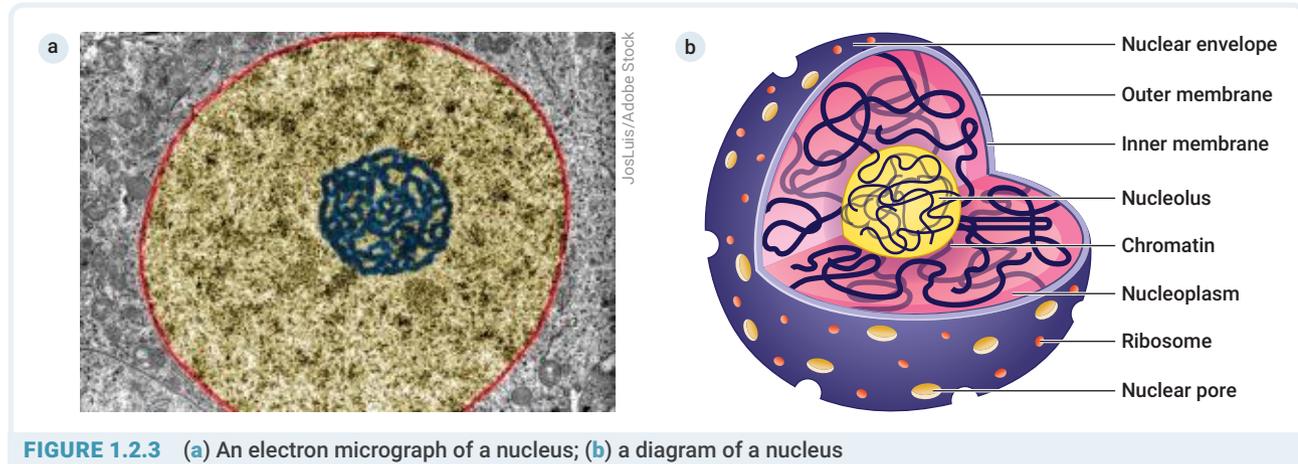


FIGURE 1.2.3 (a) An electron micrograph of a nucleus; (b) a diagram of a nucleus

Each chromosome consists of a strand of deoxyribonucleic acid (DNA) wrapped around proteins called histones. The cell's activity is controlled and regulated by the information encoded in the DNA. Information is transcribed into messenger RNA (mRNA), which leaves the nucleus through the nuclear pores to allow for protein synthesis to be completed in the cytoplasm at ribosomes.

Chloroplasts – the site of photosynthesis

chloroplast an organelle in plant mesophyll tissue that uses light energy to make glucose through photosynthesis

Chloroplasts are oval-shaped organelles in plant cells that are bound by a double membrane (**Figure 1.2.4**). Photosynthesis, a series of chemical reactions powered by light energy, occurs within the internal thylakoid membrane system and the fluid stroma. Photosynthesis combines carbon dioxide and water to produce glucose, oxygen and water (with more water used than produced). This conversion of light energy into chemical energy is made possible by chlorophyll – a green pigment contained in chloroplasts – and a number of enzymes. The thylakoid membrane system is suspended in the gel-like stroma. Thylakoids are arranged in stacks called grana and

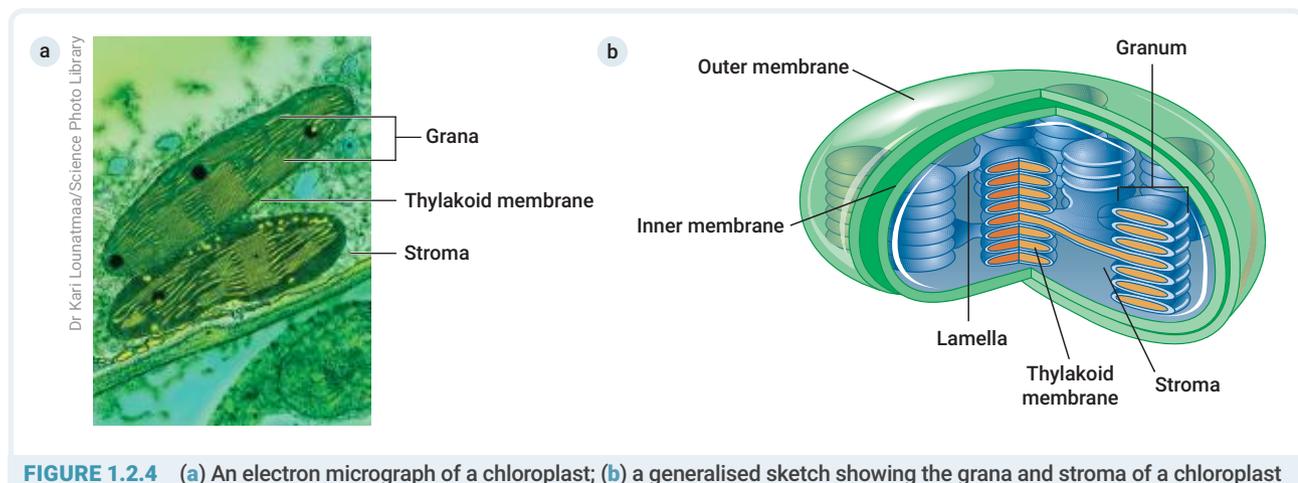


FIGURE 1.2.4 (a) An electron micrograph of a chloroplast; (b) a generalised sketch showing the grana and stroma of a chloroplast

long, interconnecting thylakoid membranes called lamellae link the stacks. Enzymes occur on the thylakoid membrane system and in the stroma of chloroplasts. Chloroplasts have their own DNA and ribosomes, reflecting their evolutionary link with prokaryotes. The starch granules that are commonly seen in the stroma are temporary stores of the products of photosynthesis.



Syllabus link
Photosynthesis will be discussed in more detail in Chapter 6.

Mitochondria – the site of cellular respiration

Cellular respiration is a series of chemical reactions that produce carbon dioxide and water from glucose and oxygen. In eukaryotic cells, the first stage of cellular respiration takes place in the cytoplasm. The remaining stages take place in the **mitochondria** (singular: mitochondrion). Mitochondria are small, rod-shaped organelles scattered throughout the cytosol of a cell (**Figure 1.2.5**). Each mitochondrion consists of an outer smooth membrane and a highly folded inner membrane. The folds in the inner membrane are called **cristae**. The enzymes for cellular respiration are mainly embedded in the cristae, and the numerous folds of the cristae provide a large surface area for the chemical reactions to occur. Mitochondria also contain their own DNA and ribosomes.

mitochondrion an organelle within the cytoplasm that is the site of aerobic cellular respiration, which releases energy for the cell

cristae the folds of the inner membrane into the matrix of the mitochondria, thus increasing the total surface area of the inner membrane

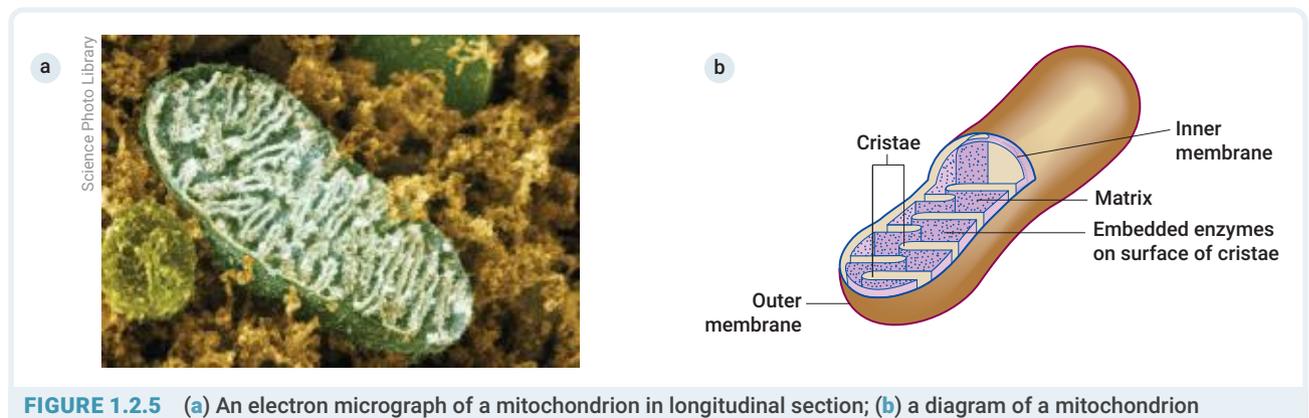


FIGURE 1.2.5 (a) An electron micrograph of a mitochondrion in longitudinal section; (b) a diagram of a mitochondrion

Rough endoplasmic reticulum – synthesis of proteins

Some ribosomes are scattered freely throughout the cytoplasm, but in eukaryotes, many ribosomes are attached to the **endoplasmic reticulum** (ER).

The ER is an interconnecting system of thin membrane tubules creating compartments and channels in the cytosol. Much of the ER is studded with ribosomes, giving it a rough appearance, and is known as the **rough endoplasmic reticulum** (rough ER) (**Figure 1.2.6**). Proteins that end up at the Golgi apparatus are transported from the ribosomes into the ER lumen, where folding, modification and assembly occur.

endoplasmic reticulum an organelle in eukaryotic cells consisting of an interconnecting system of thin membrane sheets dividing the cytoplasm into compartments and channels

rough endoplasmic reticulum endoplasmic reticulum with ribosomes attached

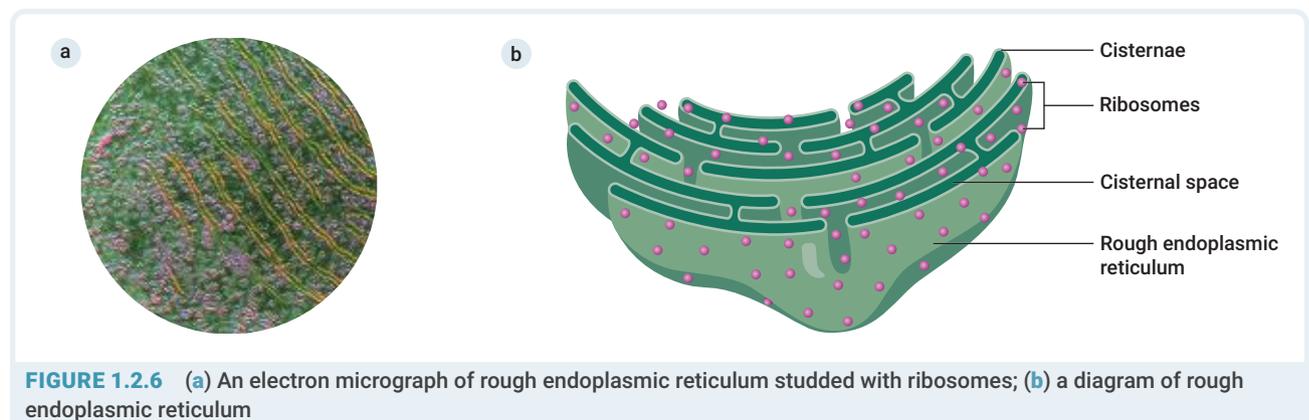


FIGURE 1.2.6 (a) An electron micrograph of rough endoplasmic reticulum studded with ribosomes; (b) a diagram of rough endoplasmic reticulum

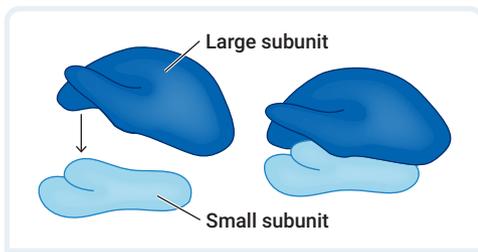


FIGURE 1.2.7 A eukaryotic ribosome, showing both subunits

Ribosomes

As mentioned previously, ribosomes synthesise proteins from amino acids. Proteins are needed for organisms to grow, repair damage and make new cells. In animals, proteins are also important digestive enzymes and hormones. Ribosomes are made of ribonucleic acid (RNA) and protein. Each eukaryotic ribosome consists of two subunits – the smaller 40S subunit that decodes genetic material and the larger 60S subunit that acts as a catalyst for peptide bond formation (**Figure 1.2.7**). Free ribosomes typically synthesise proteins that are not required by the endoplasmic reticulum. There is a difference in size between eukaryotic

and prokaryotic ribosomes, with prokaryotic ribosomes generally being smaller. Note that ribosomes are not bound by a membrane.

Smooth endoplasmic reticulum – synthesis of carbohydrates, lipids and steroids

smooth endoplasmic reticulum endoplasmic reticulum with no ribosomes attached

In certain parts of some cells, the ER has no ribosomes attached and is known as the **smooth endoplasmic reticulum** (smooth ER) (**Figure 1.2.8**). The smooth ER provides an increased surface area for the storage of key enzymes and their products. It also plays a role in the transport of materials. Smooth ER is responsible for lipid manufacture and metabolism, and has a role in detoxification and in metabolising glycogen.

Two important lipids synthesised in the smooth ER are phospholipids and cholesterol, which are the components of cell membranes. Cholesterol is also a precursor for the synthesis of another group of lipids – steroids, which are also produced by the smooth ER.

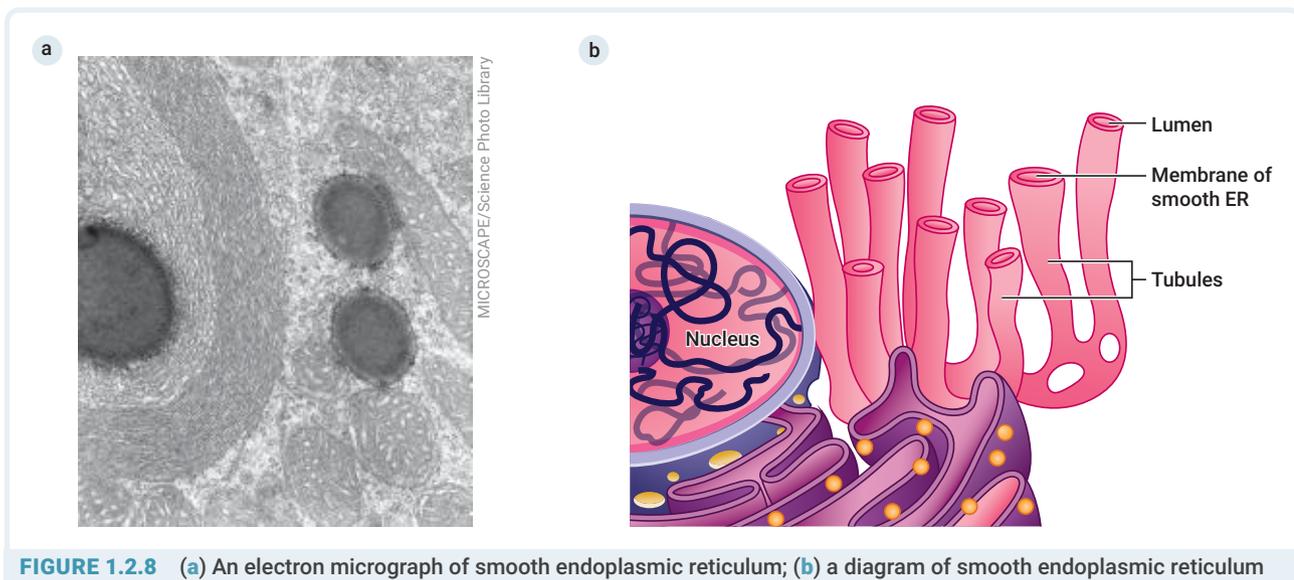


FIGURE 1.2.8 (a) An electron micrograph of smooth endoplasmic reticulum; (b) a diagram of smooth endoplasmic reticulum

Golgi apparatus an organelle in eukaryotic cells that processes, sorts and packages proteins and lipids to be transported towards the cell membrane

Golgi apparatus

The **Golgi apparatus** (or Golgi body) is an organelle that processes, sorts and packages newly formed proteins and lipids into vesicles for transport. It consists of multiple folds of tubular membranes called cisternae and is usually located near the nucleus (**Figure 1.2.9**).

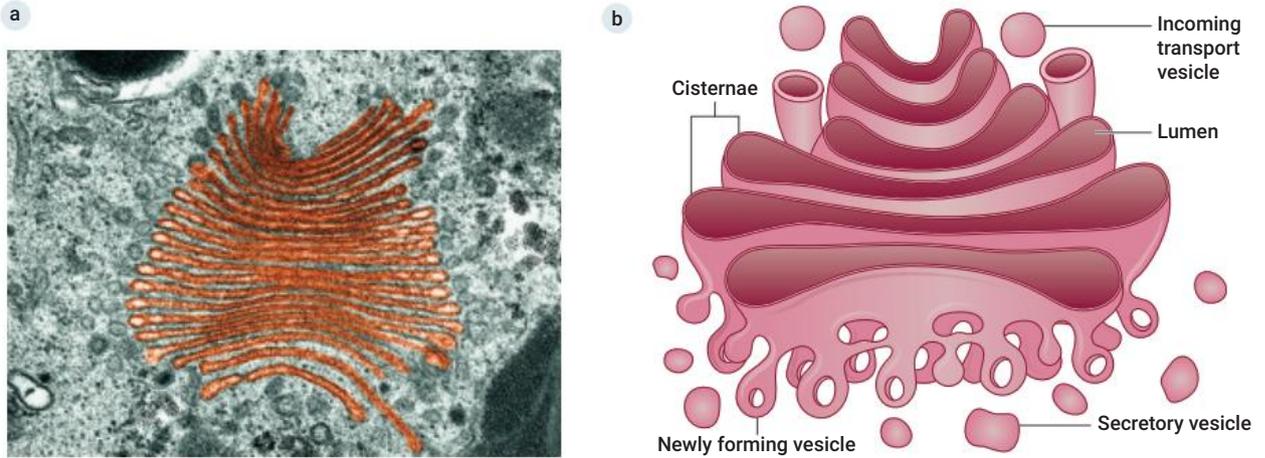


FIGURE 1.2.9 (a) An electron micrograph of the Golgi apparatus; (b) a diagram of the Golgi apparatus

Lysosomes

Lysosomes are spherical vesicles varying in size from 0.1 to 1.2 μm that are involved in the recycling and reuse of cellular material (Figure 1.2.10). They contain enzymes that can break down almost all types of biomolecules, splitting complex chemical compounds into simpler ones. These simpler subunits can then be used as building blocks for new compounds and organelles within the cell.

lysosome an organelle that contains enzymes that break down biomolecules into smaller units

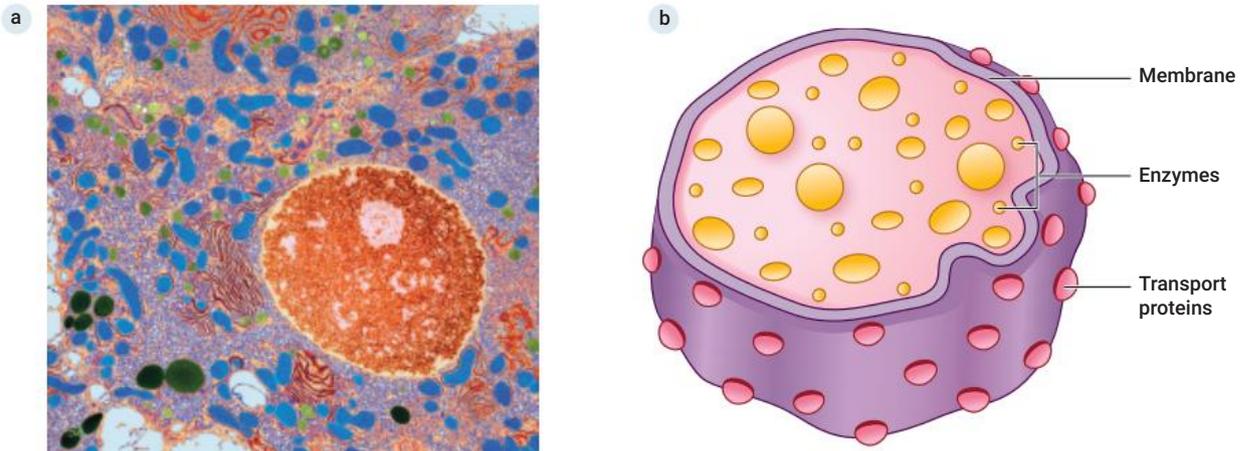


FIGURE 1.2.10 (a) An electron micrograph of a lysosome; (b) a diagram of a lysosome

Vacuoles

Vacuoles occur in both plant and animal cells and are predominantly water. The function of the vacuoles varies slightly depending on the type of cell. Animal cells typically have many small vacuoles containing waste products, toxins or water. Plant cells typically have one large vacuole that is predominantly water and takes up much of the cell's volume. In plant cells, vacuoles store different materials, while also helping to maintain water balance and the structure of the cell.

vacuole an organelle that is predominantly made up of water and stores different materials (including waste products); in plants, they also help with water balance and cell structure

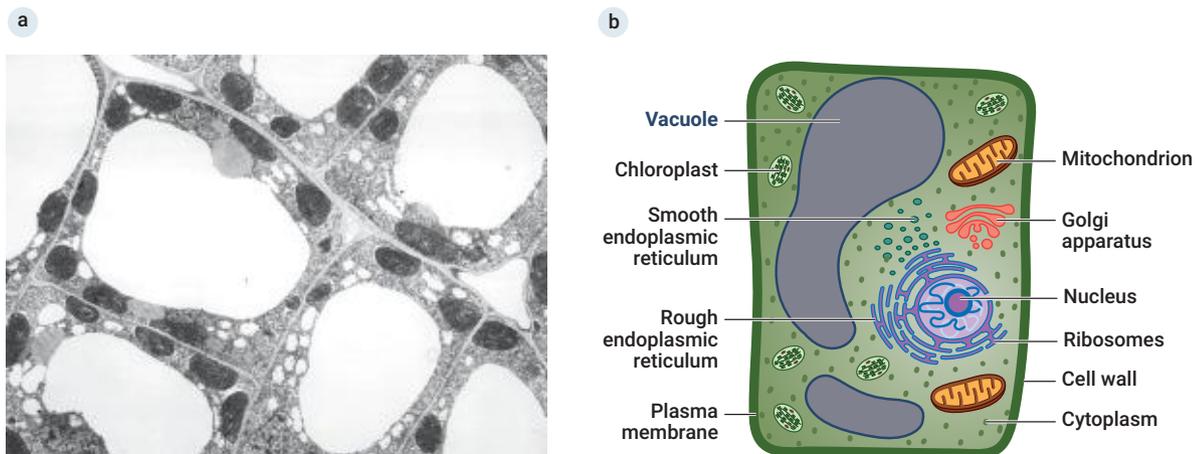


FIGURE 1.2.11 (a) An electron micrograph of a plant vacuole; (b) a diagram of a plant vacuole



Weblink
Eukaryotic cells

Other cell components

Other important structures include the centriole and the cytoskeleton. Centrioles play an important role in cell replication and the cytoskeleton helps provide structure and organisation within a cell, especially during movement and cell division.

Table 1.2.1 is a summary of the key functions and properties of the organelles above.

TABLE 1.2.1 Summary of the function and properties of key organelles

Organelle	Main function	Properties
Nucleus	Contains genetic material and controls cellular activity	Membrane-bound; contains DNA and histones; has nuclear pores Visible under a light microscope
Chloroplasts	Photosynthesis	Not found in animal cells Visible under a light microscope
Mitochondria	Cellular respiration	Has an outer smooth membrane and highly folded inner membrane Slightly visible under a light microscope but without much detail
Ribosomes	Synthesis of proteins from amino acids	Made up of two subunits (40S and 60S) Not visible under a light microscope
Rough endoplasmic reticulum	Protein synthesis as well as the transport of materials	Consists of thin membrane sheets with ribosomes attached Not visible under a light microscope
Smooth endoplasmic reticulum	Metabolism of carbohydrates, lipids and steroids Also helps with transport of materials	Consists of thin membrane sheets No ribosomes Not visible under a light microscope
Golgi apparatus	Processing, sorting and packaging proteins and lipids	Folds of tubular membranes Not visible under a light microscope
Lysosome	Breaks down biomolecules so that they can be recycled and reused in the cell	Spherical and contains enzymes Not visible under a light microscope
Vacuole	Stores materials Plant vacuoles help maintain water balance and cell structure	Contains predominantly water (plants) Visible under a light microscope

LEARNING CHECK 1.2

DESCRIBING

- 1 Match each structure with its function.

Organelle/structure	Function
a Nucleus	i Breakdown of materials
b Endoplasmic reticulum	ii Photosynthesis and storage
c Lysosome	iii Synthesis and transport
d Mitochondria	iv Control centre of the cell
e Chloroplast	v Cellular respiration, which releases energy to the cell

- 2 **Identify** the substances produced by smooth ER.
3 **Describe** the role of rough ER.

APPLYING

- 4 **Explain** the differences between:
a chlorophyll and a chloroplast
b rough and smooth endoplasmic reticulum
c a chloroplast and a mitochondrion.
- 5 **Explain** why plant cells still need mitochondria despite being able to make their own food.
6 **Explain** why you would expect to find more mitochondria in muscle cells than in skin cells.



Worksheet
Cell structure

1.3 Comparing prokaryotic and eukaryotic cells

A common evolutionary past

Evidence suggests that the first prokaryotes originated around 3.5 billion years ago; however, it was not until 1.8 billion years ago that the first eukaryotes appeared.

The **endosymbiotic theory** proposes that eukaryotic cells were formed when a bacterial cell was ingested by another primitive prokaryotic cell (**Figure 1.3.1**). The larger prokaryotic cell would have ingested the smaller cell by engulfing it in a process known as phagocytosis. Instead of being digested, the bacteria formed a symbiotic relationship with its host.

Scientists believe that mitochondria and chloroplasts evolved through this process of endosymbiosis, where one species lives inside another. When they reproduce, mitochondria and chloroplasts make copies of themselves and split in two, just like bacteria. Mitochondria and chloroplasts can only form from pre-existing mitochondria and chloroplasts. They cannot be formed in a cell that lacks them. Both mitochondria and chloroplasts have two membranes. The outer one is probably derived from the host membrane when it engulfed the bacteria, and the inner one is probably the membrane of the ingested bacteria.

The most obvious distinguishing feature between eukaryotic cells and prokaryotic cells is the presence or absence of a nucleus. Prokaryotic cells contain a single circular chromosome that lies in direct contact with the cytoplasm. By contrast, the chromosomes of eukaryotic cells are separated from the cytoplasm by a double membrane, forming a large nucleus, obvious under a light microscope.

endosymbiotic theory
a theory that suggests that chloroplasts and mitochondria arose from ancient prokaryotic cells that were ingested by other prokaryotic host cells



Weblinks
Prokaryotes and eukaryotes review

Eukaryotic and prokaryotic cell drag and drop

Worksheets
Comparing types of cells
Prokaryotic and eukaryotic cells

In both prokaryotic and eukaryotic cells, the outer boundary, the cell membrane, encloses the cell cytoplasm. The cytoplasm is made up of cytosol together with cell organelles. The cytosol is the fluid part of the cytoplasm that contains many dissolved substances where chemical reactions occur.

WORKED EXAMPLE 1.3.1

Compare prokaryotic and eukaryotic cells. Explain why eukaryotic cells are able to grow larger than prokaryotic cells.

ANSWER

1 Determine the cognitive verb in the question.

Remember that when **comparing**, you need to identify similarities and differences that are relevant.

2 Identify the similarities and differences between prokaryotic and eukaryotic cells.

Similarities: Both cell types contain genetic information in the form of DNA. The cell contents are bound by a plasma membrane that regulates exchange of nutrients and waste with the cell's environment. Both cells contain ribosomes. Both cells contain cytoplasm as the location for chemical reactions.

Differences: Eukaryotic cells contain membrane-bound organelles, including a nucleus that contains DNA. Prokaryotic cells do not have organelles. The DNA is located directly in the cytoplasm.

3 Use the similarities and differences to explain.

Both cell types contain genetic information in the form of DNA. The cell contents are bound by a plasma membrane that regulates exchange of nutrients and waste with the cell's environment. Both cells contain ribosomes. However, eukaryotic cells contain membrane-bound organelles, including a nucleus, whereas prokaryotic cells do not. Although both cells have DNA to control cell function and ribosomes for protein synthesis, eukaryotic cells can carry out more functions simultaneously because of the presence of organelles that compartmentalise cellular functions. This means that eukaryotic cells are typically larger than prokaryotic cells.

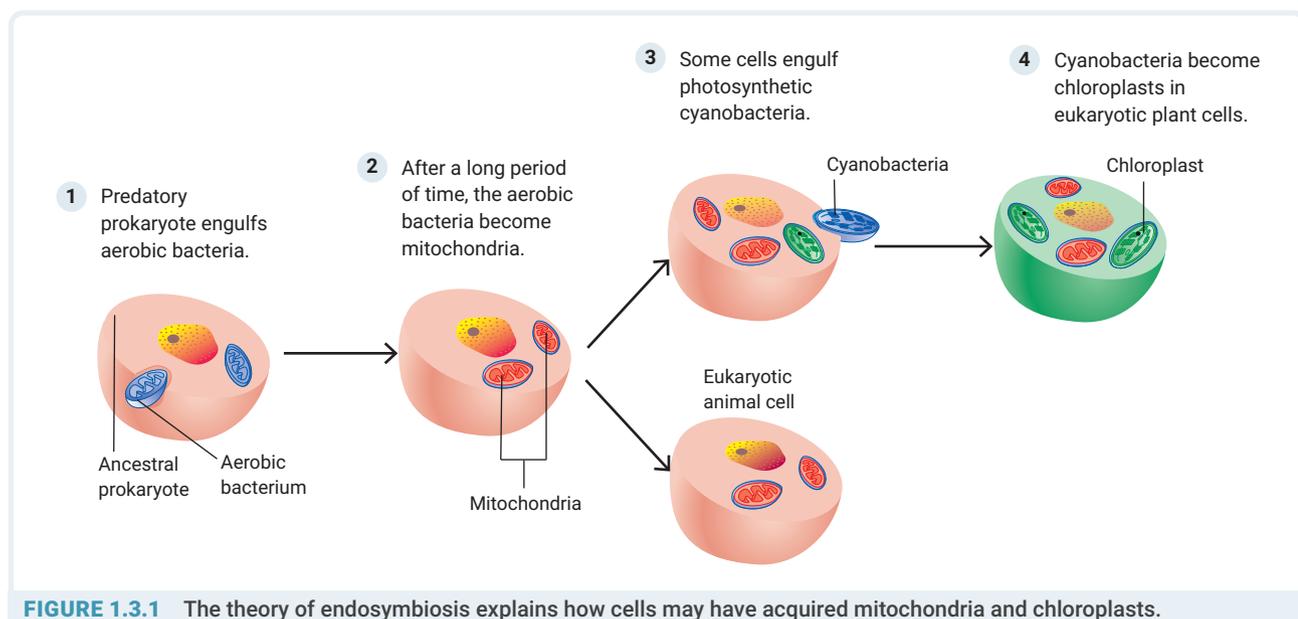


FIGURE 1.3.1 The theory of endosymbiosis explains how cells may have acquired mitochondria and chloroplasts.

Table 1.3.1 compares the structures of prokaryotic and eukaryotic cells.

TABLE 1.3.1 A comparison of prokaryotic and eukaryotic cells

Characteristic	Prokaryotic cell	Eukaryotic cell
Organelles	No internal membrane-bound organelles	Internal membrane-bound organelles
Chromosomes	Single, circular and free	Multiple, linear and inside the nucleus
Ribosomes	Present	Present but different size from prokaryotic ribosomes
Endoplasmic reticulum	Absent	Present
Microtubules	Absent	Present
Enzymes used for cellular respiration	Attached to plasma membrane	Attached to internal membrane of mitochondria
Chloroplasts	Absent: enzymes of photosynthesis attached to lamellae	Present: enzymes of photosynthesis attached to internal membranes of chloroplasts
Lysosome	Absent: enzymes similar to those in a lysosome occur in the cytoplasm	Present
Vacuole	Absent	Present
Mitochondria	Present	Present
Cell wall	Present but not made of cellulose	Present in plants and fungi

LEARNING CHECK 1.3

DESCRIBING

- 1 **Identify** the features that are common to all cells.
- 2 State the evidence for a common evolutionary origin of mitochondria and chloroplasts.
- 3 **Identify** features that are unique to:
 - a prokaryotic cells
 - b eukaryotic cells.

APPLYING

- 4 **Explain** the difference between cytoplasm and cytosol.

ANALYSING

- 5 **Compare** the structure of chromosomes in prokaryotic and eukaryotic cells.

INTERPRETING

- 6 A large cell of 0.3 mm length was observed. Ribosomes were present in the cytoplasm but no other organelles. Would this be a prokaryotic or eukaryotic cell? **Justify** your answer. **Identify** further evidence that would be useful in your argument.

1.4 Using a microscope

In a light microscope, light rays from a light source beneath the stage are transmitted through two glass lenses in series: the objective lens (usually $\times 4$, $\times 10$ or $\times 40$ magnification) and ocular (eyepiece) lenses (usually $\times 10$ magnification). Depending on their strength, these two lenses provide magnifications of up to 400 times, calculated by:

Magnification = magnification power of eyepiece lens \times magnification power of objective lens

This magnifies many cellular structures enough to be seen (**Figure 1.4.1**). More sophisticated technology is needed to view the smallest parts of cells.

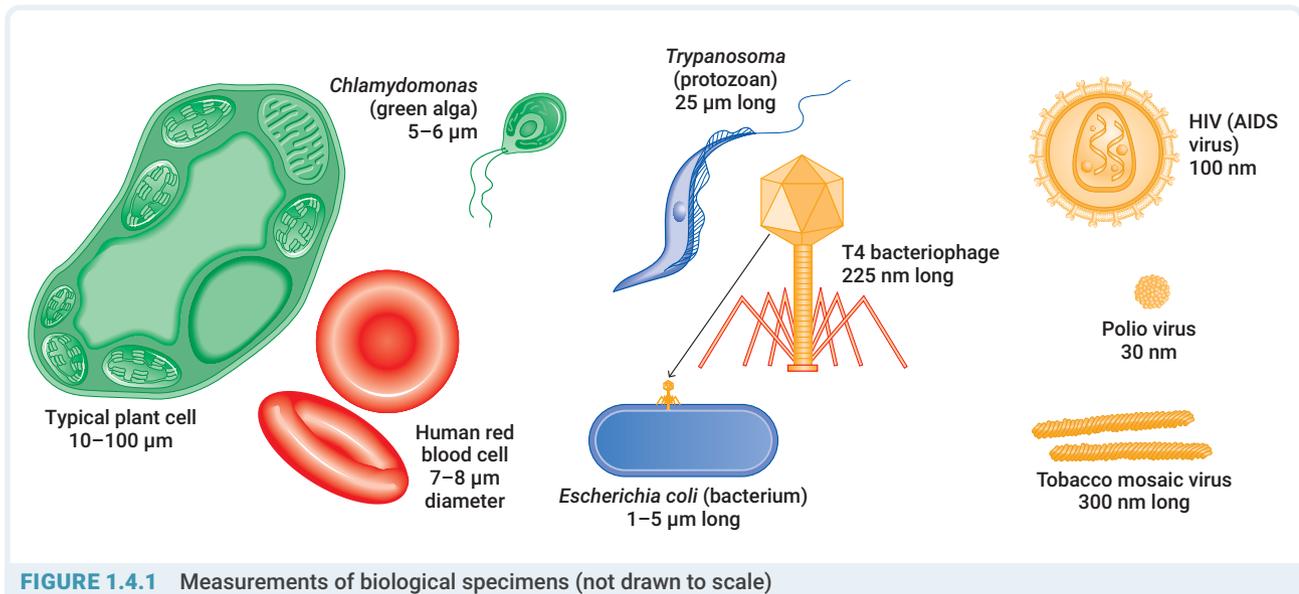


FIGURE 1.4.1 Measurements of biological specimens (not drawn to scale)

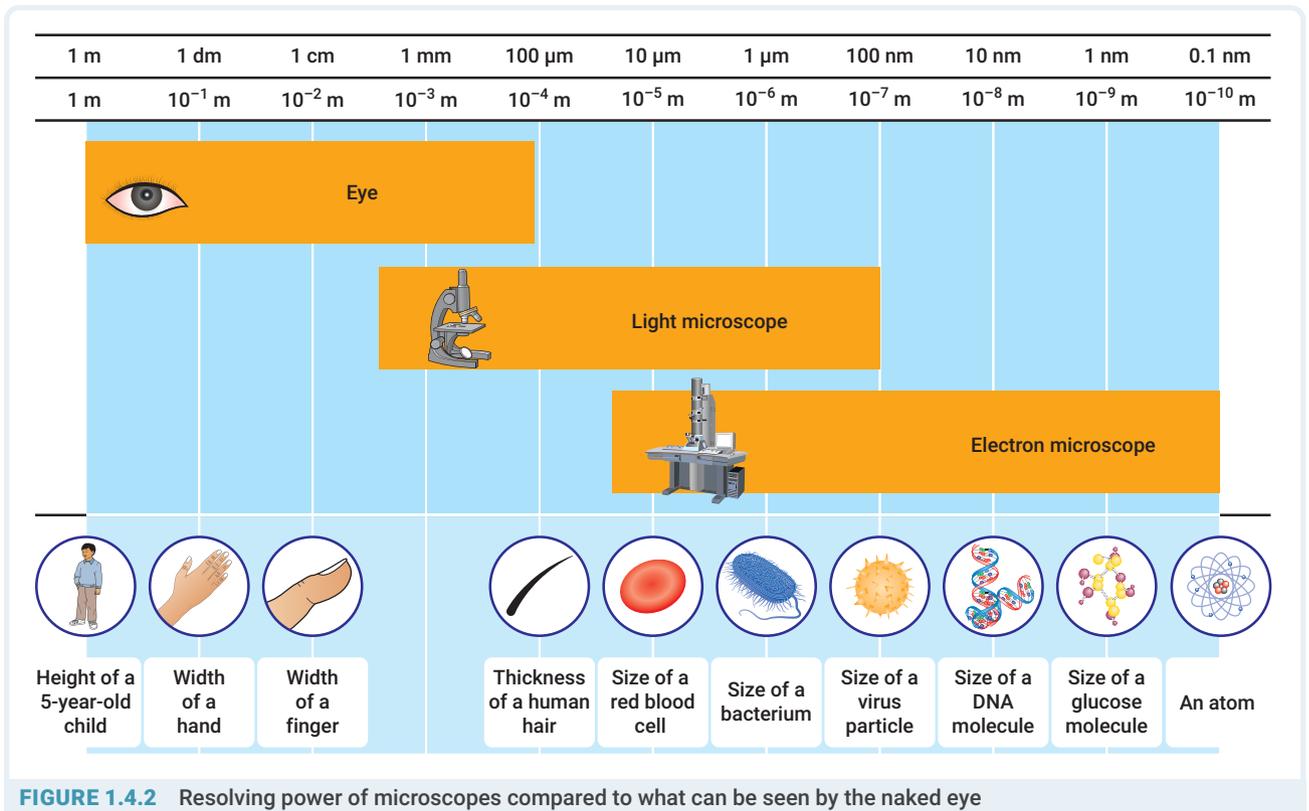
In the 1950s, cell biology was revolutionised by the development of the electron microscope. This instrument uses an electron beam instead of light, and electromagnets instead of glass lenses. The interactions between the electrons and the specimen are recorded as an image on a screen.

The electron microscope can give clear pictures of material magnified 1 000 000 times or more (**Figure 1.4.2**) as electrons pass through a specimen (transmission electron microscope or TEM) or are bounced off the specimen surface (scanning electron microscope or SEM).

Field of view (FOV) is the area visible through the lenses of a microscope. It is quantified as the diameter of the area seen through the lens of a microscope. This information can be used to estimate the size of the object being examined.

Calculating the diameter of the FOV under high power (HP) involves the lower-power (LP) magnification and the high-power (HP) magnification according to the following rule:

$$\text{Diameter (HP)} = \frac{\text{diameter (LP)} \times \text{magnification (LP)}}{\text{magnification (HP)}}$$



WORKED EXAMPLE 1.4.1

Calculate the diameter (HP) given a low-power field (LP) diameter of 3 mm and magnifications of 40 (LP) and $\times 100$ (HP).

ANSWER

1 Identify the values of each variable.

Diameter LP = 3 mm

Magnification LP = $\times 40$

Magnification HP = $\times 100$

2 Substitute the values of each variable into the appropriate equation to calculate the diameter (HP).

$$\begin{aligned} \text{Diameter HP} &= \frac{3 \times 40}{100} \\ &= 1.2 \text{ mm} \end{aligned}$$

The value of the diameter (HP) can be used to approximate the size of the cell being examined through a multistep process. However, it is also possible to determine the size of cells or cell structures using a much simpler formula:

$$\text{Actual size} = \frac{\text{image size}}{\text{magnification}}$$

By rearranging this formula it is also possible to determine magnification:

$$\text{Magnification} = \frac{\text{image size}}{\text{actual size}}$$

It is important to ensure that the units for the image and actual size are the same (e.g. both millimetres (mm) or both micrometres (μm)).

WORKED EXAMPLE 1.4.2

Determine the magnification given that the image size is 5 cm and the actual size of the cell is 50 μm .

ANSWER

- 1 **Ensure that the units of both image size and actual size are the same.**

Image size = 5 cm = 50 mm

Actual size = 50 μm = 0.050 mm

- 2 **Calculate the magnification of the microscope.**

$$\begin{aligned}\text{Magnification} &= \frac{50}{0.050} \\ &= \times 1000\end{aligned}$$

LEARNING CHECK 1.4

DESCRIBING

- 1 **Identify** the type of microscope most appropriate to view a cell of size 0.9 nm.
- 2 Copy and complete [Table 1.4.1](#).

TABLE 1.4.1 Calculation of magnification

Objective lens	Total magnification eyepiece lens \times 10	Total magnification eyepiece lens \times 5
$\times 4$		
$\times 10$		
$\times 40$		

INTERPRETING

- 3 Look carefully at the photograph of the unidentified cell in [Figure 1.4.3](#).
 - a **Determine** whether the cell is from a prokaryote or eukaryote. Give reasons for your answer.
 - b **Determine** whether this photograph was taken with an electron or light microscope. Give your reasons.
 - c Some organelles may be present in this cell but are not shown in the photograph. **Deduce** why this might be the case.
 - d **Deduce** whether this is an animal cell or plant cell, based on organelles i and ii.
- 4 A student was given cell specimens at the following widths:
 - 1.1 mm
 - 0.3 mm
 - 0.50 mm.

The student was also provided with set-up 1 and set-up 2.

Deduce whether set-up 1 or set-up 2 is best for viewing each cell. Provide reasoning.

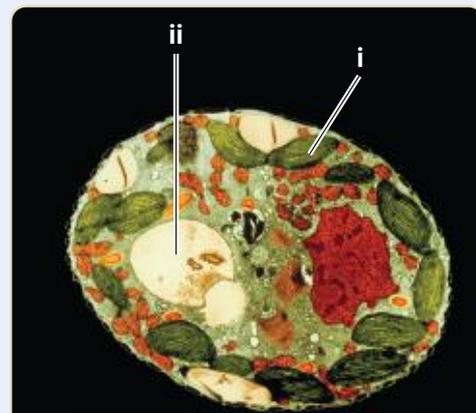


FIGURE 1.4.3 An electron micrograph of an unidentified cell

Set-up 1:

- Magnification (LP): $\times 20$
- Magnification (HP): $\times 40$
- Diameter (LP): 2.5 mm

Set-up 2:

- Magnification (LP): $\times 10$
- Magnification (HP): $\times 100$
- Diameter (LP): 4.0 mm

PRACTICAL ACTIVITY 1.4.1

CALCULATING FIELD OF VIEW AND MAGNIFICATION

Introduction

When viewing a cell under the microscope, we can determine the size of the cell using the following rule:

$$\text{Diameter (HP)} = \frac{\text{diameter (LP)} \times \text{magnification (LP)}}{\text{magnification (HP)}}$$

Once the HP diameter is known, the approximate size of the cell or cell structure can be determined.

It is also possible to determine the size of cells or cell structures using this formula:

$$\text{Magnification} = \frac{\text{image size}}{\text{actual size}}$$

$$M = \frac{I}{A}$$

Once two values are known, the final variable can be calculated. It is important to ensure that the units for the size of 'image' and 'actual' are the same, e.g. both mm or μm .

Aim

Skill development: To calculate the size of cells or cell structures

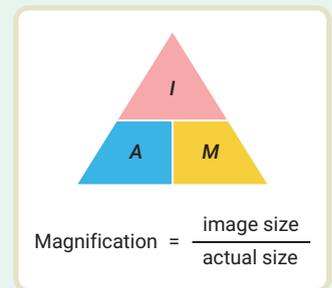
Part A – Diameter of HP magnification

Materials

- microscope
- transparent ruler

Procedure

- 1 Set up a light microscope on the LP objective lens (usually $\times 4$).
- 2 Calculate the LP total magnification.
- 3 Place a clear plastic ruler across the stage and focus on the markings.
- 4 Record the diameter of the FOV in mm. Convert this measurement to mm.
- 5 Calculate the HP total magnification.
- 6 Using the equation above, calculate the HP diameter.



Part B – Actual size of a cell

Materials

- ruler

Procedure

- 1 Look at the image of onion cells in **Figure 1.4.4** and record the magnification.
- 2 Using the ruler, measure the image size in mm.
- 3 Calculate the actual size of the cell by rearranging the equation above: $A = \frac{I}{M}$.

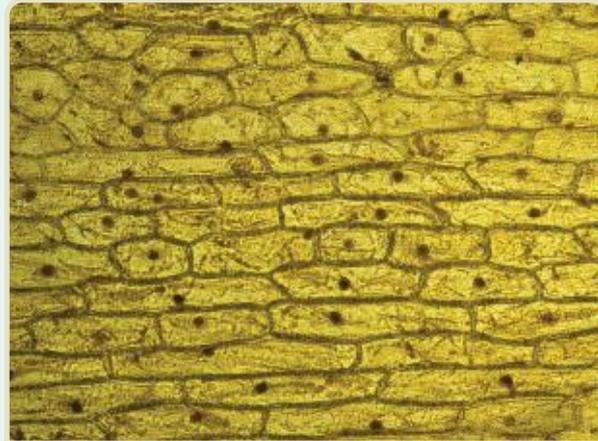


FIGURE 1.4.4 Onion cells at $\times 100$ magnification

PRACTICAL ACTIVITY 1.4.2

INVESTIGATING CELLS

Introduction

Living cells have a range of different structures that enable them to meet their needs.

Research question

Is it possible to observe differences in prokaryotic and eukaryotic cell structure using a light microscope?

Aim

- To revise and refine microscope use, including magnification and field of view
- To learn how to prepare living tissue for observation under the light microscope
- To compare and contrast the structure of eukaryotic and prokaryotic cells, and plant and animal cells

Materials

- *Elodea* plant (or an alternative from an aquarium)
- prepared slide of human cheek cells
- prepared slide of bacteria
- prepared slides of plant and animal tissues
- onion
- methylene blue stain with eye dropper
- light microscope
- microscope slides
- coverslips
- mini-grid
- knife or single-edged razor blade
- tweezers or mounted needles
- eye dropper (optional)
- paper towel
- large beaker of water for used microscope slides and coverslips



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
The knife or razor blade is very sharp.	Take care when using the knife or razor blade and do not walk around the room carrying it.
Coverslips break easily and can cut.	Take care with coverslips and do not push hard when placing them.
Environmental consideration: <i>Elodea</i> is a noxious weed.	Dispose of <i>Elodea</i> safely, away from waterways.

Procedure

- 1 Construct a data table with these headings: Magnification, FOV diameter, Observations, Cell diagram.

Field of view

- 2 Place a mini-grid onto the stage so that it can be seen through the microscope. Work out the diameter across the fields of view at increasing magnifications.
- 3 Record these measurements in a data table.

Plant cell: Onion

- 4 Cut off a piece of the onion. Peel a section of 'membrane' from between the two layers of onion. The membrane will be thin and flexible like plastic wrap (**Figure 1.4.5**).
- 5 Use the knife or razor blade to carefully cut the membrane until it is about the size of a quarter of a fingernail.
- 6 Have a microscope slide ready with a drop of cold water on it.
- 7 Place the small piece of membrane in the drop of water, making sure that it stays flat. Stop it from curling by using tweezers or mounted needles.
- 8 Carefully place a coverslip on top of the onion membrane on an angle to push out any air bubbles. This is known as a 'wet mount'. Check that there is enough water to surround the onion membrane (which should sit well within the boundaries of the coverslip). The water will seep under the coverslip by itself.
- 9 Focus on onion cells under low power and then switch to high power. In the data table, draw a diagram of two or three cells, labelling the nucleus, cytoplasm, cell wall and position of the cell membrane.
- 10 Put one drop of methylene blue stain next to one side of the coverslip (**Figure 1.4.6**). Use some paper towel on the other side of the coverslip to absorb liquid and so draw the stain across under the coverslip.
- 11 Focus on the cells again and identify whether the stain has made any structures more visible.
- 12 Use the mini-grid to measure the dimensions of an onion cell. Alternatively, use the diameter calculations to determine the size of the cells.

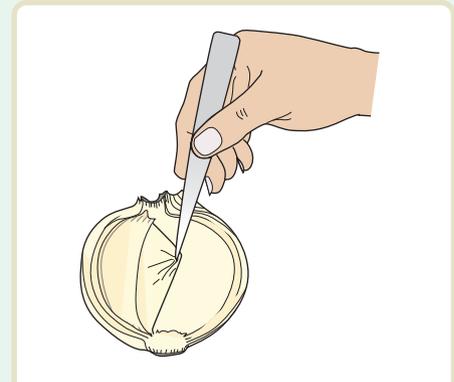


FIGURE 1.4.5 Preparing onion tissue

Plant cell: *Elodea* (or alternative)

- 13 Repeat steps 4–8 using an *Elodea* leaf from the tip of the plant. Float the tissue in warm water instead of cold water.
- 14 View the *Elodea* leaf under low and then high power. Watch it for a few minutes. Record your observations in the table.
- 15 Make a careful diagram of one cell in your data table. Label the cell wall, nucleus, chloroplasts, cytoplasm and position of the cell membrane.
- 15 Stain the *Elodea* cell using methylene blue by following the instructions in step 10.

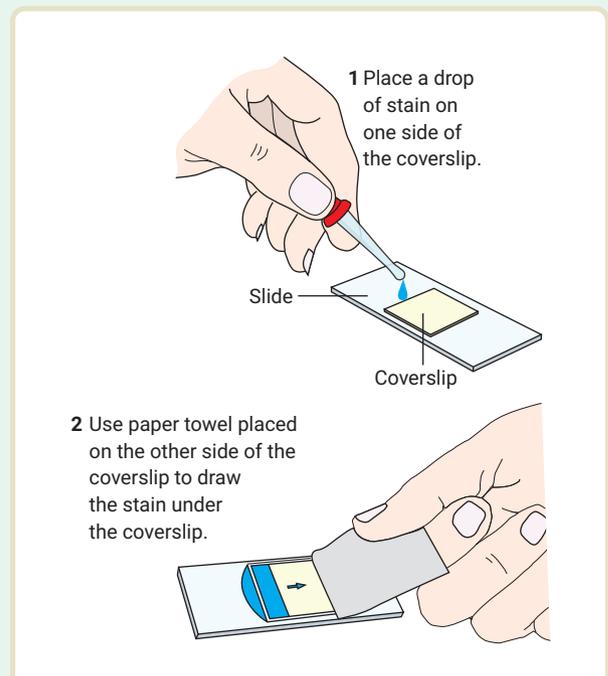


FIGURE 1.4.6 Staining a slide

Animal cell

- 16 Examine the prepared slide of a cheek cell under low power then high power. Make a careful diagram of one of the cells in your data table. Label the plasma membrane, nucleus, cytoplasm and any other structures that you can identify.
- 17 Use a mini-grid to measure the diameter of a cheek cell. Alternatively, use the diameter calculations to determine the size of the cells.
- 18 Look at any additional prepared slides using the light microscope and see if there are any different cell structures that can be identified.

Prokaryotic cell

- 19 Place a prepared slide of bacterial cells onto your microscope stage.
- 20 Use a mini-grid to estimate the dimensions of a bacterial cell.
- 21 Make observations and record any differences you note between the bacterial cell and the eukaryotic cells observed.

Results

Check that the following information has been recorded: labelled diagrams of onion cells, an *Elodea* cell and a bacterial cell. Include the magnification used and size of the cell (in μm).

Analysis of results

- 1 Identify any patterns in the observations made. Consider the:
 - structures in each cell
 - effect of the stain
 - size of each cell.
- 2 When a specimen is viewed under a microscope, it appears larger than it really is. Provide a rule that allows for the magnification of the specimen to be calculated.
- 3 State how many micrometres there are in a millimetre.

Interpretation

- 4 Discuss the detail seen in each of the cells to draw a conclusion relating to the visibility of cell structures when using a light microscope. Decide whether it is possible to distinguish between prokaryotic and eukaryotic cells.

Evaluation

- 5 Describe how the prepared slides used in this investigation compare to the ones prepared from fresh materials. Explain whether one was better to use than the other.

zygote a cell formed by the union of two sex cells; usually fertilisation of an egg cell by a sperm cell

differentiation the process by which unspecialised cells develop special characteristics to suit particular functions

specialise to develop specific features suited to specific functions

stem cell an unspecialised, immature cell capable of differentiating into a specialised cell

1.5 Properties of stem cells

Animal species, including humans, can have up to 200 different types of cells. In each individual organism, this huge variety of cells originates from just the first cell, the **zygote**, formed by the fertilisation of an egg from one parent by a sperm cell from the other parent. Cells that are able to change or **differentiate** into different **specialised** types are called **stem cells**. **Figure 1.5.1** shows undifferentiated embryonic stem cells growing together in a cluster.

All specialised cells originate from stem cells. Stem cells differ from other cells in three important ways.

1. Stem cells are unspecialised; that is, they have not yet developed into a particular type of cell.
2. Stem cells have the potential to divide and replicate for long periods of time.
3. Although stem cells are relatively unspecialised cells, they can differentiate to form different specialised cells.

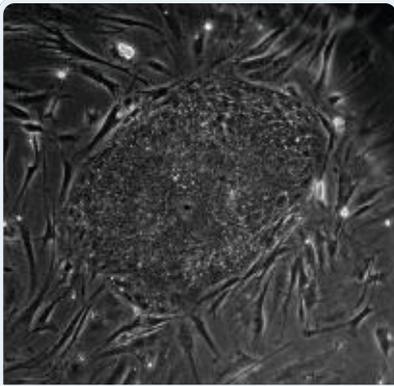


FIGURE 1.5.1 A magnified image ($\times 200$) of thousands of human embryonic stem cells growing together as a colony (the silver cluster of cells in the centre of the image) on top of mouse feeder cells (the dark filamentous structures).

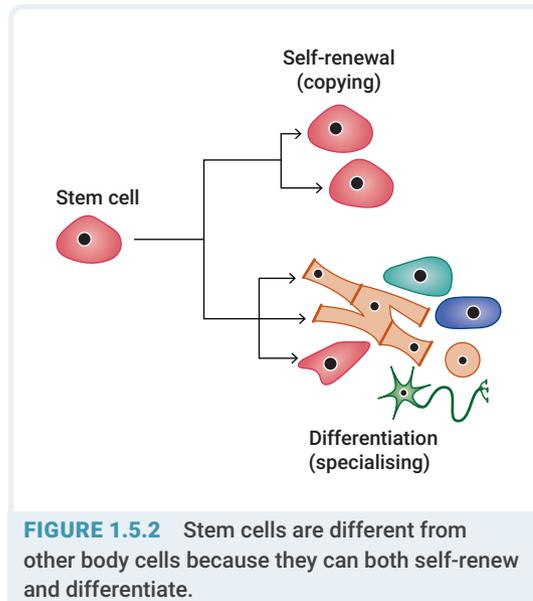


FIGURE 1.5.2 Stem cells are different from other body cells because they can both self-renew and differentiate.



Weblink

What are stem cells?

Potency of stem cells

Stem cells are categorised and named according to their potential to differentiate. A fertilised egg has the potential to develop into a complete embryo. At this point, the fertilised egg, or zygote, is a **totipotent stem cell** (*totipotent* means ‘total potential’). Totipotent stem cells have the potential to develop into any type of cell necessary for embryonic development, including the embryo itself, and all the membranes associated with embryonic development (**Figure 1.5.3**).

The zygote is the original totipotent stem cell that gives rise to all other cells in the human body. The zygote divides to form two identical totipotent cells, which divide to form four, then eight, and so on. Because these cells are still totipotent, any one of them has the potential to develop into an entire human being. Identical twins are formed when a small cluster of totipotent cells separates and two genetically identical embryos develop.

Approximately 5 days after fertilisation, the totipotent stem cells start to specialise to become **pluripotent stem cells**. At this stage, the ball of cells has an outer layer that develops into the placenta, and a distinct small inner cell mass of pluripotent cells, generally referred to as **embryonic stem cells** because they will become the embryo.

Each pluripotent cell then undergoes further specialisation into another type of stem cell, a **multipotent stem cell**. Multipotent stem cells give rise to cells that have a particular function. For example, multipotent blood stem cells give rise to red blood cells, white blood cells and platelets, and multipotent skin stem cells give rise to the different types of skin cells. Multipotent stem cells exist in both embryos and adults (**adult stem cells**), the best understood adult example being the blood stem cell. In each person’s bone marrow, blood stem cells constantly replenish the supply of red blood cells, multiple types of white blood cells and platelets. Adult stem cells in the human body function in the repair of damaged cells and to replenish those cells, such as blood, skin and intestinal lining cells that have a short life span. **Unipotent stem cells** are able to self-renew, but can make only one type of cell; for example, the germline stem cell that produces sperm. **Table 1.5.1** summarises the potency of the different types of stem cells, and **Figure 1.5.4** shows the sequential process of cell differentiation.

totipotent stem cell
a stem cell that can develop into any of the types of cells necessary for embryonic development

pluripotent stem cell
a stem cell that can develop into many, but not all, of the cell types necessary for foetal development

embryonic stem cell
a stem cell that is cultured from an embryo

multipotent stem cell
a stem cell that can develop into a limited number of cell types

adult stem cell
a stem cell harvested from tissues such as bone marrow that are not part of an embryo

unipotent stem cell
a stem cell that can develop into only one type of cell

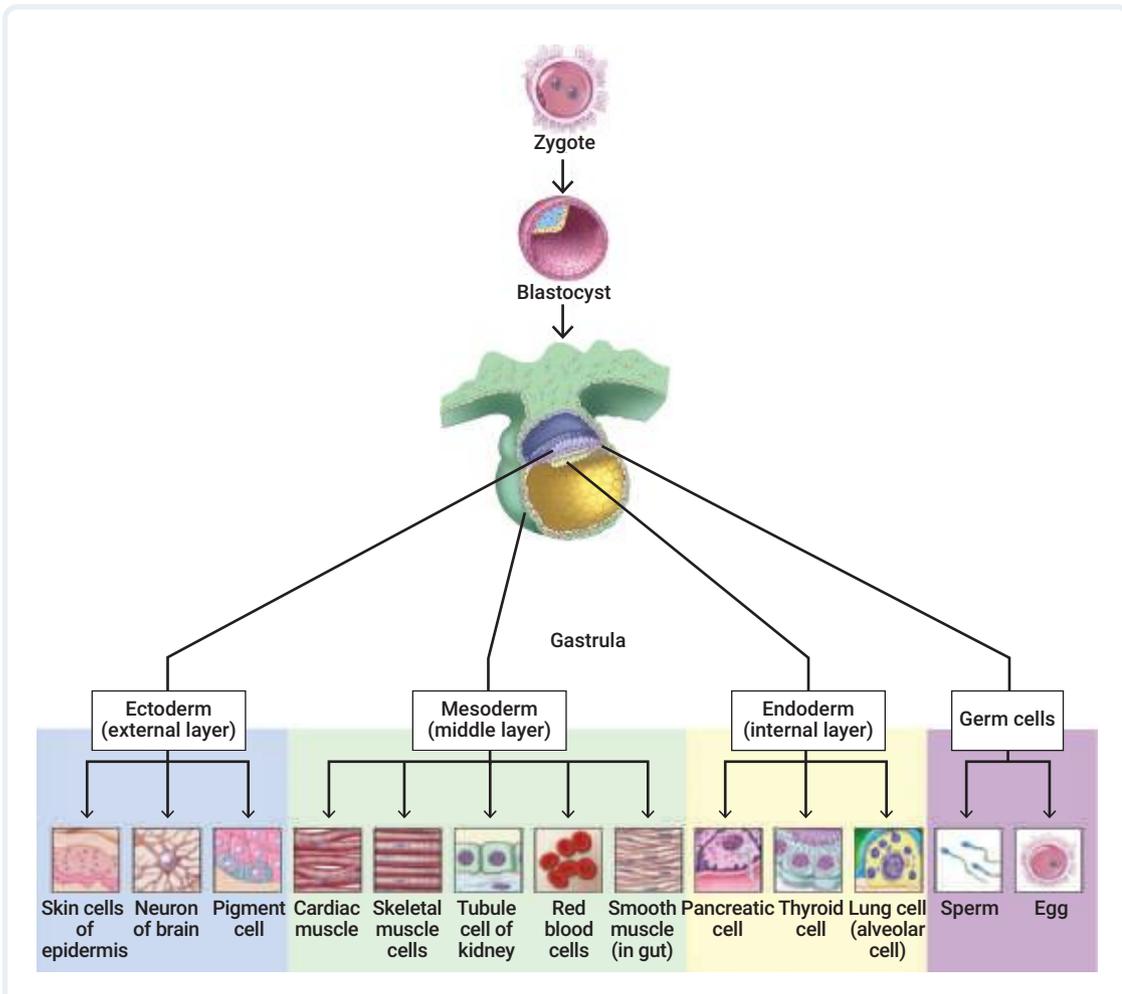


FIGURE 1.5.3 A human zygote cell, the primary stem cell, develops into the multitude of different cell types that make up the human body.

TABLE 1.5.1 The potency of stem cells

Stem cell type	Potential differentiation
Totipotent stem cells	Can give rise to all the cell types that make up the human body and the cell types that make up the membranes that surround the developing embryo (including the placenta, umbilical cord and yolk sac). They are the first few cells found in a zygote.
Pluripotent stem cells	Can give rise to all the cell types that make up the body but <i>not</i> the cell types that make up the embryonic membranes. These are often called embryonic stem cells because they are retrieved from an early embryo.
Multipotent stem cells	Develop into more than one of the cell types that make up the body but <i>not</i> all cell types, i.e. different cells of a particular tissue type such as haematopoietic stem cells that differentiate into red blood cells, white blood cells and platelets.
Unipotent stem cells	These produce only one kind of cell, but they are able to renew themselves. Adult muscle cells are an example.



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Nature of stem cells

Worksheet

Stem cell research

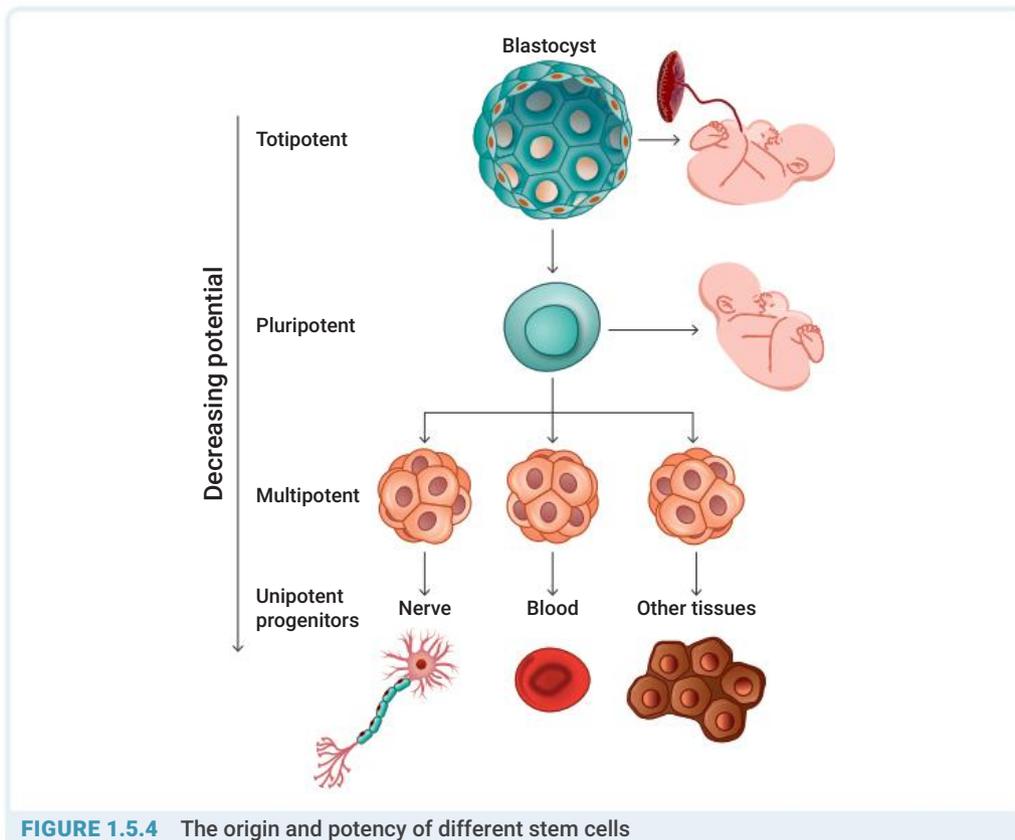


FIGURE 1.5.4 The origin and potency of different stem cells

LEARNING CHECK 1.5

DESCRIBING

- 1 **Identify** two characteristics that are unique to stem cells and not other types of cells.
- 2 **Describe** the difference between totipotent stem cells and unipotent stem cells.

APPLYING

- 3 **Explain** the importance of stem cells in adults.
- 4 The skin is made up of different layers and cells, such as hair follicles and sweat glands. Are skin cells totipotent, pluripotent, multipotent or unipotent? **Explain** your answer.

1.6 Cell cycle and differentiation

Mitosis and the cell cycle

For organisms to repair and grow, cells need to be able to grow and divide. During this process, the cell spends most of its time in interphase, which is made up of G1, S and G2. This is followed by **mitosis**. After mitosis, the cell either re-enters this cell cycle or exits the cell cycle and differentiates to carry out its function.

Cells divide by the process of mitosis and cytokinesis. The cell cycle is divided into four phases, three of which occur in interphase, shown in **Figure 1.6.1**.

mitosis a type of cell division in which a parent cell produces two daughter cells with exactly the same genetic material as each other and as the parent cell

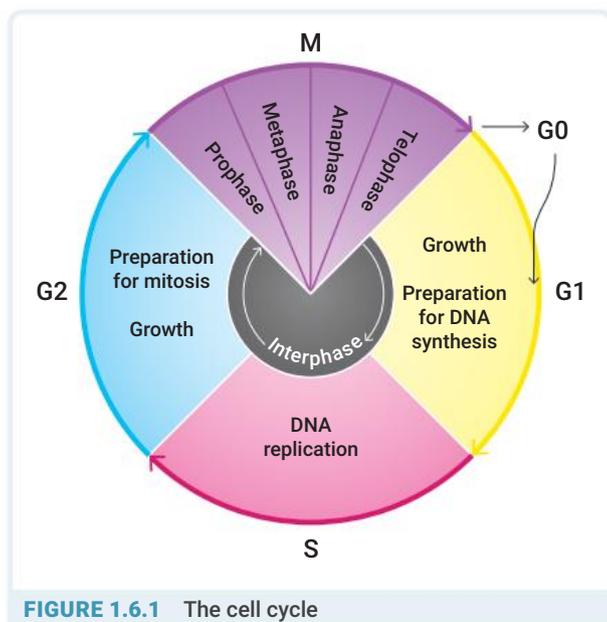


FIGURE 1.6.1 The cell cycle

- Gap 1 or G1 – the cell is preparing to divide.
- Synthesis or S – the DNA is copied (DNA replication occurs).
- Gap 2 or G2 – the DNA is organised and begins to condense.

Interphase is followed by mitosis. After mitosis, some cells continue dividing. Some exit the cell cycle (G0) as they differentiate to carry out a specific function. Others that have exited may re-start division if they get the right signals.

Mitosis is the process of copying then division of the DNA in the nucleus. The chromosomes of the cell replicate then separate to produce two identical nuclei. Mitosis is followed by **cytokinesis**, which ensures the formation of two identical daughter cells, each with one copy of the original chromosomes. All cells are produced by mitosis except sex cells, such as eggs and sperm.

DNA replication occurs during interphase, prior to mitosis. Mitosis occurs in four main phases (**Figure 1.6.2**), although some sources include another phase, prometaphase,

cytokinesis the process in which the parent cell's cytoplasm divides between the two daughter cells

which is included below. Other sources combine prophase and prometaphase as prophase.

- Prophase – DNA condenses to form sister chromatids, held together by a centromere. Centrioles appear and the spindle begins to form.
 - Prometaphase – the nuclear membrane breaks apart and the sister chromatids become attached to the spindle fibres.
 - Metaphase – the centromeres of each pair of sister chromatids line up along the spindle's equator.
 - Anaphase – sister chromatids separate as the centromere breaks down. One copy of each chromatid, now called a chromosome, is drawn to each pole of the cell as the spindle fibre shortens.
 - Telophase – chromosomes reach the poles, decondense and the nuclear membrane reforms.
- These phases are followed by cytokinesis, during which the remaining organelles and cytosol also separate.



Weblink
Cell cycle

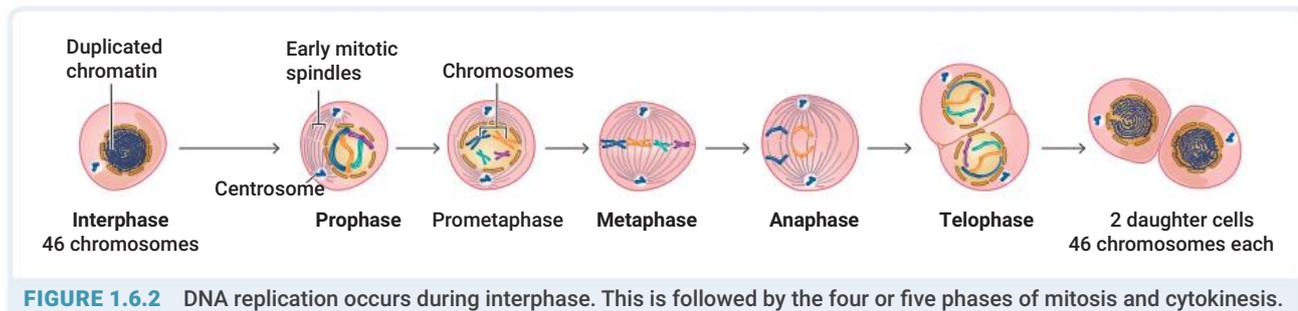


FIGURE 1.6.2 DNA replication occurs during interphase. This is followed by the four or five phases of mitosis and cytokinesis.

The process of mitosis allows bodies to grow and repair. However, specialised cells do not undergo mitosis (there are a couple of exceptions, e.g. T-cells and liver cells). This makes stem cells very important in replacing old or damaged specialised cells. When stem cells undergo mitosis resulting in differentiation, the daughter cells are more specialised than the original stem cell because of molecules within and around cells that can alter the way cells behave.

Scientists think that stem cells divide to produce either two more stem cells or two differentiated cells (symmetrical division). It is also possible for asymmetrical division to occur, where mitosis results in one stem cell and one differentiated cell.

The self-renewal process is needed so that an organism does not run out of cells. This allows for the replacement of specialised cells throughout an organism's lifetime. As a result, differentiation and self-renewal is important in the survival of the organism (Figure 1.6.3).

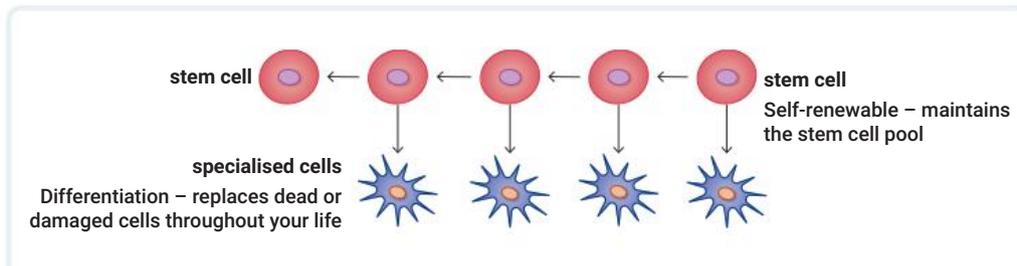


FIGURE 1.6.3 Both differentiation and self-renewal are needed to ensure that specialised cells can be replaced.

Even though the various specialised cells of a multicellular organism contain the same genetic instructions, they don't all look the same and they perform different functions. This is because not all of the genetic information is used in every cell. Only a small portion is actively 'switched on' in each cell; therefore, each cell's function depends on which of the many genetic instructions are actively expressed.

The cell's location in the developing organism, and its immediate environment, determine which genes are activated in the developing cell. The activated genes cause the cell to manufacture particular proteins for the cell to differentiate. As a specialised cell, it has a specific structure that suits its function.

Within a multicellular organism, this specialisation means that there needs to be communication and coordination between cells. Specialised cells rely on other cells to perform tasks that they cannot perform. For example, nerve cells in humans can transport nerve impulses, but they need red blood cells to deliver oxygen, heart muscle cells to pump the oxygenated blood to them and other cells to provide nutrients and remove their wastes. If a nerve cell was isolated, it would not be able to function on its own and would die.

The specialised cells in multicellular organisms are thought to increase the overall efficiency of the organisms, allowing them to carry out a wider variety of biochemical functions without too much duplication of tasks by cells. Therefore, multicellular organisms can perform more complex functions.

LEARNING CHECK 1.6

DESCRIBING

- 1 **Describe** the main phases of mitosis.
- 2 Briefly **describe** the advantages of cells becoming specialised.

APPLYING

- 3 Consider the different types of stem cells. **Explain** how their names fit their potency.
- 4 **Explain** why a zygote is considered to be a stem cell.

INTERPRETING

- 5 Determine whether each of the following is true or false. **Justify** your decisions.
 - a The process of specialisation in cells is called cellular differentiation.
 - b Different types of specialised cells contain different DNA.
 - c All specialised cells originate from stem cells.



Syllabus link

Chapter 3 explores the different systems in further detail.

1.7 Specialised cells

Tissues are made of cells that are specialised through differentiation to have a particular shape and/or proportion of organelles. The systems work together to allow organisms to gain nutrients, exchange gases and remove wastes.

For the digestive, respiratory, circulatory and excretory systems to work effectively, the cells become specialised to carry out a particular function. Below are examples of specialised cells in different systems.

Goblet cells

Goblet cells are epithelial cells with a cell membrane folded into microvilli to increase surface area. They produce mucins (proteins) that are secreted as mucus. Goblet cells have an asymmetrical structure because the cytoplasm is located at the narrow end, closer to the tissue along with the nucleus and other organelles (e.g. mitochondria) (**Figure 1.7.1**). Goblet cells have prominent endoplasmic reticulum and Golgi apparatus to allow the cell to produce and transport the high volumes of mucin proteins. There are also a high number of secretory vesicles close to the cell microvilli.

Their function means that goblet cells are commonly found in the digestive system and respiratory system.

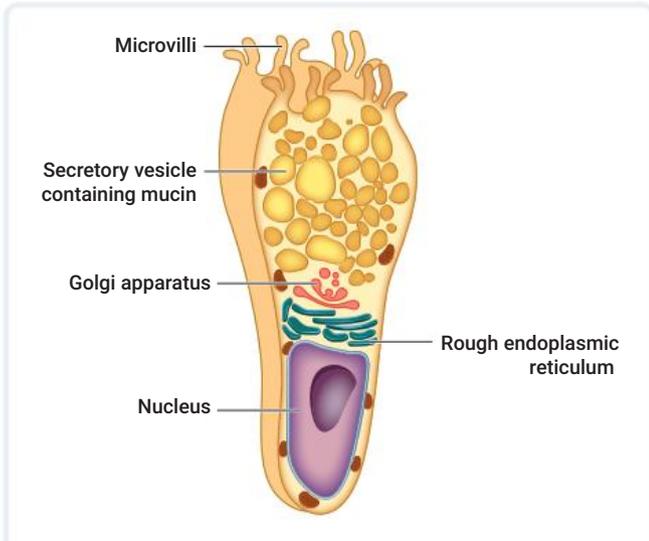


FIGURE 1.7.1 The structure of a goblet cell, showing the distribution and placement of organelles to allow for the production and secretion of high volumes of protein (mucin) as mucus

Epithelial cells

Columnar epithelial cells with microvilli are found in the small intestine. Just like the goblet cell, the cell membrane extensions increase the overall surface area of each epithelial cell (**Figure 1.7.2**). This allows for more nutrients to be absorbed.

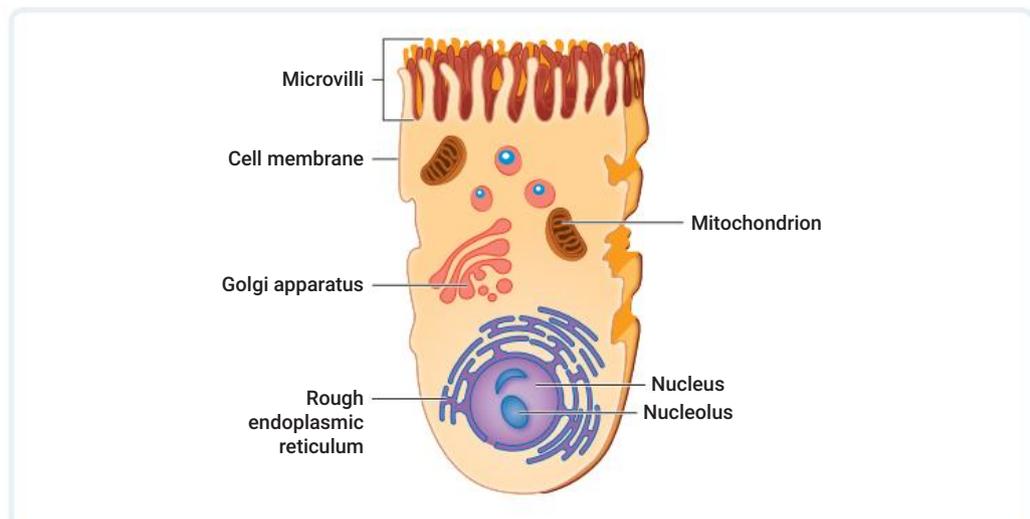


FIGURE 1.7.2 The structure of an intestinal epithelial cell, showing how the cell membrane is folded into microvilli to increase surface area.

Columnar ciliated epithelial cells line the trachea and bronchi. They are rectangular in shape with 200–300 hair-like projections called cilia that move or beat in time to move mucus away from the lungs (Figure 1.7.3). The mitochondria are usually found closer to the cilia, due to ATP (energy) requirements for movement. The nucleus is generally found at the base of the cell.

Simple squamous epithelial cells called type 1 pneumocytes form the alveoli. They have a flattened shape that reduces diffusion distance (Figure 1.7.4). They have a smaller nucleus that tends to be flat and horizontal along with fewer organelles, to facilitate gas exchange. These cells make up 95 per cent of the alveolar surface.

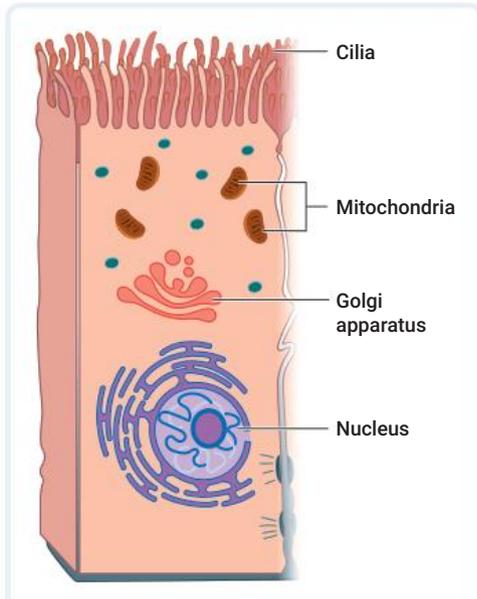


FIGURE 1.7.3 A columnar ciliated epithelial cell in the respiratory tract

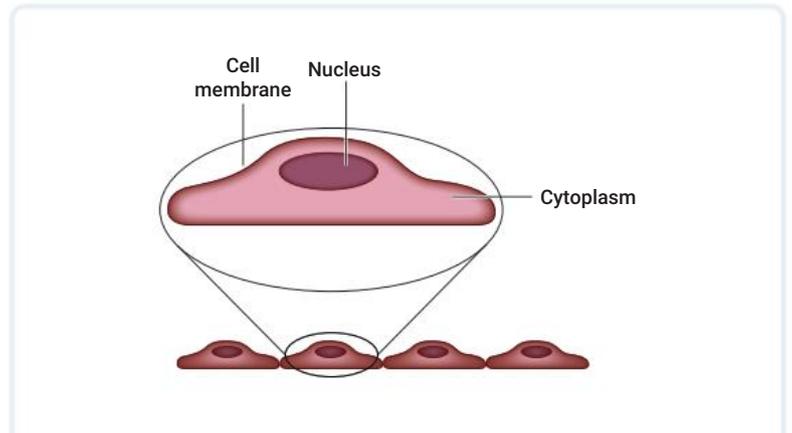


FIGURE 1.7.4 A simple squamous epithelial cell or type 1 pneumocyte in the alveoli of the lungs

Simple cuboidal epithelial cells, which have a brush border, called proximal tubule epithelial cells, are found in the proximal tubule of the nephron of the kidney. The brush border increases the surface area on the inside of the tubule (Figure 1.7.5). These cells are required to transport ions, sugars, amino acids and water, so have a high number of mitochondria. There are also many channels through the membrane on both sides of the cell to allow for the transport of ions and other substances to occur.

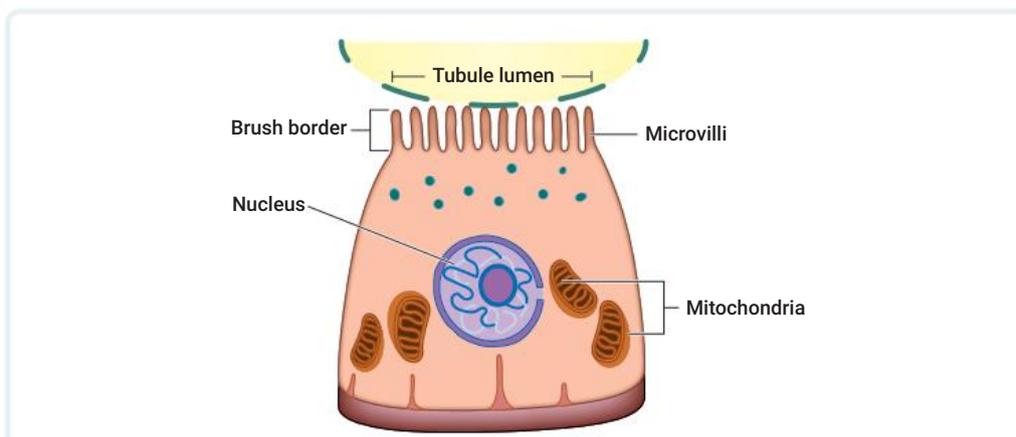
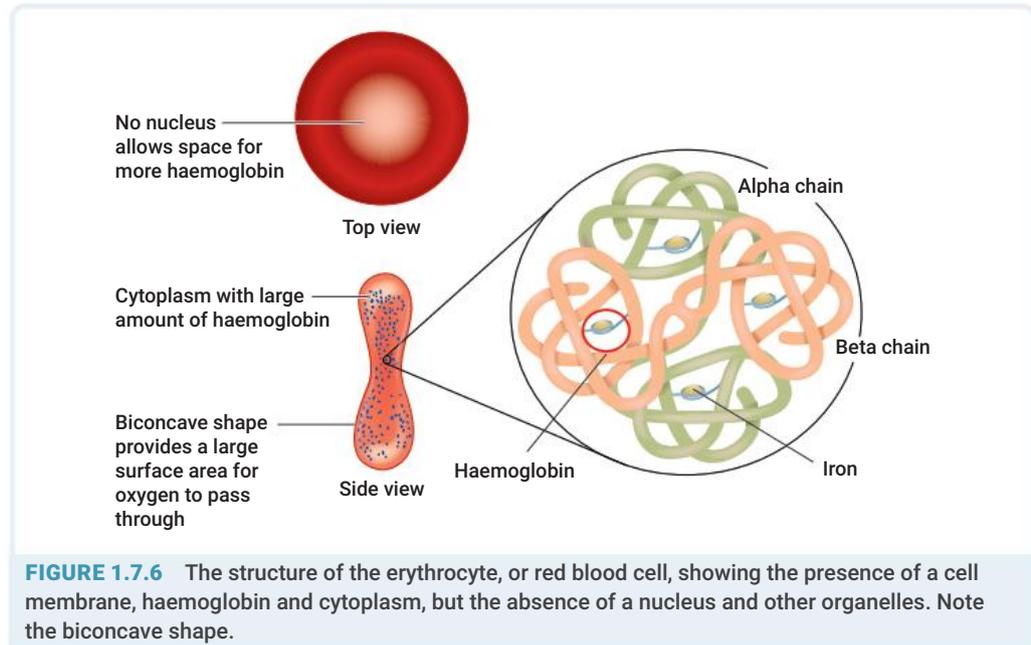


FIGURE 1.7.5 The structure of a proximal tubule epithelial cell showing the increased surface area and relatively high number of mitochondria

Red blood cells

Erythrocytes, or red blood cells, are flat, biconcave discs that do not have a nucleus or other organelles at functional maturity. This allows red blood cells to change shape to fit through narrow capillaries. The absence of organelles also maximises the amount of haemoglobin (the protein that binds to oxygen) present in the red blood cells.



LEARNING CHECK 1.7

DESCRIBING

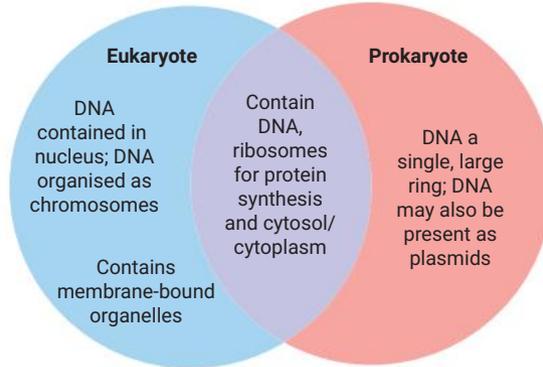
- 1 Using goblet cells as an example, **describe** how the structure of specialised cells assists the cell to perform its functions.
- 2 **Describe** why having mitochondria close to the cilia of epithelial cells in the trachea helps to efficiently remove mucus.

APPLYING

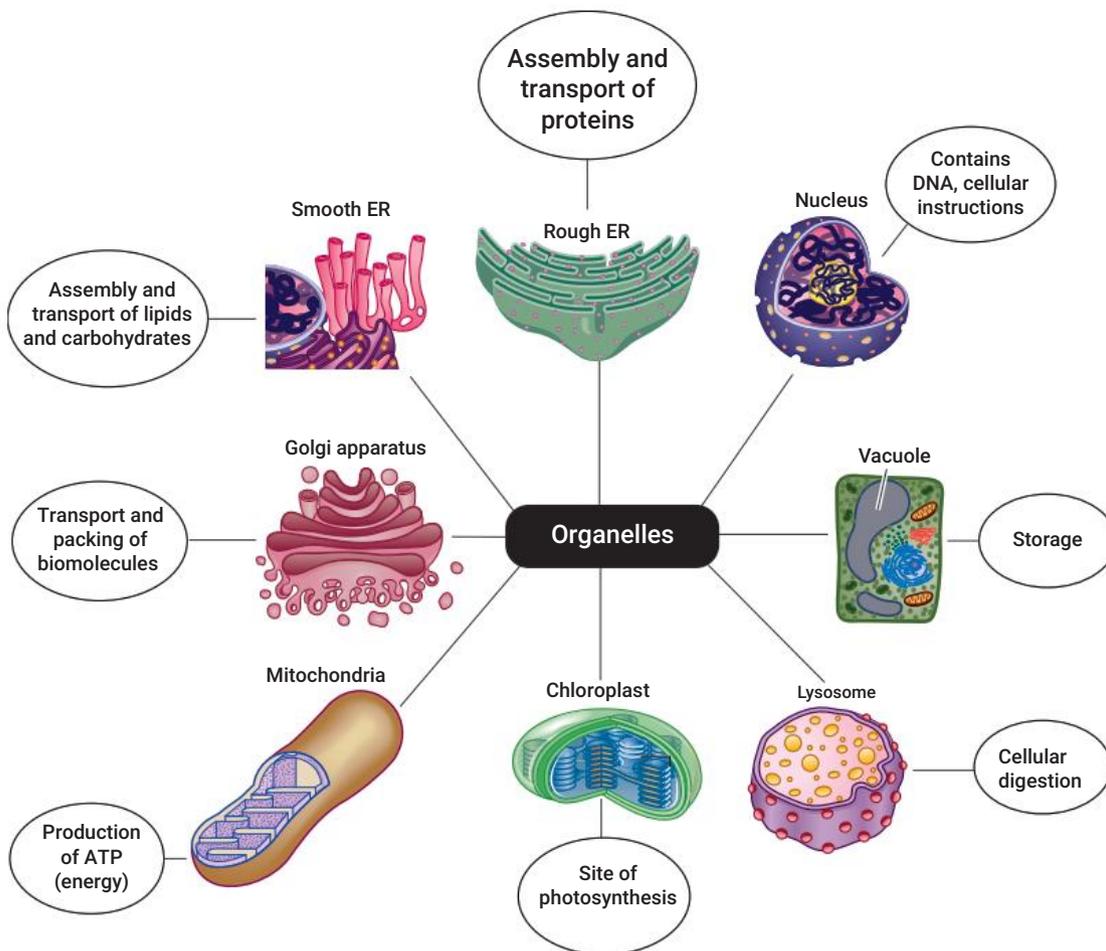
- 3 The Golgi apparatus serves an important role within the cell. Give a possible reason as to why red blood cells can function without the Golgi apparatus.
- 4 **Explain** the need for communication between cells of a multicellular organism. Use the respiratory and circulatory systems as examples in your response.
- 5 **Explain** how the structure of the following cells make them suited to their function.
 - a Alveoli
 - b Red blood cells

Similarities and differences between eukaryotes and prokaryotes

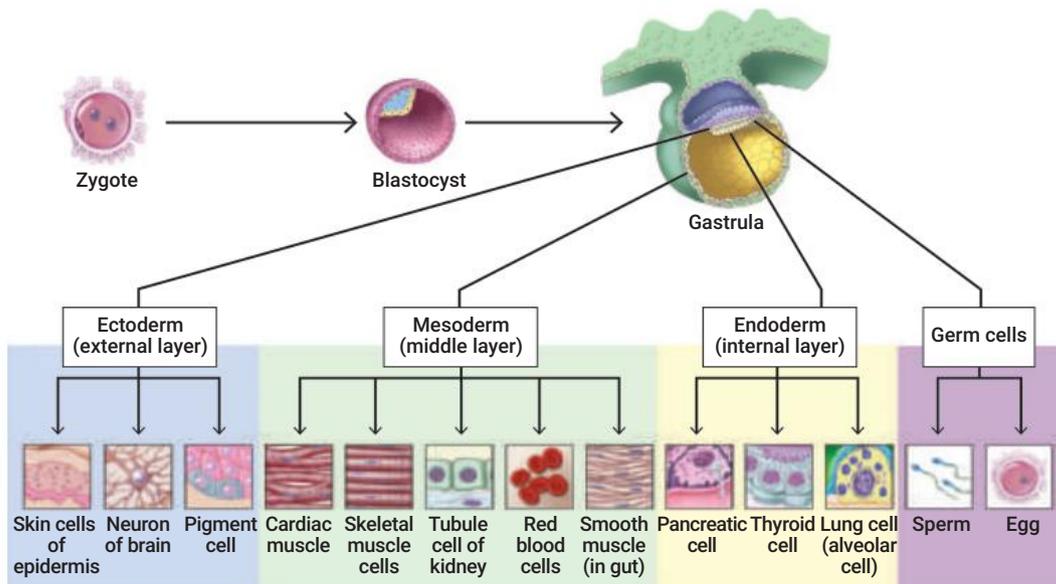
- Although both prokaryotes and eukaryotes contain DNA, the way in which they are arranged varies.



- The organelles in the cell have different functions.

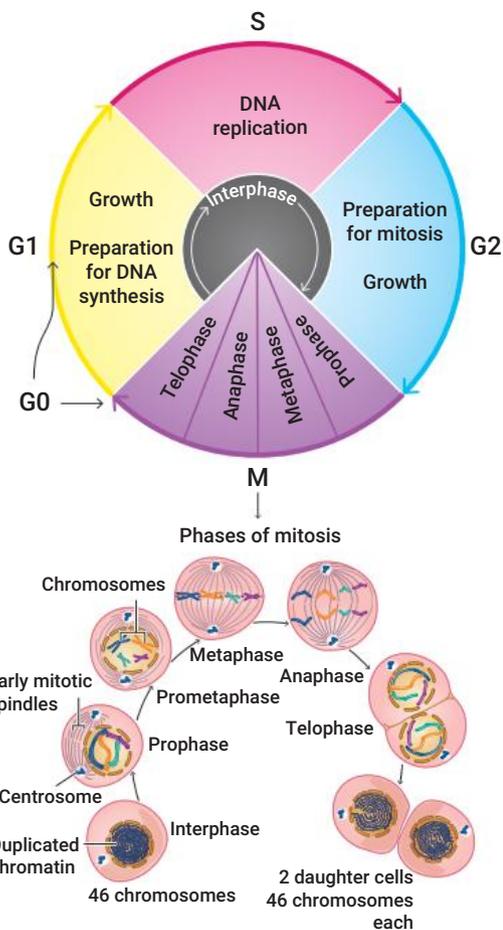


Differentiation of zygotes into specialised cells

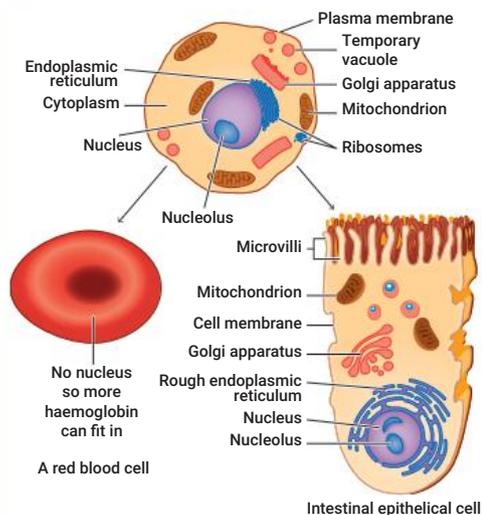


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The cell cycle



- Cell potency changes as the cells become more specialised.
- The cell cycle allows for stem cell renewal and cell differentiation.
- Cell differentiation results in cells having different shapes and combinations of organelles to complete a specific function.



MULTIPLE CHOICE

1. Choose the correct statement, with respect to stem cells.
 - A Differentiated cells are totipotent.
 - B Specialised cells have differentiated from stem cells.
 - C Stem cells have become differentiated from embryonic cells.
 - D Zygote cells have become differentiated from unspecialised stem cells.

2. Different specialised cells within an organism:
 - A have the same genetic material as each other.
 - B have different genetic material from each other.
 - C initially had the same genetic material as each other but it changed with development to become different in each of the cells.
 - D initially had genetic material from both parents but some of the parental genetic instructions were lost and the cells became different.

3. Advantages to complex multicellular organisms of having different types of specialised cells include:
 - A the ability to perform a wider variety of biochemical functions.
 - B having a simpler body plan with more duplication of functions among cells.
 - C an increased chance of mutations causing further differences between cells.
 - D an increased efficiency due to duplication with an increased number of cells performing the same functions.

4. Eukaryotic cells:
 - A have no membranes.
 - B have a single circular chromosome.
 - C may contain rings of DNA called plasmids.
 - D are significantly larger than prokaryotic cells.

5. Which of the following statements provides the best description of the term used?
 - A The cytoplasm is the fluid part of the cytosol without the cell organelles.
 - B The cytoplasm contains many dissolved substances, such as ions and sugars.
 - C The cytoplasm is all the structures and materials between the cell membrane and nucleus.
 - D The cytosol is made up of the fluid part of the cytoplasm together with cell organelles.

6. Which of these cells is most likely to contain the highest proportion of mitochondria?
 - A Muscle cell
 - B Red blood cell
 - C Small intestine columnar epithelial cell
 - D Type 1 pneumocyte

7. Which of these cells is most likely to have the largest surface area?
 - A Muscle cell
 - B Red blood cell
 - C Small intestine columnar epithelial cell
 - D Type 1 pneumocyte

8. Name the organelle responsible for packaging and transport of molecules.
 - A Chloroplast
 - B Golgi apparatus
 - C Mitochondria
 - D Nucleus

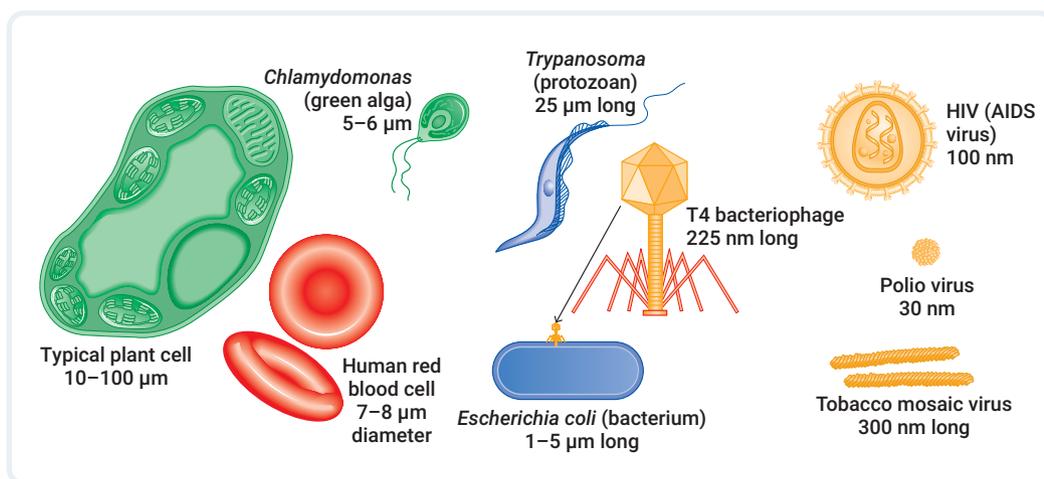
9. Mitochondria and chloroplasts:
- A both produce glucose.
 - B both produce carbon dioxide.
 - C both contain their own DNA.
 - D are found in both animal and plant cells.
10. A light microscope set to a $\times 10$ ocular lens and $\times 40$ objective lens has a total magnification of:
- A $\times 4$
 - B $\times 40$
 - C $\times 400$
 - D $\times 4000$

SHORT RESPONSE

11. **Predict** what would happen to a cell if its ribosomes failed to work. Provide reasoning.
12. **Explain** how it is possible for different types of cells to differentiate from stem cells that all have the same genetic instructions.
13. **Explain** why prokaryotic cells are unlikely to differentiate and become specialised in the same way as eukaryotic cells.

DATA ANALYSIS

Questions 14 and 15 refer to the following diagram.



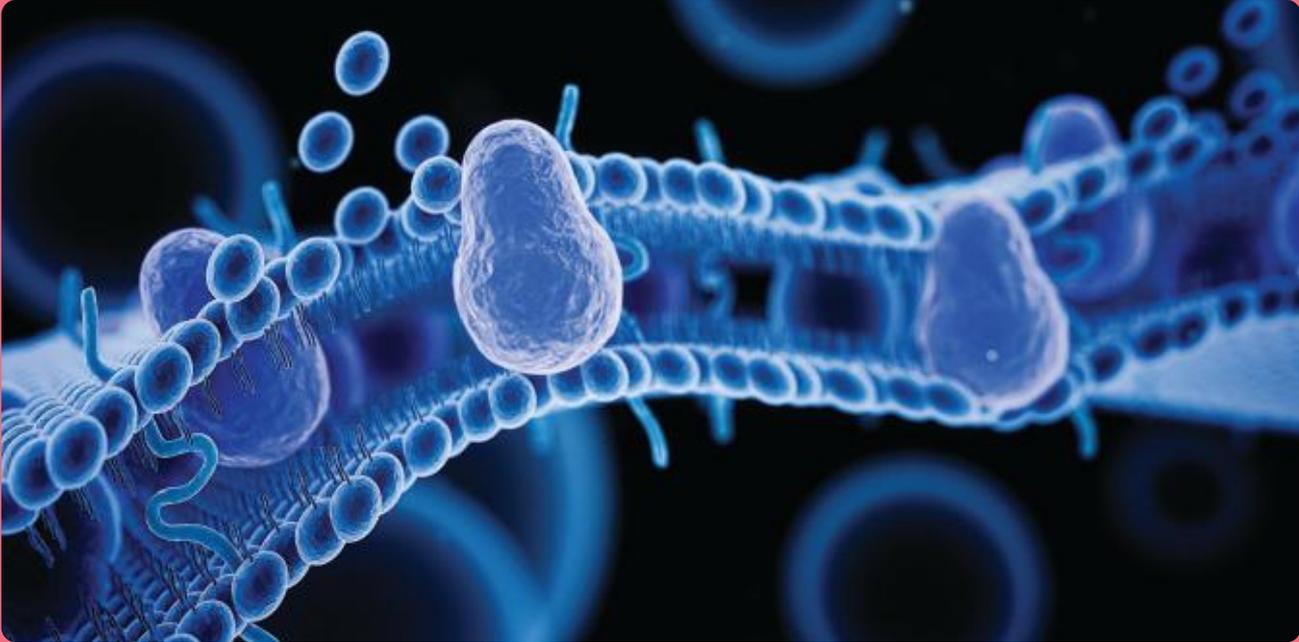
14. **Analyse evidence**

Sequence the cells pictured in the diagram above from largest to smallest.

15. **Apply understanding**

Calculate the magnification of the human red blood cell using the rule:

$$\text{Magnification} = \frac{\text{image size}}{\text{actual size}}$$



Sebastian Kaulitzki/Shutterstock.com

**SYLLABUS
DOT POINTS**
SCIENCE UNDERSTANDING

- Describe the structure and function of the cell membrane based on the fluid mosaic model, including the role of protein channels, phospholipids, cholesterol and glycoproteins.
- Explain how the cell membrane regulates movement of substances into and out of the cell via
 - osmosis
 - simple diffusion
 - facilitated diffusion
 - protein-mediated active transport
 - endocytosis and exocytosis.
- Compare active and passive transport.
- Explain how the size of a cell is limited by surface area-to-volume ratio and rate of diffusion.
- Interpret data from an experiment investigating the effect of surface area-to-volume ratio on the rate of diffusion.



SCIENCE INQUIRY

- Investigate the effect of surface area-to-volume ratio on rate of diffusion.

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Introduction

In all organisms, each cell is an independent unit enclosed by a plasma membrane known as the cell membrane. The cell membrane forms the boundary between the internal environment of the cell, the cytoplasm, and the external environment. In general, the internal cellular environment has very different concentrations of substances compared with the extracellular environment. This shows that the cell membrane can regulate the internal environment of the cell. This is because the cell membrane is selectively permeable, allowing some substances to pass across it, but not others. Both the physical and chemical properties of the plasma membrane enable it to control the exchange of materials in this way. Organelles within eukaryotic cells are also enclosed by plasma membranes.

Practical

- Investigating the effect of surface area-to-volume ratio on cell size

Worksheets

- Cell membrane
- Movement across the plasma membrane
- Surface area-to-volume ratio



 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap

ASSUMED KNOWLEDGE

- ✓ Living things are made of one or more cells.
- ✓ Cells contain organelles.
- ✓ Substances move in and out of cells, depending on cell requirements.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe which components of the membrane provide fluidity and which are the mosaic
- ✓ describe the structure and the types of particles that can move through the stated part of the membrane specific to:
 - phospholipids
 - protein channels
- ✓ describe how cholesterol contributes to the fluidity of the membrane
- ✓ describe how glycoproteins contribute to cellular recognition
- ✓ explain why water moves into and out of cells in different environments
- ✓ explain how concentration gradients allow for molecules to move through either the phospholipid bilayer or protein channels into or out of a cell, depending upon their size and charge
- ✓ explain how molecules can be moved across a membrane against a concentration gradient
- ✓ explain how large molecules are moved in bulk into and out of cells
- ✓ explain why the rate of diffusion is a limiting factor to cell size, with reference to gaining nutrients and removal of waste products
- ✓ show a clear understanding of the link between the surface area-to-volume ratio of a cell and efficient diffusion
- ✓ identify similarities and differences between active and passive transport.

cell membrane the insoluble boundary of all living cells that maintains the contents of the cell and regulates movement of substances into and out of the cell

selectively permeable a quality of a membrane that means only certain kinds of molecules can pass through it

external environment the environment surrounding a cell outside the cell membrane

fluid mosaic model the generally accepted model of membranes in which proteins are embedded in a phospholipid bilayer

bilayer a double layer

vesicle a small, membrane-bound sac in the cytoplasm that transports, stores or digests substances

internal environment all material contained within the cell membrane

2.1 Structure of the cell membrane

The **cell membrane** (also called the plasma membrane) is **selectively permeable**. Its ability to keep the concentration of substances inside the cell fairly constant and very different from the **external environment** depends on its structure.

The currently accepted model of membrane structure is the **fluid mosaic model**. This model was proposed in 1972 by Singer and Nicolson. It describes membranes as a flexible double layer of lipids, a lipid **bilayer**, with the ability to flow. This allows cells to change shape and grow. During cell division and **vesicle** formation, membranes break and reassemble themselves. The fluid nature of membranes also enables them to repair themselves. If the plasma membrane is punctured, some of the cytoplasm can leak out, but phospholipids move sideways to quickly seal the hole.

Specialised protein molecules (integral proteins) are embedded in the lipid in various patterns like a mosaic; others are attached to the surface (peripheral proteins). Some of these membrane proteins can move laterally, and others are fixed in position (**Figure 2.1.1**). The proteins, cholesterol and the phospholipid bilayer help to control the exchange of materials between the external and **internal environments**. If temperature increases, the phospholipids become less rigid and the cell membrane can become more fluid, which can increase the permeability of the membrane. If the temperature decreases, the phospholipids become more rigid and less fluid, decreasing the permeability.

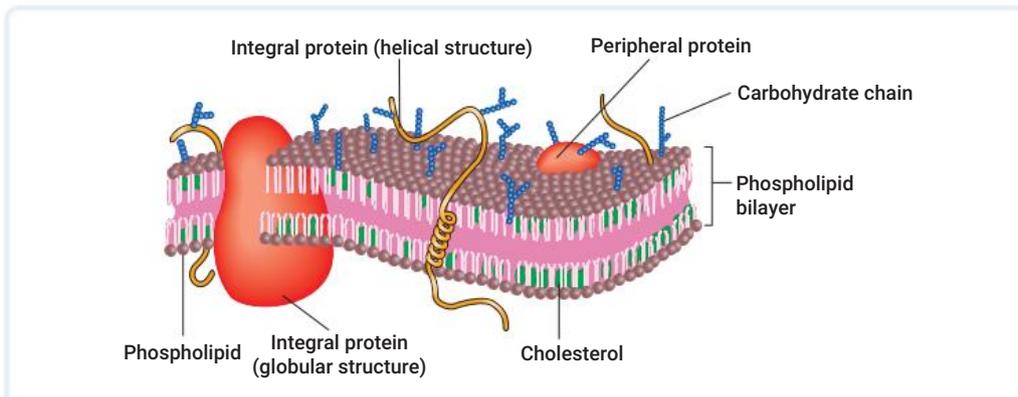


FIGURE 2.1.1 A three-dimensional view of a plasma membrane based on the fluid mosaic model



Weblinks

- Cell membrane structure and function
- Structure of the plasma membrane
- Insights into cell membranes via dish detergent

Phospholipids

Phospholipids are a type of lipid that are a major component of cell membranes. Each phospholipid can be represented by a head and two tails (**Figure 2.1.2**). A phosphate group on the head makes this end **hydrophilic** ('water loving') and the two fatty acid tails are **hydrophobic** (water avoiding or unable to dissolve in water). This means that while the heads are attracted to water, the tails are repelled. When phospholipids spontaneously form a bilayer, their fatty acid tails turn inwards, away from the watery environment and **cytoplasm**, and towards each other, rather like oil forming a film on the surface of water. This creates a barrier between the environment and the contents of the cell.

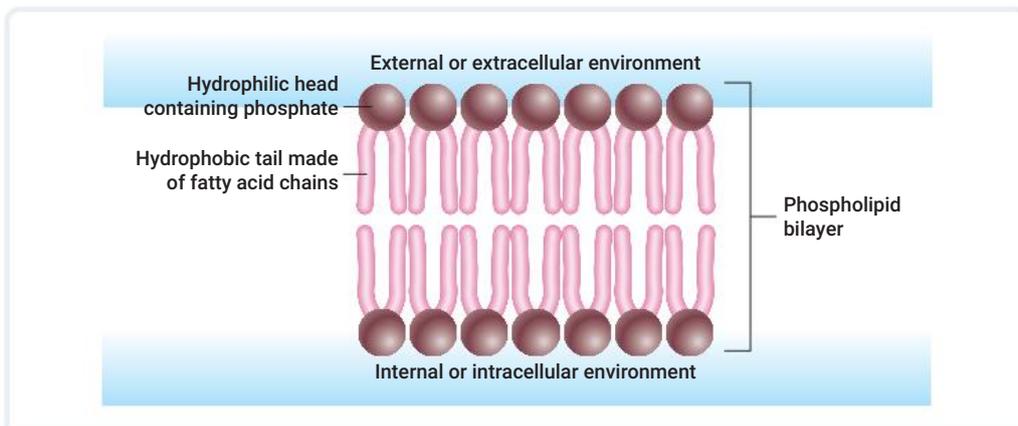


FIGURE 2.1.2 Phospholipid molecules. The hydrophilic head is attracted to water, whereas the hydrophobic tails repel water. Phospholipids form a bilayer in membranes.

phospholipid a type of lipid that has a hydrophilic head end and a hydrophobic tail end

hydrophilic tending to interact with and dissolve in water

hydrophobic avoiding association with water

cytoplasm all the fluid, dissolved materials and organelles between the cell membrane and the nuclear membrane

Cholesterol

In animal cell membranes, another type of lipid called **cholesterol** is interspersed among the phospholipid molecules. Cholesterol is an essential structural component of membranes. It stabilises and strengthens the membrane and maintains it at a suitable fluidity. It has both hydrophilic and hydrophobic properties, allowing it to reduce permeability to small water-soluble molecules, help secure peripheral proteins and prevent crystallisation of the phospholipid tails. In plants, **phytosterol**, instead of cholesterol, regulates membrane fluidity.

cholesterol a type of lipid in cell membranes that maintains membrane fluidity

phytosterol a type of plant-derived lipid compound that is similar to cholesterol in structure and function

Membrane proteins

A range of proteins are embedded in the phospholipid bilayer, with some attached to the surface while others extend from one side of the membrane to the other (**Figure 2.1.3**).



Weblink

Visualising the plasma membrane

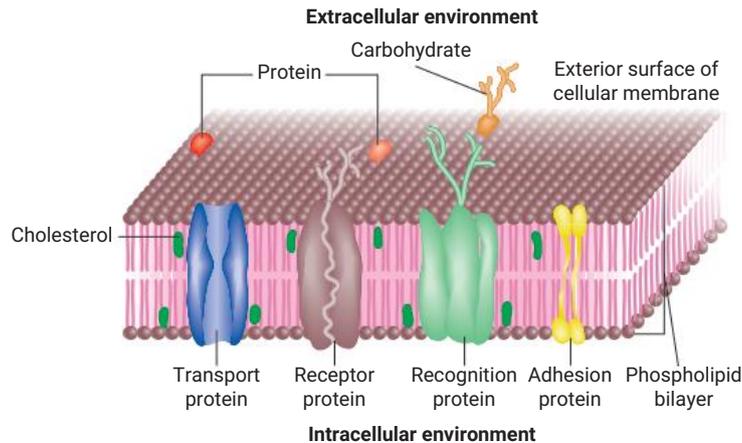


FIGURE 2.1.3 A view of part of the cell membrane showing embedded proteins: transport protein, receptor protein, recognition protein and adhesion protein

channel protein a protein that forms channels within membranes to allow substances to pass through the membrane

protein channel a passageway formed across the membrane for the movement of specific substances

glycoprotein a protein that is attached to a glycan

glycolipid a lipid that is attached to a glycan

Transport proteins span the phospholipid bilayer and help certain substances cross the membrane. **Channel proteins** are a type of transport protein. They form a **protein channel** that acts as a passageway, allowing specific substances to move across the membrane. These channels are in the cell membranes of nearly all cells and are specific to a particular substance. For example, ion channels allow the rapid movement of charged particles across the membrane when a nerve is stimulated. Aquaporins allow for the rapid movement of polar water molecules during osmosis. Channels also allow the movement of molecules, such as glucose, that would otherwise be too large to move through the membrane. Carrier proteins bind to a specific substance and undergo a series of conformational changes to move the substance across the membrane. Receptor and adhesion proteins are involved in cell signalling. Recognition proteins are involved in immune responses, both discussed in later chapters.

Glycoproteins and glycolipids

Glycans are chains of simple sugars (saccharides) that are attached to either proteins, forming glycoproteins, or lipids, forming glycolipids. **Glycoproteins**, when integral, can be associated with pore formation in the membrane. They can act as enzymes or be involved in cell–cell recognition when peripheral and attached to the membrane surface (**Figure 2.1.4**). **Glycolipids** only occur on the extracellular surface of the membrane and are also associated with cell–cell interactions. For example, blood groups are determined by the presence or absence of specific glycoproteins and glycolipids on the surface of red blood cells to give the blood types A, B, AB or O.

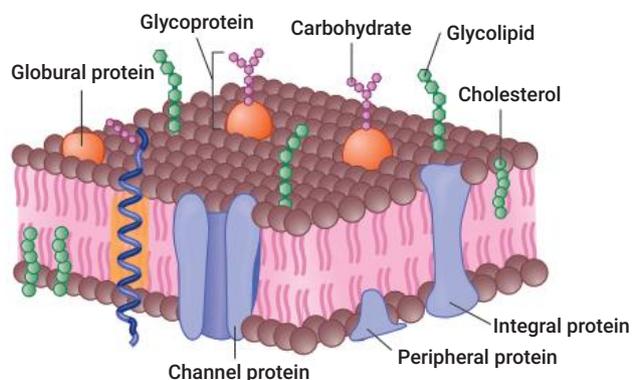


FIGURE 2.1.4 A view of part of the cell membrane showing glycoproteins and glycolipids

LEARNING CHECK 2.1

DESCRIBING

- 1 **Describe** the characteristics of a selectively permeable membrane.
- 2 **Identify** the structures or substances responsible for each of the following features of the cell membrane.
 - a Cell identification
 - b Regulation of membrane fluidity
 - c Movement of specific charged particles into or out of cells
- 3 **Describe** the role of channel proteins in cell membranes.
- 4 **Identify** which part of the cell membrane is described as fluid and which part is described as mosaic.

APPLYING

- 5 **Explain** why each of the terms 'fluid' and 'mosaic' are used.



Worksheet
Cell membrane

2.2 Passive movement

To maintain relatively stable internal conditions, the cell membrane must control the movement of materials into and out of the cell. This exchange of materials across the membrane occurs both with and without the expenditure of energy and is dependent on the nature of the molecules.

Movement that does not require energy is called **passive transport**. A simple analogy is rolling down a hill on a bicycle, without using any energy to move the pedals. Many molecules move across the cell membrane passively, without using energy. This type of movement relies on a difference in concentration, resulting in a process called **diffusion**.

Diffusion

Diffusion occurs in liquids and gases (fluids) because the particles in these substances are constantly moving. For example, scent diffuses into a room from an open perfume bottle. The particles in liquids and gases move about in constant, random motion, and over time they spread out and become evenly distributed without the input of energy (**Figure 2.2.1**).

Diffusion is the net movement of particles from a region of high particle concentration to a region of lower particle concentration. The difference in particle concentration between the two regions is called the **concentration gradient**. Diffusion always takes place wherever such

passive transport the movement of molecules that does not require the input of energy

diffusion the passive movement of molecules from a region of high concentration to a region of low concentration

concentration gradient the difference in concentration of a substance between two different regions

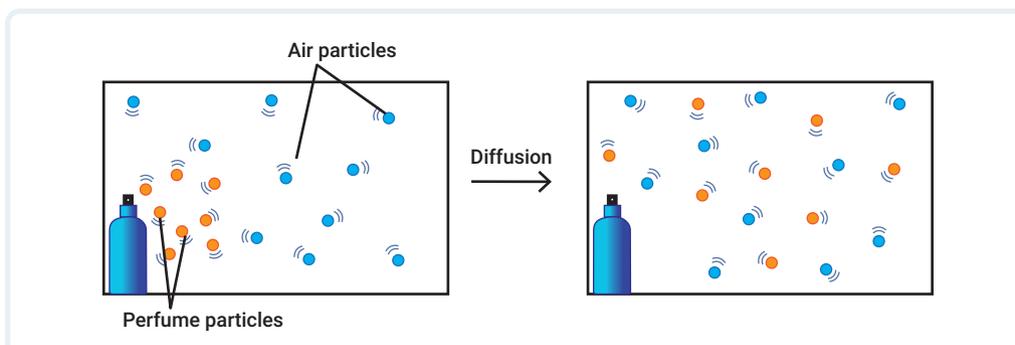


FIGURE 2.2.1 Perfume diffusing



Weblink
Diffusion simulation

equilibrium the point at which particles are distributed evenly throughout a system; they move at equal rates in all directions

a gradient exists and results in particles becoming distributed evenly throughout the system. At this point, **equilibrium** is said to have been reached. Particles will continue to move randomly, but at equilibrium they move at equal rates in all directions.

The higher the temperature, the faster the particles move. This means that increasing the temperature of a substance increases the rate of diffusion.

Increasing the concentration gradient by increasing the difference in particle concentration between two regions also increases the rate of diffusion.

Diffusion across membranes

The cell (plasma) membrane structure allows some substances to move directly through it. Others require specific proteins to act as channels or transporters. Therefore, the structure of the phospholipid bilayer determines which substances can move freely across this barrier into or out of the cell (or organelles). This means that cell membranes are described as selectively permeable or differentially permeable or partially permeable.

Substances such as oxygen, carbon dioxide and other small, uncharged particles move easily through the cell membrane of a cell by simple diffusion. **Figure 2.2.2** shows these particles passing between the phospholipid molecules from a high to a low concentration.

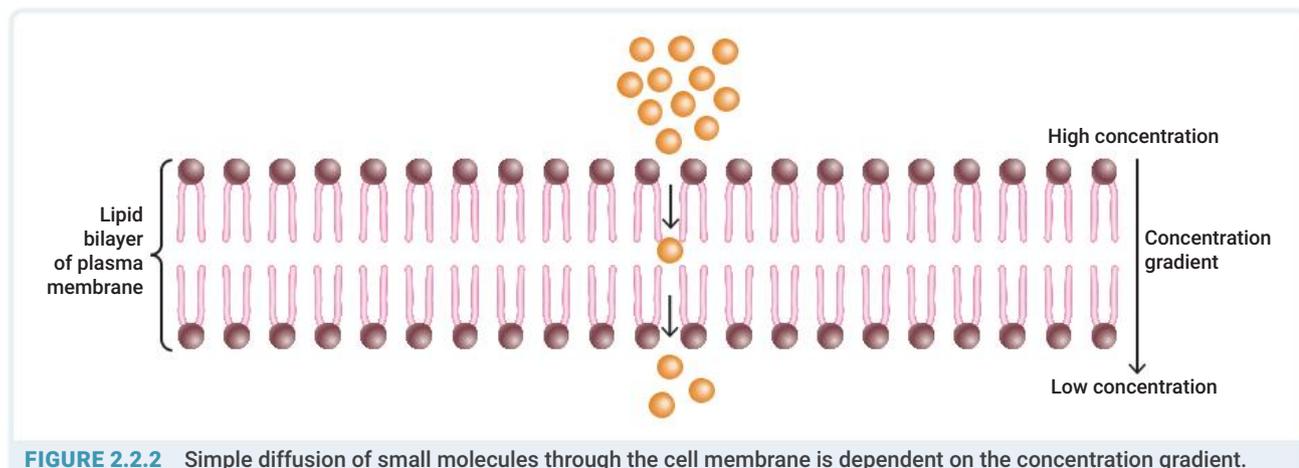


FIGURE 2.2.2 Simple diffusion of small molecules through the cell membrane is dependent on the concentration gradient.

polar a molecule with an uneven distribution of electrons, giving it distinct charged ends

facilitated diffusion a form of diffusion in which a substance attaches to a specific carrier molecule to move across a membrane

carrier protein a protein within membranes that assists other molecules to cross the membrane in facilitated and active transport

Facilitated diffusion

Small charged particles (such as sodium and potassium ions) and larger **polar** molecules (such as glucose and amino acids) do not readily pass through the phospholipid bilayer. They must be helped into or out of the cell. Membrane transport proteins assist such particles to diffuse across the plasma membrane. This process is called **facilitated diffusion**.

Two types of transport proteins are involved in facilitated diffusion: **carrier proteins** and channel proteins. Carrier proteins bind to specific molecules on one side of the membrane, change shape and release the substance on the other side (**Figure 2.2.3a**). An example is the glucose transporter protein, which is located in the plasma membrane of all mammalian cell types and carries glucose in either direction, depending on the direction of the concentration gradient.

Channel proteins form narrow passageways through which small ions can diffuse rapidly from a high ion concentration to a lower ion concentration (**Figure 2.2.3b**). Only ions of a specific size and shape can pass through a particular channel protein.



Weblink
Facilitated diffusion

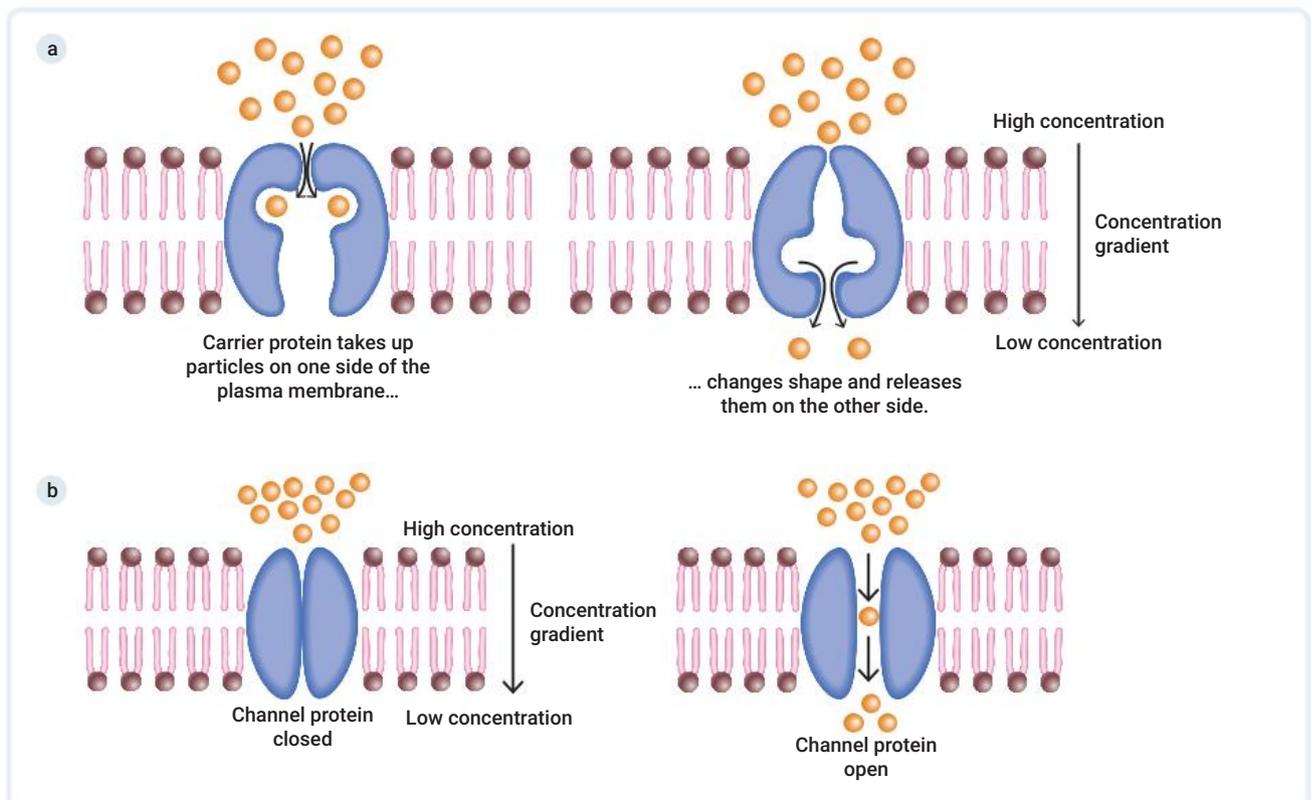


FIGURE 2.2.3 (a) Facilitated diffusion using a carrier protein in the cell membrane moves particles such as glucose down their concentration gradient. (b) Facilitated diffusion of ions through a channel protein in the cell membrane

Osmosis: a special type of diffusion

Without water, no life can survive. Water is the medium in which biochemical processes take place. Water is so important to living cells that the diffusion of water across a membrane has been given a special name – **osmosis**.

Water is the universal **solvent**. Adding sugar or salt is adding a **solute** to the solvent and making a **solution**. A dilute solution has a relatively high concentration of water molecules compared to solute particles dissolved in it, whereas a concentrated solution has a low concentration of solvent molecules and a high concentration of solute particles (**Figure 2.2.4**).

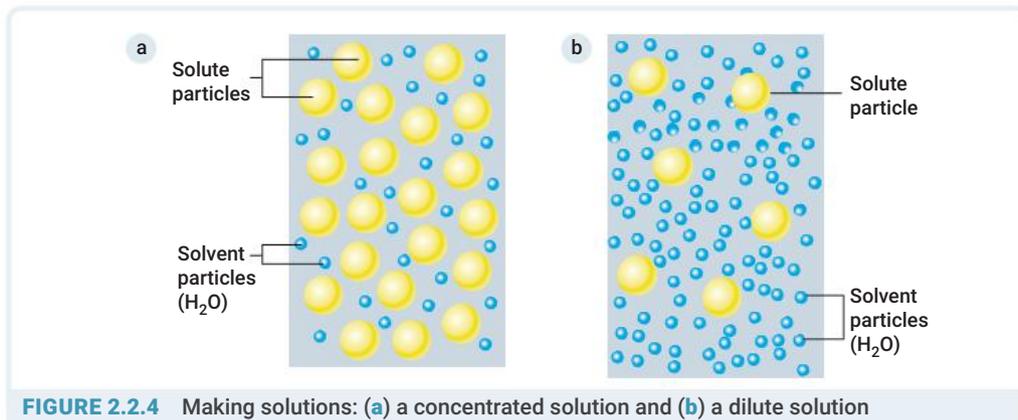


FIGURE 2.2.4 Making solutions: (a) a concentrated solution and (b) a dilute solution

osmosis the movement of water across a selectively permeable membrane from a region of low solute concentration to a region of high solute concentration

solvent a substance in which another substance can be dissolved to create a solution

solute a substance that can be dissolved in another substance

solution a mixture of solute and solvent



Weblink
Osmosis

Water molecules diffuse rapidly through specific aquaporin channels in the phospholipid bilayer, but solutes do not. If the concentration of water molecules inside a cell is lower than the concentration outside, water will diffuse into the cell until a balance or equilibrium is reached. This process of osmosis is defined as the diffusion of water across a selectively permeable membrane from an area of high water concentration (low solute) to an area of low water concentration (high solute) (Figure 2.2.5). Osmosis requires no input of energy.

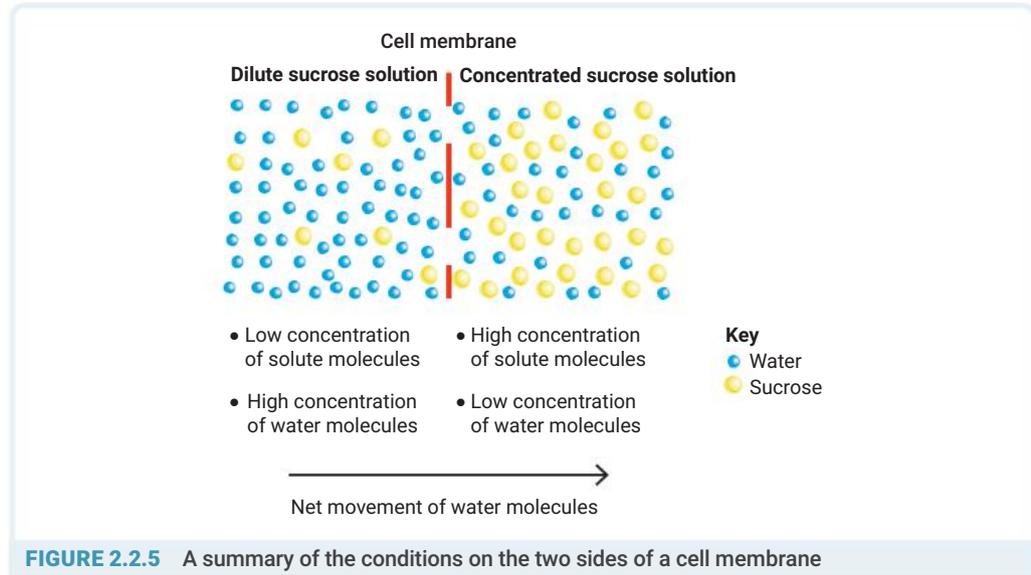


FIGURE 2.2.5 A summary of the conditions on the two sides of a cell membrane

isotonic fluid with an equal solute concentration to another fluid

hypotonic a solution with a lower solute concentration than another solution

hypertonic a solution with a higher solute concentration than another solution

If the fluids inside and outside a cell have equal solute concentration, the external solution is said to be **isotonic** (from the Greek *iso* for ‘same’) to the cells; water molecules are in motion, crossing the membrane in both directions equally. When cells are surrounded by a solution that contains a lower solute concentration than their cytoplasm, the external solution is said to be **hypotonic** (from the Greek *hypo* for ‘lower’) to the cells. Water molecules diffuse through the membrane into the cells. If too much water diffuses in, cells can burst, or lyse. The reverse applies if the cells are surrounded by a solution of higher solute concentration; the external solution is **hypertonic** (from the Greek *hyper* for ‘higher’) to the cells and water molecules diffuse out (Figure 2.2.6). If cells lose too much water, they become plasmolysed.

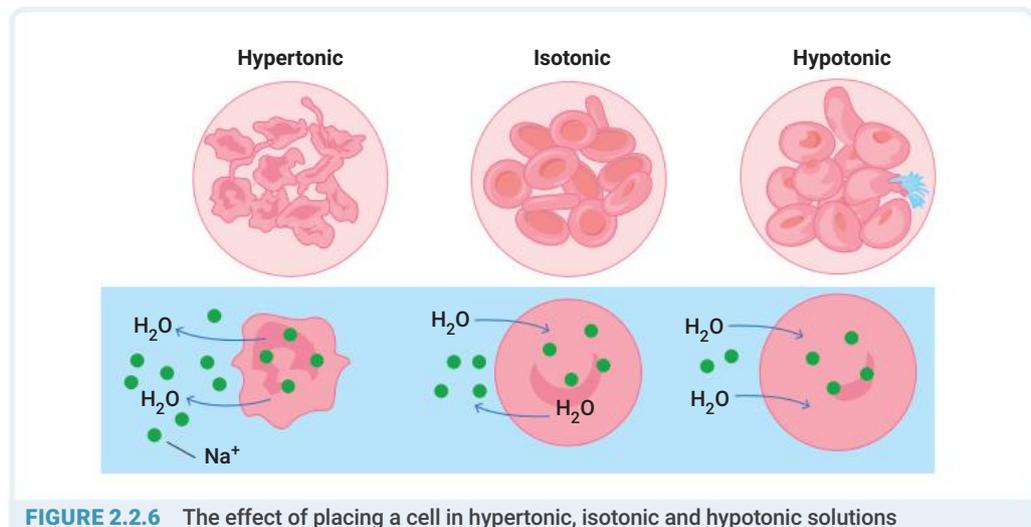


FIGURE 2.2.6 The effect of placing a cell in hypertonic, isotonic and hypotonic solutions

Osmosis in animals

The cells of unicellular eukaryotes and multicellular organisms, such as animals, are surrounded only by a cell membrane. Hypotonic solutions, such as fresh water, pose a special problem for these organisms. Water moving into their cells by osmosis can cause the cell membrane to swell and eventually burst or **lyse**, destroying the cell. This is unlike the cells of plants, fungi and bacteria, which have a rigid cell wall surrounding the cell membrane.

Unicellular organisms such as *Amoeba* that live in fresh water have important regulatory mechanisms to remove excess water by forming cytoplasmic organelles containing water called **contractile vacuoles** (Figure 2.2.7). When these vacuoles stretch to a certain point, they contract and expel the water.

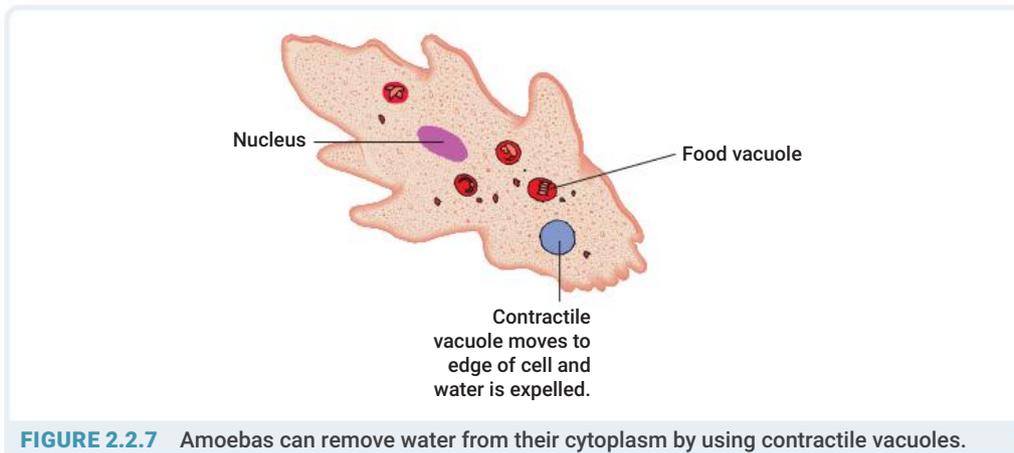


FIGURE 2.2.7 Amoebas can remove water from their cytoplasm by using contractile vacuoles.

In multicellular animals, cells are bathed in isotonic extracellular fluid. This means that cells can function efficiently because water diffuses equally in both directions, resulting in no net movement of water into or out of cells. To keep the internal environment of the body in isotonic balance, the solute concentration in the extracellular fluid is controlled by the concentration of solutes in blood plasma, which in turn is controlled by the kidneys.

Osmosis in plants

Plants have firm but permeable cell walls surrounding their cell membranes. Inside almost all plant cells is a vacuole containing cell sap with high concentration of solutes, surrounded by a plasma membrane. When a hypotonic solution surrounds a plant cell, water molecules diffuse by osmosis, first into the cytoplasm and then into the vacuole. The vacuole swells, pushing the cytoplasm and cell membrane against the cell wall. The tough cell wall prevents the cell from bursting. When the cell wall stretches as much as possible, no more water can enter and the cell is said to be **turgid** (Figure 2.2.8).

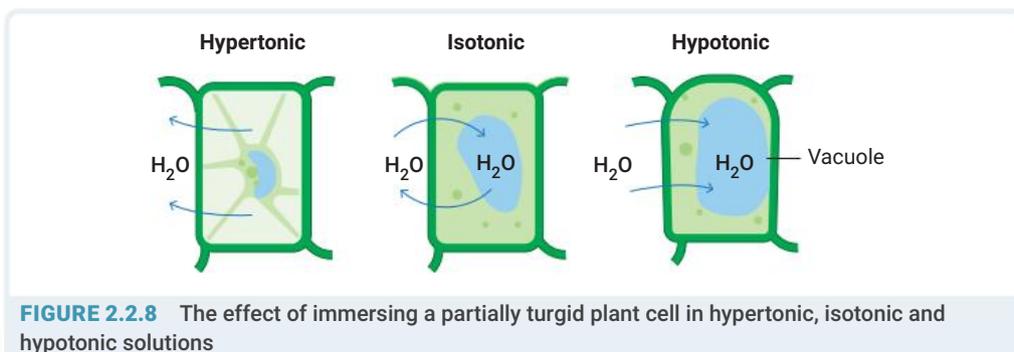


FIGURE 2.2.8 The effect of immersing a partially turgid plant cell in hypertonic, isotonic and hypotonic solutions

lyse to burst

contractile vacuule a vacuole found in some freshwater unicellular organisms that maintains osmotic balance by collecting water and emptying it from the cell



Syllabus link
Chapter 9 explains how the kidneys function to maintain isotonic balance.

turgid describes a cell that is tight and rigid from absorbing water

Turgor is very important for plants. It maintains their shape and form and helps to keep them rigid. The stems of non-woody plants are kept erect by the turgid, tightly packed cells. Turgor is also responsible for holding leaves in a flat, opened-out position.

Certain plant cells can undergo quite rapid changes in their solute concentration with consequent changes in turgor. This allows such cells to change their shape. Stomatal guard cells behave this way, as do cells responsible for the leaf movements of insectivorous plants such as the Venus flytrap (*Dionaea muscipula*).

On a hot, dry day when significant quantities of water are lost from a plant, the concentration of water molecules outside the cells becomes less than in the vacuole. Water molecules diffuse out, reducing the volume of the vacuole and causing the cells to become limp or **flaccid** and the plant to **wilt**. If enough water is lost, the cell membrane pulls away from the cell wall in a process called **plasmolysis**.

flaccid describes the condition of a plant cell that has lost water; floppy

wilt become limp and floppy

plasmolysis the point at which the cell membrane pulls away from the cell wall because of water loss

LEARNING CHECK 2.2

DESCRIBING

- 1 A salt solution is a mixture of salt and water. **Identify** which of these is the solvent and which is the solute.
- 2 State two factors that increase the rate of diffusion.
- 3 **Describe** facilitated diffusion. **Identify** four substances that enter the cell by this process.
- 4 **Identify** one reason plant cells do not burst when placed in a hypotonic solution.

APPLYING

- 5 **Explain** why red blood cells for blood transfusions are stored in saline (salt) solution rather than pure water.
- 6 If salad greens such as lettuce are left uncovered for a period of time, they become limp. **Explain** how their crispness could be restored.
- 7 **Explain** what advertisers mean when they claim their sports drinks are isotonic.

INTERPRETING

- 8 Animal cells are placed in three different solutions. After some time, cells in solution X burst. Cells in solution Y remain the same and cells in solution Z become shrivelled. **Determine:**
 - a which solution was hypertonic compared with the animal cell
 - b which cell was isotonic compared with its surroundings
 - c how plant cells would look in each of these solutions.

Provide reasoning for each choice.

2.3 Active transport

active transport the process of using energy to move a substance across a membrane from a region of low concentration to a region of higher concentration

When energy is needed to move a substance across the cell membrane, the process is called **active transport**. One example of active transport is when specific substances move through the membrane against a concentration gradient, from a region of low concentration to a region of higher concentration. This process enables cells to absorb dissolved substances from very dilute solutions.

Active transport is carried out by membrane carrier proteins, similar to those responsible for facilitated diffusion. In this case, the carrier protein is coupled to a source of energy. The carrier has binding sites that allow a specific dissolved substance to bind to the side of the membrane where it is at a lower concentration. They function in one direction only, like valves, and require energy to change shape and move the solute particle across the membrane (**Figure 2.3.1**).



Syllabus link
Chapter 3 explains the role of adenosine triphosphate (ATP) as an energy carrier.

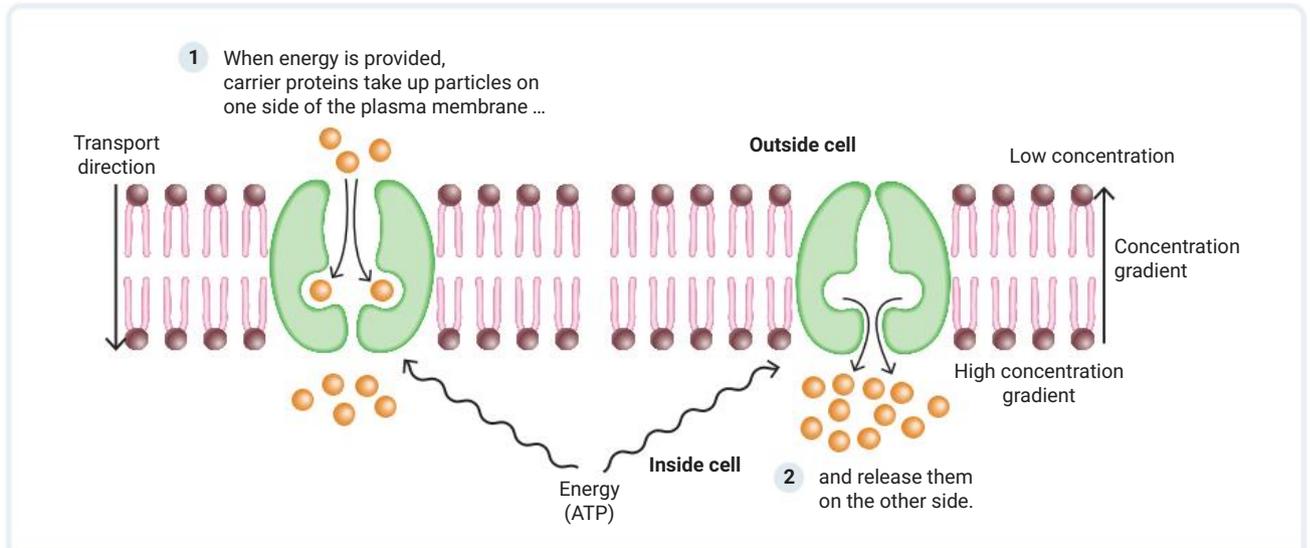


FIGURE 2.3.1 Active transport via a carrier protein in the cell membrane of a cell. Energy is transferred to the carrier protein, enabling it to move the substance against its concentration gradient.

Energy for active transport

The energy demands of active transport are significant. It has been estimated that while a person sleeps, as much as 40 per cent of the total energy budget is used for active transport. Cells engaged in this process have huge numbers of mitochondria whose function is to make energy available to the cell. These organelles build up **adenosine triphosphate (ATP)**, which is the energy source for the active transport of most substances.

An example of protein-mediated active transport

Animal cells contain high concentrations of potassium ions but low concentrations of sodium ions. The mechanism responsible for this is the **sodium-potassium pump**, which moves these two ions in opposite directions across the cell membrane. For every two potassium ions pumped in, three sodium ions are pumped out. This pump has a particular significance for nerve cells because the rapid movement of ions across the membranes of nerve cells enables the transmission of nerve impulses.

A spectacular example of active transport in plants is provided by certain seaweeds. They take up iodide ions so vigorously that this ion is more than a million times more concentrated inside the cells than in the surrounding sea water. Similarly, land plants need to absorb various mineral salts from the soil where the salts exist in very dilute concentrations. Root cells can do this because their membranes contain many types of carrier proteins, each capable of actively transporting a different mineral ion from the soil. Active transport enables these cells to take up salts from a dilute solution, against their concentration gradient. Note that these examples are not specifically stated in the syllabus.



Web link
Active transport

adenosine triphosphate (ATP) a molecule that stores and transports energy in the cell; composed of adenosine, ribose and three phosphate groups

sodium-potassium pump a membrane protein that uses energy to transport sodium ions out of, and potassium ions into, cells against their concentration gradients

Movement of large molecules

At times, very large particles or even whole cells have to be moved into or out of a cell across its cell membrane. The large size of these particles makes their movement through the membrane by diffusion or active transport impossible. In these cases of bulk transport, membranes and cytoplasmic vesicles play an important role. These are active processes, requiring energy to move vesicles around the cytoplasm and to change the shape of the cell.

Endocytosis

Substances that are too large to move through the membrane via the transport proteins are transported into the cell by **endocytosis**, including molecules, parts of cells or whole cells.

When a cell takes up a substance by endocytosis, it changes shape by sending out cell membrane projections that surround the material. When the cell membrane projections meet, the membrane fuses and forms a vesicle, which then stores or transports the substance within the cytoplasm (**Figure 2.3.2**).

endocytosis the movement of solids or liquids from the environment into a cell via vesicle formation

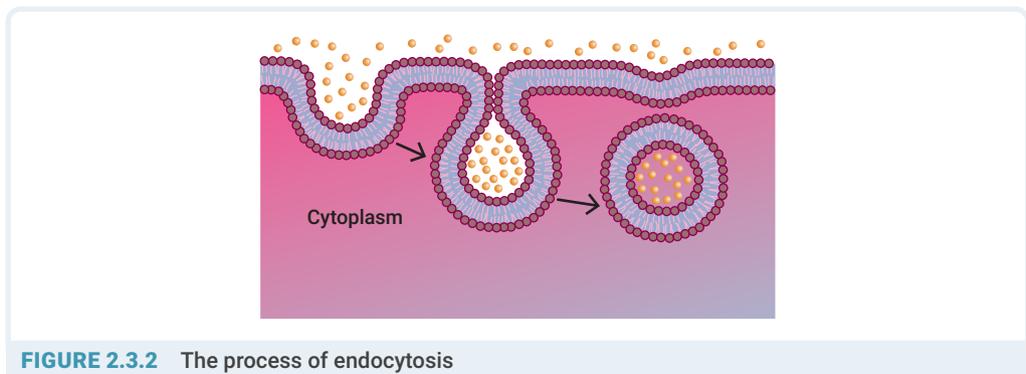


FIGURE 2.3.2 The process of endocytosis

Phagocytosis is the transport of solid particles into a cell inside a vesicle (**Figure 2.3.3**).

phagocytosis the bulk transport of solids into a cell inside a vesicle

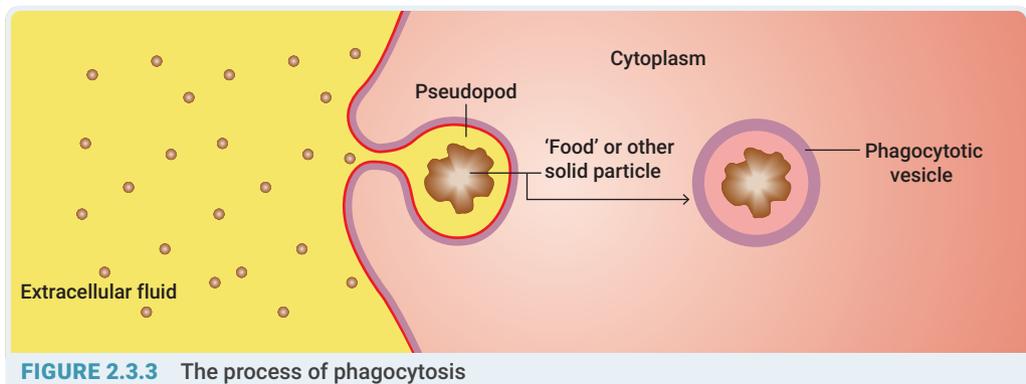


FIGURE 2.3.3 The process of phagocytosis

Phagocytosis can be observed in both unicellular organisms such as the *Amoeba* (**Figure 2.3.4**) and multicellular animals. Some white blood cells, called macrophages, are referred to as phagocytes because, in defending the body against disease, they engulf bacteria by phagocytosis.

Pinocytosis occurs when a cell takes in fluid, rather than solids.

pinocytosis the bulk transport of liquids into a cell inside a vesicle

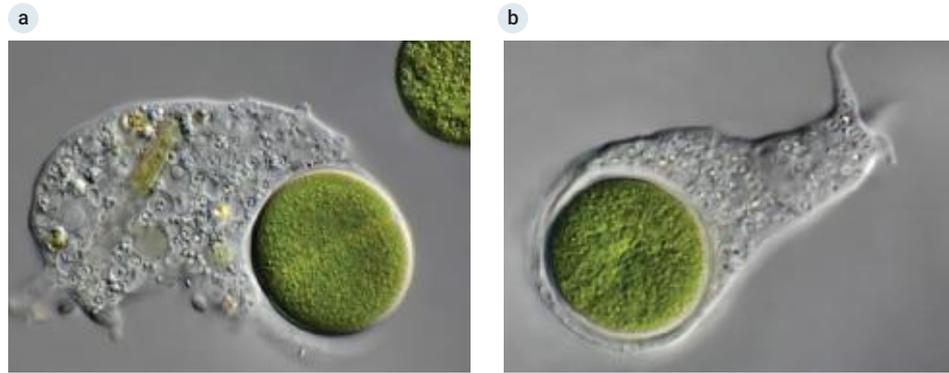


FIGURE 2.3.4 A series of micrographs of an *Amoeba* surrounding its prey (*blue-green algae*) for ingestion. Endocytosis is a selective process. For example, an *Amoeba* will ingest particles that have food value, but will rarely ingest particles that do not.

Exocytosis

Specialised animal cells produce a variety of substances, such as hormones, mucus, milk proteins and digestive enzymes, that have important functions elsewhere in the organism. Similarly, specialised cells in plants produce growth regulators and toxins to ward off predators, which have to be relocated. **Exocytosis** is the process by which large molecules held in vesicles within the cell are transported to the external environment. It is essentially the reverse of endocytosis. During exocytosis, a membrane-bound vesicle moves to the plasma membrane, fuses with it and then releases its contents to the exterior of the cell (**Figure 2.3.5**).



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Endocytosis and exocytosis

exocytosis the movement of solids or liquids from a cell to the environment via vesicle formation

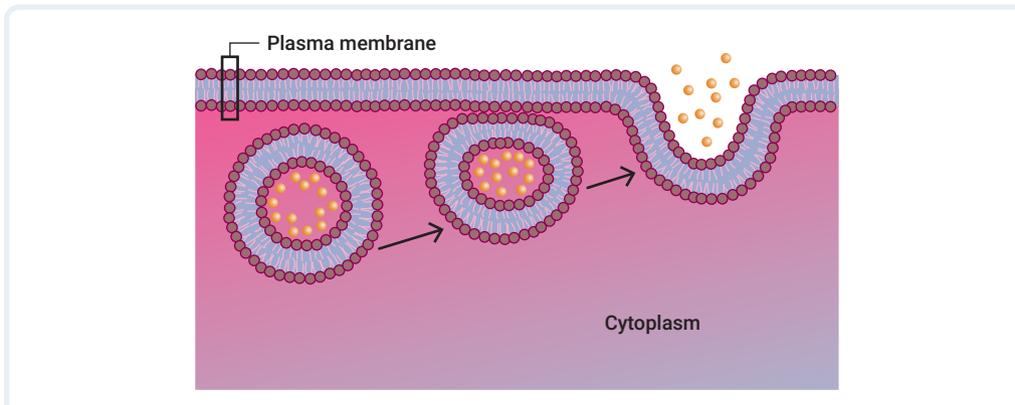
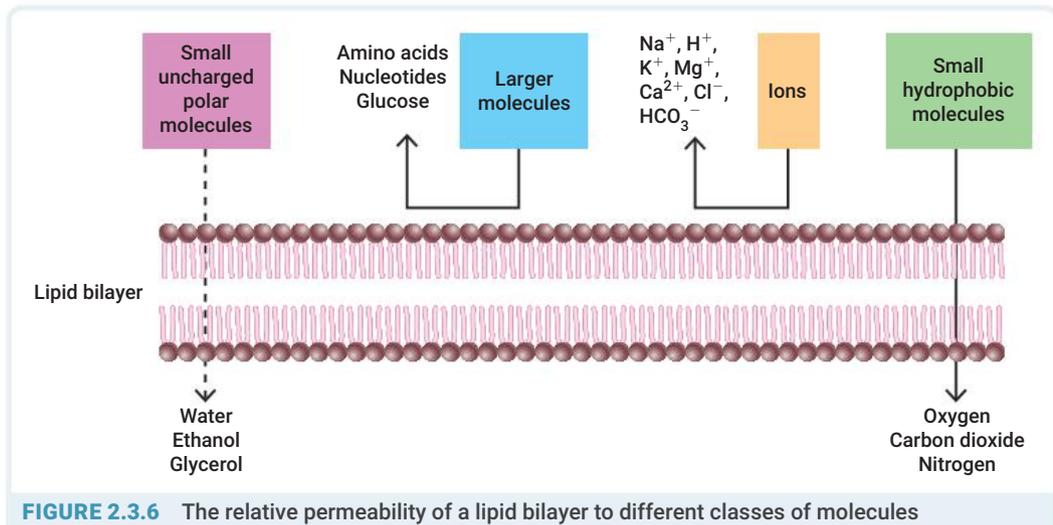


FIGURE 2.3.5 The process of exocytosis

In summary, small uncharged, non-polar molecules easily penetrate and cross membranes in either direction because they can dissolve in the phospholipid bilayer. Small uncharged, polar molecules can move through the phospholipids slowly, but typically move through a protein channel. Charged ions such as sodium (Na^+), potassium (K^+) and calcium (Ca^{2+}), which are hydrophilic, cannot cross the hydrophobic interior of the membrane (**Figure 2.3.6**). They move across membranes via membrane transport proteins – ion channels – which are specific for the substance they carry. The direction in which these substances move is determined by the concentration gradient of the material.

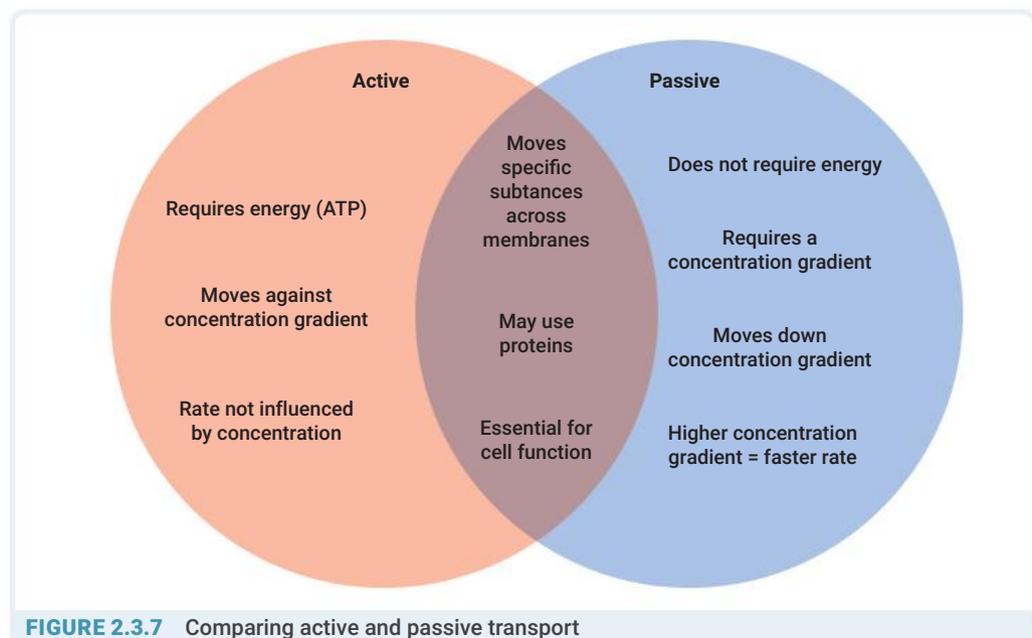


Large molecules such as glucose are transported by specific membrane carrier proteins that span the plasma membrane. The specificity of transport proteins depends on the physical shape of the molecule fitting into the carrier protein. In this process of facilitated diffusion, the direction of movement is determined by the concentration gradient of the substance, with the substance moving from a high concentration to a low concentration.

The direction of movement of a substance across cell membranes is generally determined by its relative concentration on either side of the membrane. The substance will move from where it is in a high concentration down its concentration gradient to where it is in a low concentration. The steeper the concentration gradient, the faster the substance diffuses. If the concentrations on either side of the membrane become more similar, the diffusion will be slower.

An exception is when a substance is moved with the expenditure of energy, by active transport. In this case, the substance is moved against its concentration gradient, from a low to a high concentration. The substance may move either in vesicles, by endocytosis, or via a membrane transport protein pump using energy from ATP.

A comparison between active and passive transport can be seen in **Figure 2.3.7**.



LEARNING CHECK 2.3

DESCRIBING

- 1 State the structures responsible for active transport of molecules and ions across membranes.
- 2 **Describe** how the cell membrane is involved in the process of endocytosis.
- 3 **Describe** what it means to say that phagocytosis is a selective process.
- 4 State two factors that affect the movement of substances across cell membranes.
- 5 **Describe** the effect of differing concentration gradients on the rate of diffusion of oxygen into a cell.
- 6 State two differences between active transport and simple diffusion.

APPLYING

- 7 **Identify** two types of cells in which a great deal of active transport occurs and explain why this form of transport is necessary in these cells.
- 8 **Explain** why certain white blood cells are known as phagocytes.
- 9 You overhear a claim that endocytosis is the same as phagocytosis. **Explain** why this claim is not correct.

ANALYSING

- 10 **Compare** the passive and active cellular movement of ions and water molecules.
- 11 Read the descriptions a–d. **Categorise** each situation by the direction of movement of substances, choosing from one of: into the cell, out of the cell or cannot cross.
 - a Water when an *Amoeba* is washed into the sea during a storm
 - b Carbon dioxide when muscle cells are working hard and respiring rapidly
 - c Oxygen when deep breathing into the alveoli of the lungs after a run
 - d Sodium and chloride ions when salt is sprinkled on lettuce leaves

INTERPRETING

- 12 Provide an explanation for each category chosen in Question 11.
- 13 When a person's kidneys fail, the person may be connected to a dialysis machine. Arterial blood is pumped through dialysis tubing that is made of selectively permeable membranes. Surrounding the tubing is a solution similar to blood plasma. Waste materials diffuse from the tubing into the surrounding solution. Cleaner blood then travels back into the person's veins.

Deduce what must be done to the surrounding solution so that the wastes continue diffusing out of the dialysis tube. **Predict** what would happen if this was not done.



Worksheet

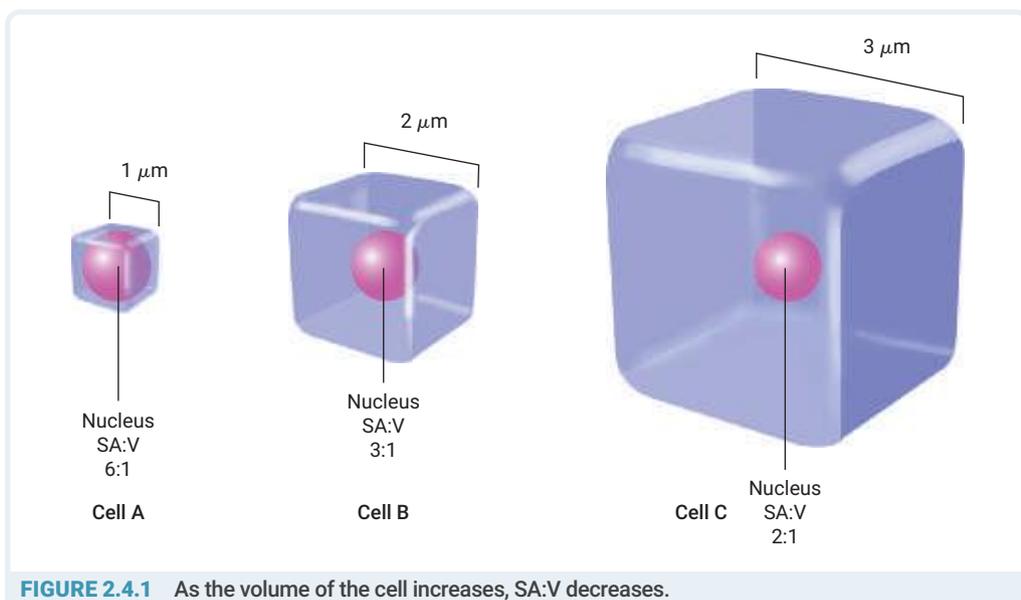
Movement across the plasma membrane

2.4 Surface area-to-volume ratio

Most cells are very small. This provides cells the ability to obtain nutrients and remove waste products efficiently and effectively. **Surface area-to-volume ratio** (SA:V) represents an important relationship between the surface area of the membrane surrounding a cell and the volume of its cytoplasm. SA:V is expressed as a ratio (e.g. 3:1).

surface area-to-volume ratio the mathematical ratio of the size of the surface area (in two dimensions) to the volume of an object (in three dimensions)

For a cell to be able to supply the cytoplasm with its metabolic requirements and remove wastes, it needs a large surface area-to-volume ratio. That is, it needs a large surface area of membrane around the cell in relation to the volume of its cytoplasm (**Figure 2.4.1**).



As a cell grows larger, both its surface area and volume increase, but its volume grows faster than its surface area. This is shown in **Table 2.4.1**. Cell A has a volume of $1 \mu\text{m}^3$ and a surface area of $6 \mu\text{m}^2$ to service it. This is a surface area-to-volume ratio of 6:1. Cell C has a volume of $27 \mu\text{m}^3$ and a surface area of $54 \mu\text{m}^2$ to service it, a surface area-to-volume ratio of only 2:1.



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Surface area-to-volume ratio

Worksheet

Surface area-to-volume ratio

TABLE 2.4.1 Surface area-to-volume ratios of three hypothetical cells

	Cell A	Cell B	Cell C
Diameter (μm)	1.0	2.0	3.0
Surface area (μm^2)	6	24	54
Volume (μm^3)	1	8	27
SA:V	6:1	3:1	2:1

As the size of a cell increases, SA:V decreases. This means the efficiency with which a cell obtains its nutrients and removes its wastes is reduced as its size increases. As a cell increases in size, it reaches a point where the inward movement of essential substances and the outward movement of wastes across the surface membrane by diffusion are not fast enough to service the increasing volume of the cell. For this reason, individual cells tend to be very small.

WORKED EXAMPLE 2.4.1

Calculate the surface area-to-volume ratio of a cube with dimensions $1\text{ cm} \times 1\text{ cm} \times 1\text{ cm}$.

ANSWER

1 Calculate the surface area. Choose the correct formula.

Surface area of a cube is $6 \times$ area of one side.

2 Substitute values into the formula.

Surface area = $6 \times 1 \times 1 = 6\text{ cm}^2$

3 Calculate the volume. Choose the correct formula.

Volume of a cube = length \times width \times height

4 Substitute values into the formula.

Volume = $1 \times 1 \times 1 = 1\text{ cm}^3$

5 Calculate SA:V.

Surface area : volume = $6 \div 1$
= $6 : 1$

Overcoming problems associated with surface area-to-volume ratio

Because of the restrictions of the surface area-to-volume ratio, most cells are too small to see without the aid of a microscope. Larger cells have special ways to offset the low surface area-to-volume ratio that comes from their size.

In giant algal cells (up to 70 mm in diameter), an inert vacuole fills most of the cell. This pushes the metabolically active cytoplasm towards the outside of the cell, just beneath the plasma membrane. This has two benefits: the distance materials need to diffuse when moving into or out of the cell is much less and the active volume of cytoplasm is less (effectively reducing the volume), thereby reducing the amount of exchange that must occur across the membrane.

The shape of a cell can significantly change its surface area-to-volume ratio. Long, thin or flat cells have relatively more membrane for a certain volume than spherical cells do. Nerve cells that connect the spinal cord to the toes are more than 1 m long but about 1 mm across. Another example is the root hairs that cover the root tips of most plants. The long thin extensions of the single cells that form root hairs can significantly increase the surface area over which water and mineral salts can be absorbed (Figure 2.4.2).



Andrew Syred/Science Photo Library

FIGURE 2.4.2 A scanning electron micrograph of root hairs in oregano, *Origanum vulgare*. Root hairs greatly increase the surface area for absorption of water.

Factors affecting rate of diffusion

Four factors affect the rate of diffusion:

- **Concentration gradient:** the greater the difference in concentration of a substance on either side of a membrane, the faster it diffuses. That is, the steeper its concentration gradient, the faster a substance moves across the cell membrane.
- **Temperature:** the higher the temperature, the more kinetic energy particles have, the faster the particles move across a membrane. Note that temperature affects the structure of proteins. When temperatures increase too much, proteins denature (lose structural integrity) and lipids become fluid, meaning that the cell membrane no longer functions as a barrier.
- **Surface area:** the larger the surface area, the more space there is for particles to move across the membrane.
- **Distance:** the shorter the diffusion distance, the faster the molecules get to the other side of the membrane.

The main way cells maintain a rapid rate of diffusion is to increase the concentration gradient across their membranes. Plant cells often carry out **cytoplasmic streaming**, a process whereby the cytoplasm flows through the cell in a circular movement. The effect is to maintain a steeper concentration gradient. This is because the materials diffusing into the plant cell are rapidly removed from the area close to the cell membrane, keeping them at a lower concentration than if the cytoplasm was stationary.

In multicellular animals, the circulatory system helps to increase the rate of diffusion. Blood circulation through the lungs rapidly removes oxygen that has diffused into the body, maintaining a steep concentration gradient between cells of the lungs and blood vessels. Similarly, at the tissues, blood flow removing a waste, such as carbon dioxide, increases its rate of diffusion out of the body cells.

Inside a cell, the conversion of a diffused substance into another substance lowers its concentration, causing an increase in its rate of diffusion.

cytoplasmic streaming
the mixing and movement of the cytoplasm



Syllabus link

Chapter 3 goes into further detail about how gases are exchanged in body systems.

PRACTICAL ACTIVITY 2.4.1

INVESTIGATING THE EFFECT OF SURFACE AREA-TO-VOLUME RATIO ON CELL SIZE

Introduction

Cells must exchange materials with their external environment. To maintain normal cell functioning, this exchange must occur at an efficient rate. The size and shape of cells can affect their surface area-to-volume ratio.

In this practical, pink agar cubes provide a simple model of a cell. The jelly was prepared using sodium hydroxide and phenolphthalein. Phenolphthalein is an indicator like litmus, changing colour depending on the acidity of its surroundings. The acid represents nutrients moving across the cell membrane into the cytoplasm. When the acid diffuses into this agar, it neutralises the sodium hydroxide, causing the phenolphthalein to change from pink-purple to colourless.

Research question

Does decreasing the surface area-to-volume ratio of a model cell (independent variable) reduce the movement of substances into the model cell (dependent variable) as shown by the percentage of uncoloured agar cube?

List variables that need to be controlled for this investigation.

Materials

Each group will require:

- 4 trays of agar/sodium hydroxide/phenolphthalein (pink-purple coloured) that have been poured 10, 20, 30 and 40 mm thick
- 150 mL of 0.1 M sulfuric acid (H_2SO_4)
- 250 mL beaker

- spoon or large spatula to stir and remove the agar cubes in the acid
- ruler
- razor blade
- clock or watch
- paper towel
- calculator



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
The acid and indicator could irritate your skin.	Avoid getting chemicals the eyes or cuts in the skin. Wash hands after the investigation. Wear gloves to handle the cubes. Wear safety glasses for eye protection.
The razor blade is very sharp.	Take care when using the razor blade and do not walk around the room carrying it.
Environmental risks	Dispose of the agar according to the teacher's instructions.

Procedure

- 1 If this has not already been done, gently pry away the agar from the tray sides and turn the trays upside down, revealing the four slabs of purple agar, 10, 20, 30 and 40 mm thick.
- 2 Pour about 150 mL of the 0.1 M sulfuric acid into the 250 mL beaker.
- 3 Using the razor blade, cut out blocks of no less than 10, 20, 30 and 40 mm in size. (Try not to destroy the remainder of the agar so that others may also use it.)
- 4 Trim the blocks of agar into 10, 20, 30 and 40 mm cubes. Do this as accurately as possible.
- 5 Carefully add the cubes to the acid in the beaker without splashing and gently stir every few minutes.
- 6 Note the time when the cubes were added. They should come out after 10 minutes.
- 7 Calculate the surface area, volume and SA:V for each of your cubes and copy and complete [Table 2.4.2](#).
- 8 After 10 minutes, remove the cubes with a spoon and pat them dry on paper towel.
- 9 Immediately cut each cube in half and measure the depth, to the nearest millimetre, of the clear parts. Decide on a typical measurement and record it in your table.
- 10 Follow the teacher's instructions when disposing of the materials.
- 11 Complete the table, ensuring the correct units are at the top of each column.

Results

TABLE 2.4.2 Results table

	Cube size (mm)			
	10	20	30	40
Surface area				
Volume				
Surface area-to-volume ratio				
Dimensions of coloured cube				
Volume of coloured cube (X)				
Volume of whole block (Y)				
Volume of uncoloured portion (Y - X)				
Percentage of block uncoloured				

Analysis of results

- 1 Draw a graph of the data. On the horizontal axis, label the size of the cubes tested. On the vertical axis, label the percentage of volume uncoloured. If the option is available, the graph can be constructed in Excel or similar software.
- 2 Identify the trend in the data relating to cube size and depth of the clear agar.
- 3 Identify the trend in the data relating to SA:V.

Interpretation

- 4 Explain why parts of the cube become clear in this activity.
- 5 What is the answer to the research question?
- 6 Explain how the loss of colour in a cube relates to nutrients diffusing into a cell.
- 7 Draw a conclusion as to whether a cell could grow into the size of a football.

Evaluation

- 8 Discuss the **validity** of this investigation. Hints: Were the necessary variables controlled? Consider the accuracy and reliability of the data.
- 9 Was this a fair test? How and why?
- 10 Does the data provide an answer to the research question?

validity how accurately a method measures what it is intended to measure

LEARNING CHECK 2.4

DESCRIBING

- 1 **Describe** the change in SA:V as a small cell grows larger.
- 2 State two ways that cells can increase the rate of diffusion of substances across their cell membrane.

APPLYING

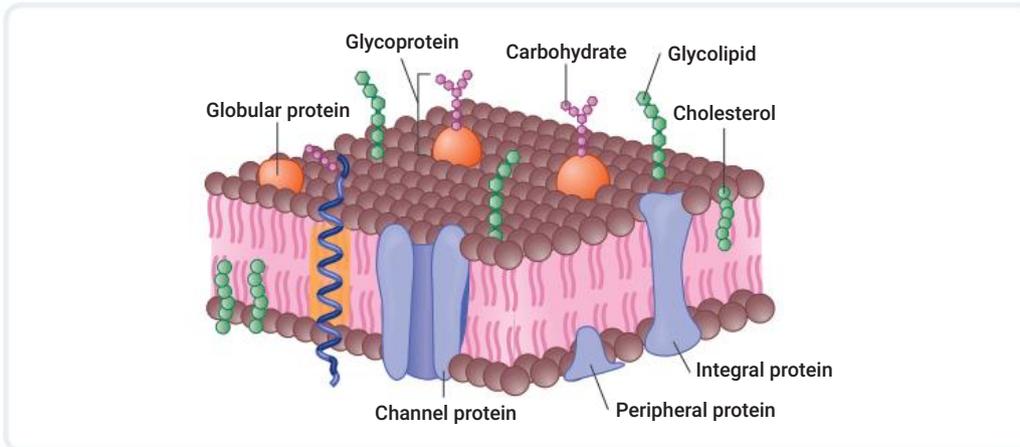
- 3 **Calculate** SA:V of a cube $2\text{ cm} \times 2\text{ cm} \times 2\text{ cm}$.
- 4 **Explain** how the shape of a cell affects its surface area-to-volume ratio.
- 5 **Explain** how increasing the size of a cell affects the cell's ability to exchange substances by diffusion.

ANALYSING

- 6 **Analyse** the data in Table 2.4.1 to identify whether there is a linear relationship between size and surface area-to-volume ratio.

Cell membrane structure

- The cell membrane contains specialised molecules that have functions such as:
 - assisting in the movement of substances into and out of the cell
 - contributing to the structural integrity of the membrane
 - being involved in cell–cell recognition.
- The membrane consists of a bilayer of phospholipids, which contains hydrophilic phosphate groups on the heads, and hydrophobic fatty acid tails.

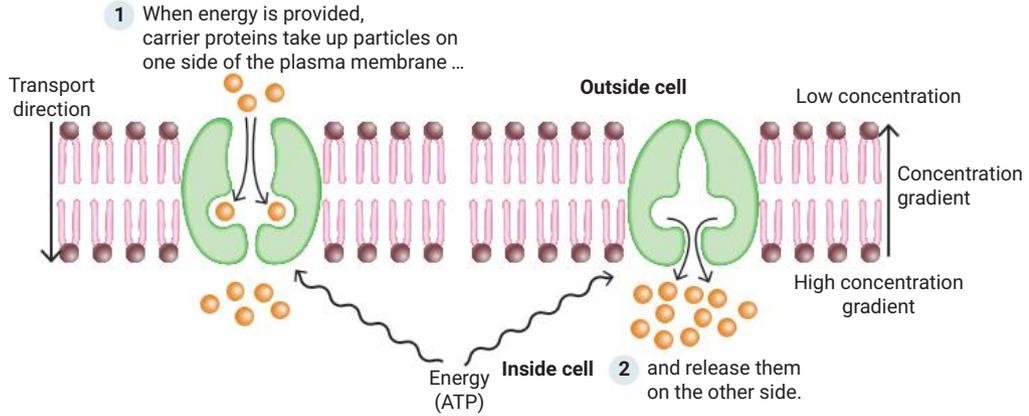


Passive transport

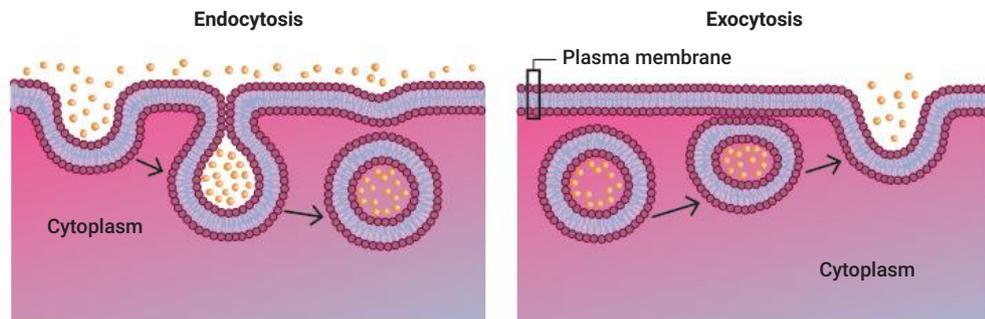
Diffusion	Facilitated diffusion	Osmosis
<p>High concentration Concentration gradient Low concentration</p>	<p>Using an ion channel protein</p> <p>Channel protein open</p> <p>Using a carrier protein</p> <p>High concentration Concentration gradient Low concentration</p>	<p>Dilute sucrose solution Concentrated sucrose solution</p>

Active transport

Active transport against a concentration gradient

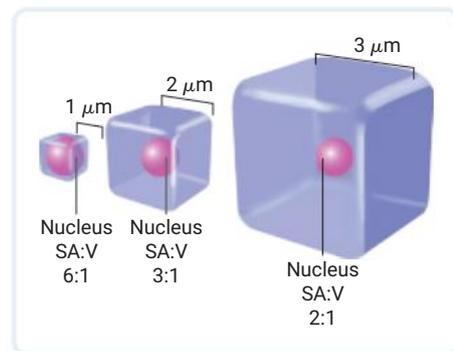


Active transport – bulk transport



Surface area-to-volume ratio

- SA:V – increased SA:V increases diffusion rate.
- Concentration gradient – steeper gradient increases diffusion rate.
- Temperature – higher temperature increases diffusion rate.
- Surface area – larger surface area increases diffusion rate.
- Distance – shorter distance increases diffusion rate.



MULTIPLE CHOICE

1. If a substance is more concentrated inside a cell than in its surroundings, which of the following processes could produce a net movement of that substance into the cell?
 - A Active transport
 - B Diffusion
 - C Facilitated diffusion
 - D Osmosis
2. If water is more concentrated outside a cell than inside a cell, the environment is considered to be:
 - A hypertonic.
 - B hypotonic.
 - C lysed.
 - D plasmolysed.
3. A student places a living cell into a drop of liquid containing a 5% sugar solution. After 30 minutes, the student finds that the liquid contains less than 5% sugar. This change would have been caused by:
 - A active transport of water out of the cell.
 - B diffusion of sugar into the cell.
 - C diffusion of water out of the cell.
 - D facilitated diffusion of sugar into the cell.
4. Which of the following statements about the phospholipid molecules in the plasma membrane is *incorrect*?
 - A The phospholipids form a bilayer.
 - B The phospholipid tails are hydrophobic.
 - C The phospholipid heads are hydrophobic (water avoiding).
 - D The phospholipid heads are hydrophilic (able to absorb water).
5. Plants with waterlogged roots are unable to obtain oxygen from soil spaces; in effect they are 'suffocated'. These plants die because they are unable to absorb enough vital mineral ions from the soil. An explanation for this observation is that:
 - A ions are transported down their concentration gradient into the cells using oxygen.
 - B the osmosis of water out of the root cells would prevent the ions entering these cells.
 - C oxygen and ions are transported into the cell linked together by membrane carrier proteins.
 - D active transport of ions into the cells requires energy from respiration, which uses oxygen.
6. The process of a white blood cell engulfing a pathogen, such as a bacterium, is called:
 - A active transport.
 - B exocytosis.
 - C osmosis.
 - D phagocytosis.
7. The process of the cell membrane pulling away from the cell wall when plant cells are placed in a concentrated salt solution is called:
 - A active transport.
 - B exocytosis.
 - C osmosis.
 - D plasmolysis.

8. Which of the following can be used to increase diffusion rate?
- A Decreasing surface area
 - B Lowering temperature
 - C Making the surface area larger
 - D Reducing the concentration gradient
9. Molecules that move easily through a phospholipid bilayer are:
- A large and non-polar.
 - B large and polar.
 - C small and non-polar.
 - D small and polar.
10. Charged particles move across the membrane by the process of:
- A diffusion down a concentration gradient.
 - B diffusion against a concentration gradient.
 - C facilitated diffusion down a concentration gradient.
 - D facilitated diffusion against a concentration gradient.

SHORT RESPONSE

11. Some students cut up three potato cubes. They placed one cube in a beaker of distilled water, and one cube in a beaker of concentrated salt water. The third cube was cooked, then placed in concentrated salt water. Each cube sat in water for 1 hour.
- a **Determine** whether each cube gained or lost mass.
 - b **Explain** any change in mass for each cube.
12. Many protozoans have a contractile vacuole within their cytoplasm. The vacuole fills with water until it reaches a particular volume. At this point, the vacuole discharges the water into the environment outside the cell.
- Describe** the pathway a water molecule would follow as it moved from the external freshwater environment into an *Amoeba* and back to the external environment via the contractile vacuole.

CROSS-CHAPTER QUESTION

13. The venoms produced by some organisms (e.g. spiders, scorpions and snakes) contain toxins capable of shutting down cells. Cardiotoxins from cobra venom are believed to be able to disrupt the packing of the lipids in the phospholipid bilayer of cells. Other studies have suggested that cardiotoxins can cause pore formation, allowing them to target mitochondria.
- a **Describe** what would happen to a cell if the phospholipid bilayer was destroyed.
 - b **Describe** the impact of the cardiotoxin interrupting the function of mitochondria in the cell.

DATA ANALYSIS

Questions 14 and 15 refer to the following information.

A study was completed to evaluate the claim that isotonic drinks have solute concentrations equal to our blood serum. A manufacturer of sports drinks provided information about an isotonic drink that has the typical composition shown in the following table.

TABLE 1 Composition of sports drinks, as provided by manufacturer

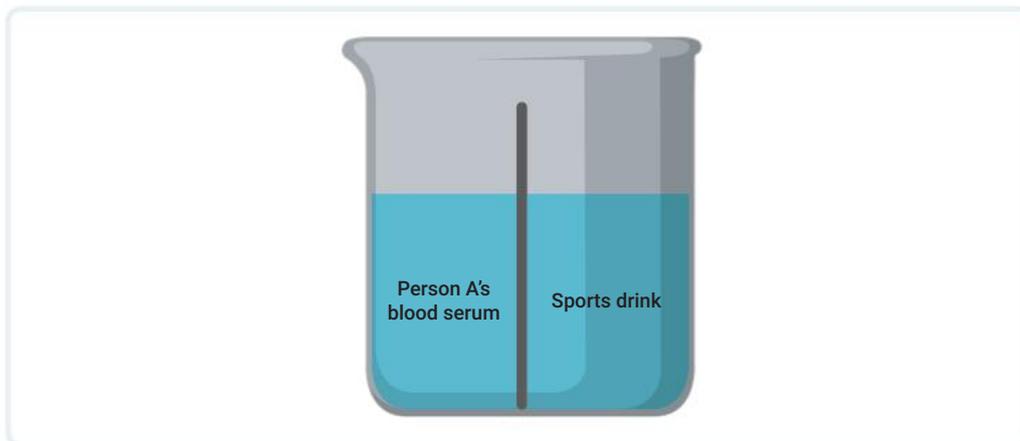
Substance	Concentration (mmol L ⁻¹)
Sodium ion	21
Potassium ion	3.5
Chloride ion	11
Sugar	333

An example of blood serum composition for person A is shown in the following table.

TABLE 2 Composition of person A's blood serum

Substance	Concentration (mmol L ⁻¹)
Sodium ion	140
Potassium ion	4.3
Chloride ion	102
Sugar	4.7

A model plasma membrane was set up in a beaker, as shown below. Person A's blood serum is on the left. The isotonic drink is on the right.



14. Analyse evidence

Compare the concentration of ions in the isotonic drink with that of person A's blood serum.

15. Interpret evidence

Draw a conclusion about water movement between the two sides of the beaker shown above.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- Pluripotent stem cells have the potential to be grown into specialised cells that can be used to repair or replace ailing organs and tissues. Advances in technology have allowed scientists to reprogram cells to become pluripotent.

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Weblink

How stem cells are used

Scientists grow a mini-kidney in lab

Stem cell research

Stem cells can differentiate into multiple types of cells. As such, they offer huge opportunities for treating disease and injury that differ from the current treatments for both chronic and infectious disease. This field of research is called stem cell therapy or regenerative medicine.

Stem cells could potentially be used to generate new cells to replace cells affected by injury or disease. They are currently used in the treatment of some diseases. In Australia, only some autoimmune diseases and blood cancers, along with skin and corneal grafting, can be treated with stem cells. The safety and effectiveness of other stem cell treatments has not yet been confirmed, so they remain experimental. However, researchers continue to investigate the possible use of stem cells in other areas, such as growing tissue.

Growing a kidney

According to the Australian Bureau of Statistics, approximately 1 per cent of the Australian population (more than 240 000 people) were reported to have suffered from

Murdoch Childrens Research Institute, Ker Sin Tan and Jessica Vanslambrouck.

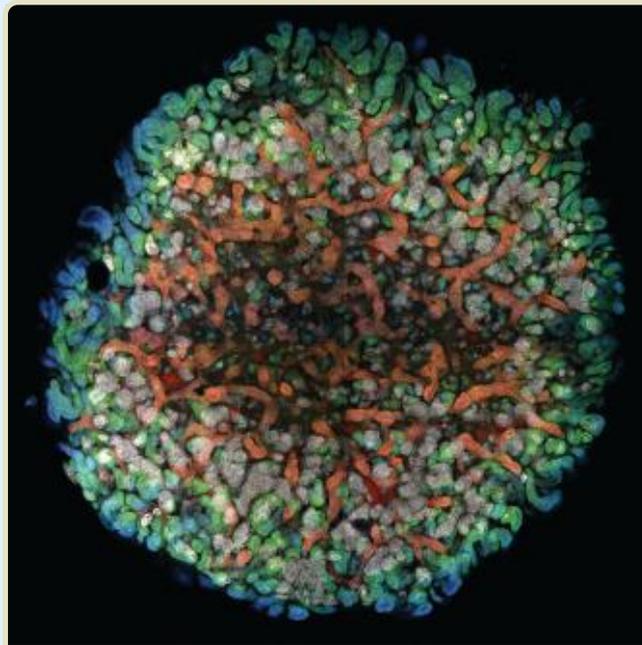


FIGURE 1 A confocal microscope image showing a kidney organoid grown in the lab from human pluripotent stem cells. This kidney organoid contains many of the different cell types and structures present in human kidneys that are important for kidney function, including nephrons (coloured green) with podocytes of the glomeruli (grey), proximal tubules (blue), and connecting segments (red).



kidney disease in 2022 (Australian Bureau of Statistics, 2023). The prevalence of kidney disease is reported to have remained steady over the last 10 years.

The University of Queensland is home to one of Australia's leading kidney disease research centres. Researchers there are working hard to find new ways to improve kidney treatment. In 2013, researchers from the University of Queensland's Institute for Molecular Bioscience were able to produce a miniature kidney from embryonic stem cells. As part of this process, researchers mimicked the conditions of normal development, providing an environment with the right combination of growth factors required for the cells to grow into kidney cells.

The initial aim of the project was to develop one type of kidney cell; however, the scientists were able to form two cell types, both of which are important in the development of the kidney. Incredibly, the cells could self-organise to form structures found in the kidney.

Observing stem cells maturing and differentiating into different cells and tissues in this way allows scientists to develop a better understanding of how diseases develop. Stem cells can also be used to test the safety and efficacy of new drugs. However, researchers must consider the ethical issues surrounding stem cell research.

Ethical issues surrounding stem cells

The main ethical issues surrounding stem cells relate to the origin of the cells and the use of the genetic material from the cell.

Retrieving pluripotent stem cells from oocytes (immature ova) and embryos results in the destruction of the embryo, so is a controversial technique. These stem cells are retrieved from embryos donated with informed consent.

To avoid the ethical concerns with embryonic stem cells, it is possible to reprogram adult cells to produce induced pluripotent stem cells. However, induced pluripotent stem cells contain the genetic material of the donor. This means an individual may no longer have total control over their own genetic material. Adult stem cells also tend to have more issues or abnormalities during the replication process.

There is a growing market for people seeking stem cell treatments when conventional medicine cannot provide a cure to a disease. Clinics offering such treatments are located all over the world, leading to the concept of 'stem cell tourism' as patients travel long distances and to other countries in the hope of being cured. Unfortunately, not all of the treatments will have undergone clinical trials to prove their effectiveness and safety.

References

The University of Queensland (2015). *Scientists grow mini-kidney in lab*. UQ News. <https://www.uq.edu.au/news/article/2015/10/scientists-grow-mini-kidney-lab>

Australian Bureau of Statistics (2023). *Kidney disease, 2022*. [www.abs.gov.au](https://www.abs.gov.au/statistics/health/health-conditions-and-risks/kidney-disease/latest-release). <https://www.abs.gov.au/statistics/health/health-conditions-and-risks/kidney-disease/latest-release>



Weblinks

Heart tissue using human embryonic stem cells

Anti-scarring agent using stem cell transplants to treat brain trauma

The stem cells of someone with type 1 diabetes



crystal light/Shutterstock.com

**SYLLABUS
DOT POINTS**
SCIENCE UNDERSTANDING

- Describe how the hierarchical organisation of cells, tissues, organs and systems allow multicellular organisms to
 - obtain nutrients, e.g. digestive and circulatory systems
 - exchange gases, e.g. respiratory and circulatory systems
 - remove wastes, e.g. respiratory, circulatory and excretory systems (Unit 1, Topic 1).
- Explain that each body system contains specialised cells and tissues that are structurally suited to function, including
 - size and shape (SA:V ratio) (Unit 1, Topic 1)
- Describe how closed circulatory systems facilitate the efficient transport of materials to and from all cells in the body.
- Explain how structural features of exchange surfaces in the respiratory and circulatory systems of mammals (alveoli and capillaries) allow for efficient gas exchange. (Unit 1, Topic 3)



- Analyse data to predict the direction that materials will be exchanged between
 - Alveoli and capillaries
 - Capillaries and muscle tissue. (Unit 1, Topic 3)
- Explain how structural features of exchange surfaces in the digestive and circulatory systems of mammals (e.g. villi and capillaries) allow for efficient nutrient exchange.
- Identify the parts of a nephron and their functions in the production of urine, i.e. glomerulus, Bowman's capsule, proximal tubule, Loop of Henle, distal tubule and collecting duct.
- Explain how glomerular filtration, selective reabsorption and secretion across nephron membranes contribute to the removal of waste.

Note: This chapter includes dot points from more than one topic.

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Introduction

Although single-celled organisms have the benefit of being highly adaptable with relatively small energy requirements, there are some functions that a single cell simply cannot perform. As more and more cells work together, new processes and functions emerge that confer significant advantages to these multicellular organisms.

However, there are challenges involved in becoming multicellular, including the issue of effective nutrient exchange when its component cells can be a long way from the external environment. The evolution of tissues, organs and organ systems, particularly the circulatory, respiratory, digestive and excretory systems, provide the necessary functions for sustaining multicellular life.

Worksheets

- Hierarchy of structural organisation
- Movement of gases
- The renal system

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ All living things are made of cells that work together in systems to increase efficiency.
- ✓ The basic structure of the digestive system includes: mouth, teeth, tongue, oesophagus, stomach, duodenum, small intestine, large intestine and rectum.
- ✓ The major organs supporting the digestive system include the pancreas and liver.
- ✓ The basic structure of the circulatory system is: heart, arteries, capillaries and veins.
- ✓ The circulatory system helps to move nutrients and remove waste from the body.
- ✓ The main components of air are: nitrogen (N₂), oxygen (O₂) and carbon dioxide (CO₂).
- ✓ Mammals acquire O₂ and release CO₂ by breathing air with their lungs.
- ✓ Gases must dissolve in liquid to pass through cell membranes.
- ✓ There are different processes of membrane transport, including osmosis, passive diffusion and active transport.
- ✓ Diffusion is the passive movement of a substance from an area of high concentration to an area of low concentration.
- ✓ Red blood cells carry oxygen around the body; they pick it up in the lungs and drop it off in the body tissues.
- ✓ Kidneys filter toxins from the blood and produce urine for excretion.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ Describe the structural features of exchange surfaces.
- ✓ Describe how closed circulatory systems facilitate efficient nutrient transport.
- ✓ Explain how the structure of the capillary allows for efficient nutrient exchange.
- ✓ Explain how the structure of the respiratory system, including alveoli and capillary networks, enables efficient gas exchange.
- ✓ Explain the function of each cellular structure of the alveolus, including the mucus lining, alveolar wall and capillary wall.
- ✓ Describe oxygen and carbon dioxide gas exchange in the alveoli.
- ✓ Predict the direction of gas exchange between alveoli and capillaries, and between capillaries and body cells.
- ✓ Explain how the structure of the villus allows for efficient nutrient absorption.
- ✓ Identify the parts of a nephron.
- ✓ Explain the function of each part of the nephron.
- ✓ Describe the journey of the filtrate through the nephron, including glomerular filtration.
- ✓ Describe the journey of the blood around the nephron structure, including selective reabsorption.

3.1 Hierarchy

In multicellular organisms, differentiated cells are organised into complex combinations to enable the performance of complex functions. To simplify the study of these complex functions, scientists break them down into a hierarchical organisation system shown in **Figure 3.1.1**.

A group of cells that have all specialised in the same basic function, such as muscle cells, are called a **tissue**. The cells in a tissue are identical, with the same shape and proportion of organelles enabling the same specialised function.

tissue a group of specialised cells working together to perform a specific function

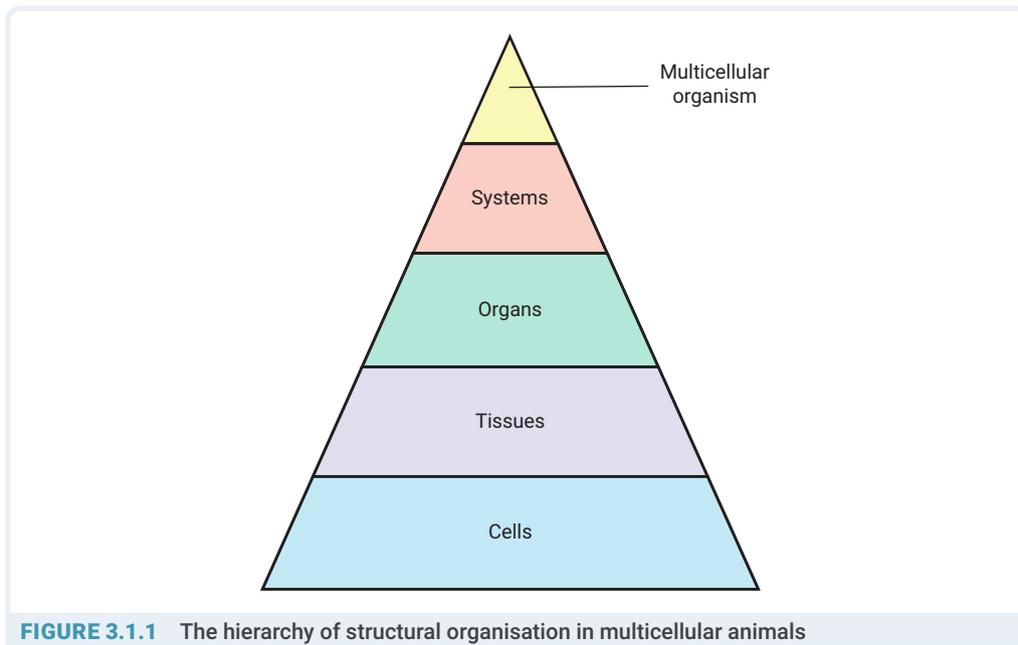


FIGURE 3.1.1 The hierarchy of structural organisation in multicellular animals

The four main tissue types are:

- connective tissue – holds body cells and organs together
- epithelial tissue – form glands, line passageways and cavities inside the body and cover the external surface
- muscle tissue – provides movement through contracting and relaxing
- nervous tissue – generates electrical impulses for communication between cells of the body.

Some functions are more complex, such as pumping blood, and require different types of tissues to work in harmony, forming an **organ**. The heart, for example, is composed of all four main types of tissue. Some functions are still more complex, such as carrying oxygen throughout the body, which requires the collective effort of several different organs, forming a **system**, such as the circulatory system. The interaction and cooperation between cells, tissues, organs and systems provide multicellular organisms with abilities that are beyond the limitations of a single cell.

Exchange surfaces

Most systems use exchange surfaces to facilitate interactions between their component organs and tissues. Effective exchange surfaces have four characteristics:

- They are moist. Moisture allows for direct contact between the membrane and the substance to be exchanged. Some surfaces have fluid on both sides of the membrane, but others require tissues in the exchange surface that produce mucus.
- They are thin, usually only a single cell thick. Fewer cells to absorb through means fewer membranes to cross. This reduces the energy cost of exchange.
- They have a large exchange surface area. More membrane available increases the rate of exchange.
- They have a **concentration gradient** across the membrane. A greater concentration of molecules on one side of the exchange surface than on the other encourages molecules to diffuse across the exchange surface. This lowers the energy cost of exchange.



Weblink
Tissues, organs and organ systems

Worksheet
Heirarchy of structural organisation

organ a collection of different types of tissues working together to perform a particular function

system a collection of organs that work together to perform a particular function

concentration gradient the difference in concentration of a substance between two different regions

LEARNING CHECK 3.1

DESCRIBING

- 1 **Describe** the hierarchy of organisation within a complex multicellular organism by drawing a flow chart.
- 2 **Identify** the key difference between categorising a body part as an organ or tissue.
- 3 **Summarise** the four key features that are essential for an efficient exchange surface.

APPLYING

- 4 The capillaries are the smallest vessels in the body. They are so narrow that cells can only move through them one at a time. **Discuss** the impact of a further increase in the surface area of capillaries.

3.2 Circulatory system

The circulatory system is different from other organ systems in the body in that it is primarily a transport and exchange system that must be able to reach every cell in the body. To facilitate the necessary exchange of materials between the body cells and the external environment, the mammalian circulatory system (**Figure 3.2.1**) has three major components:

1. a fluid (blood) in which materials are transported
2. a closed network of tubes (blood vessels) to enable the fluid to reach all body cells
3. a pump (heart) that pushes the fluid through the vessels.

The bloodstream in mammals is a **closed circulatory system**, where blood is confined to a series of paths or vessels. **Figure 3.2.2** compares our closed circulatory system with the open circulatory system found in insects. An open circulatory system does not confine the fluid to vessels but enables it to wash directly over body cells. Although open systems are a simpler

closed circulatory system a type of circulatory system in which the fluid is confined to a network of vessels



Weblinks

Circulatory system

3D model of the cardiovascular system

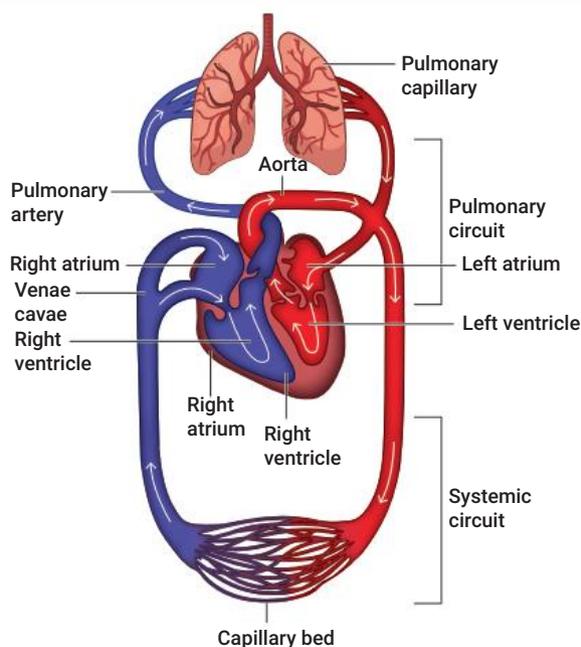
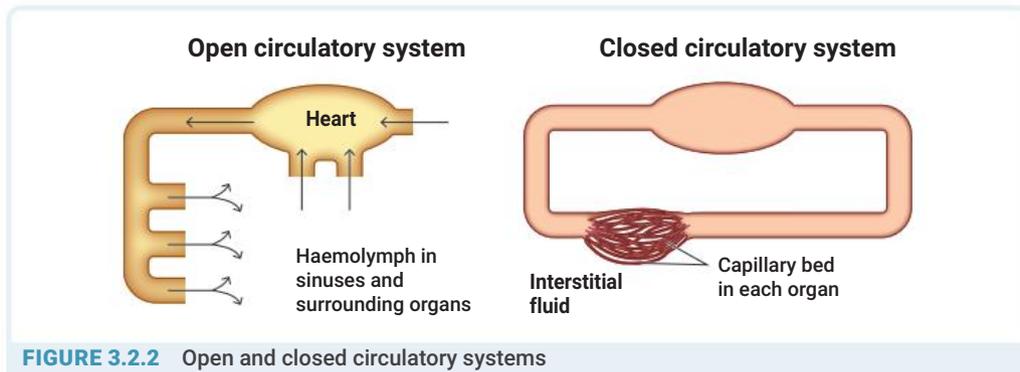
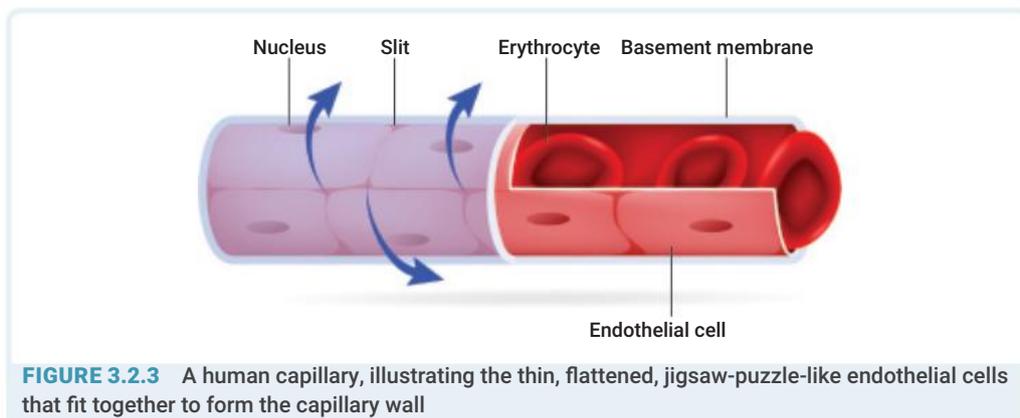


FIGURE 3.2.1 The human circulatory system



method of reaching all body cells, closed systems have the advantage of being able to better regulate the concentration and direction of the fluid flow.

While the heart is well-known as an organ, blood is considered a tissue, consisting of plasma, red blood cells, white blood cells and platelets working together to perform its many functions. The two major transport vessels, **arteries** and **veins**, are tubes made of three tissue layers: tunica intima (endothelial tissue), tunica media (muscular tissue) and tunica adventitia (connective tissue of varying elasticity). **Capillaries**, on the other hand, are the main site of exchange in this system, so their walls are a single layer of endothelial cells, kept moist by blood and with a tiny diameter to increase surface area (**Figure 3.2.3**). Red blood cells must pass through a capillary in single file.



Weblinks
Blood vessels

Vessels in the circulatory system

artery a large diameter, elastic-walled blood vessel that takes blood away from the heart

vein a non-elastic, thinner walled blood vessel that carries blood to the heart

capillary a tiny diameter blood vessel with single-cell-thick walls that facilitates nutrient exchange with body cells



Syllabus link
Chapter 2 discusses the methods for movement of substances across cell membranes.

LEARNING CHECK 3.2

DESCRIBING

- 1 State what a closed circulatory system is.
- 2 **Describe** the structure of a capillary.

APPLYING

- 3 **Explain** how the capillary structure meets each of the four characteristics of an exchange surface.
- 4 **Explain** the process of nutrient exchange between a capillary and body cell by drawing an annotated diagram.
- 5 **Explain** the benefits of a closed circulatory system.

ANALYSING

- 6 **Compare** capillaries with the other two major blood vessels.



Weblink
Respiratory system

3.3 Respiratory system

The respiratory system is a gas exchange system. It has four main layers of tissue: mucosa (**epithelial cells** in direct contact with air), submucosa, cartilage/muscular layer and adventitia (connective tissue).

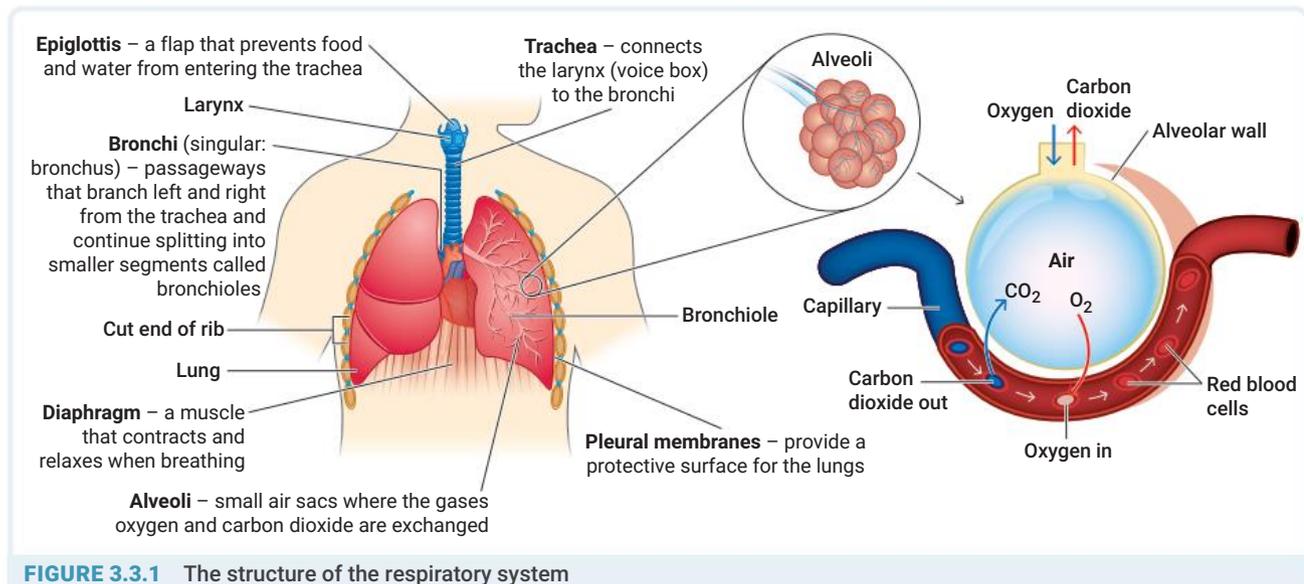


FIGURE 3.3.1 The structure of the respiratory system

epithelial cell a cell in a sheet of cells covering any external or internal surface in a multicellular organism

alveoli tiny air sacs located on the end of bronchioles; site of gas exchange in mammals

diffusion the passive movement of molecules from a region of high concentration to a region of low concentration

haemoglobin a protein within red blood cells that binds oxygen molecules for transport



Syllabus link
Chapter 5 discusses the important roles of oxygen and carbon dioxide in the body.

Within the respiratory system, gas exchange does not occur along the entire bronchial tract, but only in the approximately 700 million tiny end structures called **alveoli** (singular: alveolus) (Figure 3.3.1). The alveoli increase the internal surface area of the lung to approximately equal that of a tennis court. The lining of each alveolus is only one epithelial cell thick.

The single, flat layer of epithelial cells forming the alveolar wall is covered internally with a thin layer of mucus in which the gases can dissolve. The external surface of this wall contacts the capillary wall, also formed of a single, flat layer of epithelial cells. Gases from the air dissolve into the mucus layer, pass through the alveolar wall cell and the capillary wall cell, to reach the blood. Gases from the blood move in the opposite direction. The distance the oxygen and carbon dioxide molecules travel is much less than 1 micrometre ($1\ \mu\text{m}$), which is one-thousandth of 1 millimetre (1 mm).

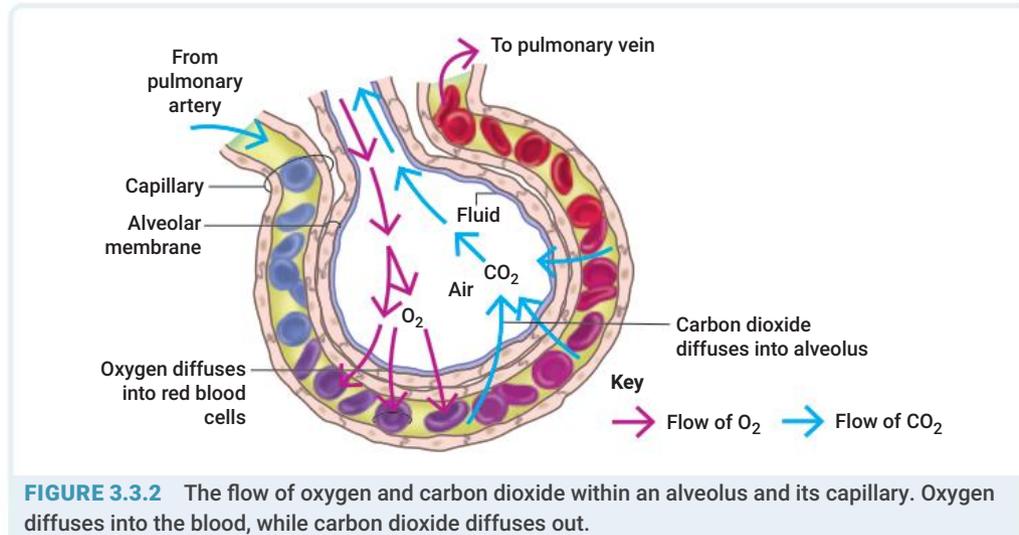
Gas exchange between the air and blood occurs by **diffusion**: there is a higher concentration of oxygen in the inhaled air than in the blood, so oxygen diffuses into the blood. Oxygen bonds to a protein in red blood cells called **haemoglobin**. Conversely, there is a higher concentration of carbon dioxide in the blood than in the inhaled air, so carbon dioxide diffuses out into the alveolus. Carbon dioxide dissolves in blood plasma, so it does not need to be carried by red blood cells.

Predicting the direction of gas exchange

If the relative difference in concentration of molecules between two different regions is known, it is possible to predict the direction of movement of these molecules.

In the alveoli

By convention, diagrams depict **oxygenated** blood cells in red and **deoxygenated** blood cells in blue. In **Figure 3.3.2**, the gradation in colour of the red blood cells is shown as blood moves along in the capillary. The direction of diffusion of the gases can be determined because it shows deoxygenated blood entering from the pulmonary artery on the left. This blood has a lower concentration of oxygen than the inhaled air and oxygen will diffuse into it. After oxygenation, the blood is returned to the heart by the pulmonary vein. Oxygen diffusion into the blood will be greatest on the left of the diagram where the blood has a low concentration of oxygen, and least on the right where the blood is fully oxygenated.



Carbon dioxide, on the other hand, is not depicted in the colours of the diagram. The deoxygenated blood returning from the body carries a higher concentration of carbon dioxide than the air. Carbon dioxide will diffuse out of the blood into the alveolus. Like oxygen, carbon dioxide diffusion is likely to be greatest on the left of the diagram where the blood hasn't lost much of its carbon dioxide load yet, and least on the right where the blood has exchanged most of its carbon dioxide waste.

Each exhale will expel the carbon dioxide laden air. Each inhale will bring fresh oxygenated air into the alveolus. Breathing, combined with the blood flow around the alveolus, resets the concentration gradients to enable continuous gas exchange.

In the body tissue

After blood becomes oxygenated in the alveoli of the lungs, it is transported back to the heart to be pumped around the body. All body cells, including muscle tissue, bone marrow and organs, exchange gases with the blood in capillaries.

Figure 3.3.3 depicts gas exchange between the blood and a series of body cells. Most body cells are within $10\mu\text{m}$ of a capillary to ensure adequate diffusion of gases and other nutrients. The direction of gas exchange can again be predicted by applying the rule that diffusion occurs from regions of higher concentration to regions of lower concentration for the particular gas. In this case, the blood in the capillary has a greater concentration of oxygen than the body cells, because they are continually using it for cellular respiration. Therefore, oxygen will diffuse from the blood into the body cells. On the other hand, that same cellular respiration will have produced a higher concentration of carbon dioxide in the cells. Therefore, carbon dioxide will diffuse from the body cells into the blood, to be carried to the lungs.

oxygenated denoting a higher concentration of oxygen

deoxygenated denoting a lower concentration of oxygen



Weblinks
Systems of gas exchange
Alveoli interactive

Worksheet
Movement of gases

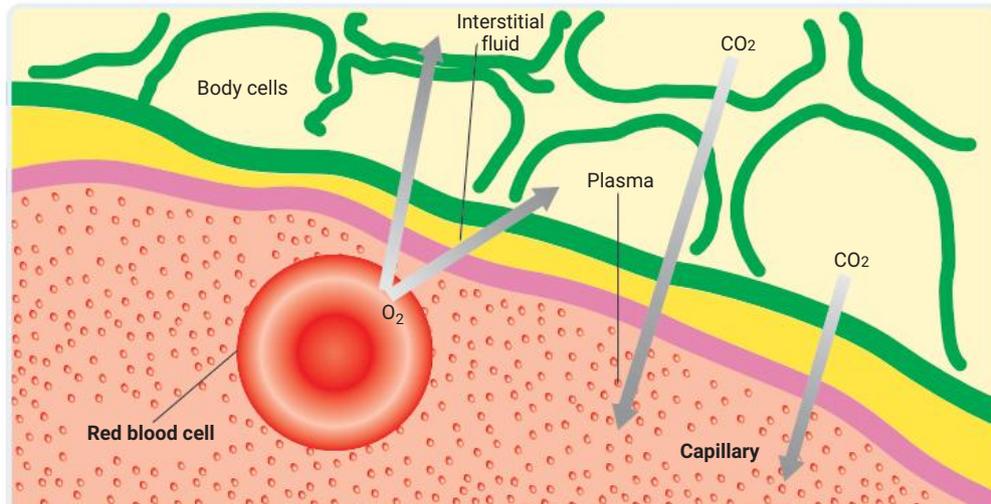


FIGURE 3.3.3 Gas exchange between the blood and body cells occurs in the reverse direction as in the lungs.

LEARNING CHECK 3.3

DESCRIBING

- 1 **Describe** the ways that the alveolus meets each of the characteristics of an efficient exchange surface.
- 2 **Identify** the gas that must be:
 - a taken *into* the body from the external environment.
 - b expelled *from* the body to the external environment.
- 3 **Identify** the structures through which gases move to diffuse between the internal blood environment and external air environment.
- 4 State the rule for determining the direction of gas exchange across an exchange surface.

APPLYING

- 5 Use **Figure 3.3.4** to answer the following questions.

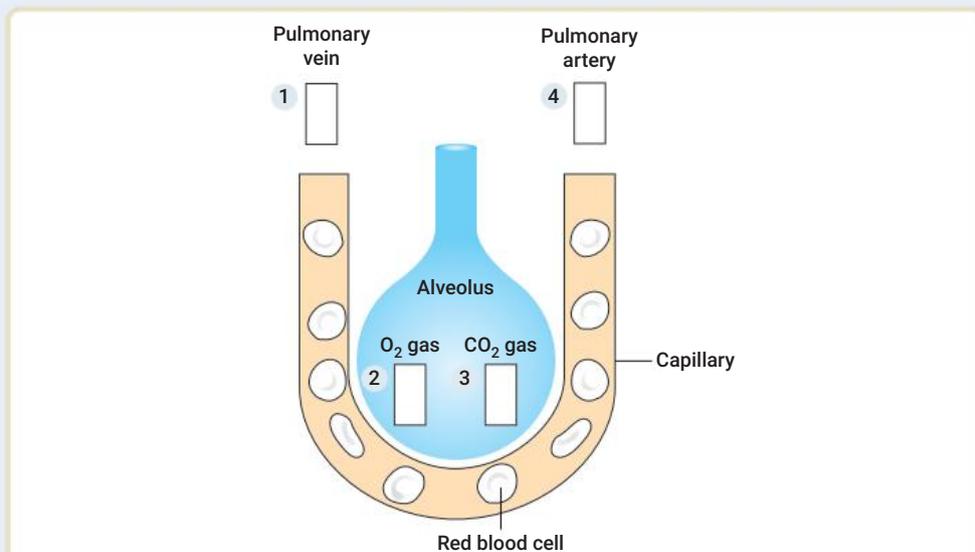


FIGURE 3.3.4 A schematic diagram of the basic structure of an alveolus and its capillary

- a **Identify** where blood enters the capillary in the diagram.
- b **Determine** whether rectangle 4 should contain an arrow pointing up or down.
- c **Determine** whether the capillary at rectangle 4 is carrying oxygenated or deoxygenated blood.
- d **Determine** whether the higher concentration of oxygen is in the air or in the blood at rectangle 4.
- e **Determine** the direction in which oxygen will diffuse and indicate this with an up or down arrow in rectangle 2.
- f **Determine** whether the higher concentration of carbon dioxide is in the air or in the blood at rectangle 3.
- g **Determine** if rectangle 3 should contain an arrow pointing up or down.
- h **Determine** if rectangle 1 should contain an arrow pointing up or down.

INTERPRETING

- 6 **Predict** the effects of too much or too little mucus in the alveoli.

3.4 Digestive system

The human digestive system is essentially one long tube (about 7 metres in adult humans) divided into several organs as shown in **Figure 3.4.1**. Each of these organs is made up of four main layers of tissue: mucosa (epithelial cells in direct contact with food), submucosa (connective tissue, blood vessels and lymphatic tissue), muscularis (muscular tissue) and serosa (connective tissue).



Weblink
Digestive system

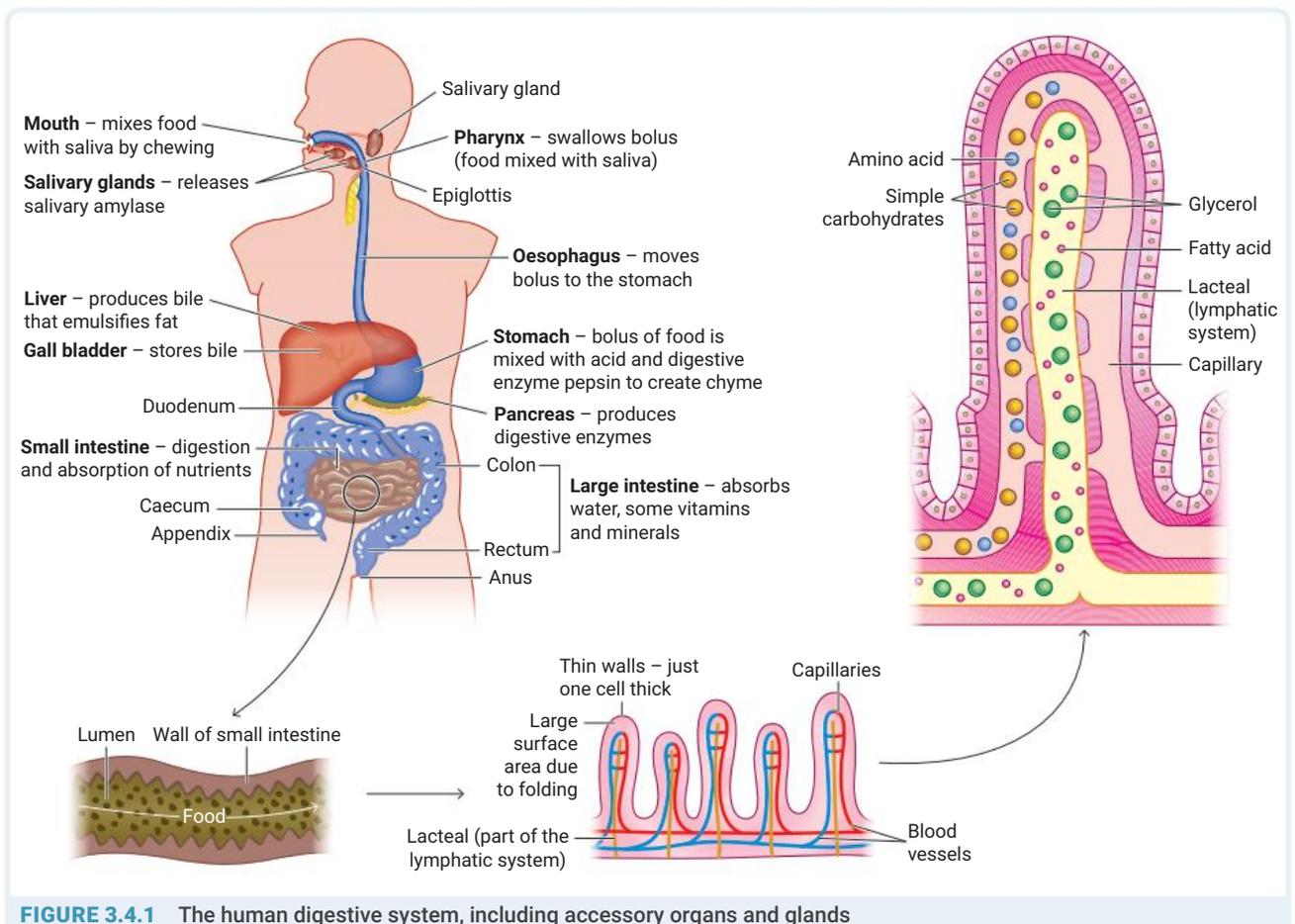


FIGURE 3.4.1 The human digestive system, including accessory organs and glands

villi elongated projections from the lining of the small intestine that hugely increase the surface area and thus the capacity for exchange of materials

lacteal a vessel that transports non-water-soluble materials to and from the villi of the small intestine; a branch of lymph vessel

lymphatic system a drainage system in the body that helps maintain a balanced fluid level

Villi

The main exchange surface of the digestive system is in the small intestine. The mucosa here is folded into many finger-like projections called **villi** (single: villus) to increase the surface area in contact with food. The epithelial cells that form the villi boundaries also have a cell membrane that is convoluted into multitudes of microvilli. The villi and their microvilli massively increase the surface area of the intestinal lining and facilitate maximum and efficient absorption. Mucus-producing cells are embedded in this single-celled lining to ensure the exchange surface is moist.

To maintain a concentration gradient, each villus is supplied with capillaries and **lacteals** in the submucosa to carry away absorbed nutrients (**Figure 3.4.1 top right**). The structure of the villus creates an extremely small distance, just two cells thick, across which nutrients have to move to reach the internal environment of the body. Glucose and amino acids are water-soluble, so they are absorbed into the capillary network of the circulatory system. Fatty acids and glycerol are not water-soluble, so they bypass the capillary network and are absorbed by the lacteals to enter the **lymphatic system**. The lymphatic system absorbs extracellular fluid and drains into the circulatory system at the subclavian vein just above the heart.

LEARNING CHECK 3.4

DESCRIBING

- 1 **Identify** the structure that produces microvilli in the small intestine.
- 2 **Describe** the two structures into which most biomolecules are absorbed for transportation to the body.
- 3 **Describe** the features of the villi that make them capable of functioning as an exchange surface between the body's internal and external environments.

APPLYING

- 4 **Explain** the result of a lack of villi on the efficiency of the digestive system.

3.5 Excretory system

The excretory system in mammals is designed to remove the waste products of metabolism. Its major organs are the liver, which processes toxins, and the kidneys, which filter out wastes, specifically water and solutes, such as **urea**. The amounts of these materials filtered out are adjusted to suit the body's requirements for those materials at that particular time.

Nephrons

The main exchange site in the kidney is the **nephron** (**Figure 3.5.1**). There are about 1 million in each kidney to maximise the surface area for exchange and all parts of the nephron have moist, thin walls. Nephron structure makes optimal use of concentration gradients to support exchange along its length.

urea a nitrogenous waste that is excreted in mammalian urine

nephron a specialised structural and functional unit within the kidney which eliminates waste molecules and regulates solute and water levels in the blood

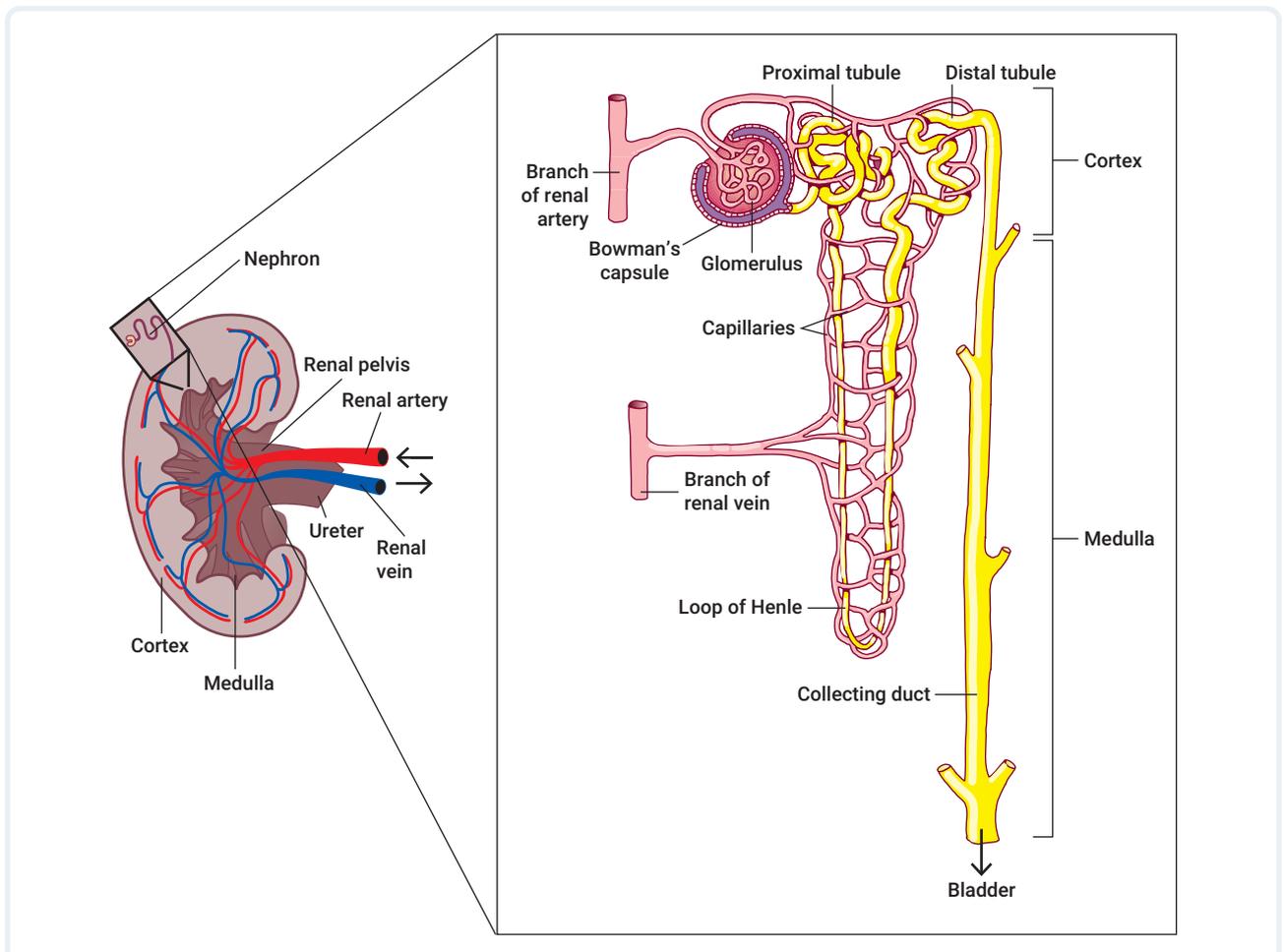


FIGURE 3.5.1 The structure of the human kidney and the functional unit, the nephron

When blood enters the nephron, it passes at high pressure through a ball of capillaries called a **glomerulus**. The glomerulus is situated inside the **Bowman's capsule**, which looks like a hollow rubber ball that has been pressed in on one side. The capillaries of the glomerulus are tightly bound into the Bowman's capsule, and the high pressure forces some of the water, along with all its solutes (except large proteins and blood cells), out of the blood through the thin glomerulus wall and into the Bowman's capsule. This process is called **glomerular filtration** and the liquid in the capsule is referred to as the **filtrate**.

Following the filtrate

The Bowman's capsule connects to the **proximal tubule**, then to a hairpin-shaped **loop of Henle**, extending down into the medulla, and finally to the **distal tubule**. A **collecting duct**, the last structural component of the individual nephron, collects the filtrate, now containing wastes, from the distal tubule. The collecting duct passes down through the medulla and empties the waste filtrate into an extensive drainage collection system in the **renal pelvis**, the kidney's central cavity. From here, the filtrate passes down the ureter to be stored in the bladder for excretion. **Table 3.5.1** contains more specific detail of the function of each of the nephron structures.

glomerulus a network of capillaries contained within the Bowman's capsule, where high pressure forces the blood contents into the capsule

Bowman's capsule the nephron structure in which the glomerulus is positioned, and into which the filtrate from the glomerulus is forced

glomerular filtration the process of removing some water and most solutes from the blood for excretion or reabsorption in the kidneys

filtrate a liquid that has passed through a filter

proximal tubule the nearest tubule; a section of the nephron that leads from the Bowman's capsule to the loop of Henle

loop of Henle the portion of a nephron that connects the proximal tubule to the distal tubule; the site of selective reabsorption of water

distal tubule the distant tubule; a section of the nephron between the loop of Henle and the collecting duct

collecting duct a duct in the kidney that collects and transports fluid from several distal tubules to the renal pelvis

renal pelvis the section of the kidney where urine is collected and directed to the ureter

interstitial fluid extracellular tissue fluid; fluid in spaces surrounding cells



Weblinks
Kidney function
Kidney structure and function

secretion the process of balancing the pH of the interstitial fluid by moving substances such as ammonia and H^+ into the distal tubule and collecting duct

TABLE 3.5.1 Detailed functions of nephron structures

Name and structure	Function
Glomerulus	Filtration: pressure of blood forces about one-fifth of its plasma out through the capillary walls, along with everything small enough to pass through. This includes urea, glucose, amino acids and mineral ions, such as sodium (Na^+), chloride (Cl^-) and potassium (K^+), but not blood cells, platelets or large proteins.
Bowman's capsule	Filtration: plasma with dissolved materials diffuses across the single-cell thickness of the Bowman's capsule wall and into the hollow space of the capsule and is passed on into the proximal tubule.
Proximal (convoluted) tubule: a winding, large-diameter tube	Reabsorption: water is reabsorbed, as is 100% of glucose and amino acids, and approximately 65% of mineral ions, by both active and passive transport depending on the substance, with most of the urea staying inside the tubule.
Loop of Henle – descending limb: extended straight part of small-diameter tubule moving away from the proximal tubule	Reabsorption: water flows out of the tubule and into the interstitial fluid and capillaries by osmosis because the concentration of dissolved ions in the fluid inside the tubule is lower than that in the surrounding interstitial fluid and capillaries. The urea (and other solutes) inside becomes more concentrated in the urine the further down the descending tube it goes.
Loop of Henle – ascending limb: extended straight part of loop leading to the distal tubule	Reabsorption: mineral ions are moved out of the thick-walled section of the tubule initially by active transport, and later out of the thin-walled section, by passive transport, as part of the overall mechanism for concentrating the urine. Water remains inside because the tubule walls are impermeable to water. Waste concentration in urine is lower by the end of this part of the loop.
Distal (convoluted) tubule: a winding, large-diameter tube	Reabsorption: some useful mineral ions, and water if necessary, are reabsorbed. If the body cells require more water, the permeability of the distal tubule increases to allow water to move out into the interstitial fluid and capillaries. If there has been a large water intake to the body, permeability decreases, so water remains within the tubule and dilutes the urine that leaves the body.
Collecting ducts: a system of urine-collecting ducts that widen as they near the renal pelvis	Reabsorption: sodium ions (Na^+) and more water, if necessary, move from collecting ducts into the surrounding interstitial fluid and capillaries. Urea may also be reabsorbed into the interstitial fluid. Secretion: additional wastes are transferred as necessary from the capillary network and interstitial fluid into the ducts.

Following the blood

All of the useful components of the blood that were forced out of circulation into the Bowman's capsule are not lost to the external environment. The substances left inside the glomerulus capillaries, including the remaining water, flow into a branching network of capillaries threading around the nephron's tubular parts. Water and solutes required by body cells are reabsorbed from the nephron tubules into the surrounding capillaries, which converge into a branch of the renal vein and return to the body.

Producing urine

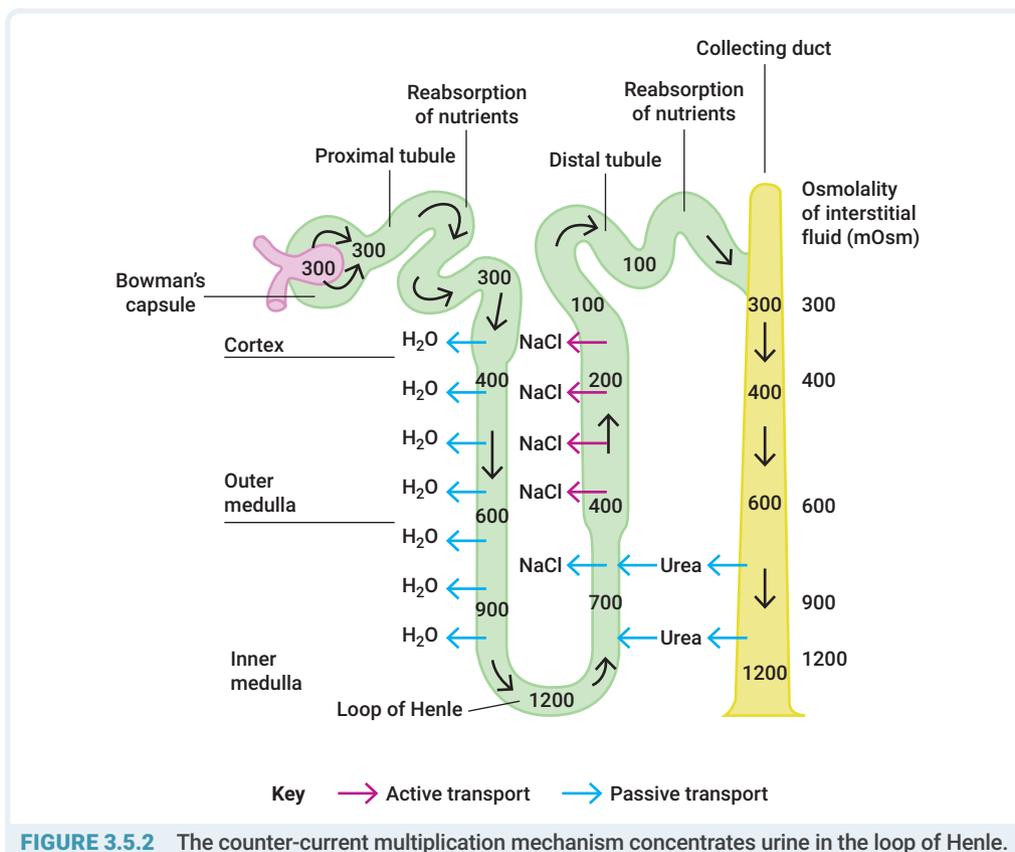
On average, about 600 mL of blood flows through each kidney every minute. Approximately 20 per cent of the volume (120 mL) is removed through glomerular filtration, which, if excreted, would have to be replaced by drinking at least 1 L of liquid every 10 minutes just to maintain water balance in your body. Fortunately, **selective reabsorption** ensures that 119 mL of this water, along with many essential dissolved molecule particles, is returned to the body's circulatory system. The remaining 1 mL from each kidney each minute is used to produce **urine**.

The complex production of urine can be best understood by following the filtrate and the blood at the same time, as annotated in **Figure 3.5.2**. After glomerular filtration in the Bowman's capsule and glomerulus, the filtrate passes through the proximal tubule while the blood flows into the **peritubular capillaries**. In the proximal tubule, selective reabsorption brings key molecule substances such as glucose, amino acids and salts back into the blood. Some molecule particles are secreted directly from the interstitial fluid of the kidney into the proximal tubule, such as additional ammonia and H^+ to balance the pH.

selective reabsorption
the process of returning selected molecules from the nephron filtrate to the blood

urine a fluid containing water, urea and other wastes; it is excreted from the kidneys

peritubular capillaries
tiny blood vessels that surround the tubules in the nephron and facilitate selective reabsorption and secretion



The descending limb of the loop of Henle is primarily concerned with water reabsorption, sending water back to the blood in the peritubular capillaries and leaving the filtrate much more concentrated than before. The **osmolality** of the filtrate begins at around 300 mOsm L^{-1} in the Bowman's capsule but reaches a peak of 1200 mOsm L^{-1} at the bottom of the loop of Henle.

The ascending limb of the loop of Henle is the site of significant reabsorption of mineral ions and other salts. The lower part of this limb allows the salts to diffuse out of the loop, but by the upper part, the concentration of salts in the interstitial fluid is too high to allow passive diffusion. This upper part actively transports mineral ions and other salts out of the loop of Henle, which reduces the osmolality of the filtrate to a low of 100 mOsm L^{-1} .



Weblinks
Formation of urine – a nephron function animation
Tubular reabsorption animation

osmolality the concentration of all solutes in a solution measured in the number of particles per litre of solution

counter-current multiplication a system operating within a hairpin bend, where energy is used to transport particles across the membrane of one arm, enabling the passive diffusion of particles from the other arm, which reinforces further passive diffusion in the original arm



Syllabus link
Chapter 9 discusses the mechanism of water balance in animals.



Worksheet
The renal system

The interstitial fluid around the loop of Henle is therefore flooded with water by the descending limb and flooded with salts by the ascending limb. These two actions in the same local area maintain a consistent osmolarity in the interstitial fluid of the kidney, with the active secretion of salts by the upper part of the ascending limb forcing further reabsorption of water from the descending limb, and that reabsorption forcing passive diffusion of salts in the lower part of the ascending limb. The process of reabsorption and secretion support and drive each other with very little energy required by the body. This is called **counter-current multiplication**.

When the filtrate leaves the loop of Henle, it passes through the distal tubule, where potassium (K^+), sodium (Na^+) and chloride (Cl^-) ions are selectively secreted or reabsorbed to fine-tune their concentrations in the blood.

Finally, the peritubular capillaries rejoin to form a renal vein and leave the kidney to return to the body, while the filtrate enters the collecting duct. The cells lining this duct can change their sensitivity to water depending on the body's requirements. In dehydration conditions, the collecting duct will absorb relatively larger amounts of water from the filtrate, producing more concentrated urine. The urine leaves the collecting duct via the renal pelvis, which drains through the ureter into the bladder.

LEARNING CHECK 3.5

DESCRIBING

- 1 **Describe** the order of the structures through which waste molecules travel, starting with the renal artery carrying blood into the kidney, and ending outside the body by drawing a flow chart.
- 2 **a** With respect to nephron function, briefly **describe** what is meant by:
 - i filtration
 - ii reabsorption
 - iii secretion**b** **Identify** in which structures the above three processes occur.

APPLYING

- 3 **Identify** whether each of the following structures contain blood or filtrate.
 - a Glomerulus
 - b Bowman's capsule
 - c Tubules of the nephron
 - d Capillary network surrounding the nephron tubules
 - e Renal vein
 - f Ureter
- 4 **Explain** the differences between glomerular filtration, selective reabsorption and secretion.

INTERPRETING

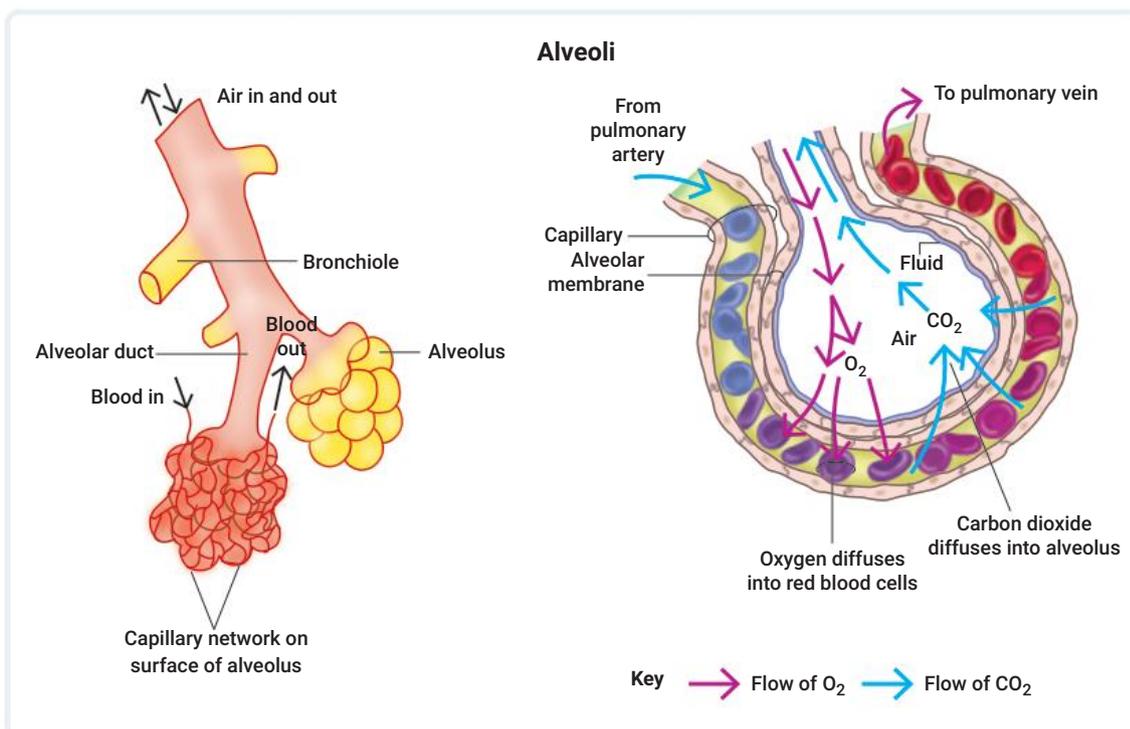
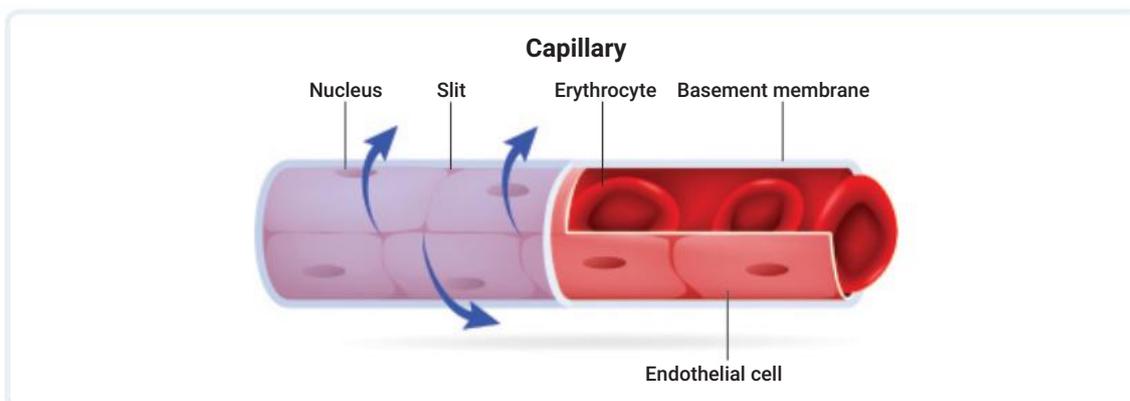
- 5 **Explain** why the colour of urine is a good indicator of hydration levels.
- 6 For a healthy person, the normal range for protein in urine is approximately 30 mg g^{-1} ; however, individuals with nephron syndrome can have protein urine levels of $>300 \text{ mg g}^{-1}$. Based on your understanding of the nephron, **predict** the structure most likely to be damaged in individuals with nephron syndrome. **Explain** your answer.

Cell hierarchy and properties of exchange surfaces

- Cells are organised in a **hierarchy**, from cells to tissues to organs to systems.
- Effective **exchange surfaces** have four key properties. They:
 1. are moist to allow efficient membrane transport
 2. are thin to reduce the distance required
 3. have a large surface area to increase the rate of exchange
 4. have a concentration gradient to decrease the energy required.

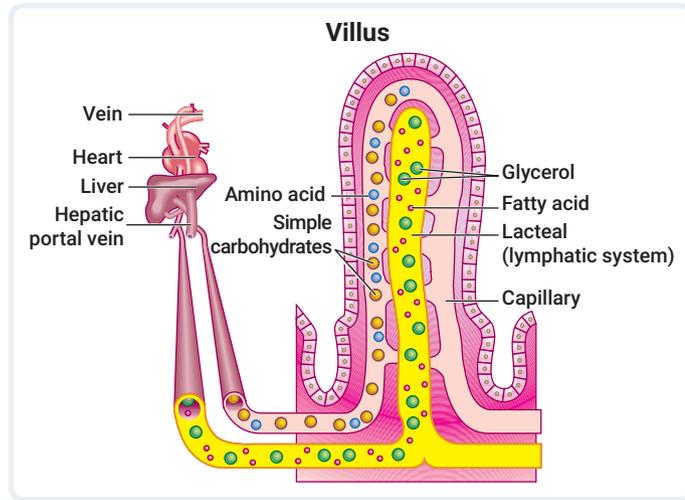
Circulatory system

- A closed circulatory system is one in which blood is confined to a network of vessels, providing better control of concentration and flow.



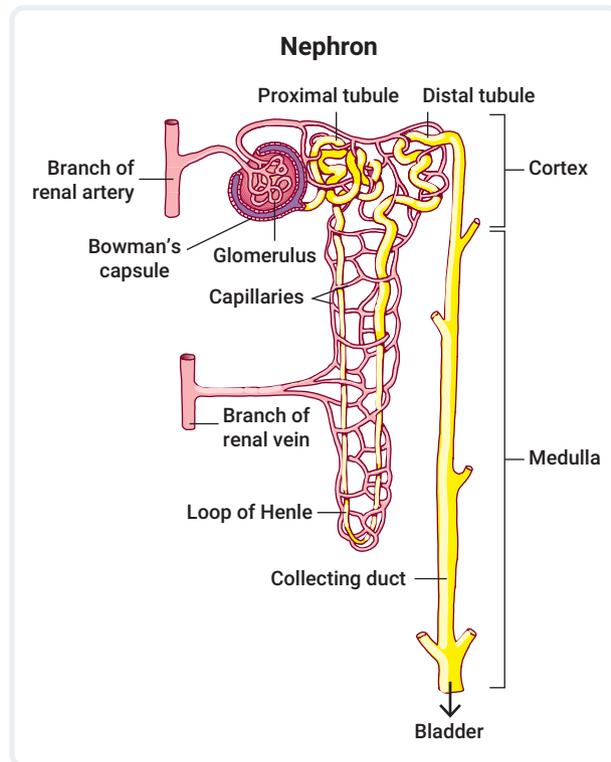
Digestive system

- The digestive system is responsible for absorbing nutrients into the body.
- Villi allow for the absorption of nutrients.
- The structure of villi results in a high surface area.



The excretory system

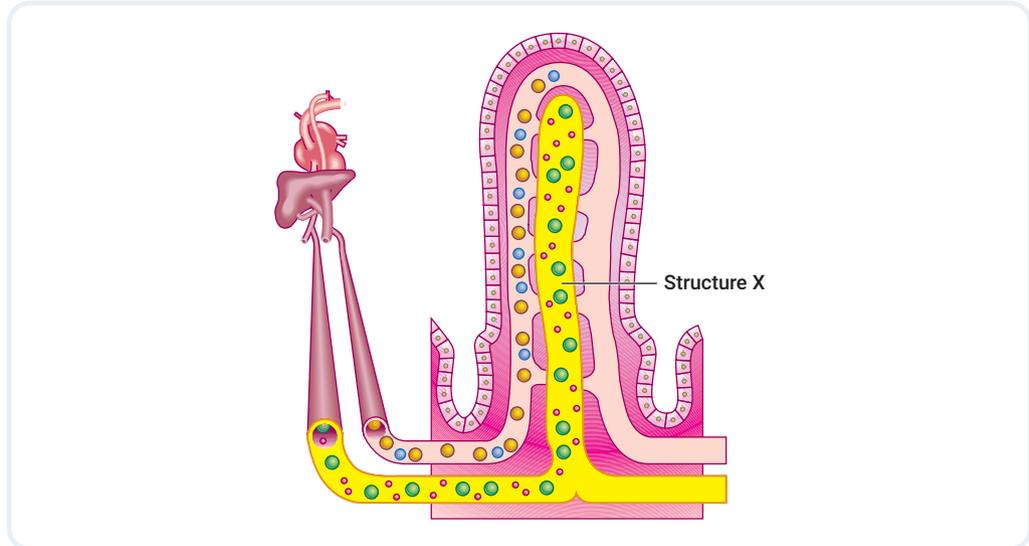
- The kidneys help to filter waste from the body.
- The nephron is the main exchange site in the kidney.
- **Glomerular filtration** is the process of high pressure forcing water and solutes out of the blood in the glomerulus.
- **Selective reabsorption** is the process of key particles returning to the capillaries from the proximal tubule (glucose, amino acids and salts), loop of Henle (water) and distal tubule (sodium, potassium and chloride ions).
- **Secretion** is the active transport of salts out of the ascending limb of the loop of Henle (to balance the interstitial fluid) and distal tubule (to balance the blood).



MULTIPLE CHOICE

- The hierarchical levels of structural organisation in multicellular organisms, in order, are:
 - cells make up tissues, which make up organs, which make up systems.
 - tissues make up cells, which make up organs, which make up systems.
 - systems make up cells, which make up organs, which make up tissues.
 - atoms make up molecules, which make up compounds, which make up chemicals.
- Exchange surfaces can:
 - absorb nutrients.
 - excrete wastes.
 - deliver nutrients.
 - all of the above.
- The circulatory system is a closed loop. This means that:
 - blood components come into direct contact with body cells.
 - blood continues to circulate without interacting with body cells.
 - membrane transport is required for blood components to interact with body cells.
 - membrane transport is required for blood components to circulate past body cells.
- Capillaries are:
 - large in diameter.
 - thick walled.
 - between veins and the heart.
 - between arteries and veins.
- Oxygen molecules arrive in the alveolus by:
 - breathing in air.
 - diffusing from surrounding body cells.
 - dissolving in the mucus layer.
 - returning from blood in the capillary.
- At body tissues, such as muscle tissue and bone marrow:
 - oxygen diffuses into the capillary and carbon dioxide diffuses into the capillary.
 - oxygen diffuses out of the capillary and carbon dioxide diffuses into the capillary.
 - oxygen diffuses into the capillary and carbon dioxide diffuses out of the capillary.
 - oxygen diffuses out of the capillary and carbon dioxide diffuses out of the capillary.
- The structures that increase the surface area of the small intestine are called:
 - alveoli.
 - capillaries.
 - nephrons.
 - villi.

8. The structure labelled X is a:
- A capillary.
 - B lacteal.
 - C villus.
 - D projection.



9. The order of nephron structures through which fluids containing wastes pass is:
- A collecting duct, loop of Henle, glomerulus, proximal tubule, Bowman's capsule and distal tubule.
 - B glomerulus, Bowman's capsule, loop of Henle, proximal tubule, distal tubule and collecting duct.
 - C glomerulus, Bowman's capsule, proximal tubule, loop of Henle, distal tubule and collecting duct.
 - D renal artery, glomerulus, peritubular capillary, loop of Henle, collecting duct and renal vein.
10. In healthy kidneys, blood never leaves the blood vessels. Which of the following also does not leave the blood vessels?
- A Water
 - B Glucose
 - C Salts
 - D Proteins

SHORT RESPONSE

11. **Compare** the exchange surfaces of the respiratory system with those in the digestive and excretory systems.
12. **Compare** selective reabsorption and glomerular filtration.

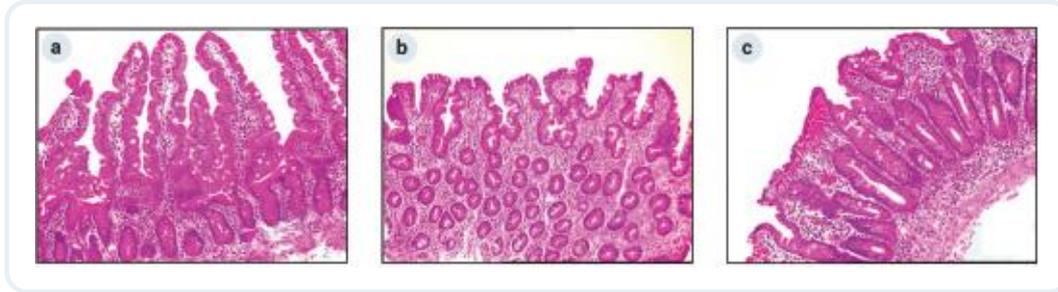
CROSS-CHAPTER QUESTION

13. **Discuss** the impact on breathing if the atmosphere was made of larger gas molecules that cannot passively diffuse across a cell membrane.

DATA ANALYSIS

Questions 14 and 15 refer to the following information.

Coeliac disease is an autoimmune condition in humans where the presence of gluten in the small intestine triggers the body to attack the cells absorbing it. The villi become progressively shorter and wider. The following three micrographs are of the small intestine lining, taken from three different individuals.



Ludvigsson, J.F., Brandt, L., Montgomery, S.M. et al. Validation study of villous atrophy and small intestinal inflammation in Swedish biopsy registers. *BMC Gastroenterology*, 9, 19 (2009). <https://doi.org/10.1186/1471-230X-9-19>.

14. Analyse data

Sequence the images from least affected to most affected by coeliac disease.

15. Interpret evidence

Given the role of the villi in the body, **justify** the impact this disease is likely to have on an individual as it progresses, referring to the sequence of images.



Yurchanka Siarhei/Shutterstock.com

SYLLABUS
DOT POINTS**SCIENCE UNDERSTANDING**

- Describe the structure and function of carbohydrates, proteins and lipids.
- Describe the role of amylase, protease and lipase in chemical digestion.
- Explain how metabolic processes, such as digestion, are controlled and regulated by enzymes.
- Describe the structure and function of enzymes, including the role of the active site.
- Compare the induced-fit and lock-and-key models of enzyme function.
- Explain how enzyme activity is affected by factors such as temperature, pH, presence of inhibitors and substrate concentration.
- Interpret data from an experiment investigating factors affecting enzyme activity.

SCIENCE INQUIRY

- Investigate the effect of temperature/pH/substrate concentration on the reaction rate of different enzymes.
- Explore how understanding enzymes, and their roles in metabolism, can be used to diagnose and treat metabolic disease.



SCIENCE AS A HUMAN ENDEAVOUR

- Appreciate that to make sense of the complexity of biological systems, scientists often divide them into simpler components that are easier to study, but at each level of the biological hierarchy, new properties emerge.
- Appreciate how understanding the anatomy and physiology of different body systems allows medical professionals to predict, diagnose, monitor and treat disease.

Biology 2025 v1.1 General Senior Syllabus © QCAA 2024

Introduction

Every living cell requires biological molecules to build cellular structures and maintain biochemical processes. These biomolecules are categorised according to their chemical composition and structure into four classes: carbohydrates, lipids, proteins and nucleic acids. Nucleic acids only have a direct role in DNA, whereas the other three are involved in a wide range of biochemical processes and can be metabolised by the body for energy. The human body acquires and digests these energy-carrying biomolecules with specific enzymes in complex enzymatic processes called chemical digestion.

Practical

- Factors affecting enzyme activity

Worksheets

- Enzyme reaction rate: temperature

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ The basic chemical structure of biological molecules is built from four main elements: carbon (C), hydrogen (H), oxygen (O) and nitrogen (N).
- ✓ Nutritional molecules have formal scientific names.

Informal name	Formal scientific name
Carbs	Starches
Sugars	Monosaccharides
Fibre	Cellulose
Fats and oils	Lipids or triglycerides*
Proteins	Protein or polypeptide

*The fatty acids of triglycerides can be saturated or unsaturated.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe the monomers of:
 - carbohydrates as monosaccharides
 - proteins as amino acids
 - lipids as glycerol and fatty acids
- ✓ describe the structure of carbohydrates, including simple and complex molecules
- ✓ identify and describe several functions of carbohydrate molecules, including energy sources and energy storage
- ✓ describe the structure of lipids as triglycerides, including saturated and unsaturated fatty acid chains
- ✓ identify and describe several functions of lipids
- ✓ describe the structure of amino acids, including the role of the R group
- ✓ describe how bonding within a protein produces the four different levels of protein structure
- ✓ identify and describe several functions of protein molecules, including structural, communication and regulation and catalysis of metabolic reactions
- ✓ describe how the structure of enzymes, including the active site, determines their function
- ✓ compare the induced-fit and lock-and-key models of enzyme function
- ✓ describe the roles of amylase, protease and lipase in chemical digestion
- ✓ explain how enzyme structure and activity are affected by temperature, pH, substrate concentration and the presence of inhibitors
- ✓ conduct an experiment investigating the effects of temperature and pH on enzyme activity.

macromolecule a large molecule that has an important structural or functional role in cells

polymer a large molecule built up from linking smaller molecules together in a repeating pattern

monomer a small molecule that is a building block for polymers

4.1 Biomolecules

The three categories of energy-carrying biomolecules are shown in **Table 4.1.1**. Each category includes at least one **macromolecule**, most of which are **polymers**. Polymers are long chains of repeating units, which are disassembled during chemical digestion into their component parts, or **monomers**, for use in the body.

TABLE 4.1.1 The three categories of energy-carrying biomolecules

	Carbohydrates	Proteins	Lipids
Macromolecules	Starches Glycogen Cellulose	Structural proteins Functional proteins Enzymes	Triglycerides Phospholipids Steroids
Component parts	Glucose	Amino acids	Glycerol Fatty acids

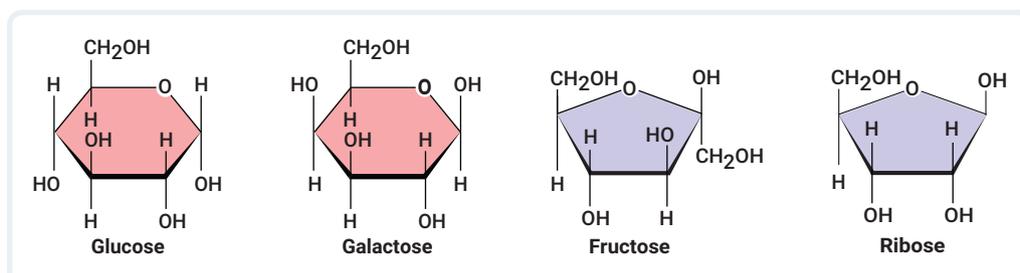
Carbohydrates

The most common compounds in living organisms are **carbohydrates**. Organisms use carbohydrates both as an energy source and as a starting point for the synthesis of important macromolecules. Each carbohydrate molecule consists of carbon, hydrogen and oxygen atoms in the ratio of 1 : 2 : 1, giving the general formula for carbohydrates as $n\text{CH}_2\text{O}$.

Simple carbohydrates are known as **monosaccharides** (from the Greek for ‘single sugar’) (**Figure 4.1.1**). Glucose is the most common monosaccharide. It is produced by the process of photosynthesis and is the molecule used in cellular respiration by virtually all organisms. Glucose is stored as glycogen in animals and as starch in plants and plays a vital role in the production of cellulose, the indigestible fibre of plant cell walls.

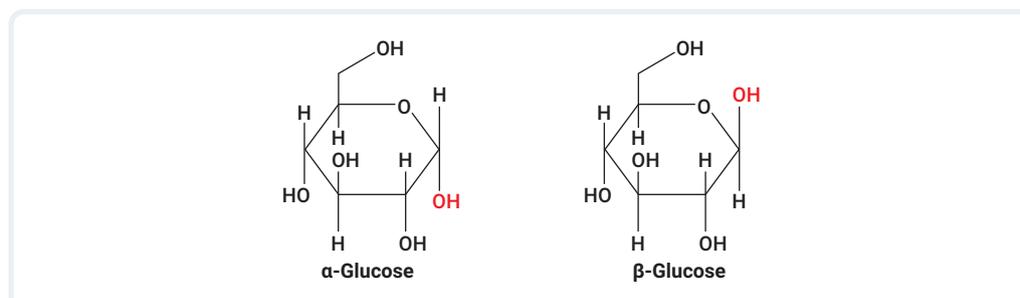
carbohydrates a group of compounds containing carbon, hydrogen and oxygen; important as structural components and as energy sources

monosaccharide a simple sugar, such as glucose, which cannot be broken down into smaller sugar molecules

**FIGURE 4.1.1** Examples of different monosaccharides

Syllabus link
Chapter 5 explores the role of glucose as the starting molecule in both anaerobic and aerobic respiration.

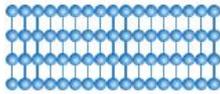
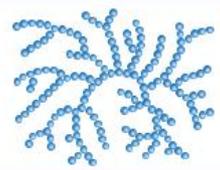
Glucose has two structural forms, α -glucose and β -glucose (**Figure 4.1.2**). The α -glucose form is less stable and is used as a monomer in starch and glycogen. The β -glucose form is more stable and is used by plants to produce cellulose. Knowledge of the molecular structure of glucose is not required as part of the syllabus.

**FIGURE 4.1.2** The structures of α -glucose and β -glucose. They differ in the orientation of an $-\text{OH}$ group, which affects their stability and the macromolecules they are used for.

When many monosaccharides join together, they form a **polysaccharide** (from the Greek for ‘many sugars’) (**Table 4.1.2**). Organisms use polysaccharides both as energy storage and as structural components.

polysaccharide a complex carbohydrate that is made by linking together simple sugars

TABLE 4.1.2 Cellulose, starch and glycogen – important polysaccharides in living organisms

Polysaccharide	Source	Function	Subunit	Shape
Cellulose	Plant	Structural	β -Glucose	
Starch – amylose	Plant	Energy storage	α -Glucose	
Starch – amylopectin	Plant	Energy storage	α -Glucose	
Glycogen	Animal	Energy storage	α -Glucose	

cellulose a polysaccharide made of β -glucose subunits that is the main component of plant cell walls

starch an important energy-storing polysaccharide for plants, made of α -glucose with some branching

glycogen an important energy-storing polysaccharide in animals, made of α -glucose with extensive branching

polypeptide a polymer of amino acids, also known as a protein

amino acid a nitrogen-containing compound that is the building block of proteins

R group a side chain in a molecule that confers distinguishing properties to the molecule; the R group is what differentiates the 20 different kinds of amino acids

Cellulose is a polysaccharide composed of many β -glucose molecules joined together. The special linking patterns between these glucose molecules mean that cellulose fibres are tough and insoluble and resist being crushed and bent. This makes them ideal as the structural components of plant cell walls. The efficient functioning of plants depends on tough cellulose cell walls.

Starch is an important plant polysaccharide composed of α -glucose molecules. Some starches contain more than 6000 monomers, making them useful for glucose storage. Most plants store excess starch in their roots, such as in potatoes, and break it down into glucose when it is required for respiration.

Animals store excess glucose in the form of the polysaccharide **glycogen**. Like the starches, it is made up of α -glucose monomers, but has significantly more branching, which makes it more soluble and easier to rapidly release glucose when required. Glycogen is stored in the liver and muscles and is converted back into glucose to balance the blood glucose concentration during vigorous exercise or between meals.

Proteins

Proteins, also called **polypeptides**, are polymer macromolecules composed of hundreds of **amino acids**. Virtually everything a cell does depends on the proteins it contains, because they contribute to building many different structures and, as enzymes, control thousands of chemical reactions that maintain life processes.

Like carbohydrates, amino acids are made up of the elements carbon, hydrogen and oxygen. However, they also contain nitrogen, and the **R group** may contain sulfur or phosphorus as well (**Figure 4.1.3**). Although more than 100 different kinds of amino acids exist, only 20 are used to form proteins in eukaryotes. This may seem a small number, but the number of unique sequences that can be formed from a pool of 20 different monomers is 20^n , where n is the number of amino acids in the chain. Given that the average number of amino acids in a functional protein is about 1000, this is an enormous number of possible sequences. However, the sequence of amino acids is extremely important in the protein's function; even small changes in the sequence can render a protein completely useless.

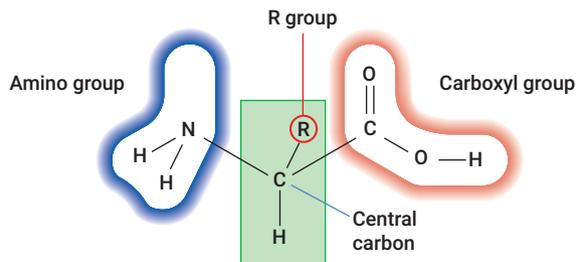


FIGURE 4.1.3 The basic structure of an amino acid. The R group represents one of 20 different side chains.

Proteins have four levels of structure, shown in **Table 4.1.3**. The primary structure is the sequence of amino acids, which lays the foundation for the structure and function of the final protein. Secondary structures, such as α -helices and β -pleated sheets, are formed through the amino and acid groups in the backbone of the chain interacting with other amino and acid groups further along the chain. The tertiary structure of a protein is formed when the R groups interact with each other, folding the secondary structures into a highly specific conformation. For smaller proteins, this is the level in which the active site is formed and at which the protein is functional. Larger proteins, or those with more complex functions, may have quaternary structure, where two or more tertiary structures come together as subunits of a larger whole.



Weblink
Protein structures

TABLE 4.1.3 The four levels of protein structure, a small change in any of these levels can render a protein functionless

	Structure level			
	Primary	Secondary	Tertiary	Quaternary
Formation	Sequence of amino acids	Bonds between amino acid groups	Bonds between R groups	Multiple tertiary structures together
Diagram				

Proteins are the most versatile molecules in the cell, with a wide range of functions (Table 4.1.4).

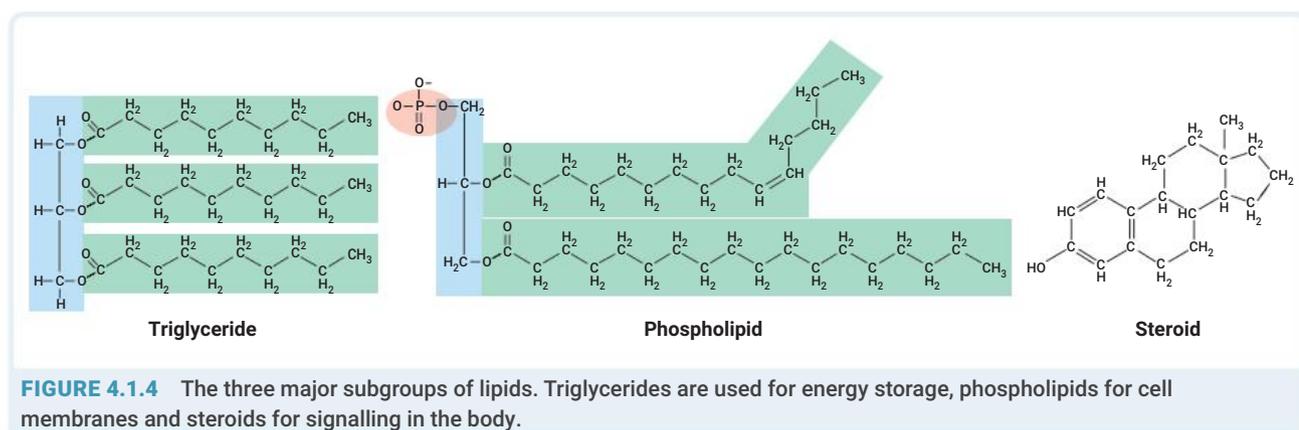
TABLE 4.1.4 Examples of proteins that perform each of seven key functions in the body

Biological function	Example
Reaction catalysis	Amylase breaks down starch into glucose.
Structure	Keratin forms hair and fingernails.
Cell movement	Myosin and actin work to contract and relax muscles.
Substance transport	Haemoglobin transports oxygen around the body.
Membrane transport	Channel proteins and pumps allow substances to move into and out of cells.
Regulation of other proteins	Insulin regulates the cell membrane proteins that take up glucose from the blood.
Immune response	Antibodies recognise and flag foreign pathogens in the body.

Lipids

triglyceride a simple lipid formed by linking glycerol with three fatty acids

Lipids are non-polymer macromolecules that are insoluble in water. There are three important subgroups of lipids – **triglycerides**, phospholipids and steroids (Figure 4.1.4). Triglycerides are the energy-carrying lipids, and are used by the body for dense energy storage. Phospholipids are the major structural component of cell membranes. Steroids are a diverse group of signalling molecules – their structures and functions are beyond the scope of this chapter.



fatty acid a type of organic acid that combines with glycerol to form a triglyceride

glycerol a molecule that combines with three fatty acids to form a triglyceride

saturated referring to an organic molecule that only has single bonds between its carbons

Unlike carbohydrates and proteins, triglycerides are not polymers because they are not formed from long strings of repeating units. Instead, they are made up of two distinct types of components, **fatty acids** and **glycerol**.

Triglycerides consist of three fatty acid chains attached to a glycerol backbone (Figure 4.1.5). Many different fatty acids can be joined to a glycerol molecule and the three attached to the glycerol are usually slightly different.

Fatty acids can be a range of lengths and **saturated** (having only single bonds between the carbons) or **unsaturated** (having at least one carbon-carbon double bond). Saturated fatty acids are straight and stack neatly against each other. They form dense areas of solid fat when the triglyceride contains only saturated fatty acids. Most animal fats, including butter, are saturated triglycerides. Unsaturated fatty acids have a kink in the chain caused

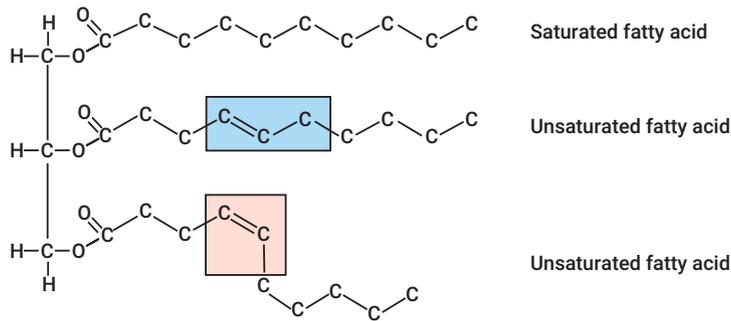


FIGURE 4.1.5 A triglyceride molecule contains a glycerol unit and three fatty acid chains, which can be saturated or unsaturated.

by a double bond. They are unable to stack neatly against each other and do not form solids; instead, they form liquids called oils. Heating can cause a change in the position of the double bond, meaning the fatty acids can still stack. These fats are called ‘trans-fats’ because they now contain *trans*-unsaturated fatty acids. Most result from industrial processes.

unsaturated referring to an organic molecule that has at least one double bond along its carbon chain; a prefix, such as mono- or poly-, refers to how many double bonds are present

LEARNING CHECK 4.1

DESCRIBING

1 **Summarise** the structures of biomolecules by copying and completing the following table.

Biomolecule	Carbohydrates	Proteins	Lipids
Macromolecules			
Component parts			

2 State the group with the largest number of biomolecules.

3 **Identify** two monosaccharides.

4 **Describe** one function that is shared by carbohydrates and lipids.

5 **Describe** one function that is shared by carbohydrates and proteins.

6 **Identify**, with examples, two functions of proteins that are not shared by carbohydrates or lipids.

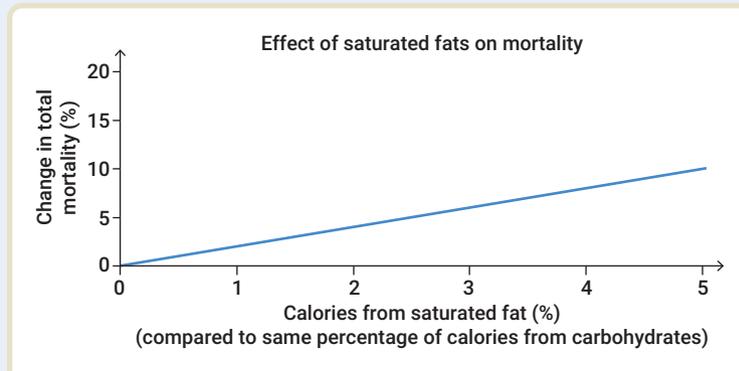
APPLYING

7 **Explain** a potential impact of a low-protein diet on cell function.

ANALYSING

8 **Compare** saturated and unsaturated fatty acids.

- 9 The following graph was extracted from a study that compared the effects of carbohydrates and fats on mortality. **Identify** the effect that an increased consumption of saturated fats has on mortality.



4.2 Chemical digestion

Digestion is the process of breaking down food to be absorbed into the body. Most food is consumed in the macromolecular form, such as starch, which is much too large to be absorbed, even after chewing. **Chemical digestion** is the process of systematically disassembling macromolecules into their component parts. Each category of biomolecules is broken down by a specific set of enzymes. Carbohydrates are broken down by amylases, proteins are broken down by proteases and lipids are broken down by lipases (**Table 4.2.1**).

chemical digestion the process of breaking a macromolecule into its component parts, e.g. starch to glucose

TABLE 4.2.1 Overview of digestive enzymes

Type of digestive enzyme	Macromolecule	Component parts
Carbohydrases (including amylase)	Carbohydrates (including starches)	Monosaccharides (e.g. glucose, fructose)
Proteases	Proteins	Amino acids
Lipases	Lipids	Fatty acids and glycerol

LEARNING CHECK 4.2

DESCRIBING

- Describe** the function of each of the following enzyme groups.
 - Carbohydrases
 - Proteases
 - Lipases
- Describe** the role of digestive enzymes in the upkeep of the body.

APPLYING

- Lactose is a carbohydrate in milk. People who are lactose intolerant lack the enzyme lactase and often experience bloating and abdominal pain after consuming milk. **Explain** how the presence of lactose affects digestion in lactose-intolerant individuals.

4.3 Enzymes

Digestive enzymes are referred to in sets because of the specific nature of proteins. Each protein has a very specific shape that determines its very specific function. For example, different amylases are required for the branched and unbranched portions of starch, and the amylase that hydrolyses unbranched portions of starch (made of α -glucose molecules) cannot hydrolyse cellulose (made of β -glucose molecules). Carbohydrates such as sucrose (a molecule made up of a glucose and a fructose joined together), which are made of other monosaccharides, cannot be digested by the same amylases that digest starch. The specificity of enzymes is what makes biochemical processes so complex and diseases so difficult to treat.

The discovery of enzymes

Towards the end of the 19th century, the German chemist Eduard Buchner was experimenting to find a way of preventing yeast extracts from going bad. In one trial, he added sugar to yeast extract and, rather than preventing change, he found that the sugar was fermented and converted to alcohol. Louis Pasteur had already demonstrated that yeast was responsible for the fermentation of sugar, but Buchner took the research further. He showed that the juice extracted from living yeast cells was responsible for fermentation, not the yeast cells themselves. The term 'enzyme' (from the Greek word *en-zumē*, meaning 'within leaven/yeast'), which was first used by German physiologist Wilhelm Kühne, has come to refer to any protein that functions as a **catalyst**.

catalyst a substance that speeds up a chemical reaction but is not used up in the reaction

Enzymes control metabolic processes

Without enzymes, biochemical reactions would be so slow as to hardly proceed at all, and life in its current form would never have evolved. Thousands of different reactions take place in a cell. The functional organisation required for this is achieved by a highly controlled system of metabolism, where specific enzymes are in particular places within the cell acting as catalysts for each individual reaction.

Enzymes are divided into two broad groups based on where they act: inside or outside the cell. **Intracellular enzymes** act inside cells, where they speed up and control metabolic reactions. **Extracellular enzymes** are produced by cells but achieve their effects outside the cells. These include the digestive enzymes, which break down food in the stomach and small intestine.

intracellular enzyme an enzyme that functions inside the cell that produces it, to speed up and control metabolic reactions

extracellular enzyme an enzyme that is produced by cells but functions outside of the cell

Enzyme structure and function

Enzymes, like all proteins, have a highly specific shape formed by their tertiary structure (Figure 4.3.1). It is this shape that allows it to bind with a specific reactant, called its **substrate**. Enzymes are generally named according to the substrate they catalyse with the suffix '-ase'; for example, sucrase, lipase and maltase. When an enzyme-controlled reaction takes place, the enzyme and substrate molecules join for a short time to form an **enzyme-substrate complex**. The substrate is converted to the **end product** by the action of the enzyme.

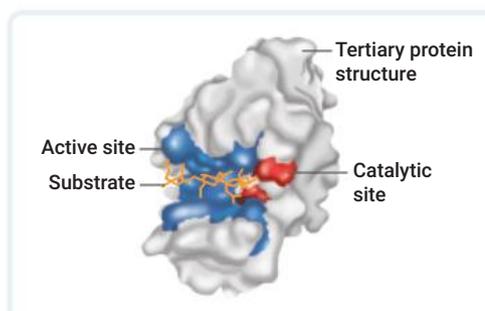


FIGURE 4.3.1 The basic structure of an enzyme. The active site is a small cleft where the substrates bind and catalysis occurs, while the rest of the shape is required to create and support the active site.

substrate a substance that enters a reaction; also called reactant or precursor

enzyme-substrate complex a substance formed when an enzyme and a substrate molecule join

end product a substance that is formed by the action of an enzyme



Weblink
Enzymes

The enzyme is unchanged by the reaction and can be used again. This means enzymes are often only needed in small quantities within a cell. The process of enzyme catalysis can be summarised as:



active site the place on the surface of an enzyme molecule where substrate molecules attach

lock-and-key model an old model suggesting that the shape of an enzyme's active site is an exact, static fit for the shape of its substrate molecule

induced-fit model a model of enzyme activity in which an enzyme's active site undergoes specific changes, induced by the substrate, to achieve a high degree of specificity with the substrate

conformation the shape of a molecule that is determined by the three-dimensional arrangement of its atoms and bonds; important for molecular functioning

Lock-and-key model

Within each enzyme's shape is a precise area to which the substrate can become attached, called the **active site**. In 1894, German chemist Emil Fischer proposed the **lock-and-key model** to explain the substrate-specificity of enzymes (**Figure 4.3.2**). It involved viewing the enzyme as a lock that can only be operated by inserting a particular substrate or key. Unfortunately, this model assumes that the enzyme's shape is static and it cannot explain how the enzyme is actually catalysing the reaction from substrate to end product.

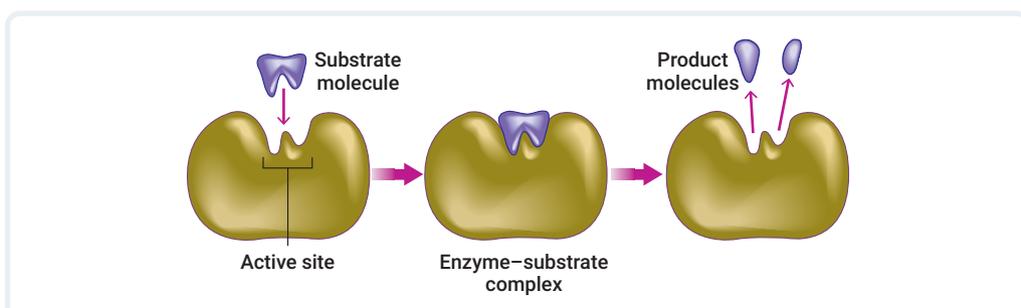


FIGURE 4.3.2 The lock-and-key model of enzyme action, from 1894. This model proposed that the substrate fits into a specific, static active site on the surface of the enzyme.

Induced-fit model

In 1958, in response to many experiments that demonstrated that enzymes changed their shape after they bound to their substrate, Daniel Koshland, an American biochemist, proposed a new model of enzyme action. It combined this shape change with the understanding that an enzyme-substrate complex must do something to catalyse the reaction. Known as the **induced-fit model** of enzyme action (**Figure 4.3.3**), it proposes that the unbound enzyme is in a relaxed **conformation**, much like a hand waiting to hold its substrate. Many molecules

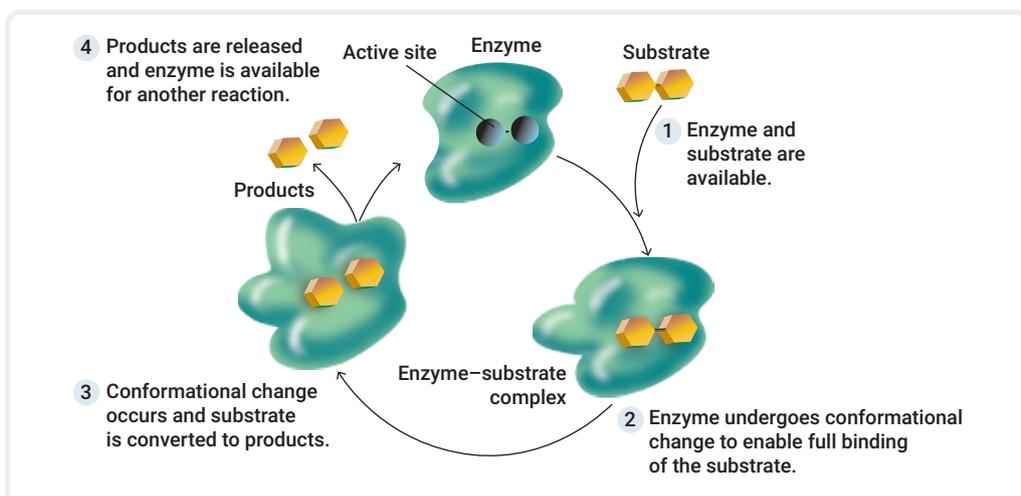


FIGURE 4.3.3 The induced-fit model of enzyme action. The substrate enters the enzyme's active site, causing the enzyme to change its shape and bring about catalysis of the reaction.

can enter the active site, but only its specific substrate can activate all the parts of the active site required to trigger catalysis. When the substrate enters the active site, the enzyme undergoes a conformational change, much like a hand closing over an object. This brings the substrate into contact with the catalytic site, which converts the substrate to the end product. This end product is a slightly different shape from the substrate, so it no longer activates all the required parts of the active site and the enzyme relaxes back into its original conformation, releasing the end products.

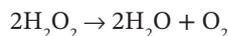
The induced-fit model more accurately reflects the ways enzymes and substrates interact with each other. The bonds that form between an enzyme and its substrate at the active site modify the shape of the enzyme so that the substrate can be fully accommodated and brought to the catalytic site. This change in conformation stretches the bonds within the substrate molecule, which lowers the **activation energy** required to initiate the reaction.

activation energy the energy required to initiate a reaction

Activation energy

The mechanism that occurs in the active site of the enzyme is complex and still being researched, but evidence shows that it provides a reaction pathway that requires less energy to activate. Lowering the activation energy for a reaction means that the reactants don't need as much energy from the cell to begin the process of becoming products, which makes the reaction faster and more efficient for the cell.

Consider a match. A reaction can quickly convert the thin stick of wood to charcoal, but without the energy input of a spark, the match will remain unchanged for years. The spark that lights the match provides the activation energy for the reaction to proceed. In a similar way, hydrogen peroxide (H_2O_2), a toxic by-product of metabolism, remains unchanged in the body for hours; 71 kJ of energy is required to kickstart the reaction that converts hydrogen peroxide to water and oxygen:



hydrogen peroxide \rightarrow water and oxygen

Given its toxicity, it is essential that the cell removes hydrogen peroxide as fast as possible. In the liver, an enzyme called catalase lowers the activation energy for the reaction to just 8 kJ by stretching the bonds of hydrogen peroxide within its active site. In the presence of catalase, this reaction can proceed up to 100 million times faster than without it (**Figure 4.3.4**).

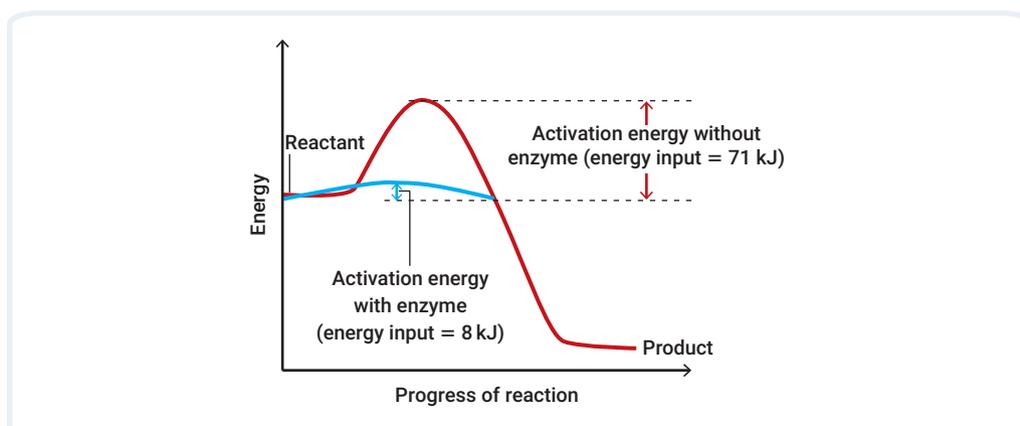


FIGURE 4.3.4 The effect of catalase on the activation energy required for the decomposition of hydrogen peroxide

LEARNING CHECK 4.3

DESCRIBING

- 1 **Describe** the physical structure of an enzyme.
- 2 **Describe** what happens to an enzyme after it has catalysed a reaction.
- 3 State a definition for the 'enzyme–substrate complex'.

APPLYING

- 4 **Explain** how enzymes affect the activation energy required for a reaction to occur.
- 5 **Explain** why complex chemical reactions in cells require multiple enzymes.

ANALYSING

- 6 **Compare** the induced-fit model of enzyme action with the original lock-and-key model.
- 7 **Compare** intracellular and extracellular enzymes.

4.4 Factors affecting enzyme function

Enzymes, like all proteins, function most efficiently within an optimal range of pH and temperature. This is because the action of an enzyme depends critically on its shape, and its shape is provided by the bonds of the polypeptide backbone and the amino acid side chains in its tertiary protein structure (see section 4.1). These side chain bonds are based on three key interactions:

- positive and negative side chains attracting each other
- polar side chains orienting towards water and non-polar side chains orienting away from water
- large side chains taking up a considerable amount of space in the structure.

When a change in environment, such as temperature or pH, affects any of these three interactions, the shape of the enzyme changes, which affects its ability to function effectively.

Temperature

As temperature increases, molecules move more and collide more often. With more frequent collisions, there are more opportunities for a substrate to bump into its enzyme so that it binds at the active site. Therefore, the rate of reaction generally increases as temperature increases. However, an increased temperature causes the atoms, including those in the side chains of the enzyme, to move and vibrate more. Most side chain interactions can survive minor increases in temperature, but large increases cause so much movement that the bonds begin to break. Breaking those interactions affects how much space there is for large side chains and allows water to enter parts of the structure that are meant to be non-polar. When these key interactions are broken, the enzyme loses its functional shape in a process called **denaturation**. Often, denatured proteins cannot regain their functional shape, even when conditions return to optimal.

Denaturation of enzymes by temperature increases can be a useful tool for the body. During infection, a fever raises the body temperature in an attempt to denature the enzymes in the pathogen. However, if a fever gets out of control, our own critical enzymes could also be denatured, leading to seizures and death.

Enzymes are not denatured at low temperatures because the shape is not disrupted with a decrease in movement. However, low temperatures reduce the reaction rate because slower molecules have less energy and will not encounter the active site as often.

Enzymes have evolved to work optimally in the temperature range of their organism (**Figure 4.4.1**). In general, human enzymes work best at about 37°C. Psychrophiles are



Worksheet
Enzyme reaction
rate: temperature

denaturation the process by which the functional structure of a protein is lost due to factors such as pH and temperature



Syllabus link
Chapter 11 discusses the role of fever in immunity.

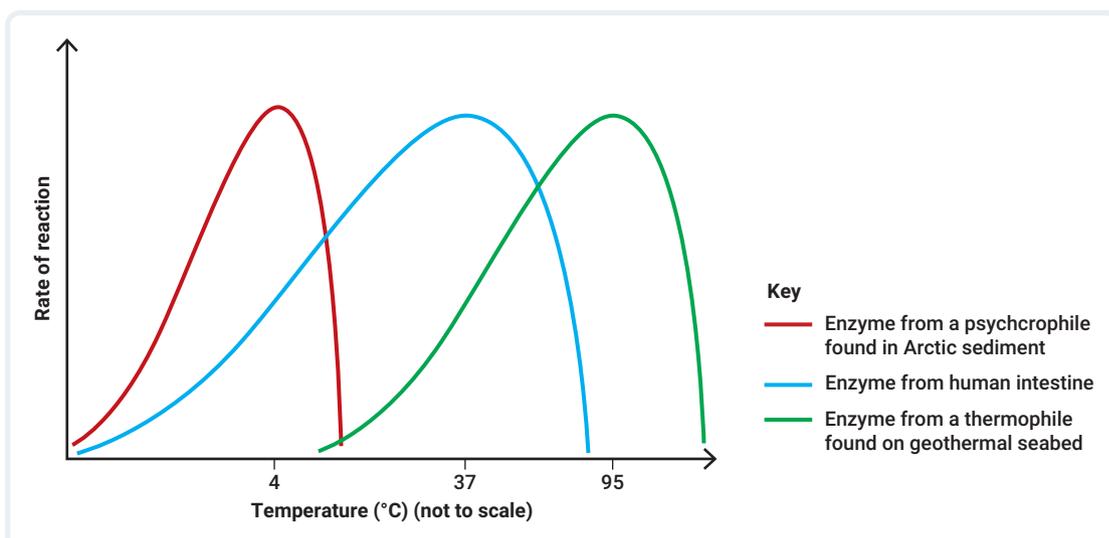


FIGURE 4.4.1 Optimal activity ranges for enzymes of different organisms. Activity gradually increases until enzymes begin to denature and the reaction rate decreases.

micro-organisms that live in near-freezing environments such as the wind-blasted rocks on snow-covered mountains. Their enzymes have evolved to operate at very low temperatures. Alternatively, the micro-organism *Pyrodictium* lives in geothermal-heated areas of the sea floor. It is a thermophile and its enzymes operate best at temperatures of 95–105°C.

Taq polymerase is an enzyme from another thermophile, *Thermus aquaticus*. It operates at a temperature of 70–90°C, which makes it useful in a biotechnological technique called the polymerase chain reaction (PCR), which amplifies DNA fragments for analysis.

pH

The pH of the surrounding environment depends on the presence of H⁺ (hydrogen) ions and/or OH⁻ (hydroxide) ions. The charges on these ions affect interactions of positive and negative R group side chains on the enzyme. For example, too many H⁺ ions will pull the negative side chains away from their positive side chain partners and denature the protein by destroying the bonds that would otherwise have kept the protein in its functional shape. Too many OH⁻ ions will pull the positive side chains away, which has the same effect.

Different enzymes have different optimum pH ranges (Figure 4.4.2). Some enzymes can function in a broad range of pH environments, whereas others are very sensitive and only function in a narrow pH range. The change in reaction rate that results from changing pH is not



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Enzyme simulation

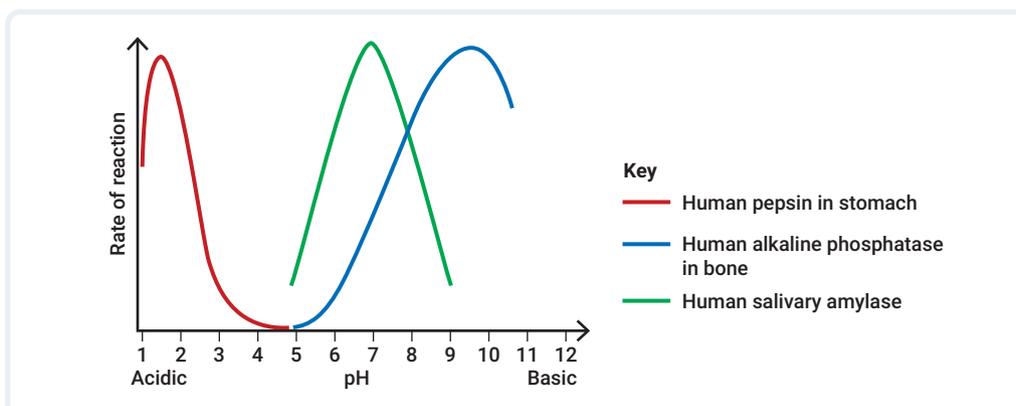


FIGURE 4.4.2 The optimum pH range for three human enzymes: pepsin, alkaline phosphatase and amylase

related to how fast the enzyme is working or how often the substrate encounters the active site, as is the case for changing temperature. Instead, the change in reaction rate is directly caused by the denaturation of the enzyme.

Substrate concentration

Although substrate concentration does not affect the function of an enzyme and cannot denature an enzyme, it does affect the reaction rate. The concentration of substrate in a reaction mix can change the amount of product made. Increasing substrate concentration results in faster production until all the enzyme active sites are working at their maximum capacity (**Figure 4.4.3**). At this **saturation point**, increasing the substrate concentration no longer increases the reaction rate because there are no more free enzymes in the solution.

saturation point the point at which all active sites are filled with substrate, resulting in maximum reaction rate

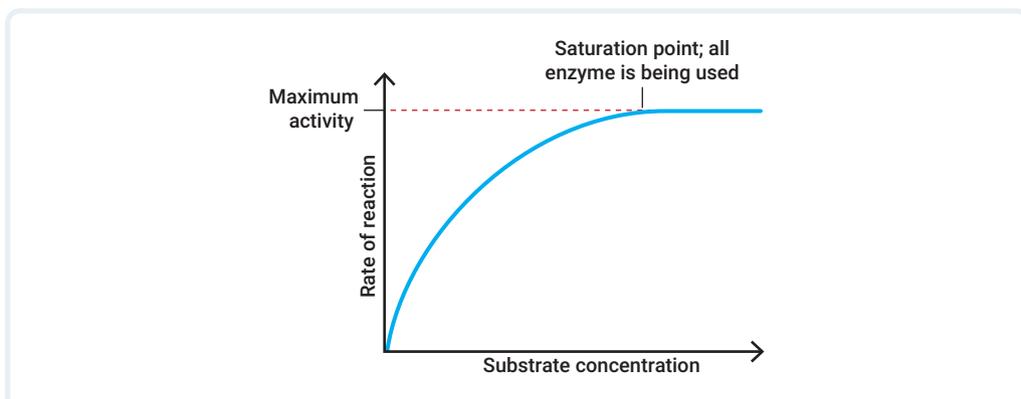


FIGURE 4.4.3 The effect of increasing substrate concentration on the rate of an enzyme-catalysed reaction

Inhibitors

Enzyme production is expensive for a cell, which makes denaturation a wasteful method of turning off their function. Enzyme **inhibition** is the process of blocking enzyme activity by **inhibitors** rather than by denaturation.

For example, when a cell is low in energy, an enzyme called phosphofructokinase-1 (PFK-1) works with other enzymes in cellular respiration to produce adenosine triphosphate (ATP) as energy for the cell. When the cell has plenty of energy, the excess ATP binds to PFK-1 to change its shape and inhibit its function, stopping cellular respiration only until the cell needs energy again. Many substances that are toxic to humans, including those produced by animals and plants in defence, are enzyme inhibitors that turn off vital functions in our cells.

inhibition the process of blocking enzyme activity

inhibitor a molecule that blocks enzyme activity



Syllabus link
Chapter 5 discusses the production of ATP through cellular respiration in more detail.

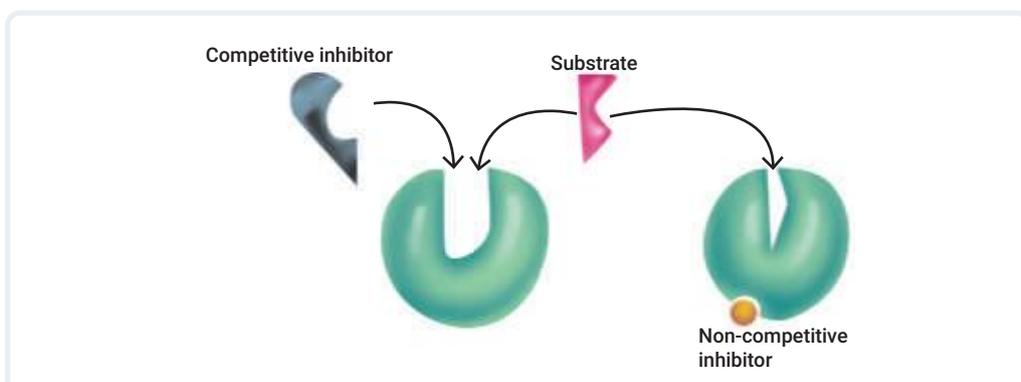


FIGURE 4.4.4 The two mechanisms of enzyme inhibition to reduce enzyme activity

There are two mechanisms of enzyme inhibition (Figure 4.4.4). The first, and simplest, is physically blocking the active site. Because of its substrate specificity, the inhibitor molecule needs to be structurally similar to the substrate to fit into the active site, but different enough to avoid catalysis itself. Because they compete with the substrate for the active site, these inhibitors are called **competitive inhibitors**.

The second mechanism exploits the fragility of the functional shape of an enzyme. This happens when an inhibitor binds to a separate site on the molecule and disrupts the tertiary structure that supports the active site. The active site only needs to experience a minor change in shape for it to no longer fit the substrate or be able to catalyse the reaction effectively. Because it is not attempting to enter the active site, the inhibitor is called a **non-competitive inhibitor** and does not need to have a similar structure to the substrate.

competitive inhibitor a substance that competes with a substrate for an enzyme's active site

non-competitive inhibitor a substance that binds to an enzyme at a site other than the active site; this changes the shape of the enzyme so that the substrate can no longer bind to the active site

LEARNING CHECK 4.4

DESCRIBING

- 1 State a definition for:
 - a denaturation
 - b saturation point
 - c inhibition.
- 2 **Describe** four factors that affect the activity of an enzyme.
- 3 **Describe** how a very low substrate concentration affects an enzyme's activity.

APPLYING

- 4 **Explain** why a doctor would get worried if their patient developed a body temperature of more than 42°C.
- 5 **Explain** why a low pH denatures enzymes whereas a low temperature does not.

ANALYSING

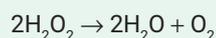
- 6 **Distinguish** between a non-competitive inhibitor and a competitive inhibitor.
- 7 **Compare** what happens to an enzyme when it is denatured by high temperatures and by pH.

PRACTICAL ACTIVITY 4.4.1

FACTORS AFFECTING ENZYME ACTIVITY

Introduction

Enzymes are sensitive biological machines that require specific conditions to work optimally. Catalase is an enzyme in several organs and tissues, including the liver, where its role is to decompose toxic hydrogen peroxide (H_2O_2) into water and oxygen:



The production of oxygen is especially useful for experimentation because the gas bubbles can be trapped and measured.

Research question

Part A: Does increasing the temperature (independent variable) change the rate of reaction as shown by height of foam produced mm s^{-1} (dependent variable) as an indication of enzyme activity?

Part B: Does increasing the pH (independent variable) change the rate of reaction as shown by height of foam produced mm s^{-1} (dependent variable) as an indication of enzyme activity?

Aim

To determine the optimum temperature and pH for catalase activity

Materials (for each group)

- 22 mL (10 mL for Part A, 12 mL for Part B) catalase mix (from freshly blended chicken liver)
- 24 mL (12 mL for each part) 3% hydrogen peroxide
- access to 2 mL of each sodium phosphate buffer solution (approximately pH 5.5, 6, 6.5, 7, 7.5) in dropper bottles (for Part B)
- distilled water
- detergent
- 12 test tubes and 2 test-tube racks
- container to hold 6 test tubes in allocated temperature water bath without floating
- 2 × 5 mL pipettes (labelled 'Catalase' and 'Hydrogen peroxide')
- 25 mL measuring cylinder
- glass stirring rod
- access to one of five pre-prepared water baths (10, 20, 30, 40, 50°C)
- clock or timer
- ruler
- permanent marker
- thermometer



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Hot water baths can burn.	Do not touch the water bath container or the water in it.
Chicken liver is a biological hazard.	Avoid contact with the liver and dispose of it in a biohazard bin. Ethical consideration: liver is sourced from animals used for foods.
Hydrogen peroxide can burn skin and bleach clothing.	Wear gloves and an apron and take care to avoid spills. Clean spills immediately with paper towel. In the event of contact, wash the skin or clothing with copious water and hand soap. Environmental consideration: at these concentrations, it is safe to pour the solution down the sink.

PART A – TEMPERATURE

Procedure

- 1 Each group will be allocated a temperature to investigate. Identify the correct water bath and use a thermometer to monitor the temperature.
- 2 Label six test tubes 1–6 and with the allocated temperature.
- 3 Add 5 mL of distilled water to test tube 1.
- 4 Add 2 mL of catalase mix and 3 mL of distilled water to test tubes 2–6.
- 5 Place the test tubes in the water bath for 10 minutes.
- 6 During these 10 minutes, add 12 mL hydrogen peroxide and 6 drops of detergent to the measuring cylinder. Stir slowly to avoid bubbles.
- 7 After 10 minutes in the water bath, remove the test tubes from the water and place them in the test-tube rack.
- 8 Start the timer and at the same time add 2 mL of the hydrogen peroxide solution to each test tube. Stir to combine.
- 9 Return the test tubes to their water bath. Monitor the height of their foam over the next 2 minutes.
- 10 Remove the test tubes from the water bath and use a permanent marker to mark the height of the foam.
- 11 Measure the distance between the solution and the foam height mark. Record it in the results table.
- 12 Divide the height of the foam (mm) by time (120 s) to get a reaction rate.
- 13 Dispose of the substances according to your teacher's directions.

Results

Copy and complete the results table and summary table.

Results table

Temperature _____	Reaction time (s)	Foam height (mm)
Control 1		
Trial 2		
Trial 3		
Trial 4		
Trial 5		
Trial 6		
Average of trials		

Summary table

Temperature (°C)	10	20	30	40	50
Reaction rate (mm s ⁻¹)					

Analysis of results

- 1 Graph the average data points from the summary table.
- 2 Identify a trend and/or relationship between temperature and reaction rate.
- 3 Identify any limitations of the data collected.

Interpretation

- 4 From the graph, deduce the optimum temperature for chicken liver catalase.
- 5 Explain why catalase has evolved to operate best at this temperature.

Evaluation

- 6 Explain whether the five trials produced reliable data.
- 7 Describe two benefits of using five trials instead of three.
- 8 Describe two methodological features of this experiment that promoted quality data and two features that did not.
- 9 Decide whether it is scientifically valid to deduce the optimum pH for chicken liver catalase from this data.
- 10 Evaluate the quality of data from this experiment, including reference to uncertainty.

PART B – pH

Procedure

- 1 Based on the class data from Part A, set all water baths to the optimal temperature of catalase.
- 2 Each group will be allocated a pH to investigate.
- 3 Label the other six test tubes A–F and with the allocated pH.
- 4 To test tubes A–F, add 2 mL of catalase mix and 3 mL of distilled water.
- 5 To test tube A, add another 2 mL of distilled water.
- 6 To test tubes B–F, add 2 mL of the sodium phosphate buffer that matches the allocated pH.

- 7 Place the test tubes in the water bath for 10 minutes.
- 8 During these 10 minutes, add 12 mL of hydrogen peroxide and 6 drops of detergent to the measuring cylinder. Stir slowly to avoid bubbles.
- 9 After 10 minutes in the water bath, remove the test tubes from the water and place them in the test-tube rack.
- 10 Start the timer and at the same time add 2 mL of the hydrogen peroxide solution to each test tube and stir to combine.
- 11 Return your test tubes to their water bath. Monitor the height of their foam over the next 2 minutes.
- 12 Remove the test tubes from the water bath and use a permanent marker to mark the height of the foam.
- 13 Measure the distance between the solution and the foam height mark. Record it in the results table.
- 14 Divide the height of the foam (mm) by time (120 s) to get a reaction rate.
- 15 Dispose of the substances according to your teacher's directions.

Results

Copy and complete the results table and summary table.

Results table

pH _____	Reaction time (s)	Foam height (mm)
Control A		
Trial B		
Trial C		
Trial D		
Trial E		
Trial F		
Average of trials		

Summary table

pH	5.5	6	6.5	7	7.5
Reaction rate (mm s ⁻¹)					

Analysis of results

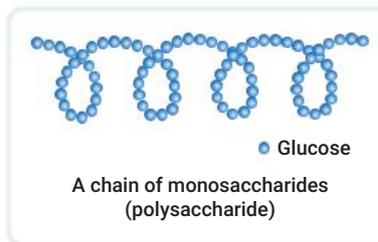
- 1 Graph the average data points from the summary table.
- 2 Identify a trend and/or relationship between pH and reaction rate.
- 3 Calculate the uncertainty of the data collected for the allocated pH $\left(\frac{\text{highest value} - \text{lowest value}}{2} \right)$.
- 4 Add error bars that represent the uncertainty of the data.

Interpretation

- 5 Explain the effect of temperature and pH on chicken liver catalase.

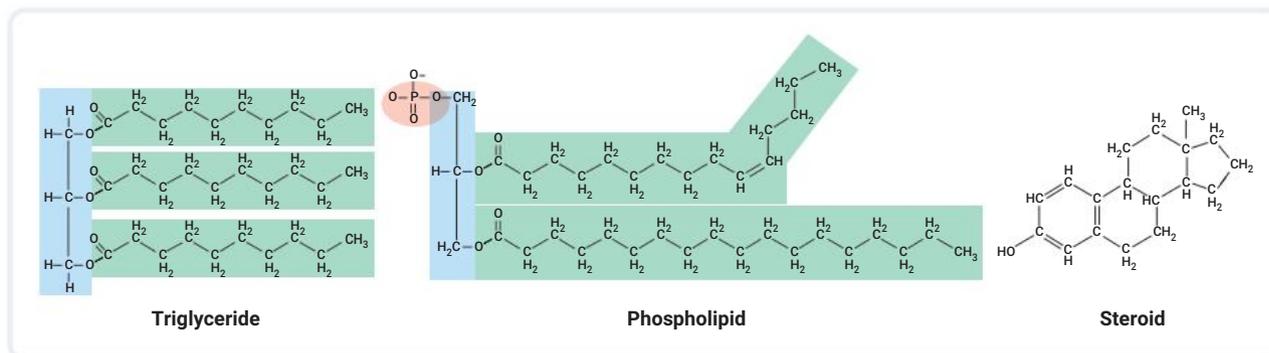
Biomolecules

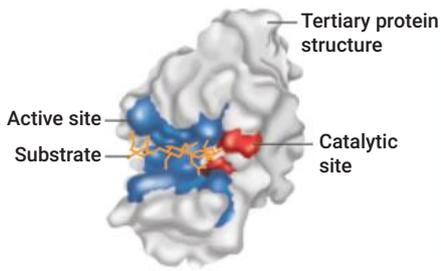
- The three categories of energy-carrying biomolecules are carbohydrates, proteins and lipids.
- Complex carbohydrates are made up of many monosaccharides (e.g. glucose) joined together.
- Proteins are polymers of amino acids.
- Proteins have four levels of structure: primary, secondary, tertiary and quaternary.



Structure level			
Primary	Secondary	Tertiary	Quaternary
Sequence of amino acids	Bonds between amino acid groups	Bonds between R groups	Multiple tertiary structures together

- Lipids are non-polymer macromolecules, with three important subgroups: triglycerides, phospholipids and steroids.
- Triglycerides consist of three fatty acid chains attached to glycerol.





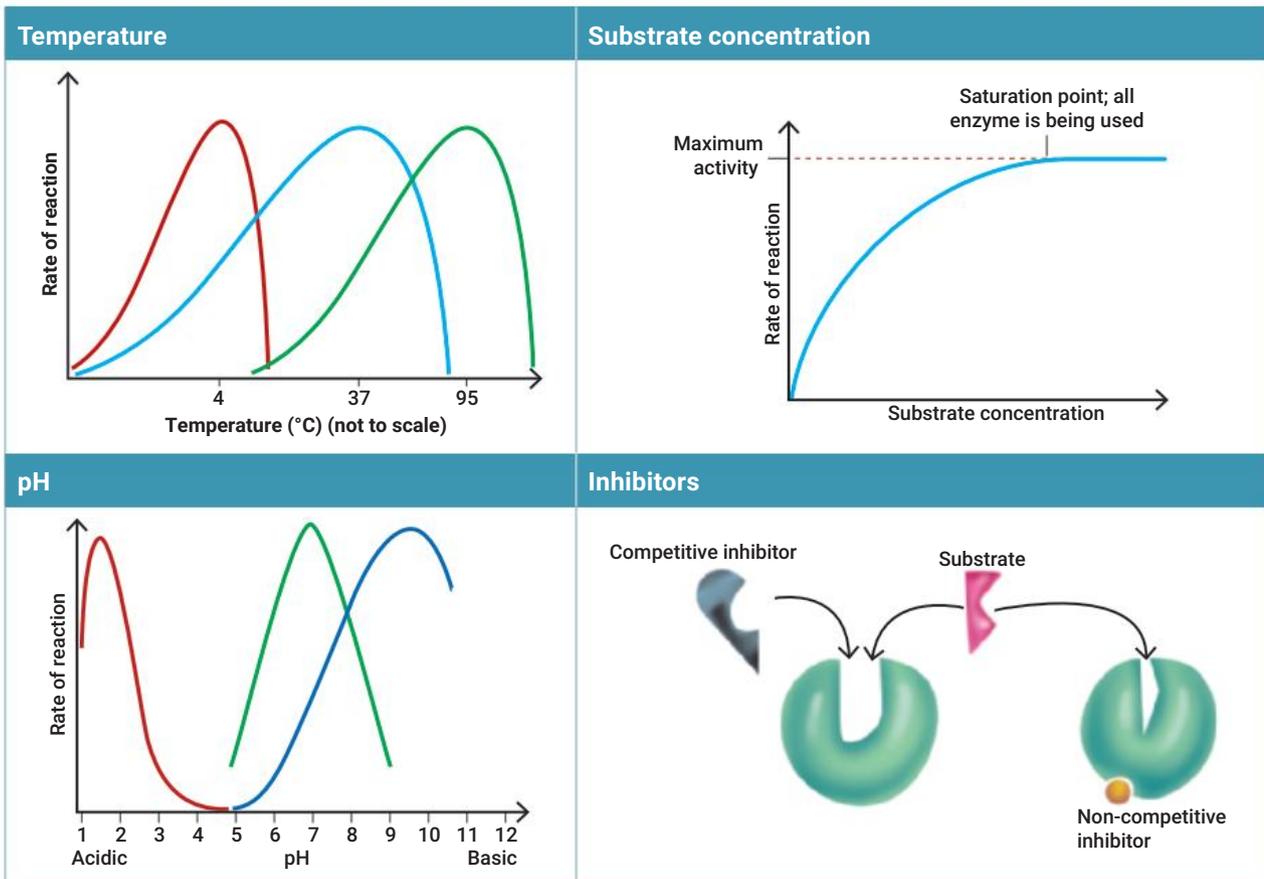
Enzymes

- Enzymes lower the activation energy required to initiate a reaction.
- The active site of an enzyme is a small cleft where the substrates bind and catalysis occurs; the rest of the shape is required to create and support the active site.
- There are two proposed mechanisms for enzyme function: the induced-fit and the lock-and-key models.

Feature	Induced-fit model	Lock-and-key model
Proposed active site	Dynamic	Static
Explains catalysis	Yes	No
Explains multisubstrate enzymes	Yes	No
Currently accepted	Yes	No

Factors affecting enzyme function

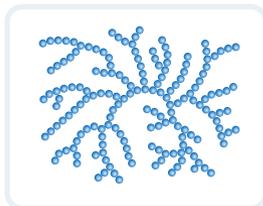
- Many factors affect enzyme function, including temperature, pH, substrate concentration and inhibitors.
- Denaturation renders an enzyme functionless by disrupting the bonds that hold the tertiary structure of the protein together, which causes the loss of its functional shape.



MULTIPLE CHOICE

- Many biomolecules are polymers, large molecules made up of smaller subunits. Biological polymers include:
 - cellulose composed of glucose.
 - glycogen composed of glycerol.
 - proteins composed of fatty acids.
 - starches composed of amino acids.

- The following image depicts the structure of which biomolecule?

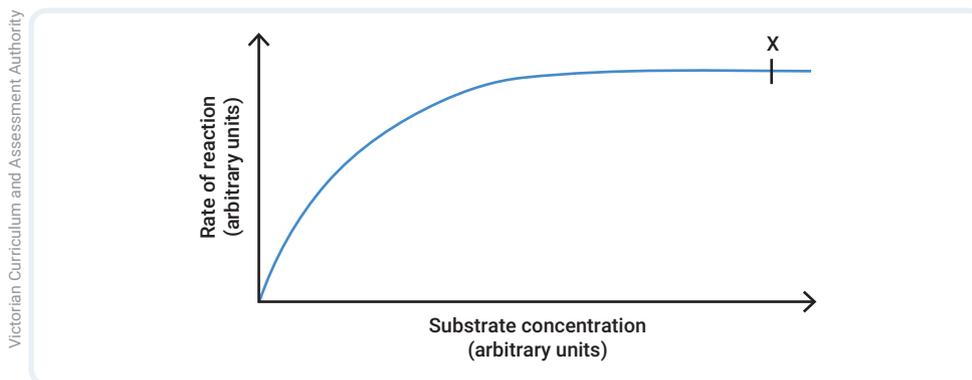


- Cellulose
 - Glucose
 - Glycogen
 - Protein
- Which of the following correctly links the biomolecule with their enzyme type and component parts?
 - Carbohydrate – amylase – monosaccharides
 - Carbohydrates – lipase – glycerol
 - Lipids – amylase – amino acids
 - Protein – protease – fatty acids
 - Enzymes are a subset of:
 - carbohydrates.
 - proteins.
 - lipids.
 - cells.
 - The primary function of an enzyme is to:
 - act as substrate molecules.
 - decrease the activation energy.
 - increase the activation energy.
 - keep products from interacting.
 - The induced-fit model of enzyme activity proposes that the:
 - active site does not match the substrate shape at all.
 - enzyme undergoes a conformational change when the substrate enters the active site.
 - enzyme undergoes a conformational change when the substrate leaves the active site.
 - substrate shape exactly matches the active site shape of an enzyme.
 - The shape of the active site of an enzyme can be destroyed by:
 - excess pH.
 - an increase in activation energy.
 - the presence of molecules with a similar shape to the active site.
 - the presence of molecules with a complementary shape to that of its substrate.

8. In an enzyme-catalysed reaction, as temperature increases, the rate of reaction will:
- A not change.
 - B increase and then level off.
 - C decrease and then level off.
 - D increase and then decrease rapidly.

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9. The following graph illustrates the effect of different concentrations of a substrate on the rate of a cellular reaction.



In this series of experiments, the amount of enzyme, the pH and the temperature remain constant. **Identify** the limiting factor at point X.

- A pH
 - B Temperature
 - C Amount of enzyme
 - D Substrate concentration
10. When investigating enzyme activity, it is important to keep:
- A temperature and pH within the enzyme's normal active range.
 - B temperature but not pH within the enzyme's normal active range.
 - C pH but not temperature within the enzyme's normal active range.
 - D neither temperature nor pH within the enzyme's normal active range.

SHORT RESPONSE

11. **Compare** the structures and functions of carbohydrates, proteins and lipids.
12. **Explain** why enzymes only work on specific substrates.

CROSS-CHAPTER QUESTION

13. Cells have many membrane-bound organelles and other methods of compartmentalising the internal environment. **Explain** which factor(s) compartmentalisation uses to increase enzyme activity rates.

DATA ANALYSIS

Questions 14 and 15 refer to the following information.

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The following shows the results of an experiment that investigated the effect of pH on an enzyme breaking down a substrate. The time it took the substrate to completely break down was recorded. A maximum time of 60 seconds was allowed before timing was stopped. The same volumes and concentrations of enzyme and substrate were added to each pH buffer solution.

pH	1	3	5	7	9	11	13
Time taken for substrate to break down (s)	15	5	3	1	3.5	4	15

The following table shows the pH of different parts of the body.

Location	Approximate pH
Blood	7.35–7.45
Stomach	1.0–2.0
Small intestine	4–7
Saliva	6–7.5
Pancreas	7.5–8

14. Analyse evidence

Identify a relationship present in the data.

15. Interpret evidence

Deduce whether this enzyme would function in the human body by using information from the tables above to provide reasoning.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- Appreciate how understanding the anatomy and physiology of different body systems allows medical professionals to predict, diagnose, monitor and treat disease.

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Kidney disease

In Australia, approximately 11 per cent of adults suffer from kidney disease. While it is often associated with older people (present in more than 44 per cent of adults over 75), it is most commonly comorbid with type 2 diabetes, and affects slightly more females than males.

In 2021, chronic kidney disease (CKD) contributed to more than 20 000 deaths, 12 per cent of all deaths that year. Given the role of the kidneys in cleaning toxins from the blood, CKD is quickly fatal without a transplant or regular dialysis. However, with dialysis, life expectancy increases to 5–10 years, and some patients survive up to 30 years.

Predicting and diagnosing kidney disease

CKD patients have such a short life expectancy in part because it is a very difficult condition to catch early. The kidney's main functional mechanism is through filtering and reabsorption in the loop of Henle and it only takes 5 minutes for all of the body's blood to pass through once. A weakening kidney that only removes 95 per cent of toxins in a single pass has another chance to remove those toxins every 5 minutes as the blood cycles through. Symptoms often don't present until several years after the kidneys have started deteriorating.

However, knowledge of kidney physiology can direct us to several conditions that cause CKD. The capillaries in the kidney are extremely small and delicate. They are damaged by conditions such as high blood pressure, which bursts capillary walls, and high cholesterol, which causes fat deposits to accumulate. The filtration functions also rely on an accurate balance of concentrations inside and outside the loop of Henle. Diabetes upsets this balance because it drastically increases the concentration of glucose in the blood. Unfortunately, the kidneys can also be damaged by the extended use of medication for many other conditions, so CKD is often a heartbreaking side effect of fighting another disease.

Diagnosing this damage is fairly straightforward and usually non-invasive. Urine tests, or dip-sticks, can detect the presence of molecules that should have been reabsorbed, such as glucose, or should never have been filtered out in the first place, such as proteins and blood cells.

Monitoring and treating kidney disease

The first step in treating kidney disease is to switch to a kidney-friendly lifestyle. This includes:

- bringing blood concentrations back into balance by:
 - reducing glucose in the diet
 - drinking plenty of water
- stopping further damage to the capillaries by:
 - reducing blood pressure
 - reducing cholesterol.

A kidney-friendly lifestyle may be able to postpone end-stage kidney failure by several years. However, it is only a postponement, not a cure. A damaged kidney cannot yet be repaired.

Instead, treatments for end-stage kidney failure are limited to:

- replacing the damaged kidneys with a healthy donor organ in a kidney transplant
- replacing the functions of the kidney with a dialysis machine (**Figure 1**).

Both options come with limited pros and heavy cons (**Table 1**), so the decisions for treatment are highly personal ones, made between the patient, their family and their doctors.

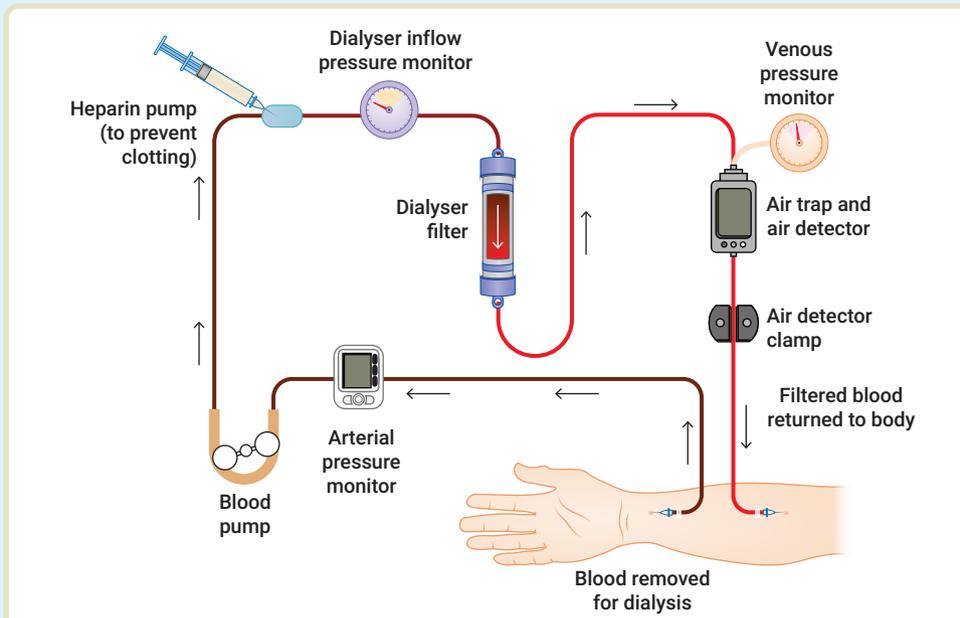


FIGURE 1 The function of a hemodialyser, which runs a patient's blood through a synthetic filter before returning it to the body. A hemodialyser requires 4–5 hours to clean the blood sufficiently for 2–3 days of life.

TABLE 1 Comparison of treatments for kidney failure: transplant vs dialysis

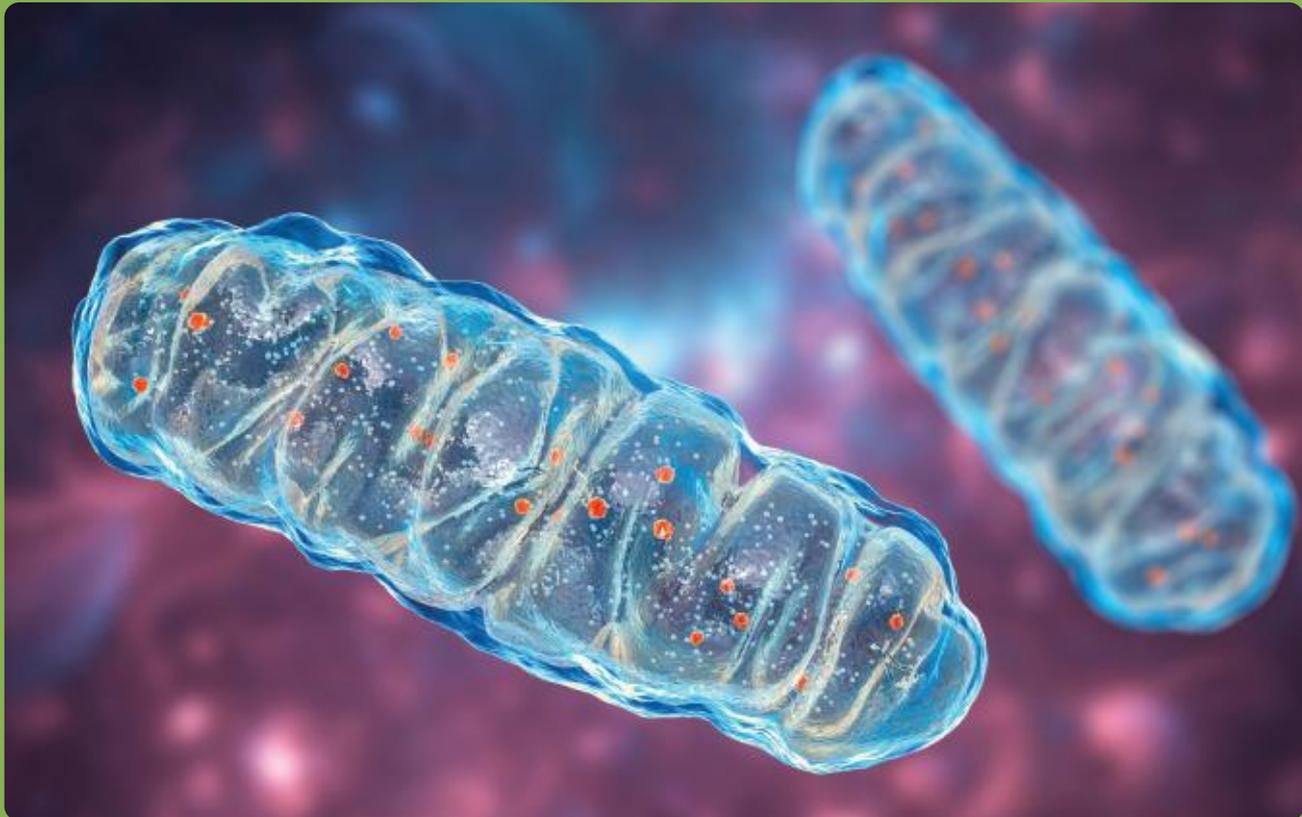
Kidney transplant	Dialysis
Involves highly invasive abdominal surgery	Involves only insertion of entry and exit catheters
Requires a biologically matched donor	Requires a dialysis machine
Requires only a single surgery, assuming no further complications from the surgery itself	Requires treatment three times a week for life, each session taking 4–5 hours
Requires daily anti-rejection medication for life, which also contributes to further kidney failure	Requires extensive medications to manage kidney function, which also contribute to further kidney failure
Average life extension: 19.2 years	Average life extension: 5–10 years

Although lifestyle changes can help manage kidney disease, it is not a cure. More research and awareness are needed to improve prevention, early detection, and treatment options for kidney disease to reduce its impact on individuals and society.



Weblinks
What is CKD?

How dialysis works



Dr_Microbe/Adobe Stock Photos

SYLLABUS
DOT POINTS**SCIENCE UNDERSTANDING**

- Distinguish between catabolism and anabolism.
- Explain how ATP allows energy from catabolic reactions to be used in anabolic reactions.
- Describe the process of aerobic respiration, identifying the location in the cell and net inputs and outputs of:
 - glycolysis
 - Krebs cycle and electron transport chain
 - the overall reaction ($C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36-38 \text{ ATP}$).
- Compare aerobic and anaerobic respiration.

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Introduction

Important processes such as digestion, absorption and gas exchange require energy. It is common to think that our energy comes from food; although this is not incorrect, it is also missing a large part of the process. To obtain energy from food, it must be digested into biomolecules and absorbed into the body before it can be used to produce energy from a process called cellular respiration.

Worksheet

- Cellular respiration and energy

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ Biomolecules, such as glucose, are used to produce energy in cells.
- ✓ ATP is the energy-carrying molecule in cells.
- ✓ Biological reactions are catalysed by enzymes.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ distinguish between catabolism and anabolism
- ✓ distinguish between endergonic and exergonic reactions and their links to catabolism and anabolism
- ✓ explain the structure and function of ATP in transferring energy from catabolic reactions to anabolic reactions
- ✓ describe the process of glycolysis, including its reactants, products and location in the cell
- ✓ describe the Krebs cycle, including its reactants, products and location in the cell
- ✓ describe the electron transfer chain, including its location and the molecules involved in each of its three parts
- ✓ synthesise the stages of aerobic respiration into a cohesive overall reaction
- ✓ describe the reactants and products of anaerobic respiration in plants and animals
- ✓ compare aerobic and anaerobic respiration by identifying relevant similarities and differences.

5.1 Metabolism

metabolism the sum of chemical reactions that maintain life within an organism

catabolic reaction a reaction in which complex molecules are broken down to simpler products, e.g. cellular respiration

anabolic reaction a reaction in which complex molecules are built up from simple molecules

Metabolism is the sum of all of the chemical reactions that occur within an organism to maintain life. Metabolic reactions include many cell processes, such as photosynthesis, respiration, digestion and DNA replication.

Metabolic reactions in which a complex molecule is broken down into simpler molecules are called **catabolic reactions**. The chemical digestion of starch into individual glucose units, and the respiration of glucose into carbon dioxide and water are both catabolic reactions. The key feature of catabolic reactions is that they break larger molecules into smaller ones.

Anabolic reactions are the opposite kind of reaction – simple molecules are combined to form more complex ones. For example, in photosynthesis, glucose is produced from carbon dioxide and water. The production of enzymes from amino acids also occurs through anabolic reactions. The key feature of anabolic reactions is that they combine smaller molecules to form larger ones.

Catabolic reactions release energy

All metabolic reactions require energy. Catabolic reactions require energy to break apart the bonds between the molecules and anabolic reactions require energy to form bonds between small molecules (**Figure 5.1.1**). This initial energy requirement is the activation energy of the reaction.

However, molecules actually store energy within their bonds, so when bonds are broken, energy is released, and when bonds are formed, energy is absorbed into them. In catabolic reactions, the energy released from breaking bonds is greater than the energy required to break them. For example, lighting a match, which needs the input of a small amount of energy

(striking it against the box) releases a large amount of energy (fire). The net effect is that energy is produced by catabolic reactions. The term **exergonic** (*ex* meaning ‘out’) is used to describe reactions that produce energy. All catabolic reactions are exergonic.

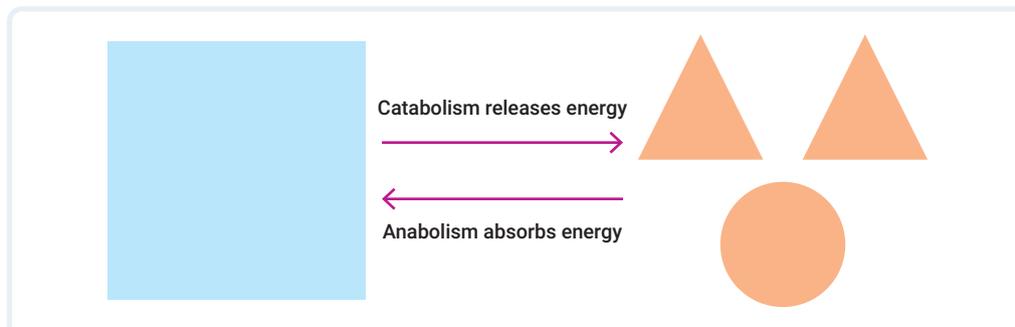


FIGURE 5.1.1 The relationship between catabolic and anabolic reactions in a cell. Molecules may be either built up into more complex compounds or broken down into simpler molecules.

exergonic reaction a chemical reaction that produces more energy than it requires to start, resulting in a net release of energy

Anabolic reactions absorb energy

Anabolic reactions also require activation energy to start, but they form bonds instead of breaking them. The net effect is that energy is absorbed by anabolic reactions. The term **endergonic** (*endo* meaning ‘in’) is used to describe reactions that absorb energy. All anabolic reactions are endergonic. **Figure 5.1.2** summarises catabolic and anabolic reactions.

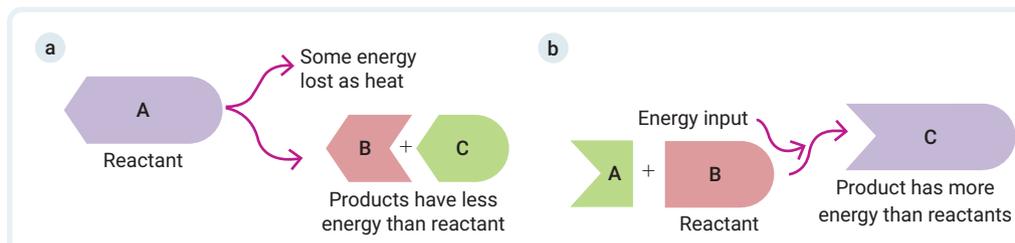


FIGURE 5.1.2 (a) Catabolic reactions are exergonic – they release energy. (b) Anabolic reactions are endergonic – they absorb energy.

endergonic reaction a chemical reaction that requires energy, resulting in a net absorption of energy

ATP transfers energy from catabolic to anabolic reactions

Cells use the energy released from catabolic reactions to fuel their anabolic reactions. However, the two types of reactions are often not occurring at the same time or in the same place. To capture and store this energy temporarily and move it between locations in the cell, an energy transfer molecule called **adenosine triphosphate (ATP)** is used (**Figure 5.1.3**). ATP is a free nucleotide containing adenosine attached to a ribose, which is bound to a chain of three phosphate groups. The structure of ATP makes it suitable as a renewable energy source.

When the energy is released through catabolism, it is immediately captured by the enzyme **ATP synthase**. It uses the energy to add a third phosphate to **adenosine diphosphate (ADP)**. In forming this new bond, adenosine with three phosphates (ATP) now carries the energy that was released by the catabolic reaction. Most catabolic reactions produce enough energy to create several molecules of ATP, which can then be stored or transported around the cell to be used in anabolic reactions.

When an anabolic reaction requires energy, the enzyme responsible for the reaction breaks the third phosphate off ATP, releasing the energy for use in the reaction. The resulting adenosine

adenosine triphosphate (ATP) a molecule that stores and transports energy in the cell; composed of adenosine, ribose and three phosphate groups

ATP synthase an enzyme that captures energy by creating ATP

adenosine diphosphate (ADP) a low-energy compound made up of adenine and ribose and two phosphate groups attached; it is converted to ATP for energy storage when it gains a phosphate group



Syllabus link
Chapter 4 discusses enzymes and how they operate.

with two phosphates (ADP) and the free phosphate (P) are transported around the cell to be remade in catabolic reactions.

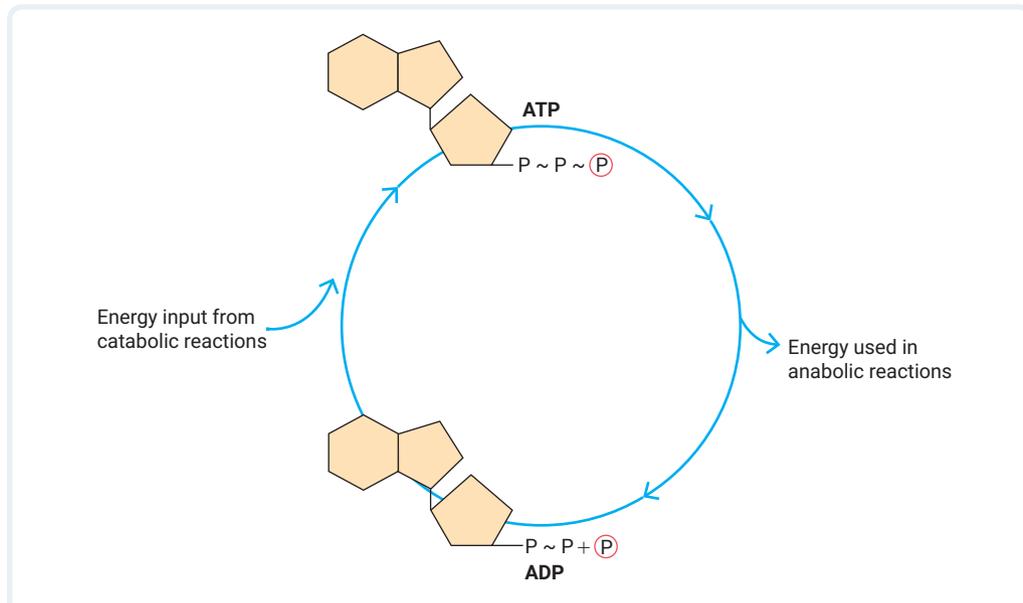


FIGURE 5.1.3 ATP is used to capture energy from catabolic reactions and provide it to anabolic reactions throughout the cell.

LEARNING CHECK 5.1

DESCRIBING

- State a definition for:
a metabolism b anabolic reaction c catabolic reaction.
- Identify** the type of reaction that is:
a exergonic b endergonic.
- Describe** the molecule that captures and transports energy between catabolic and anabolic reactions.
- Describe** the relationship between:
a anabolic reactions and endergonic reactions
b catabolic reactions and exergonic reactions.

APPLYING

- Determine** whether each of the following is an anabolic process or a catabolic process.
a Protein synthesis
b Digestion
c DNA synthesis
d Photosynthesis
e Cellular respiration
- Explain** how ATP synthase captures the energy of a catabolic reaction.
- Explain** how the ATP–ADP cycle is similar to a battery.

ANALYSING

- Compare** anabolic reactions and catabolic reactions and give an example of each.

5.2 Cellular respiration

The main catabolic reaction in the cell is the breaking down of glucose to release energy for capture in ATP, which is called **cellular respiration**. It can be summarised in the following equation.

KEY FORMULA

Aerobic cellular respiration

Word equation: glucose + oxygen → carbon dioxide + water + energy

Chemical equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36-38ATP$

The word **aerobic** is used when oxygen is present, whereas **anaerobic** refers to reactions that do not involve oxygen. Cellular respiration has both aerobic and anaerobic stages. The equation above shows the overall reactants and overall products for respiration, but there are approximately 20 linked reactions that occur in this biochemical pathway, each catalysed by specific enzymes and having specific intermediary reactants and products.

Glycolysis

The breakdown of glucose to supply the cell with energy, regardless of whether oxygen is present, starts with a biochemical pathway called **glycolysis** (*lysis* meaning ‘splitting’). Glycolysis takes place in the cytosol of cells. It has 10 reaction steps, and each step is controlled by a specific enzyme. The initial reactant is glucose and the final products are two molecules of a 3-carbon compound called **pyruvate**, two hydrogens loaded onto **hydrogen carriers** and an excess of two ATP molecules (**Figure 5.2.1**). Two ATP are required to start the process, while four are produced, leaving net two ATP produced overall. Since this process does not use oxygen, glycolysis is anaerobic.

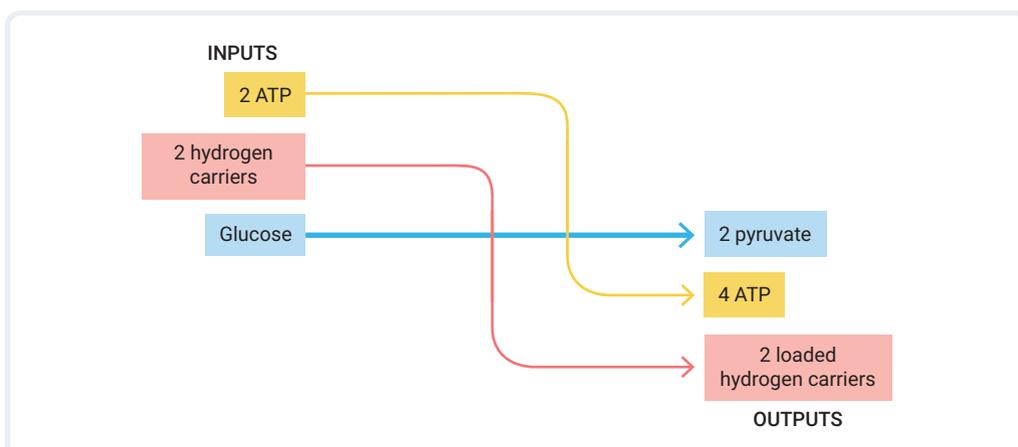


FIGURE 5.2.1 Glycolysis breaks down glucose into two pyruvate molecules. Although it requires two ATP molecules to start the process, it produces four so there is a net positive of two ATP overall.

KEY FORMULA

Glycolysis

Word equation: glucose → pyruvate + loaded hydrogen carriers + energy

Chemical equation: $C_6H_{12}O_6 \rightarrow 2C_3H_4O_3 + 2H^+ + 2ATP$

cellular respiration a catabolic reaction that breaks down glucose to produce energy for the cell

aerobic requiring oxygen

anaerobic not requiring oxygen

glycolysis an energy-yielding process occurring in the cell cytosol in which glucose is partially broken down to pyruvate in enzyme reactions that do not require oxygen; this first stage of cellular respiration produces two ATP molecules

pyruvate a 3-carbon compound that is the end product of glycolysis

hydrogen carrier a molecule that accepts hydrogen from reactions and releases it to other reactions; transports hydrogen around the cell



Weblinks

Cellular respiration 1

Cellular respiration 2

The ATP molecules, which can be used by the cell immediately, may be sufficient for the needs of certain micro-organisms but one glucose molecule releasing only two ATP molecules is not sufficient for multicellular organisms. All multicellular organisms carry out glycolysis as the first step in a more elaborate pathway to gain sufficient ATP for their needs.

Krebs cycle

In eukaryotic cells, the two molecules of pyruvate formed in glycolysis enter a mitochondrion, where a complex cycle of reactions produces more ATP and large volumes of hydrogen carriers. This process involves an initial conversion followed by a cycle called the **Krebs cycle** (Figure 5.2.2).

Krebs cycle a biochemical pathway that requires oxygen and takes place in the mitochondria as the second stage of aerobic cellular respiration



Weblink
Krebs Cycle interactive

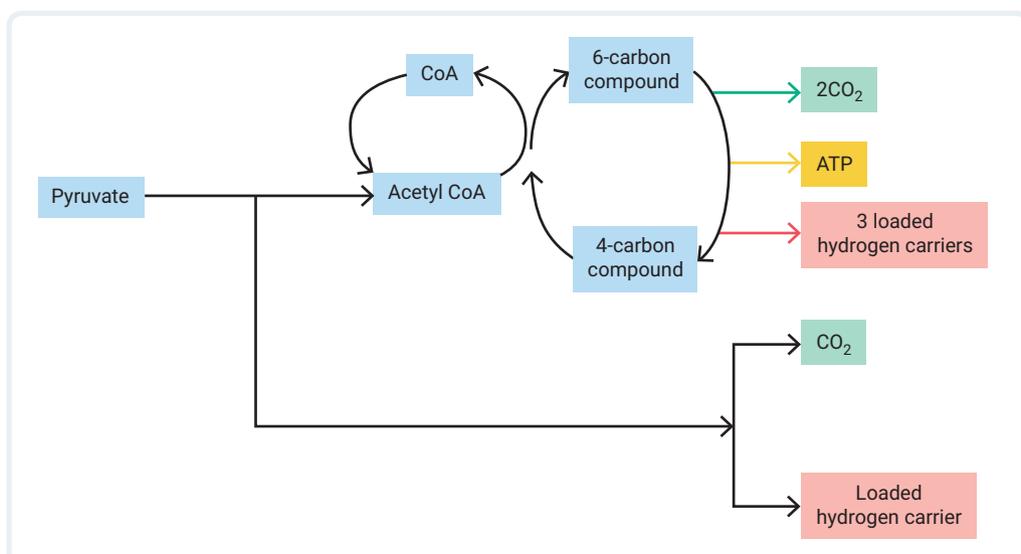


FIGURE 5.2.2 The Krebs cycle involves two steps: a preliminary conversion of the pyruvate from glycolysis to acetyl CoA, and the cycle that produces ATP and hydrogen carriers for the next stage of respiration. Carbon dioxide is released as waste.

For each molecule of pyruvate that enters the mitochondrion, three carbon dioxide molecules are produced. Because pyruvate only has three carbons, it is completely converted to waste by the Krebs cycle. During this process, one ATP and four hydrogen carriers are also produced, which carry on into the final stage of aerobic cellular respiration. Given that one glucose made two pyruvates in glycolysis, the Krebs cycle runs twice. This produces a total of six carbon dioxide molecules, two ATP molecules and eight hydrogen carriers for each glucose molecule originally broken.

KEY FORMULA

Krebs cycle

Word equation: pyruvate → carbon dioxide + loaded hydrogen carriers + energy

Chemical equation: $2C_3H_4O_3 \rightarrow 6CO_2 + 8H^+ + 2ATP$

Electron transport chain

The **electron transport chain** is the third and final stage of aerobic cellular respiration (**Figure 5.2.3**). This stage has three parts: the electron flow, the oxygen uptake and the ATP synthesis.

electron transport chain
the third and final stage of aerobic respiration involving the flow of electrons through the mitochondrial membrane, their uptake by oxygen, and the production of ATP

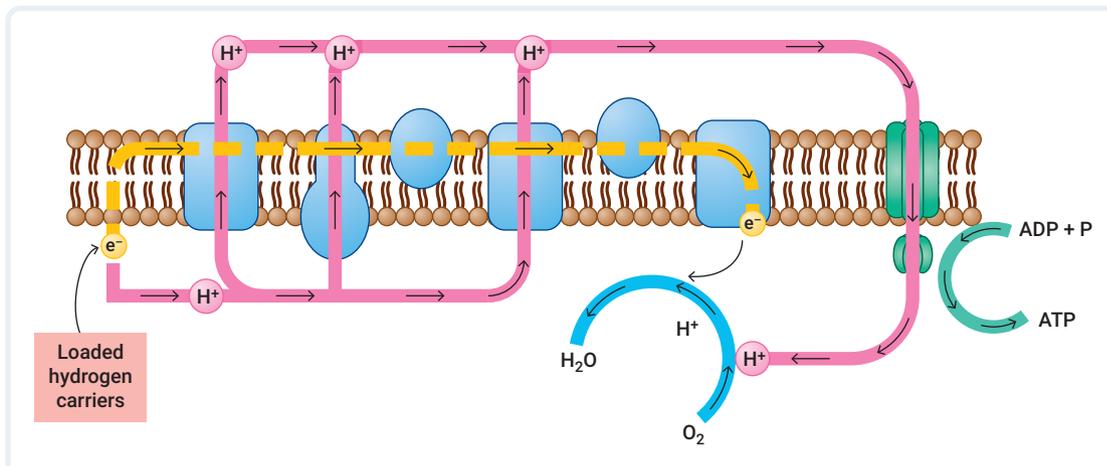


FIGURE 5.2.3 The electron transport chain is composed of three parts: electron flow (yellow), oxygen uptake (blue) and ATP synthesis (green). The cycle of hydrogen ions around the mitochondrial membrane (pink) is crucial to the massive ATP production of aerobic respiration.

Electron flow

The electron flow is the movement of electrons from molecule to molecule along the mitochondrial membrane, fuelled by the hydrogen carriers that have been produced in glycolysis and the Krebs cycle. As the electrons flow along the membrane, they drive several proton pumps to actively transport hydrogen ions from one side of the membrane to the other.

Oxygen uptake

The final destination of the electrons is to be taken up by oxygen. Oxygen that was breathed in has travelled to the mitochondria, where the electrons combine it with hydrogen to form water. The two hydrogen carriers from glycolysis and eight from the Krebs cycle produce six water molecules.

ATP synthesis

The hydrogen ions that were pumped to one side flow back through a channel in the enzyme ATP synthase. This drives the enzyme to produce dozens of ATP molecules, fuelled by a continuous flow of hydrogen ions through its channel. The 10 total hydrogen carriers from glycolysis and the Krebs cycle are sufficient to run ATP synthase for approximately 32 to 34 ATP molecules.

KEY FORMULA

Electron transport chain

Word equation: hydrogen carriers + oxygen → water + energy

Chemical equation: $10\text{H}^+ + 6\text{O}_2 \rightarrow 6\text{H}_2\text{O} + 32\text{--}34\text{ATP}$



Weblink
Electron transport chain
made easy



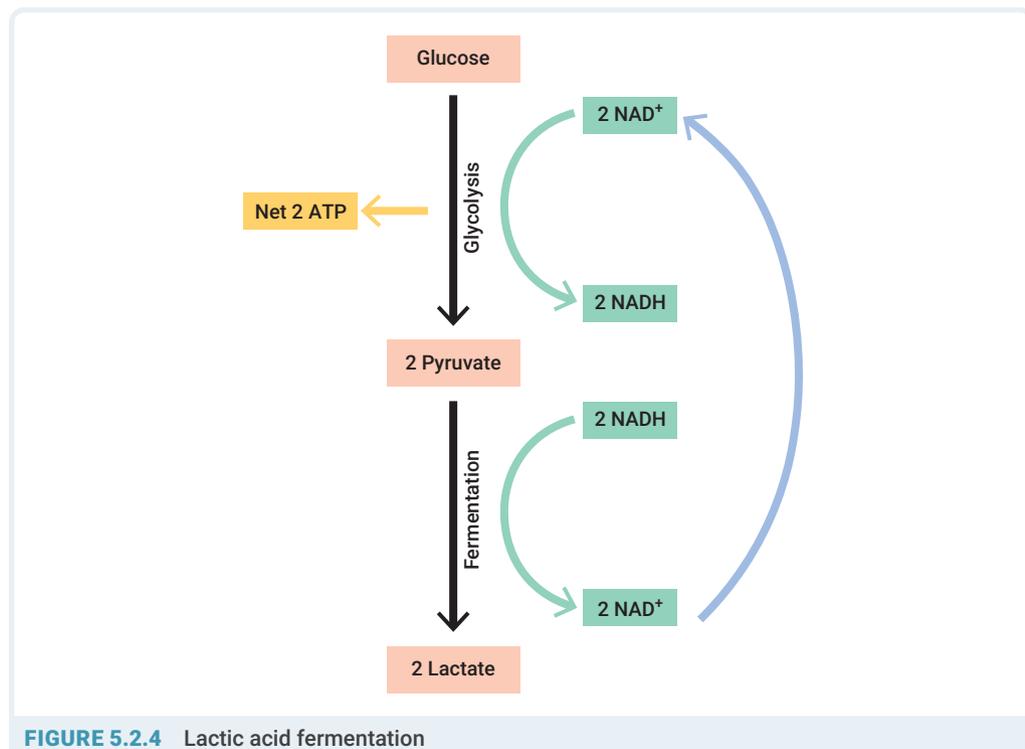
From all the reactions associated with aerobic cellular respiration (glycolysis, Krebs cycle and the electron transport chain) it is possible to produce many ATP molecules from one glucose molecule. Although the syllabus gives 36–38 ATP as a total for aerobic respiration, the exact number is still a topic of active research.

Cellular respiration without oxygen

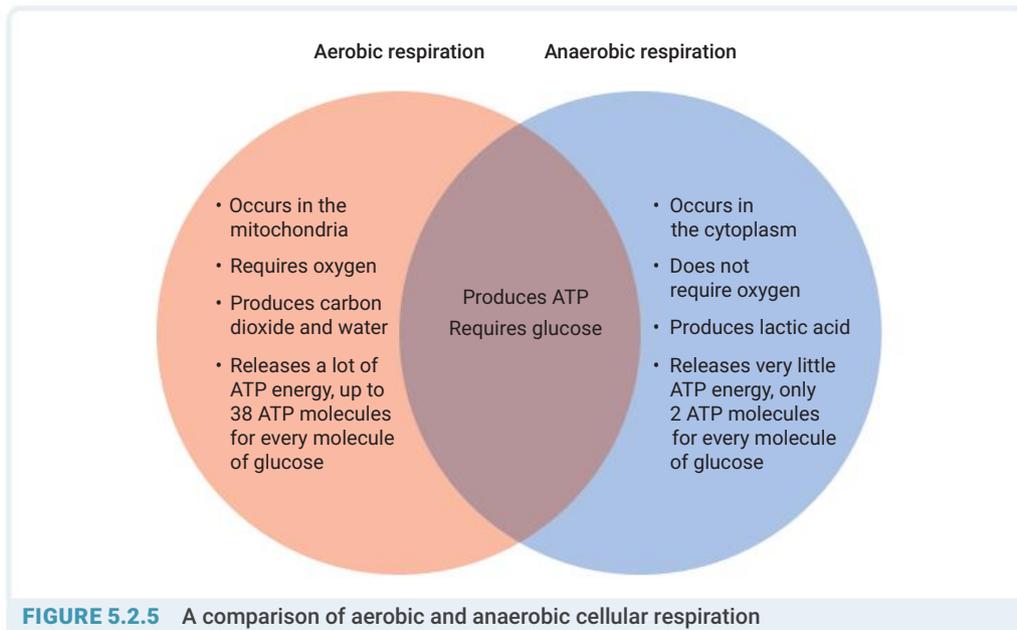
Most animals, plants, protists, fungi and bacteria use complete aerobic cellular respiration. However, sometimes oxygen is not readily available to cells. There are micro-organisms living in environments without oxygen or those that do not have mitochondria (or oxygen reductases), so they cannot use aerobic stages of cellular respiration. Instead, they have developed biochemical pathways that allow respiration to continue in the cytosol using molecules other than oxygen. Generally, these processes produce only small amounts of ATP and often toxic by-products. Prokaryotes have evolved many anaerobic pathways, but eukaryotes commonly use a process called **fermentation**.

fermentation a form of anaerobic respiration (no oxygen present); glucose is converted to ethanol, a type of alcohol

In many multicellular animals, when there is an absence of oxygen, there is nothing available to accept electrons. This means the Krebs cycle and electron transport chain cannot complete their reactions. As a result, pyruvate builds up in the cytosol and is converted into lactic acid (lactate). This process is called lactic acid fermentation. Lactic acid is slightly less toxic to cells, but still produces a painful burning sensation that can lead to cell death. The net production of ATP is two molecules. When oxygen becomes available again, the lactate is converted back into pyruvate. This pyruvate then enters the Krebs cycle and electron transport chain and aerobic respiration is completed (**Figure 5.2.4**).



Plants and yeasts switch to alcohol fermentation in the absence of oxygen. The end products are ethanol, carbon dioxide and two ATP. Ethanol is toxic to cells, so a prolonged lack of oxygen tends to kill the organism. **Figure 5.2.5** compares aerobic and anaerobic respiration in animals.



LEARNING CHECK 5.2

DESCRIBING

- 1 State the balanced equation for aerobic cellular respiration.
- 2 **Identify** the initial substrate and the final products of the glycolysis pathway.
- 3 **Describe** where the three stages of aerobic respiration take place in cells.
- 4 **Describe** the inputs and outputs of the three stages of aerobic respiration.

APPLYING

- 5 **Explain** the sources of the by-products carbon dioxide and water in aerobic cellular respiration.
- 6 **Explain** why multicellular organisms tend to use aerobic respiration.
- 7 **Discuss** why a cell might use fermentation when the by-products are toxic to itself.

ANALYSING

- 8 **Compare** the products of anaerobic respiration with those of aerobic respiration in animals and plants.

CHAPTER SUMMARY

Anabolic and catabolic reactions

- Catabolic reactions involve breaking large molecules into simpler molecules, releasing energy.
- Anabolic reactions use small molecules to make larger molecules, absorbing energy.
- Catabolic reactions are exergonic. Anabolic reactions are endergonic.
- ATP captures energy from catabolic reactions and provides it to anabolic reactions throughout the cell.

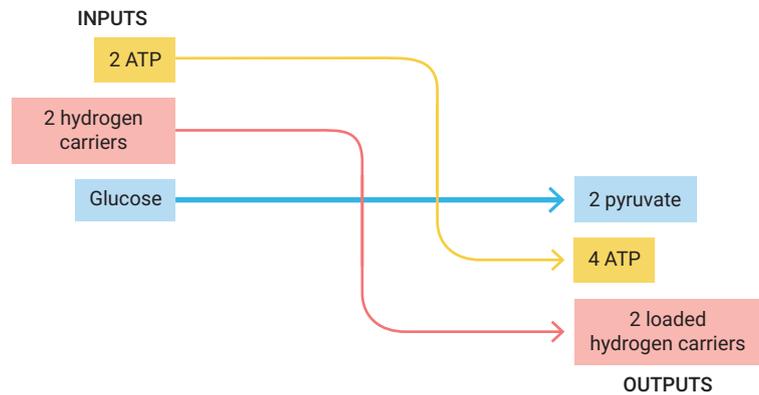
Cellular respiration

- Cellular respiration is a multistep reaction that produces energy from glucose.
- Aerobic cellular respiration:

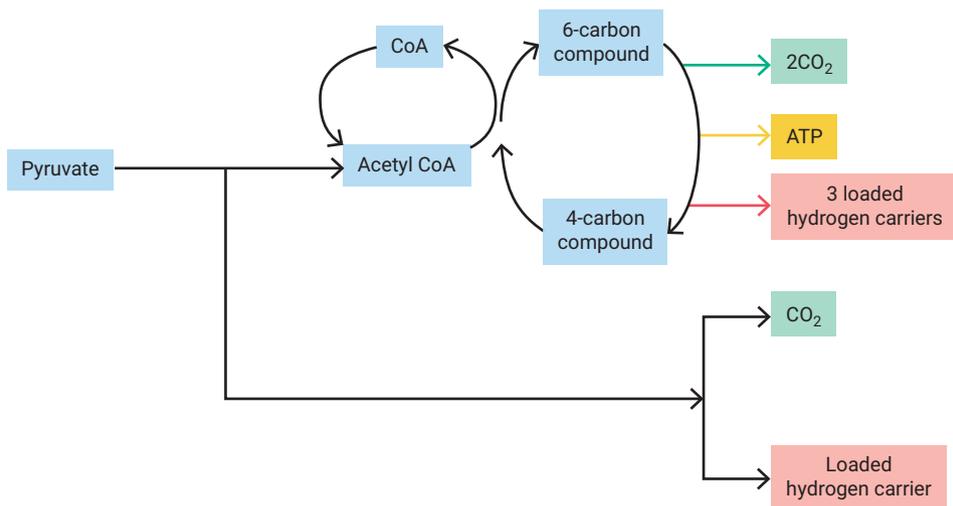
Word equation: glucose + oxygen → carbon dioxide + water + energy

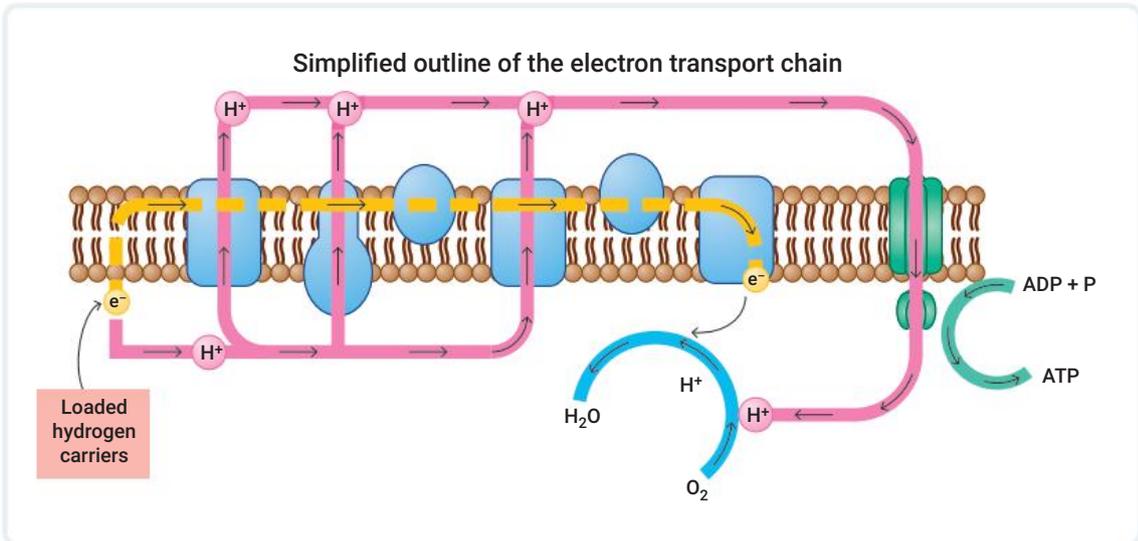
Chemical equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36-38ATP$

Simplified outline of glycolysis



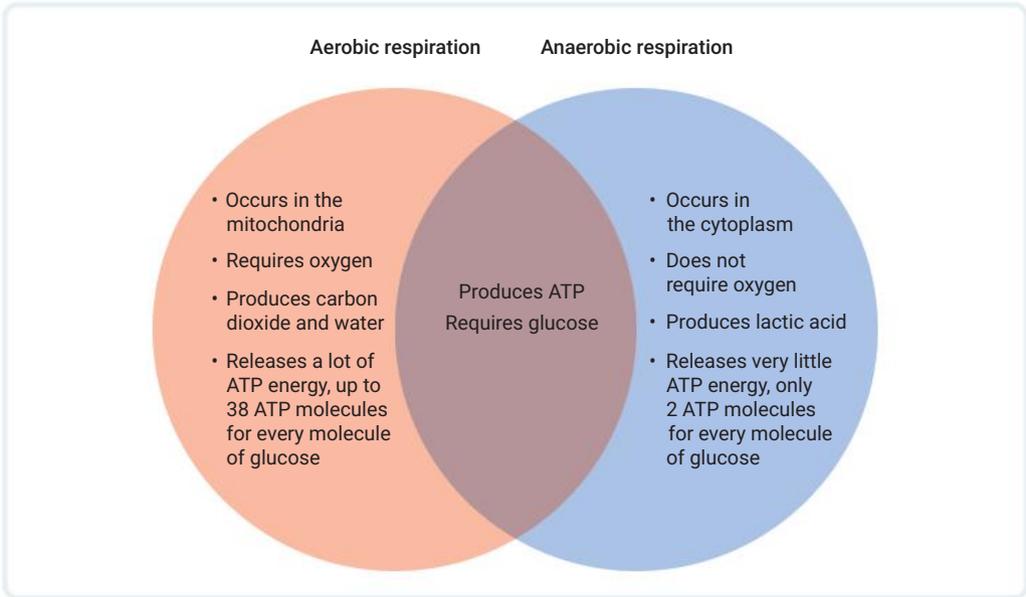
Simplified outline of the Krebs cycle





Differences and similarities between aerobic and anaerobic respiration

- Both anaerobic reactions and aerobic reactions require glucose.
- Aerobic respiration requires oxygen, whereas anaerobic respiration occurs in the absence of oxygen.
- The two reactions occur in different places and release different amounts of energy.



CHAPTER EXAM

MULTIPLE CHOICE

- Two types of chemical reactions in metabolism are:
 - catabolic (breaking down) and anabolic (building up).
 - anabolic (breaking down) and catabolic (building up).
 - metabolic (breaking down) and anabolic (building up).
 - anabolic (breaking down) and metabolic (building up).
- Select the best description from the following.
 - ATP is a hydrogen carrier in living cells.
 - Endergonic reactions are used to fuel exergonic reactions.
 - The enzyme ATPase catalyses the reactions of glycolysis.
 - When ATP is converted to ADP, the energy released drives cellular reactions.
- A human uses approximately 100 mol of ATP per day. However, there is only 0.1 mol available to the body at any given time. The ATP needed can be supplied because:
 - ATP is regenerated through respiration.
 - some cells use less ATP than other cells.
 - more ATP is broken down than is synthesised.
 - ATP can be used in more than one reaction simultaneously.
- The main product of glycolysis is:
 - ATP.
 - CO₂.
 - glucose.
 - pyruvate.
- Before entering the cyclic component of the Krebs cycle, pyruvate is converted to:
 - CO₂.
 - glucose.
 - acetyl CoA.
 - a four-carbon compound.
- The electron transport chain has all the following components except:
 - electron flow.
 - ATP synthesis.
 - hydrogen cycling.
 - oxygen production.
- Aerobic respiration is summarised in the equation:
glucose + oxygen → carbon dioxide + water + ATP
Select the compound that is, chronologically, the last to be seen in the process.
 - ATP
 - Carbon dioxide
 - Oxygen
 - Water
- Select the process that occurs in both aerobic and anaerobic respiration.
 - Electron transport chain
 - Fermentation
 - Glycolysis
 - Krebs cycle

9. In animals, including humans, the following substance is produced anaerobically during strenuous exercise:
- A Ethanol
 - B Glucose
 - C Glycogen
 - D Lactic acid
10. A cell that has a high proportion of mitochondria is most likely to be specialised to produce:
- A ATP.
 - B enzymes.
 - C glucose.
 - D starch.

SHORT RESPONSE

11. **Describe** the process of aerobic respiration.
12. **Compare** aerobic respiration and anaerobic respiration.

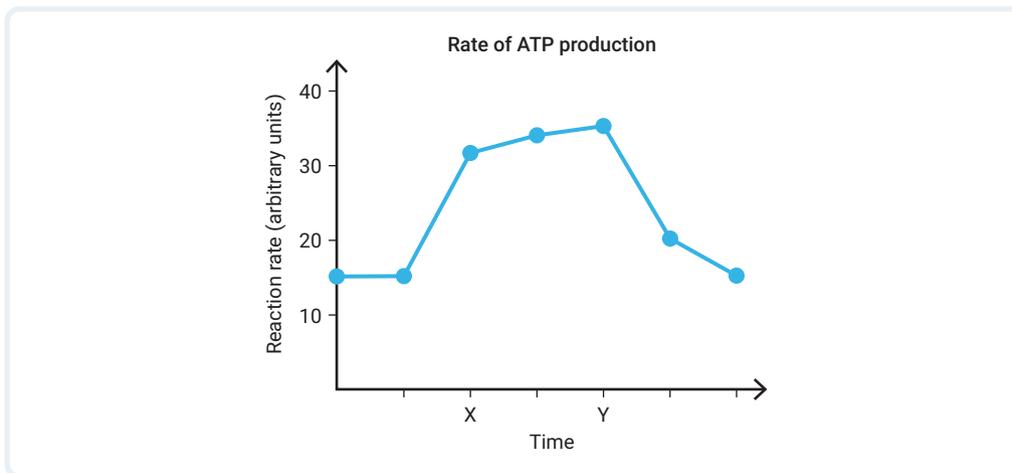
CROSS-CHAPTER QUESTION

13. **Discuss** which body tissues are likely to have large quantities of mitochondria in their cells and how this reflects the need for energy in those tissues.

DATA ANALYSIS

Questions 14 and 15 refer to the following information.

The following graph shows the rate of ATP production in a sample of muscle tissue during and after a period of strenuous exercise.



14. **Analyse data**

Determine the approximate rate of ATP production:

- a before beginning strenuous exercise
- b at time X
- c at time Y
- d after time Y.

15. **Interpret evidence**

Deduce when the muscle tissue exhausted its supply of oxygen.



Alamy Stock Photo/Archeophoto

SYLLABUS
DOT POINTS**SCIENCE UNDERSTANDING**

- Describe the process of photosynthesis, identifying the location in the cell and net inputs and outputs of:
 - light-dependent reactions
 - light-independent reactions
 - the overall reaction ($6\text{CO}_2 + 6\text{H}_2\text{O} + \text{light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$).
- Compare the structure and function of xylem and phloem tissues.
- Explain how stomata and guard cells facilitate gas exchange in plants.
- Interpret data from an experiment investigating the effect of light intensity, temperature, wind or humidity on the rate of transpiration.



- Explain the structural and homeostatic mechanisms that maintain water balance in plants, including the roles of stomata, vacuoles, cuticle and abscisic acid. (Unit 2, Topic 1)
- Interpret data from an experiment comparing the number and distribution of stomata in plants adapted to different environments. (Unit 2, Topic 1)

SCIENCE INQUIRY

- Compare the number and distribution of stomata in plants adapted to different environments. (Unit 2, Topic 1)

Note: This chapter includes dot points from more than one topic.

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Introduction

The tallest flowering tree species in the world is *Eucalyptus regnans*. Known as mountain ash in Victoria and swamp gum in Tasmania, there is one specimen outside Hobart that is 101 metres tall. Aptly named 'Centurion', this particular swamp gum is about 400 years old and represents the tallest flowering plant, the tallest hardwood tree and the tallest eucalypt in the world.

Glucose acquisition without eating, gas exchange without a set of lungs and nutrient transport without a beating heart are some of the most fascinating marvels of terrestrial plants.

Practicals

- Stomata and guard cell distribution
- Factors that affect transpiration
- Extraction of chlorophyll from leaves (online-only resource)
- Effect of light on photosynthesis (online only resource)

Worksheets

- Photosynthesis
- Gas exchange in plants
- Transport systems in plants: phloem
- Plant systems

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ Photosynthesis is the process by which plants produce food.
- ✓ Plants take in carbon dioxide and release oxygen.
- ✓ Plant cells contain specialised organelles called chloroplasts where photosynthesis occurs.
- ✓ Plants take up water through their roots and lose it through their leaves.
- ✓ Photosynthesis requires water, whereas respiration produces it.
- ✓ Conditions that increase water evaporation include hot, sunny, dry and windy environments.
- ✓ The overall reaction for photosynthesis is the reverse process of respiration:
- ✓ Respiration: glucose + oxygen → carbon dioxide + water
- ✓ Photosynthesis: carbon dioxide + water $\xrightarrow{\text{light energy}}$ glucose + oxygen
- ✓ Respiration consists of three phases – glycolysis, the Krebs cycle and the electron transfer chain – which have inverse analogues in photosynthesis.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe the net inputs and outputs of photosynthesis
- ✓ explain the location and role of chlorophyll in photosynthesis
- ✓ outline photosynthesis as a two-stage process
- ✓ describe the light-dependent reactions, including light-driven electron flow, water splitting and ATP synthesis
- ✓ explain the role of hydrogen cycling in the production of ATP
- ✓ describe the light-independent reactions of photosynthesis
- ✓ investigate the effect of light on the efficiency of photosynthesis
- ✓ outline the leaf structures, including stomata, that support efficient gas exchange
- ✓ explain how guard cells facilitate the opening and closing of stomata
- ✓ describe the conditions under which guard cells open and close stomata to balance gas exchange with water loss
- ✓ describe the structure and function of xylem tissue, including vessel elements and tracheids
- ✓ describe the structure and function of phloem tissue, including sieve tube cells and companion cells
- ✓ compare the structure and function of xylem and phloem tissues
- ✓ conduct and interpret data from an experiment investigating the effect of light intensity, temperature, wind or humidity on the rate of transpiration
- ✓ explain how structural and homeostatic mechanisms maintain water balance in plants
- ✓ conduct an experiment investigating stomata in plants adapted to different environments

6.1 Photosynthesis

chlorophyll the green pigment in chloroplasts; it can absorb light energy, making it available for photosynthesis

Photosynthesis is the process by which plants use light energy to break down water and carbon dioxide molecules to build glucose and oxygen. Rather than a single reaction, photosynthesis is a biochemical pathway that involves a series of stages that are catalysed by many enzymes. It uses light as an energy source, which is captured by the pigment **chlorophyll**.

The process can be summarised by the following equation.

KEY FORMULA

Photosynthesis

Word equation: carbon dioxide + water $\xrightarrow{\text{light energy}}$ glucose + oxygen

Balanced chemical equation: $6\text{CO}_2 + 6\text{H}_2\text{O} \xrightarrow{\text{light energy}} \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$

Photosynthesis occurs within a specialised organelle called a **chloroplast** which has a double membrane, similar to mitochondria. Chlorophyll is embedded within the thylakoid membrane in the chloroplast.

The photosynthetic reaction pathway takes place in two distinct stages: the **light-dependent reactions**, which harness light to produce ATP, and the **light-independent reactions**, where ATP is used to produce glucose (**Figure 6.1.2**).

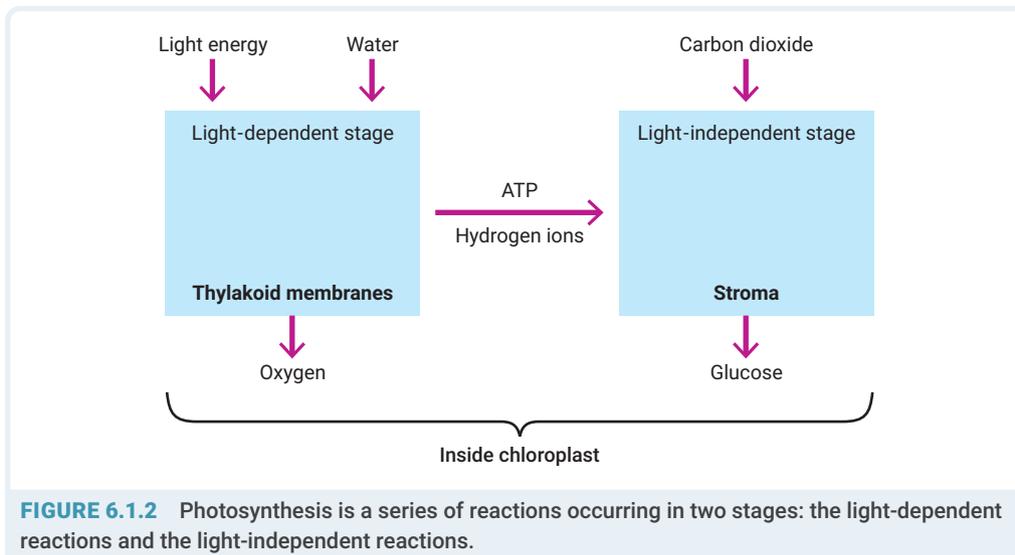


FIGURE 6.1.2 Photosynthesis is a series of reactions occurring in two stages: the light-dependent reactions and the light-independent reactions.

Light-dependent reactions

When light energy encounters an object, it can be bent, reflected or absorbed. Light that is reflected becomes the colour seen, so leaves are green because green light is reflected from them. Light that is absorbed provides energy to the object, such as heating up a surface. Some molecules can absorb light to excite their electrons, such as chlorophyll. These are confined within special proteins called **photosystems**, which are embedded in the thylakoid membrane.

Plants have evolved an intricate biochemical pathway to harness the light-absorbing properties of chlorophyll. There are three parts to the light-dependent reactions: light-driven electron flow, water splitting and ATP synthesis (**Figure 6.1.3**).

chloroplast an organelle in plant mesophyll tissue that uses light energy to make glucose through photosynthesis

light-dependent reactions the first stage of photosynthesis; it requires light energy that is absorbed by chlorophyll; water molecules split to produce oxygen, hydrogen ions and ATP

light-independent reactions the second stage of photosynthesis; carbon dioxide, hydrogen ions and ATP react to produce glucose



Weblink

Photosynthesis interactive

Practical activities

Extraction of chlorophyll from leaves

Effect of light on photosynthesis

photosystems special proteins embedded in the thylakoid membrane that house chlorophyll molecules for photosynthesis

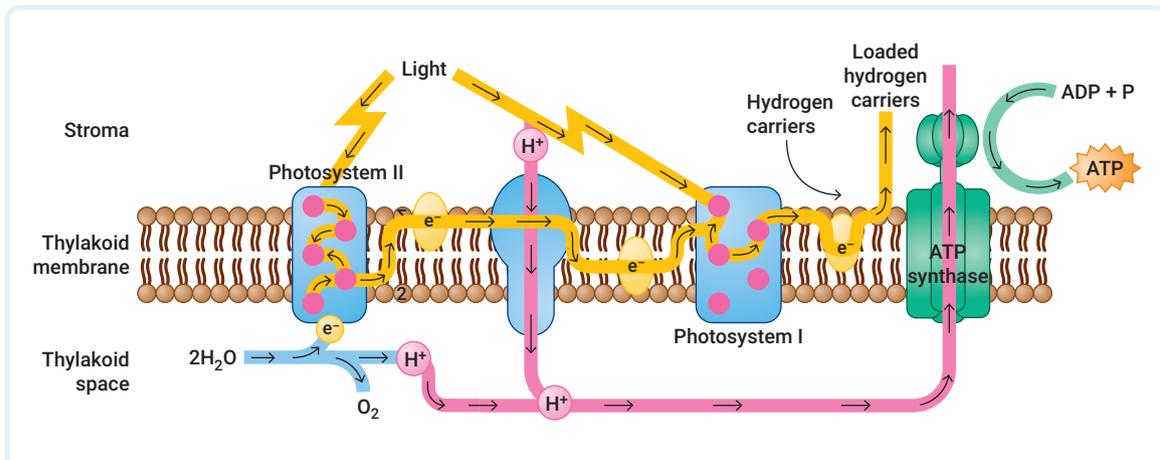


FIGURE 6.1.3 The light-dependent reactions have three parts: light-driven electron flow (yellow), water splitting (blue) and ATP synthesis (green). The cycle of hydrogen ions around the mitochondrial membrane (pink) is crucial to ATP production.

Light-driven electron flow

Sunlight that reaches a photosystem in the thylakoid membrane is absorbed by the chlorophyll molecules within it. This excites the electrons, which trigger a cascade of further excited electrons in the photosystem. These electrons flow down the thylakoid membrane, gaining momentum from other photosystems and driving membrane proteins to pump hydrogen ions into the thylakoid space. The electrons are finally used to load **hydrogen carriers** in the stroma.

hydrogen carrier
a molecule that accepts hydrogen from reactions and releases it to others; transports hydrogen around the cell

Water splitting

Given that electrons are leaving the photosystems during light-driven electron flow, they must be replenished. To do this, electrons are taken from water molecules in the thylakoid space. This process splits the water into oxygen, which is released as a by-product, and hydrogens, which continue to build up in the thylakoid space.

ATP synthesis

Similar to the mitochondrial electron transfer chain, the hydrogen ions that build up in the thylakoid space flow back to the stroma through the channel of ATP synthase, driving the continuous production of ATP. The relationship between the amount of light absorbed and the amount of ATP produced is still unknown.

Light-independent reactions

Although a plant could use the ATP produced by the light-dependent reactions, it is not a long-term energy storage molecule and degrades quickly. This means that when it is dark or there is extended low light conditions, ATP reserves would be quickly exhausted. When there is insufficient light, a long-term storage material such as glucose is required to fuel the plant. This is synthesised in the light-independent reactions (**Figure 6.1.4**).

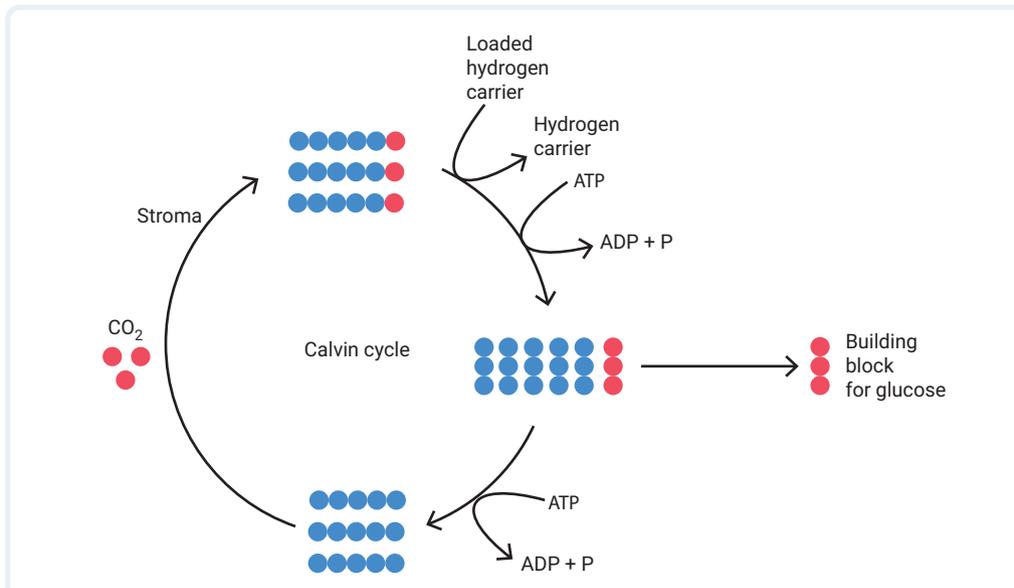


FIGURE 6.1.4 The light-independent reactions, or Calvin cycle, fixes three CO₂ molecules to create a 3-carbon building block for glucose. Two rounds of the Calvin cycle are required to produce one molecule of glucose.

The light-independent reactions, also called the Calvin cycle, occur in the stroma of the chloroplast and do not require light to operate. To begin, three CO₂ molecules are fixed to three molecules of a 5-carbon compound, producing three molecules of a 6-carbon compound. These are quickly converted to six molecules of a 3-carbon compound, using the ATP and hydrogen carriers from the light-dependent reactions. One of these 3-carbon compounds is released while the other five 3-carbon compounds are converted back (using ATP) into the three 5-carbon compounds from the beginning of the cycle.

Two rounds of the Calvin cycle produce two 3-carbon compounds, which are combined to form glucose.



Weblink
The Calvin cycle

Worksheet
Photosynthesis



Syllabus link
See Chapter 5 for the production of ATP from glucose through cellular respiration.

LEARNING CHECK 6.1

DESCRIBING

- 1 **Identify** the products or outputs of the light-dependent reactions that are used as inputs for the light-independent reactions of photosynthesis.
- 2 **Identify** the product of photosynthesis that contributes to the growth of plants.
- 3 State the balanced equation for the overall process of photosynthesis.

APPLYING

- 4 **Explain** whether all plant cells carry out photosynthesis.
- 5 **Discuss** the differences between the light-dependent reactions and the light-independent reactions of photosynthesis in terms of location, requirements and products.
- 6 **Discuss** the similarities between photosynthesis and respiration.

6.2 Gas exchange in the leaf

Unlike aquatic plants, which can exchange gases directly with their environment, terrestrial plants require specialised tissues with specific functions to survive. These functions include obtaining energy, producing organic compounds, distributing materials, removing wastes and exchanging gases (Figure 6.2.1). The structure of a **vascular** plant ensures that each organ – the leaves, stem, roots, flowers and seeds – receives what it needs.

vascular relating to plant vessels that conduct fluid

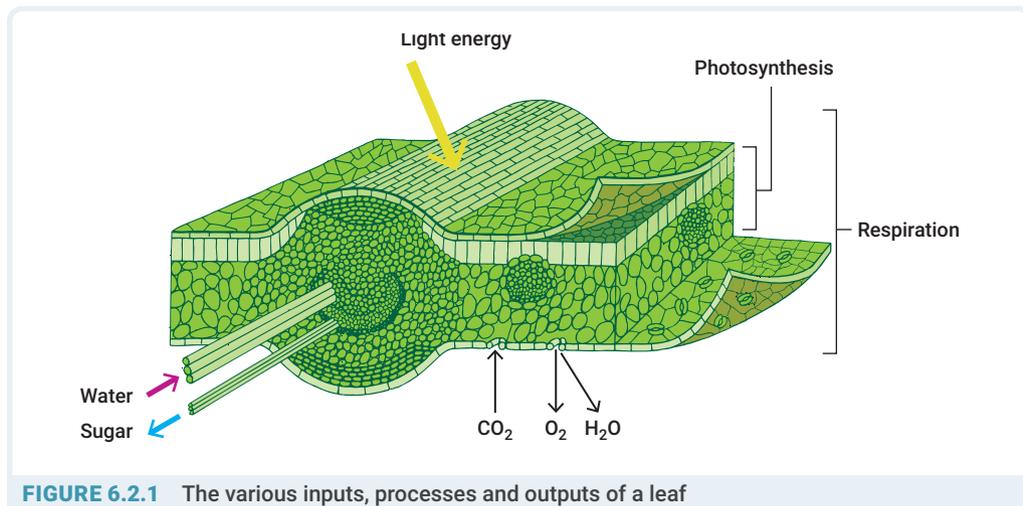


FIGURE 6.2.1 The various inputs, processes and outputs of a leaf

Gases such as oxygen and carbon dioxide are exchanged locally throughout the plant. They do not need to be transported from one part of the plant to another; instead transport occurs entirely through passive diffusion. The structure of leaves supports this. Leaves may be large but are generally flat, which maximises the surface area available for gas exchange. They also contain open-air spaces (Figure 6.2.2), which provide even greater surface area to allow the gases to move freely through much of the leaf without having to pass through cells.

Stomata and guard cells

Carbon dioxide and oxygen that enter the leaf through the **epidermis** are essential for photosynthesis and cellular respiration. However, other gases such as water vapour are also free to pass into and out of the leaf by **transpiration**. This can be a problem if too much water evaporates from the leaf during the heat of the day because water is required in the leaves for photosynthesis.

The solution to this problem is the combination of a waxy **cuticle**, which prevents water from evaporating from the leaf surface, and the presence of closable pores usually found in the lower epidermis called stomata (singular: **stoma**). When the stomata are open, gases pass freely into and out of the leaf, including carbon dioxide moving into the leaf and oxygen and water vapour moving out. When the stomata are closed, gases cannot enter or leave and water is conserved.

Stomata are surrounded by **guard cells**, a pair of crescent-shaped cells shaped to form an opening (Figure 6.2.3). When the guard cells absorb water, they swell and become rigid and banana-shaped, which opens the stoma. When they lose water, they become soft (flaccid) and fall closed. As a result, stomata tend to be open when a plant is experiencing moist conditions and closed when a plant is experiencing dry conditions.

The timing of the opening and closing of stomata also depends on several environmental factors. Under normal conditions, stomata open at daybreak and close at night because the leaves need CO₂ for photosynthesis during the day. However, other conditions can override the effects

epidermis the surface layer of cells in an organism

transpiration the loss of water from plants through evaporation

cuticle a thin, transparent layer of wax on the outside of a leaf's epidermis to reduce water loss

stoma a controlled opening in leaves and young stems that controls the movement of gases into and out of a plant

guard cells a pair of crescent-shaped cells that enable the opening and closing of a stoma

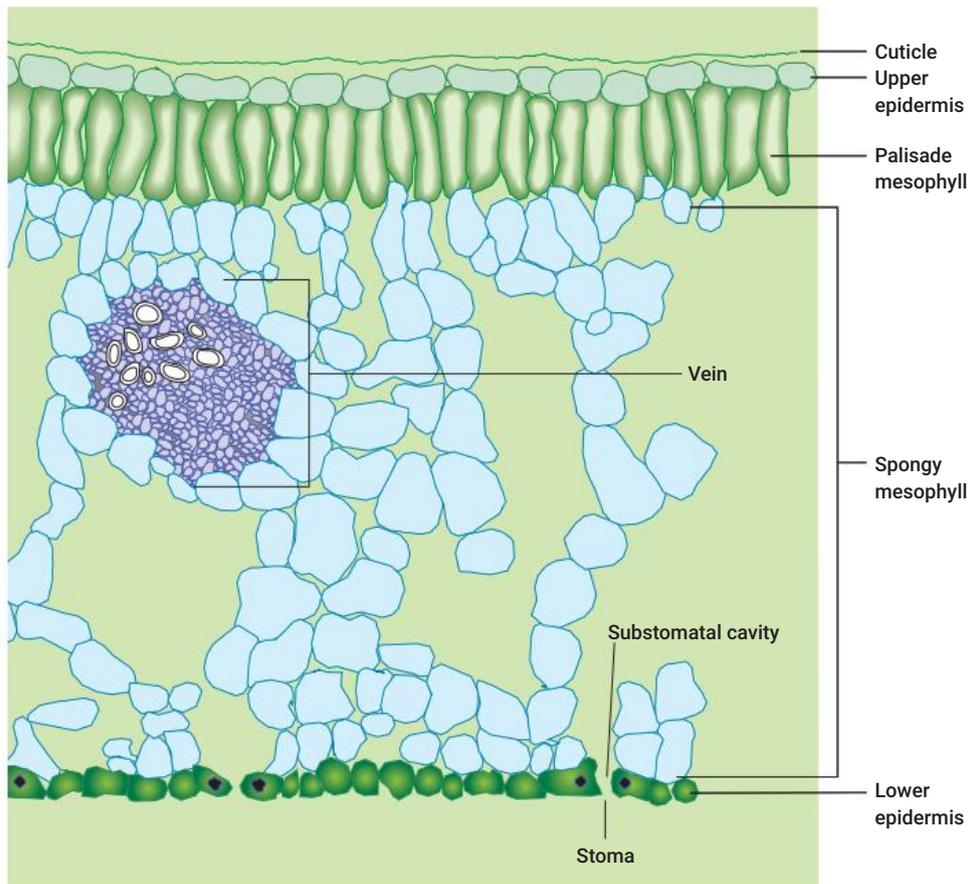


FIGURE 6.2.2 A general cross-section of a leaf. The air spaces within the leaf allow passive diffusion of gases to every cell.

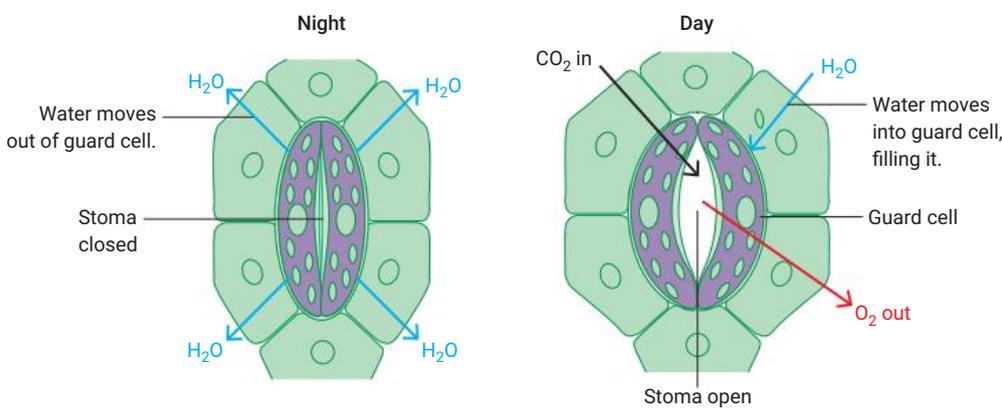


FIGURE 6.2.3 Stomata control the passage of air through the leaf. At night and at times of low humidity, water leaves the guard cells and the stomata close, sealing the leaf off from the outside. During the day and at times of high humidity, water enters the guard cells and the stomata open, allowing gases to enter and leave.



Weblink
Stomata and guard cells
in plants

of light. For example, on a warm sunny day as the temperature increases, more and more water vapour is lost through the open stomata. This loss of water triggers cells in the roots and leaves to produce **abscisic acid** (ABA), which accumulates in the guard cells. As ABA concentration increases, the guard cells lose water and the stomata close.

abscisic acid a plant hormone produced in response to water stress that closes the stomata



In situations of severe water stress, such as in a drought, the guard cells may lose water frequently and close the stomata. Although this reduces water loss, it also cuts off the supply of CO_2 , which restricts the capacity of the leaf to carry out photosynthesis and restricts the overall growth of the plant.

A few plants have evolved mechanisms for storing carbon compounds for later use, allowing them greater control over when and under what conditions they open their stomata. CAM plants, such as cactuses, open their stomata during the evening, when it is cooler, to store CO_2 and close their stomata during the hottest part of the day while using stored CO_2 for photosynthesis.

PRACTICAL ACTIVITY 6.2.1

STOMATA AND GUARD CELL DISTRIBUTION

Introduction

Most plants have a waxy cuticle to prevent uncontrolled water loss. Stomata provide a way for the plant to exchange gases with the cells and control the release of water to the atmosphere. The more stomata per unit area (stomata density), the more water is lost to the environment. If water is not readily available, such as in dry, terrestrial environments, excessive water loss might lead to plant stress and reduction of metabolic functions.

Research question

Does the plant's environment (independent variable) affect the number and distribution of stomata (dependent variable)?

Aim

To compare the number and distribution of stomata and guard cells in plants adapted to different environments

Materials

- freshly picked green leaves from a range of terrestrial and aquatic environments
- light microscope
- microscope slides
- coverslips
- tweezers
- water dropper
- dissecting needle
- clear nail varnish
- clear sticky tape

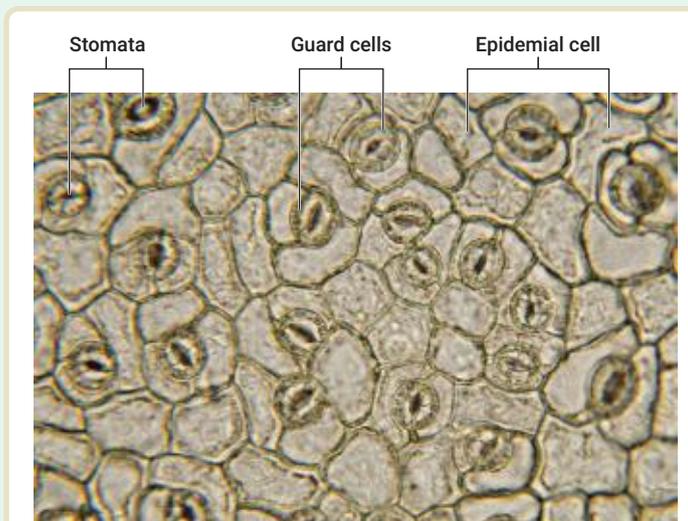


FIGURE 6.2.4 Water evaporates to the atmosphere through stomata.

NNeiring/E+/Getty Images



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Coverslips can break easily and can cut.	Take care with coverslips and do not push hard when placing them.
Environmental: damage to plants and surroundings when collecting leaves	Ensure that leaves are not all taken from one plant. Consider returning leaves to leaf litter.

Procedure

- 1 Cut a fresh green leaf from one of the plants provided.
- 2 Fold the leaf and carefully pull along the fold as shown in Figure 6.2.5. This should leave a small area of very thin, transparent lower epidermis.



- 3 Use tweezers to pull off a section of this lower epidermis.
- 4 Put the section of tissue onto a microscope slide. Try to avoid getting folds in it. Add one or two drops of water and, using the dissecting needle, carefully lower the coverslip.
- 5 Repeat steps 3 and 4 with the upper epidermis of the leaf.
- 6 If it is not possible to obtain a section of the cuticle tissue, make an impression of a leaf surface. Use the following procedure to examine both upper and lower epidermal surfaces.
 - a Apply a thick layer of clear nail varnish to a small area on the surface of the freshly picked leaf. The nail varnish makes an exact replica of the leaf surface.
 - b When the nail varnish is dry (about 5 minutes), stick a very clear piece of sticky tape to the area that contains the dried nail polish. Slowly peel off the tape with a pair of tweezers. The nail polish should come with it.
 - c Without touching it, place the tape with the layer of dried nail polish on the microscope slide.
- 7 Repeat steps 1–6 using tissues from the different species of plants provided.
- 8 Examine each tissue under low power.
- 9 Copy [Table 6.2.1](#) and add the name of the plant and type of environment it grows in (terrestrial or aquatic). Extend the table as required. Count all stomata whose guard cells are more than half contained in the field of view for each tissue.
- 10 Move the slide to another section of cells from the same tissue.
- 11 Repeat steps 9 and 10 for a total of three stomata counts from each tissue.
- 12 Find the average number of stomata from the three stomata counts from the upper side and lower side of the leaf.

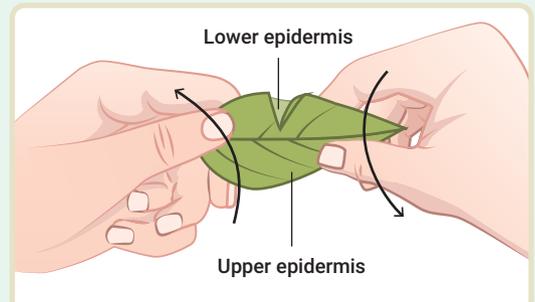


FIGURE 6.2.5 The method of exposing epidermal tissue

Results

TABLE 6.2.1 Number of stomata on upper and lower leaf surfaces

Plant name	Type of environment	Average number of stomata – upper surface	Average number of stomata – lower surface

Analysis of results

- 1 Identify any patterns in the data.
- 2 Compare the number of stomata on each surface from plants in different environments.

Interpretation

- 3 Outline why stomata occur mostly on the undersides of leaves.
- 4 Name the plants for which stomata are only on the upper leaf surface. Explain why this is an adaptation for those plants.
- 5 Relate the difference in the distribution of stomata and guard cells as an adaptation for osmoregulation in different environments.

Evaluation

- 6 Explain why counts of stomata were made in three separate fields of view and then averaged.

LEARNING CHECK 6.2

DESCRIBING

- 1 **Describe** the differences between stoma, stomata and guard cells.
- 2 State three gases that move in or out of stomata.
- 3 **Identify** the factors that cause stomata to open and close.

APPLYING

- 4 **Explain** the function of the:
 - a cuticle
 - b stomata
 - c abscisic acid (ABA)
 - d guard cells.
- 5 **Explain** how most plants respond to very high temperatures in order to limit the loss of water from leaves.
- 6 **Explain** how guard cells operate during the day and night by drawing an annotated diagram.
- 7 **Discuss** how the number and location of stomata in the leaf could be used to infer the plant's natural environment.

6.3 Plant transport systems

Most terrestrial plants need transport vessels to carry oxygen around the plant, store and deliver starch and bring water from the roots to the leaves. The structure of these vascular tissues is very different from the blood vessels of an animal. There are separate vessels for water and nutrients – the **xylem** and **phloem** respectively. There is also no pump system, and therefore movement in the vessels instead occurs because of two processes – passive diffusion and transpiration – which rely heavily on the external environment. **Figure 6.3.1** shows the locations of various tissues associated with transport in plant leaves.

xylem vascular tissue in plants, consisting of dead cells, responsible for the bulk transport of water and minerals

phloem vascular tissue in plants, consisting of living cells, responsible for the bulk transport of sugars

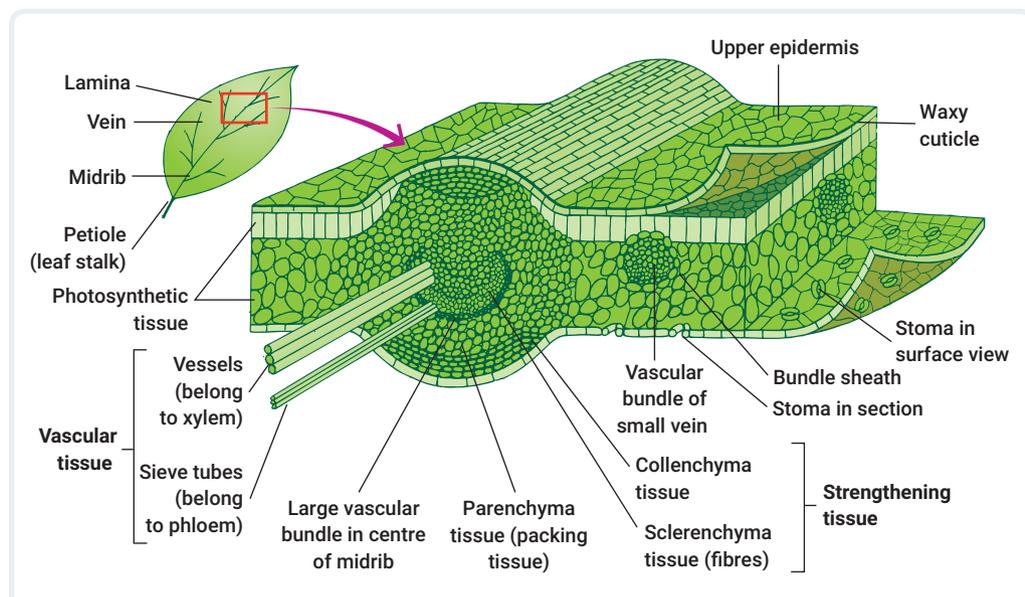


FIGURE 6.3.1 The structure of leaves includes many tissues involved in the transport of gases, water and nutrients.

Source: M Roberts, M Reiss and G Monger. Advanced Biology (Nelson Thomas, 2000)

Xylem structure and function

Xylem tissue is responsible for the transport of water, along with nutrients and minerals absorbed from the soil through the root system. All xylem cells are dead, hollow spaces supported by the remaining cell walls, which are ideally suited to the mass movement of water. There is not any living cytoplasm to be washed away by the flow of water, nor are there cell membranes to transport across. Xylem tissue also forms the woody part of many plant stems and trunks, so it serves a second purpose in providing the main support for large plants, such as trees. Depending on the type of plant, xylem tissue can be composed of two types of cells: **tracheids** and **vessel elements** (Figure 6.3.2).

Tracheids are present in all vascular plants and are formed when mature plant cells die, leaving only an interconnected stack of empty cell walls. Adjacent cell walls share gaps, called pits, that allowed nutrient exchange between the cells when they were alive. Now that the cells are dead, these pits allow water to move from space to space as it is drawn up the plant. Tracheids do not require particular effort from the plant to form, but their haphazard arrangement and small pits mean that water flow is particularly inefficient.

Vessel elements, on the other hand, are highly specialised and organised in a way that is specific to their function. Flowering plants developed these structures so that they would not have to rely on randomly dying cells for water transport. In flowering plants, cells in the vascular bundles differentiate into vessel elements, which are specialised tubular cells that align with each other. These break down their neighbouring cell walls before they die. Thus, vessel elements are still empty cell wall spaces, but they form straight 'straws' that are extremely efficient at moving water.

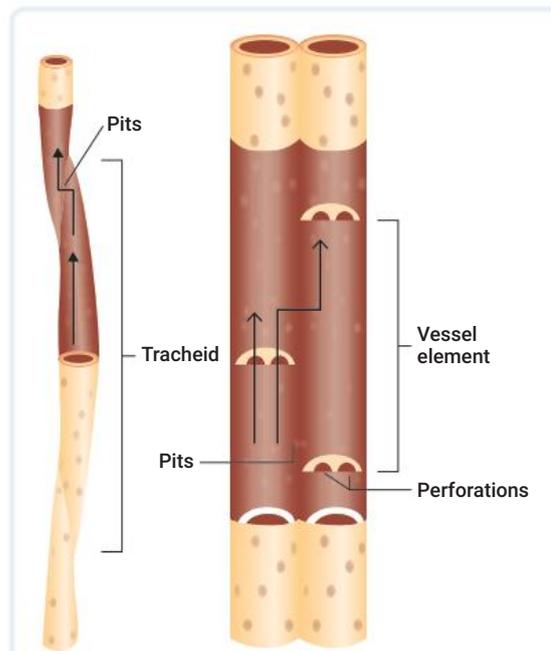


FIGURE 6.3.2 Vessel elements are a more advanced and efficient method of water transport than tracheids. In tracheids, water moves only through gaps in the dead cell wall, called pits. In vessel elements, water moves through specialised perforations as well as pits.

Phloem structure and function

Unlike xylem tissue, phloem tissue is composed of thin-walled, living cells that transport sugars and other plant products. While xylem is unidirectional, from roots to leaves, phloem tissue is multi-directional, transporting nutrients between all areas of the plant. There are two types of phloem cells: **sieve tube cells** and **companion cells** (Figure 6.3.3).

Sieve tube cells, also called sieve tube elements, are different from normal plant cells. They are aligned end to end, forming long sieve tubes, which facilitates an efficient stream for transport. The cell walls between adjacent cells are called **sieve plates**. This is because the large pores resemble a sieve (similar to the perforations in vessel elements in the xylem). Unlike in the xylem, the sugars and other substances transported in the phloem require cytoplasm, so the sieve tube cells are alive and directly connected. Their cell membranes have fused through

tracheid a dead elongated cell that forms the xylem of all vascular plants

vessel element a dead cell that is perforated at each end and stacked vertically, forming the advanced xylem beside tracheids in flowering plants



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Xylem and phloem – transport in plants

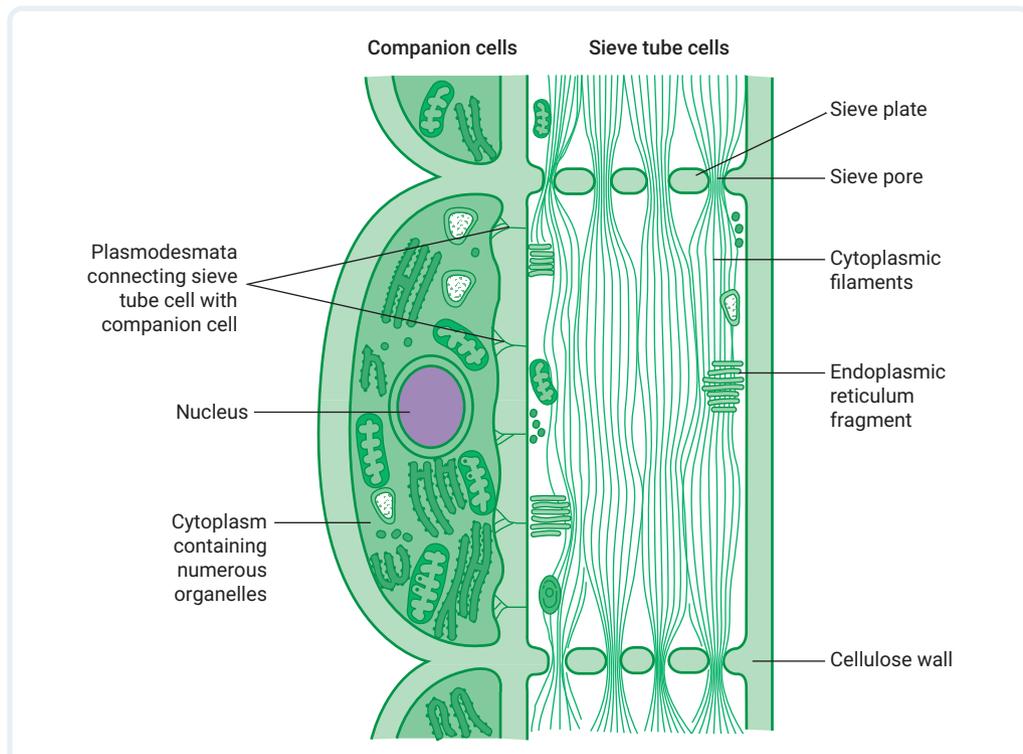
Worksheet

Transport systems in plants: phloem

sieve tube cell a long, tubular plant cell, without a nucleus, that forms sieve tubes, the main component of the phloem

companion cell a specialised plant cell in the phloem, which provides most of the cell functions for the sieve tube cell it is connected to

sieve plate the tough cellulose walls between sieve tube cells that contain pores to allow the cytoplasm to flow between cells



Adapted from Cowes, F. A. L. & Juniper, B. E. (1968) *Plant Cells*, Blackwell Scientific, Oxford.

FIGURE 6.3.3 Sieve tube cells are missing key organelles, such as a nucleus and vacuole, and would die and become useless without the companion cells acting as life support. Their cytoplasm flows directly into adjacent sieve tube cells, forming one long stream of cytoplasm.

the sieve plate, allowing the cytoplasm to flow directly between the cells. This is not an ideal situation for a living cell because its organelles would also be swept along in the cytoplasm flow. To avoid this and to create space to transport the sugar and nutrients, sieve tube cells have no nuclei, mitochondria or vacuoles. Instead, they are kept alive by companion cells, which provide essential life support through tiny channels in their shared cell wall, called plasmodesmata (singular: **plasmodesma**).

Companion cells are specialised life-support cells that connect to their sieve tube cell. Companion cells are dense with organelles and provide communication, enzymes, ATP, waste removal and other essential services to the sieve tube cells by sharing their cytoplasm through the plasmodesmata. These channels are so tiny to separate the strong flow of cytoplasm in the sieve tube from the relative calm of the companion cell's internal environment.

plasmodesma a tiny channel through a plant cell wall that allows communication and life support between companion cells and sieve tube cells

LEARNING CHECK 6.3

DESCRIBING

- 1 **Summarise** two ways plant transport systems are different from animal transport systems.
- 2 **Describe** the two types of cells in xylem tissue.
- 3 **Describe** the two types of cells in phloem tissue.
- 4 **Describe** the services that companion cells provide for their sieve tube cells.

APPLYING

- 5 **Explain** how it is possible for dead cells to perform useful functions.

6 **Figure 6.3.4** shows an example of ringbarking, a method of killing trees that removes a thin collar of bark from the trunk of a tree. In flowering trees such as this one, phloem tissue is in the bark and xylem tissue is in the wood. Use your knowledge of xylem and phloem to **explain** how ringbarking affects a tree.



FIGURE 6.3.4 Ringbarking causes a cruel and slow death for a tree.

Alamy Stock Photo/adrian davies



Weblink
Transport of water and sugar in plants animation

ANALYSING

7 **Compare** the structures and functions of the xylem and phloem tissues.

6.4 Transpiration

All plants require water. It is initially absorbed through the roots by **osmosis** and moves against the pull of gravity through the stem to the leaves. Plants lose water from their leaves through transpiration, the evaporation of water through the stomata (**Figure 6.4.1**). Some of these leaves can be more than 100 metres above the ground and the process that draws water that far up the tree without the support of a pump is called the **transpiration stream**.

osmosis the movement of water across a selectively permeable membrane from a region of low solute concentration to a region of high solute concentration

transpiration stream a continuous column of water inside xylem tissue that moves up the stem of a plant

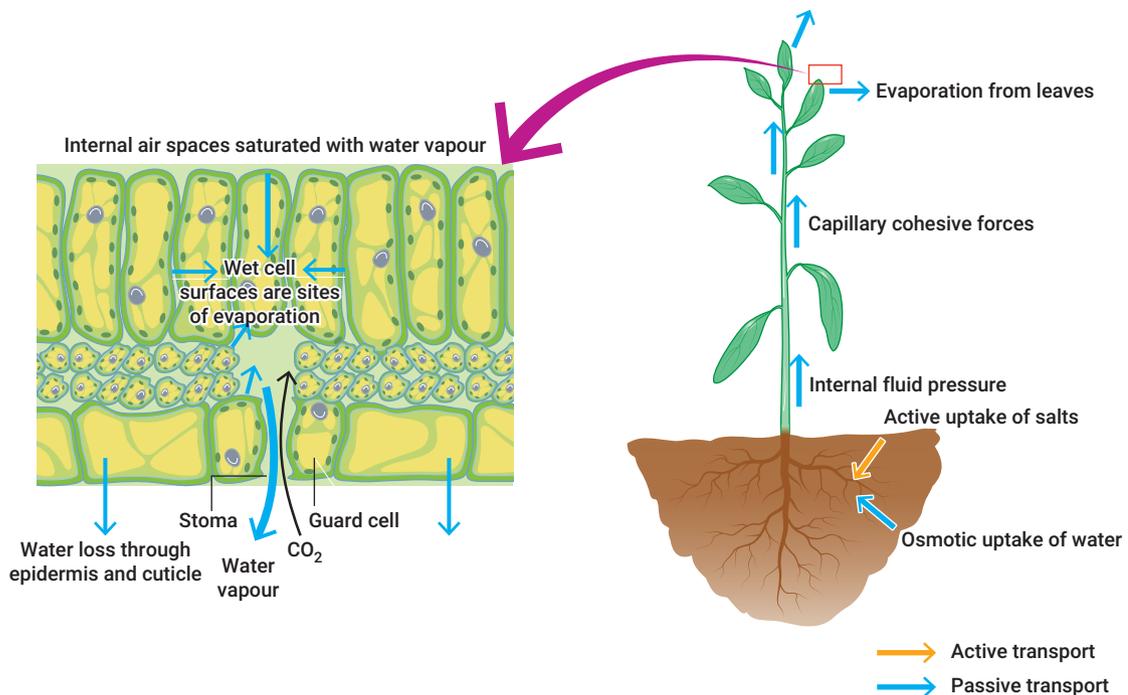


FIGURE 6.4.1 The process of transpiration in plants is largely driven by the Sun. Transpirational pull results from pressure in the roots, adhesion and cohesion of water in the xylem vessels, and evaporation from the stomata of leaves.

Factors affecting the rate of transpiration

When a plant loses more water through transpiration than it takes up through its roots, it wilts and suffers from water stress. Conversely, if a plant cannot lose enough water through transpiration, the transpiration stream stops and water is not taken up from the soil, leading to waterlogging and suffocating of the root system. Therefore, the rate of transpiration must be maintained at an optimal level to keep the transpiration stream flowing without resulting in water stress. This is also why it is important to consider changes in transpiration rate when watering indoor plants.

Several factors affect the rate of transpiration, including factors that affect the evaporation of water from leaves, such as temperature, humidity and wind, and factors that increase photosynthetic use of water, such as strong sunlight.

- High temperatures increase the evaporation of water molecules in the top of the xylem whereas lower temperatures decrease it.
- Humidity refers to the amount of water vapour in the air. Low humidity (dry air) increases the evaporation of water into vapour, whereas high humidity (damp air) increases the condensation of water vapour into liquid form.
- Wind physically disrupts the cohesive bonds between water molecules and increases the evaporation of water into vapour, whereas calm air reduces this effect.
- Sunlight drives photosynthesis, so strong sunlight promotes the use of water from the top of the xylem vessels for this process. Similarly to evaporation, photosynthesis is also a driver of the transpiration stream.

Adaptations to manage the rate of transpiration

Plants in hot, dry places with strong winds or sunlight are called **xerophytes**, and tend to evolve extra structural and homeostatic protection against excessive water loss through transpiration. For example, some plants have thick waxy leaves and minimal stomata. The leaves of other plants have become rolled or fuzzy (due to small hairs) to reduce the effects of wind (**Figure 6.4.2**), or modified entirely to spines so the stem conducts photosynthesis. The category of xerophytes called **succulents** have a modified homeostatic mechanism where they maintain their vacuoles at around 90 per cent of cell volume rather than the usual 70–80 per cent. By increasing the volume of water each cell stores, succulents can take advantage of short periods of rain to survive long periods of drought.

Plants in warm, wet places without strong winds or sunlight, such as in the lower canopy of a rainforest, have evolved adaptations that increase the rate of transpiration. These can include large, broad leaves to increase photosynthetic use of water, and dense stomata or extremely lobed leaves to maximise airflow through them.

Plants in cold places tend to evolve differently to produce tiny or highly modified leaves that reduce exposure to the cold rather than to increase the transpiration stream. Plants in cold places do not tend to increase their transpiration stream because this could lead to water stress during winter when the water in the soil is frozen and, therefore, unavailable.

xerophyte a plant adapted to dry conditions

succulent a plant with thick, fleshy leaves and stems that stores more water in its cell vacuoles than usual



Weblink

How plants prevent water loss

Worksheet

Plant systems

Gerd Guenther/Science Photo Library



FIGURE 6.4.2 Stomata occur in the furrows on the inner side of a marram grass leaf (*Ammophila arenaria*) to conserve water. Hairs help to hold in water vapour. The outer side of the leaf has a thick cuticle and lacks stomata.

PRACTICAL ACTIVITY 6.4.1

FACTORS THAT AFFECT TRANSPIRATION

Introduction

The rate of transpiration in a plant depends on two mechanisms: the rate of evaporation of water from the stomata of leaves and the rate of photosynthesis using water in the leaves. To distinguish between these two mechanisms, plant cuttings can be left to transpire under different evaporative and photosynthetic conditions.

Research question

How do light, wind and humidity (independent variables) affect the mass (g) and volume (mL) of water lost (independent variable) as a measure of transpiration?

Aim

To compare the effect of evaporative and photosynthetic conditions on the rate of transpiration

Materials

- plant cuttings with stems about 8 cm long and leaves at the top – plants with adaptations to increase transpiration (broad, soft leaves with dense stomata) will work best
- beaker of tap water
- cooking oil
- measuring cylinders (10 or 25 mL)
- 2 teat pipettes, one for oil and one for water
- scissors
- sticky tape
- trays to contain the experiment while it runs
- marker pen
- electronic balance, sensitive to at least ± 0.01 g



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Plant cuttings and sap can irritate the skin.	Choose plants with clear sap. Avoid contact with skin and eyes. If irritation occurs, rinse the affected area immediately with plenty of water and report any incidents to your teacher. Eyewash facilities and equipment should be readily available.
The experiment requires extended time to complete.	Take care to arrange the experiment equipment in a safe place, away from potential spills and other classes of students.

Procedure

- 1 Put approximately 5 cm³ water in a measuring cylinder.
- 2 Place one plant cutting in the measuring cylinder.
- 3 Use a teat pipette to adjust the water level to an exact level (e.g. 8 cm³).
- 4 Make a note of the date, time and initial volume of water.
- 5 Use the second pipette to add about 1 cm³ of oil to the measuring cylinder so that the oil sits on top of the water. Try not to get oil on the leaves. Do not remove the cutting to add the oil.
- 6 Place the apparatus on the balance and record the initial mass (**Figure 6.4.3**).
- 7 Tape the measuring cylinder to the tray so that it remains safely upright.
- 8 Repeat steps 1–7 for each cutting to be used in the experiment.

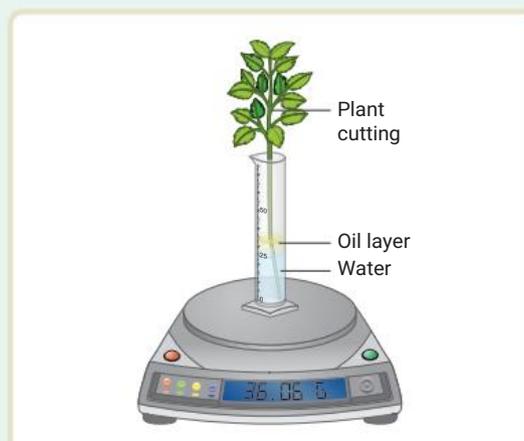


FIGURE 6.4.3 The experimental set-up of a plant cutting in a measuring cylinder of water with an oil layer. The mass of the entire set-up can provide information on the rate of water use by the cutting.

9 Place pairs of cuttings under the following conditions.

Condition	Light	Wind	Temperature	Humidity
Effect of light	Full/reduced	Room	Room	Room
Effect of wind	Full	Room/fan	Room	Room
Effect of humidity	Full	Room	Room	Room/high

For full light, place the cutting near a window. For reduced light, place the cutting under a bench. For the fan condition, place the cutting in front of a fan and for the room condition place the cutting away from fans. For high humidity, spray the leaves with water and enclose them in very clear plastic, such as cling wrap.

10 Record the changes in mass and volume after 24–48 hours.

Results

- 1 Draw up a table to record the results of the investigation.
- 2 Calculate the change in mass for each condition. If the class was able to conduct multiple trials, calculate the average change in mass for each condition.
- 3 Calculate the change in volume for each condition. If the class was able to conduct multiple trials, calculate the average change in volume for each condition.
- 4 Construct a graph that shows the change in mass. Construct another graph that shows the change in volume. Ensure an appropriate style of graph is selected.
- 5 Identify any trends, patterns and/or relationships in the data.

Interpretation

- 1 Describe what the layer of oil does in this investigation.
- 2 Calculate the effect of light on the rate of transpiration and explain why this is so.
- 3 Calculate the effect of wind on the rate of transpiration and explain why this is so.
- 4 Calculate the effect of humidity on the rate of transpiration and explain why this is so.

Evaluation

- 5 Compare the water loss and mass loss results.
- 6 Explain whether water or mass was a more valid source of evidence for transpiration.
- 7 Describe two changes to this method that would produce more reliable results.

LEARNING CHECK 6.4

DESCRIBING

- 1 **Identify** the process that draws water up a plant.
- 2 **Identify** four factors that affect the transpiration rate in plants.
- 3 **Describe** an environment that would decrease the rate of transpiration in plants.
- 4 **Describe** the structure and function of a cuticle.



APPLYING

- 5 **Explain** how surrounding the epidermis with fine hairs reduces water loss.
- 6 **Explain** one adaptation of a plant to cold, dry conditions.
- 7 **Explain** where the energy for transpiration originates.

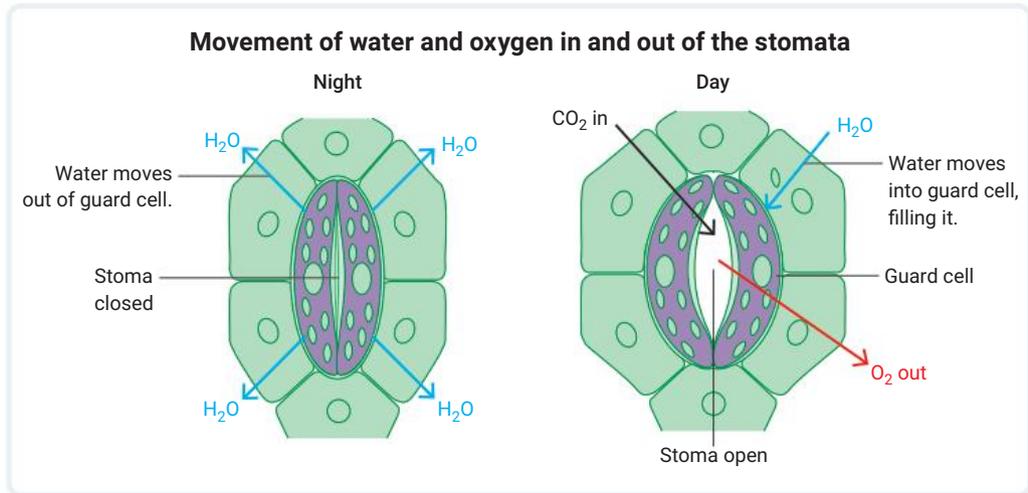
INTERPRETING

- 8 A student puts a stick of celery in a vase of coloured water. Over the next few hours, the leaves on top of the stick become coloured. **Deduce** whether this is sufficient information to determine if the celery was living or dead.

CHAPTER SUMMARY

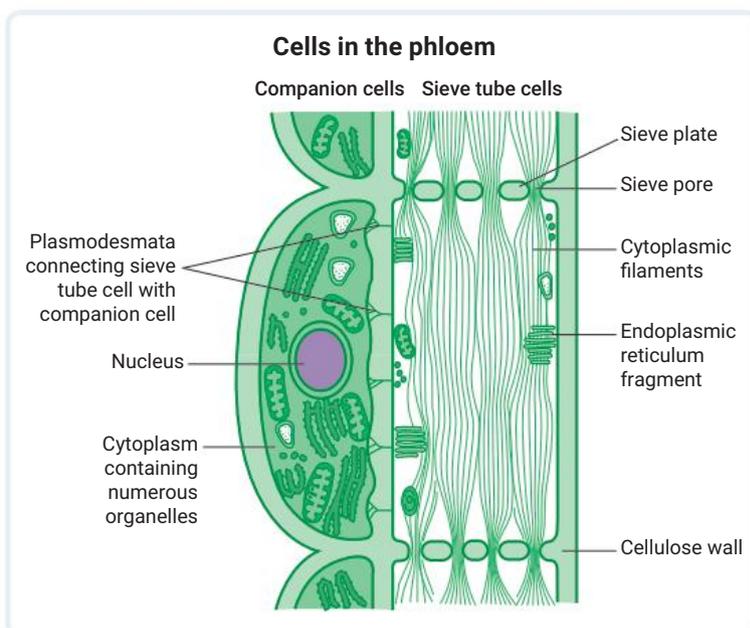
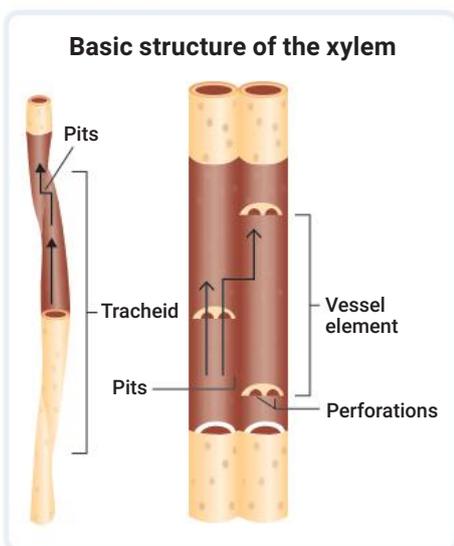
Gas exchange in plants

- Stomata control the passage of air through the leaf.
- At night and at times of low humidity, water leaves the guard cells and the stomata close, sealing the leaf off from the outside.
- During the day and at times of high humidity, water enters the guard cells and the stomata open, allowing gases to enter and leave.

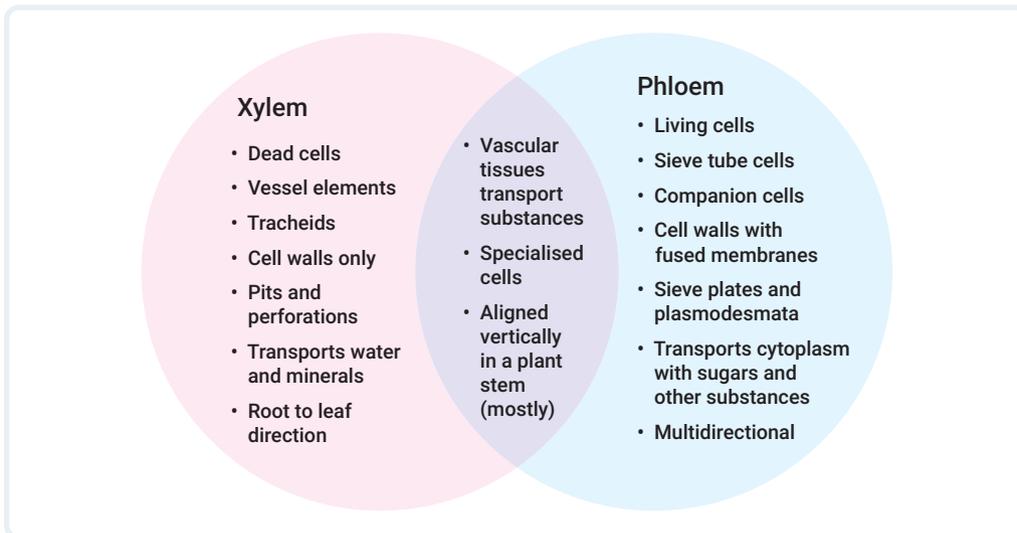


Structure and function of xylem and phloem

- The xylem helps transport water, nutrients and minerals absorbed from soil through the roots.
- The phloem is multidirectional and allows for transport of nutrients between all areas of the plant.

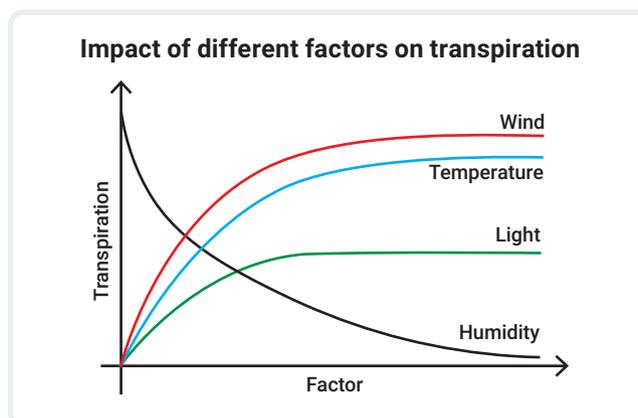


Adapted from Cowes, F. A. L. & Juniper, B. E. (1968) Plant Cells, Blackwell Scientific, Oxford.



Factors that affect transpiration

- Factors that affect transpiration include:
 - wind
 - temperature
 - light
 - humidity.
- Plant adaptations to minimise water loss through transpiration include:
 - thick waxy cuticle on the leaf surface
 - fewer, smaller stomata generally located on the underside of leaves
 - reduced airflow over stomata, including sunken stomata pits or fine hairs on the epidermis
 - rolled leaves, fewer leaves or highly modified leaves like spines or needles
 - increased water storage in the vacuoles of cells.

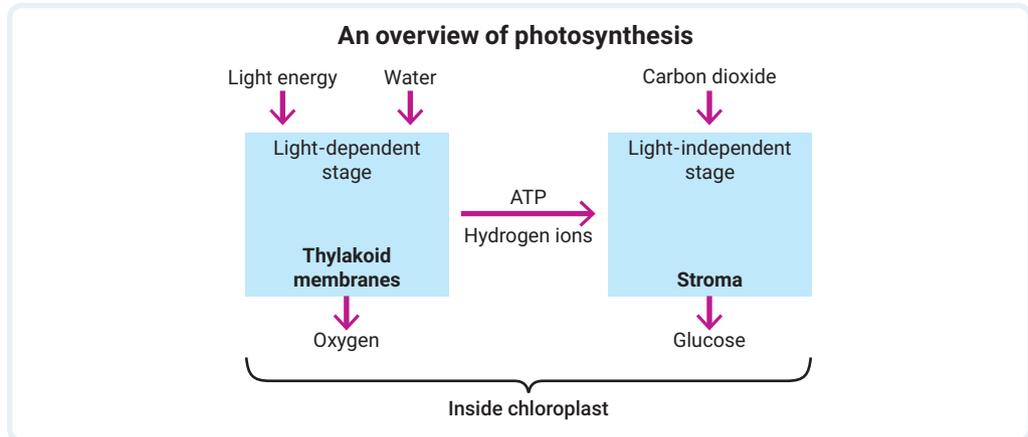


Photosynthesis

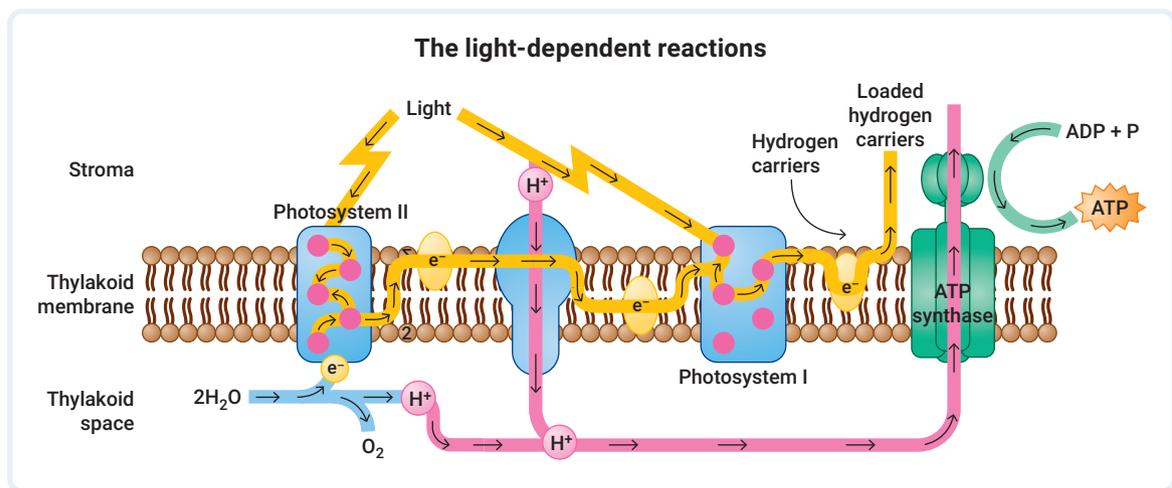
- Overall photosynthetic reaction:

Word equation: carbon dioxide + water $\xrightarrow{\text{light energy}}$ glucose + oxygen

Balanced chemical equation: $6\text{CO}_2 + 6\text{H}_2\text{O} \xrightarrow{\text{light energy}} \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$



Light-dependent reactions



Light-independent reactions

- Light-independent reactions of photosynthesis, also known as the Calvin cycle, produce glucose; however, this is not a long-term energy storage solution.
- These reactions require ATP and produce two 3-carbon molecules that are turned into glucose.

MULTIPLE CHOICE

1. Plants harvest light energy using a molecule called:
 - A chlorine.
 - B chloroform.
 - C chloroplast.
 - D chlorophyll.
2. During photosynthesis, ATP is produced in the:
 - A Calvin cycle.
 - B Krebs cycle.
 - C light-dependent reactions.
 - D light-independent reactions.
3. To produce one glucose molecule, the Calvin cycle must be completed:
 - A once.
 - B twice.
 - C four times.
 - D six times.
4. In wet conditions, guard cells:
 - A swell and open.
 - B swell and close.
 - C relax and open.
 - D relax and close.
5. Xylem tissue is composed of:
 - A companion cells and tracheids.
 - B vessel elements and tracheids.
 - C vessel elements and sieve tube cells.
 - D sieve tube cells and companion cells.
6. Phloem tissue is composed of:
 - A companion cells and tracheids.
 - B vessel elements and tracheids.
 - C vessel elements and sieve tube cells.
 - D sieve tube cells and companion cells.
7. Water is transported in:
 - A one direction in the phloem.
 - B one direction in the xylem.
 - C all directions in the phloem.
 - D all directions in the xylem.
8. Companion cells:
 - A help to construct vessel elements.
 - B provide life support to sieve tube cells.
 - C store sugars produced by photosynthesis.
 - D allow water to pass into the xylem.
9. Which of the following factors has an inverse relationship with transpiration rate?
 - A Temperature
 - B Humidity
 - C Wind
 - D Light

10. A plant growing in a desert environment is likely to have:

- A leaves that are large and thin.
- B stomata located in sunken pits.
- C stomata mostly on the upperside of the leaf.
- D a waxy cuticle mostly on the underside of the leaf.

SHORT RESPONSE

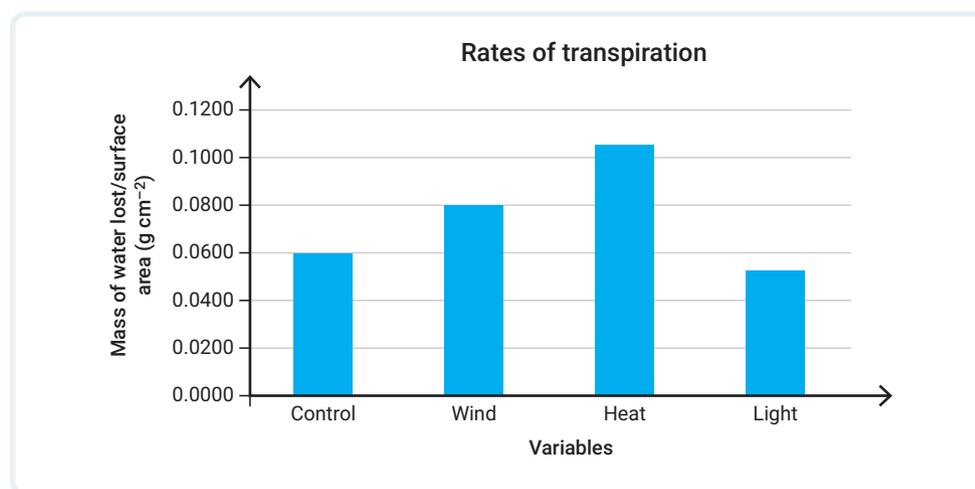
11. **Explain** how stomata and guard cells facilitate both gas exchange and water balance in plants.
12. **Describe** the process of photosynthesis, including the light-dependent and light-independent reactions.

CROSS-CHAPTER QUESTION

13. In order to grow, plants need to photosynthesise more than they respire. **Explain** how more photosynthesis than respiration would affect the transpiration stream of a plant.

DATA ANALYSIS

Questions 14 and 15 refer to the following graph.



14. **Apply understanding**

Calculate the mass of water a plant would lose in hot conditions if the leaf surface area is 15 cm².

15. **Analyse evidence**

Sequence the conditions from most to least impact on rate of water loss.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- Appreciate how scientists use their understanding of natural systems to develop new technologies.

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Solar power from plants

At the University of Maryland, USA, Lahari Saha and her colleagues are attempting to do what was once thought impossible – use photosynthesis to generate useable electricity. The premise is both simple and terrifyingly complex – if plants can do it, so can we.

Photosynthesis operates in two stages: the light-dependent reactions and light-independent reactions. The light-dependent reactions begin when the energy in sunlight excites the electrons of the molecule chlorophyll. These electrons bounce between molecules in their photosystem before travelling down the thylakoid membrane, driving pump proteins to shuttle hydrogens into the thylakoid space. However, it is not the hydrogen flow that has researchers excited; it is the electron flow. Flowing electrons is electricity and if those electrons could be coaxed to flow down a wire instead of down a thylakoid membrane, it could be harnessed for human use (Figure 1).

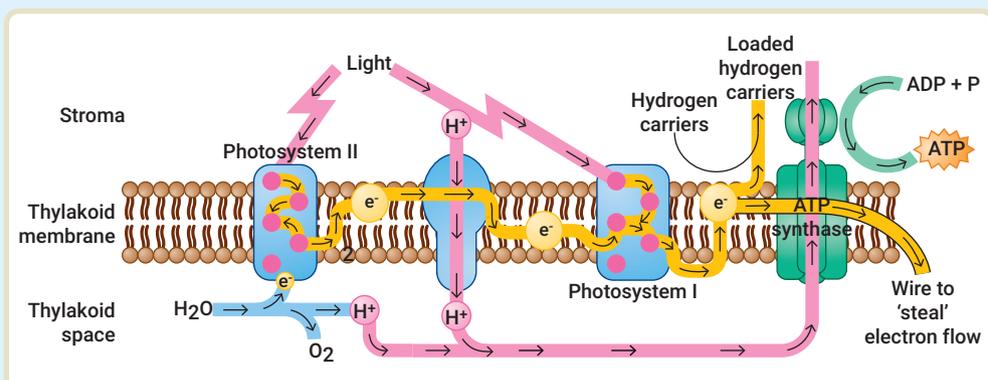


FIGURE 1 Using photosynthesis to generate useable electricity

Saha hopes to coax the electrons into a wire, using metal nanoparticles in a technique called fluorophore-induced plasmonic current. In this technique, a liquid containing the fluorophores (molecules that absorb and transmit light, similar to chlorophyll) flows over a thin film of plasma. Saha's most recent research has focused on determining the optimal concentration of fluorophores to use in the liquid, so that a strong and stable electrical current is produced.

Saha is thrilled to have presented her work at the 2023 Annual Biophysical Society Meeting in California, but notes that there are considerable challenges remaining before plant-based solar panels are commercially viable. For example, chlorophyll is extremely fragile when exposed to heat, chemicals or moisture, which makes it very difficult to stabilise outside of a laboratory environment. By itself, chlorophyll is also relatively inefficient, with plants harnessing multiple different fluorophores that absorb different wavelengths of light.

Work is underway on synthetic fluorophores that are more efficient and more stable in outside environments, but for the moment, at least, Saha's work takes us one step closer to harnessing the power of photosynthesis.

References

Saha, L., & Geddes, C.D. (2024) Enhancing fluorophore-induced plasmonic current for converting solar energy, *Biophysical Journal*, 123(3). <https://doi.org/10.1016/j.bpj.2022.11.2447>



Weblink
New insights into
photosynthesis-based
electricity generation

UNIT

2

Maintaining the internal environment



Alex Ford-Robertson/peopleimages.com/
Adobe Stock Photos

Topic 1: Homeostasis – thermoregulation and osmoregulation

CHAPTERS RELATED TO THIS TOPIC AREA: 6–9

Topic 2: Infectious disease and epidemiology

CHAPTERS RELATED TO THIS TOPIC AREA: 10–12

Organisms live in a variety of environments that include many different factors that affect their survival. Organisms use different strategies to keep their internal environments stable and to ensure that their bodies function at maximum efficiency. Plants and animals must balance their heat and water gains and losses, and fight off infection. The solutions to these challenges are achieved through adaptations. Like all organisms, humans are affected when internal conditions are not optimal. This unit examines the strategies humans employ to protect against changing conditions.

UNIT OBJECTIVES

By the end of this unit, students should be able to:

1. describe ideas and findings about homeostasis, thermoregulation and osmoregulation, infectious disease and epidemiology
2. apply understanding of homeostasis, thermoregulation and osmoregulation, infectious disease and epidemiology
3. analyse data about homeostasis, thermoregulation and osmoregulation, infectious disease and transmission and epidemiology
4. interpret evidence about homeostasis, thermoregulation and osmoregulation, infectious disease and epidemiology
5. evaluate processes, claims and conclusions about homeostasis, thermoregulation and osmoregulation, infectious disease and epidemiology
6. investigate phenomena associated with homeostasis, thermoregulation and osmoregulation, infectious disease and epidemiology.

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CHAPTER
7

Nervous system



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**SYLLABUS
DOT POINTS**

SCIENCE UNDERSTANDING

- Identify the different types of sensory receptors and their stimuli, including chemoreceptors, thermoreceptors, mechanoreceptors, photoreceptors and nociceptors.
- Describe the structure and function of nerve cells, including dendrites, soma, body, axon, myelin sheath, nodes of Ranvier, axon terminal and synapse.
- Distinguish between sensory neurons, interneurons and motor neurons.
- Explain the passage of a nerve impulse in terms of transmission of an action potential and synaptic transmission, referring to neurotransmitters, receptors, synaptic cleft, vesicles, postsynaptic and presynaptic neurons and signal transduction.

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Introduction

The brain alone contains one trillion neurons that are connected to each other and to the peripheral nerves to form circuits. The peripheral nerves pick up messages and transmit them to the central nervous system (CNS) for processing. They also deliver messages to muscles lining glands, skeletal muscles, hairs and ducts in a response coordinated by the CNS. To function within this circuit, a neuron must receive, process and relay signals to the correct neurons, while blocking transmission along incorrect pathways.

Practical

- Chicken nerve dissection

Worksheets

- Neuron structure and function
- Nerve impulses

 Nelson MindTap

To access resources above, visit
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stimulus an internal or external signal that causes a response

sensory receptor an organ or a structure that detects or receives a stimulus

chemoreceptor a receptor that detects a chemical stimulus such as blood glucose concentration and pH

mechanoreceptor a receptor that detects a physical stimulus such as touch and sound vibration

photoreceptor a receptor that detects light energy

thermoreceptor a receptor that detects changes in temperature

nociceptor a receptor that detects only intense (painful) chemical, mechanical or thermal stimulation

homeostasis the maintenance of a relatively constant internal environment within small tolerance limits, despite changes in the external environment

exteroceptor a receptor that specifically receives signals from outside the body, such as air temperature, painful pressure or odours

interoceptor a receptor that specifically receives signals from inside the body, such as body temperature, oxygen concentration or pH

interstitial fluid extracellular tissue fluid; fluid in spaces surrounding cells

ASSUMED KNOWLEDGE

- ✓ A cell consists of different structures that carry out distinct functions, enabling the cell to function effectively.
- ✓ The levels of organisation of multicellular organisms go from systems to cells (macro to micro).
- ✓ The circulatory system is made up of different organs and tissues whose main function is to transport nutrients and waste products throughout the body.
- ✓ Homeostasis is the maintenance of a stable internal environment.
- ✓ The cell membrane regulates movement of substances into and out of the cell.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ recognise the different types of sensory receptors in the body
- ✓ identify the role of each sensory receptor
- ✓ identify the different structures in neurons
- ✓ describe the function of different structures in neurons
- ✓ differentiate between different types of neurons
- ✓ identify the function of each type of neuron
- ✓ explain how a nerve impulse is generated and propagated.

7.1 Sensory receptors

An organism and its cells receive many different types of **stimuli**. Fundamental to homeostasis is the detection of different stimuli by **sensory receptors**. This means receptors come in all shapes and sizes and are categorised by the type of stimulus they detect. Signals may come from the external environment, from other parts of the organism or from within the cell. Stimuli may be physical (e.g. light, heat and pressure) or chemical (e.g. hormones, glucose and neurotransmitters). There are millions of external and internal receptors that allow an organism to respond to stimuli. These receptors are grouped into five main categories based on the type of stimulation they detect: **chemoreceptors**, **mechanoreceptors**, **photoreceptors**, **thermoreceptors** and **nociceptors**.

Detection of external and internal signals

Homeostasis is the term used to describe the maintenance of a relatively constant internal environment. Homeostasis requires that organisms detect signals from their external and internal environments. **Exteroceptors** receive signals from the external environment. They can work as individual receptors or together as a group. They are either distributed evenly throughout the body (e.g. pain receptors across the surface of the skin) or concentrated in organs (e.g. the eye). Exteroceptors work by receiving outside information and converting it to a chemical or electrical signal that can then be relayed within the body either by the endocrine (Chapter 8) or nervous systems.

Interoceptors receive signals from within the body's internal environment, which is composed of the **interstitial fluid** that bathes the cells, and the blood plasma (**Figure 7.1.1**). Interoceptors help maintain the internal environment within narrow tolerance limits, allowing maximum cellular efficiency. **Table 7.1.1** lists some examples of exteroceptors and interoceptors in the body.

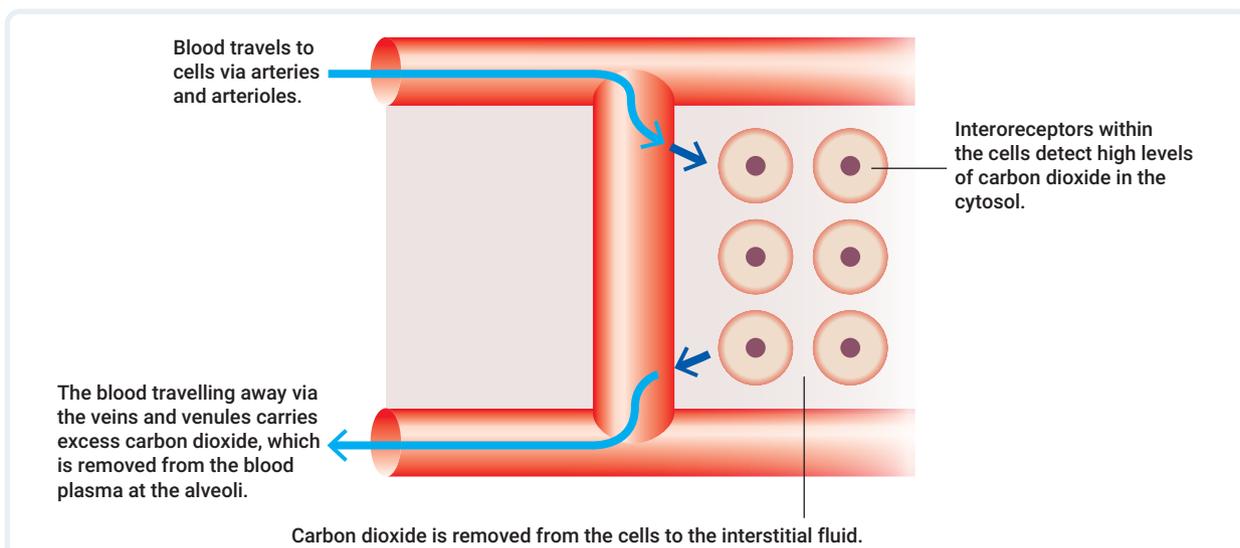


FIGURE 7.1.1 Interoceptors are vital to homeostasis because they monitor the internal environment. Interoceptors homeostatically monitor carbon dioxide, oxygen, pH and ion levels.

TABLE 7.1.1 Some examples of exteroceptors and interoceptors

Type of receptor	Type of stimulus	
	Exteroceptor stimuli	Interoceptor stimuli
Chemoreceptor	Smells and tastes in nose and mouth	Oxygen and ion levels in blood vessels
Mechanoreceptor	Pressure, touch, sound vibrations	Pressure, vibrations, balance
Photoreceptor	Light in the eyes and on the body surfaces of some invertebrates	None
Thermoreceptor	Air temperature on skin	Internal temperature in hypothalamus
Nociceptor	Painful heat, cold, pressure, light	Painful pressure, tension



Weblink
Sensory receptors

LEARNING CHECK 7.1

DESCRIBING

- 1 **Identify** the five main types of receptors and provide an example of each.
- 2 **Describe** what is meant by the 'internal environment' of an organism.
- 3 **Describe** the differences between exteroceptors and interoceptors.

APPLYING

- 4 For a pet dog, **identify** three signals that could be categorised as from its:
 - a external environment
 - b internal environment.
- 5 Nociceptors are a special category of receptor that detect pain. **Explain** why nociceptors evolved in multicellular organisms in addition to the four other types of receptors.

7.2 Cells that transport nerve impulses

The nervous system helps maintain homeostasis by detecting stimuli in either the internal or external environments using specialised receptors. Communication is sent to other systems via nerve cells or **neurons**. Effectors in other systems bring about responses that restore the body to optimum levels.

The nervous system consists of the central nervous system (CNS) and peripheral nervous system (PNS). The brain and the spinal cord form the CNS, which is responsible for processing, storing and coordinating information. All the other neurons in the nervous system form the PNS, which is responsible for transmitting information to and from the CNS.

Nerve impulses travel along defined pathways. From the source of stimulation, nerve impulses travel along the **sensory neurons** to the CNS. From the sensory neurons, the electrical impulses are relayed to interconnecting neurons (**interneurons**) in the CNS to the appropriate **motor neurons**. From the CNS, motor neurons relay the signal to the effectors (muscles or glands) (**Figure 7.2.1**).

neuron a nerve cell that transmits electrical impulses in the body

sensory neuron a cell that transmits nerve impulses from the receptor to the central nervous system

interneuron a cell that transmits nerve impulses within the central nervous system, between sensory and motor neurons

motor neuron a cell that transmits nerve impulses from the central nervous system to the effector

soma the main cell body of a neuron containing the nucleus

dendrite a fine, thread-like extension of the neuron that converts external signals to nerve impulses within the neuron

axon the tubular extension of a neuron soma that conducts the nerve impulse

myelin sheath the fatty layers of insulation surrounding the axon of a neuron; made of Schwann cells

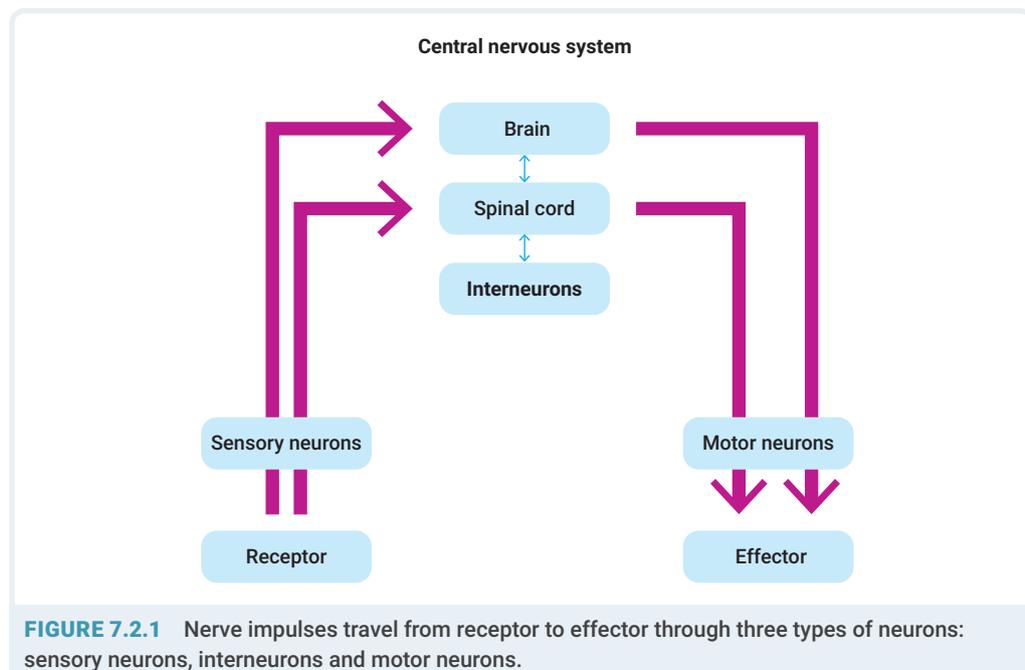


FIGURE 7.2.1 Nerve impulses travel from receptor to effector through three types of neurons: sensory neurons, interneurons and motor neurons.

Neuron structure

Neurons are the basic cellular units of the nervous system. Billions of neurons are interconnected and communicate with each other by electrical and chemical means. There are different types of neurons; however, there are general features common to all neurons (**Figure 7.2.2**).

Each neuron has a **soma**, the main cell body that contains the nucleus. At one end of the neuron, there can be up to 10000 protrusions known as **dendrites**. Dendrites receive information from adjoining neurons, so the more dendrites a neuron has, the more information it can receive. At the other end, a single **axon** protrudes. The axon is the long, thin extension of the soma that gives neurons their characteristic elongated shape. Axons are wrapped in a protective fatty layer called the **myelin sheath**.

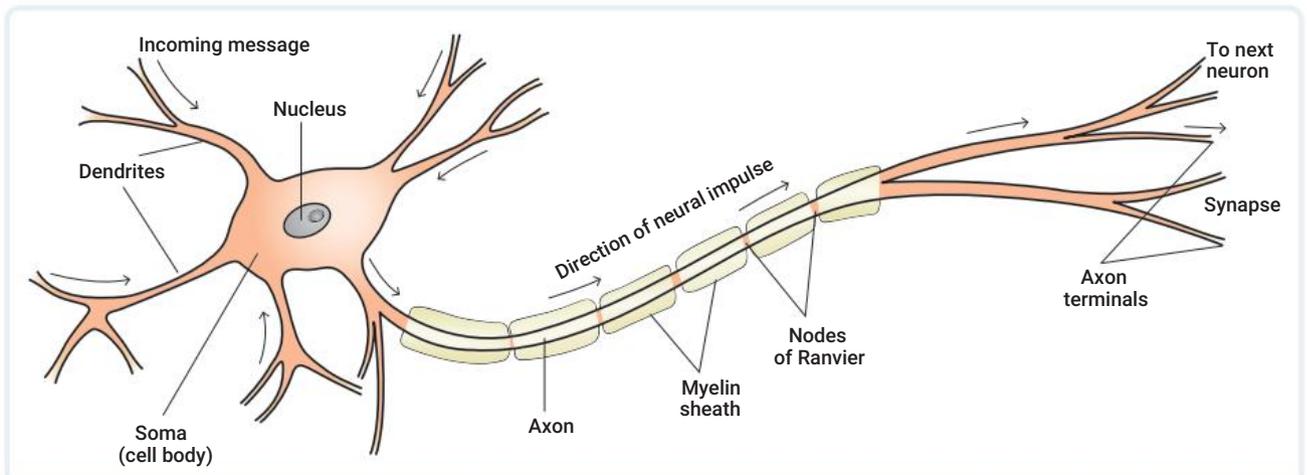


FIGURE 7.2.2 A typical neuron showing all its component parts

Together, the axon and the myelin sheath make up a nerve fibre. A bundle of nerve fibres comprises a nerve and each nerve is wrapped in a tube of connective tissue (**Figure 7.2.3**).

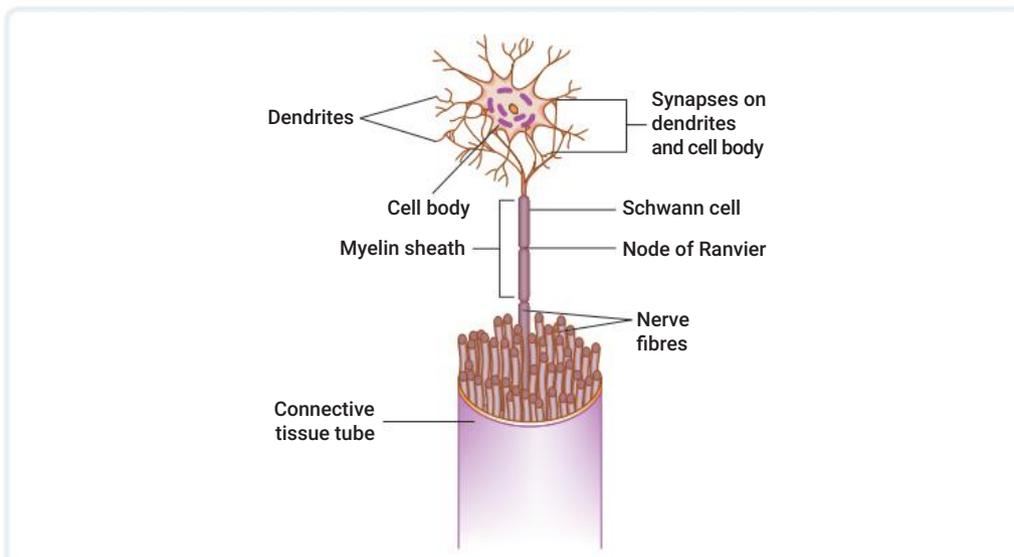


FIGURE 7.2.3 Generally, nerves are bundles of nerve fibres, and each fibre is the myelin-wrapped axon of a neuron.

The myelin sheath is made of thin **Schwann cells** that wrap tightly around the axon (**Figure 7.2.4**), leaving small sections of bare axon in between the next Schwann cell of the myelin sheath. These bare sections are known as **nodes of Ranvier**, after the French physician who discovered them. The Schwann cells making up the entire myelin sheath act as a fatty layer of insulation around the axon, allowing an electrical impulse to jump from node to node. This arrangement allows the electrical impulse to travel faster along the length of the nerve. The myelin sheath also keeps the message from accidentally crossing over to adjacent neurons. Damage to the myelin sheath hinders the transmission of the nerve impulse and is the cause of multiple sclerosis and other debilitating neurodegenerative conditions.

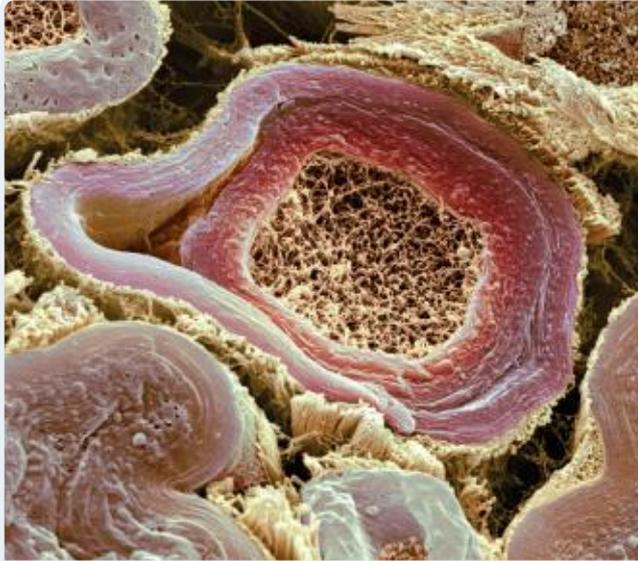


Weblink
Parts of a neuron

Worksheet
Neuron structure and function

Schwann cell a cell that wraps tightly around the axon of a neuron to form the myelin sheath

node of Ranvier a small space between the Schwann cells along the axon of a neuron



Steve Gschmeissner/Science Photo Library

FIGURE 7.2.4 The thick insulation around a neuron is made from a single Schwann cell, wrapped thousands of times around the axon so tightly you can barely see the layers.

LEARNING CHECK 7.2

DESCRIBING

- 1 State a definition for:
 - a soma
 - b axon
 - c myelin sheath
 - d Schwann cell
 - e nodes of Ranvier.
- 2 **Describe** the direction of neural impulse within a neuron.
- 3 **Describe** the differences between neurons, nerve fibres and nerves.
- 4 **Describe** some of the key features that differentiate neurons from other cells in the body.
- 5 **Create** a labelled diagram of a general neuron structure.

APPLYING

- 6 **Explain** how the myelin sheath is formed and outline its function.

INTERPRETING

- 7 **Predict** one consequence of a lack of myelin in the nervous system.

7.3 Different types of neurons

There are three kinds of neurons: sensory, motor and interconnecting (interneuron). The structure of neurons is directly related to their function (**Figure 7.3.1**).

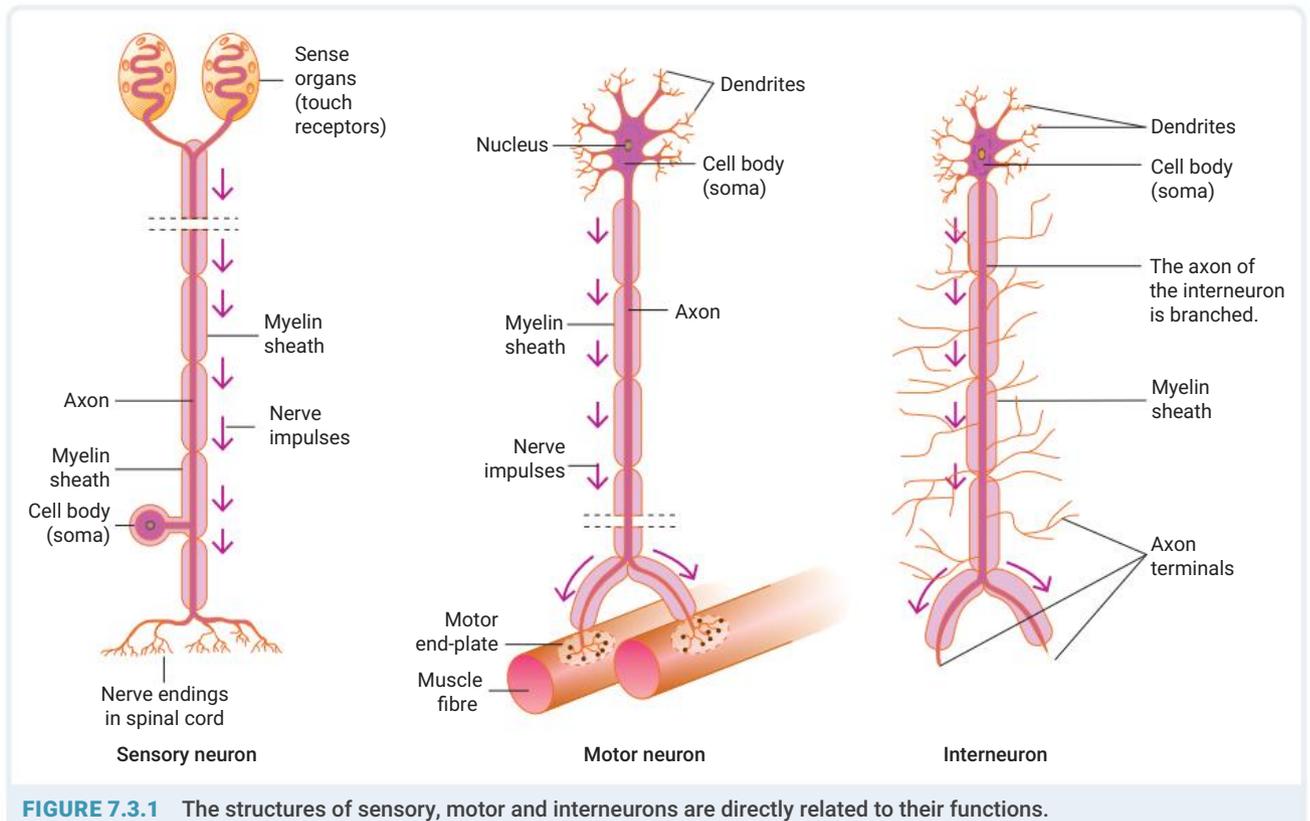


FIGURE 7.3.1 The structures of sensory, motor and interneurons are directly related to their functions.

Sensory neurons

Sensory neurons are the nerve cells that detect specific internal and external stimuli. For example, sensory neurons in the ear only respond to sound waves; sensory neurons in the eye only respond to light waves. Once stimulated by their specific form of energy, they transmit impulses towards the CNS.

At the dendritic end, dendrites house the sensory receptors that detect stimuli, while at the terminal end, dozens of nerve endings link with interneurons in the spinal cord or brain.

The soma is usually located as a side bulge somewhere along the length of the axon. Although the soma of the sensory neuron is only 0.1 mm in diameter, the axon can be as long as 1.5 metres in adults, such as those reaching from the receptors in the soles of the feet to the axon terminals in the lower spinal cord.

Sensory neurons often have multiple receptors on the dendritic end that can send signals individually for finely tuned detection (such as when reading braille) or send signals as a group for large-scale sensation (such as the feeling of wearing clothes). These neurons are responsible for feeding every piece of information about both the internal and external environments to the brain and spinal cord, making them vital to successful homeostasis.

Interneurons

Interneurons, or interconnecting neurons, are the nerve cells that combine into neural circuits to make decisions and conduct what we know as 'thinking'. They are primarily located in the brain and spinal cord and make up the vast majority of neurons in the CNS. Their ability to connect with many other neurons sets them apart from the sensory and motor neuron categories. Of the three categories, only interneurons can form the complex webs required for memory, thought and emotion.

Interneurons perform two functions in the nervous system.

- They receive sensory information from the sensory neurons and send response information to the motor neurons. By connecting to the other two types of neurons, interneurons can detect the environment and control the body.
- They process the information received by sending the impulse through a convoluted series of interneurons that result in the appropriate response signal. Neuroscientists are still trying to understand how different pathways produce different outcomes.

In order for interneurons to connect with many other neurons, they need to have many terminals off their axon and many dendrites off their soma. As shown in **Figure 7.3.2**, the soma is located in the middle of this sea of fine threads, all of which connect to a new neuron.



Science Photo Library/CNRI

FIGURE 7.3.2 Interneurons in the brain connect with each other in vast and complex webs.

Motor neurons

Motor neurons are the nerve cells that transmit impulses away from the CNS to effectors such as muscles or glands to trigger responses. The dendrites receive signals from the interneurons of the CNS and pass them through the cell body and down the axon. However, the axon terminals of motor neurons are slightly different depending on the effector they are linked to. When linked to muscles, the axon terminates in a structure called an end plate – a multi-pronged series of terminals directly on the muscle fibre (**Figure 7.3.3**). When linked to glands, the axon terminates within the gland structure.



Sergi Reboredo/Alamy Stock Photo

FIGURE 7.3.3 When motor neurons are linked to muscles, they terminate at end plates lodged deep in the muscle fibre.

Distinguishing between sensory and motor neurons

Although very similar, sensory and motor neurons have four key differences in their structure and function: the soma, dendritic terminals, axon terminals and the direction of the impulse.

TABLE 7.3.1 An overview of the structures of sensory and motor neurons

Structure	Sensory neuron	Motor neuron
Soma – contains nucleus and other organelles	Located as a bulge along the axon (possibly related to signal speed)	Located at dendritic end. Axon and dendrites branch directly off it.
Dendritic terminals	Dendrites branch off one end of the axon (not the soma) and terminate as sensory receptors to detect stimuli.	Soma branches into fine thread-like extensions that terminate at synapses with interneurons.
Axon terminals (opposite end to the dendritic terminals)	Terminates in synapses that link with interneurons.	Terminates in structures called end plates that interface with the muscle or gland directly
Impulses for both travel from dendrite to axon terminals; direction in relation to the body differs	Towards CNS	Away from CNS



Weblink
Types of neurons

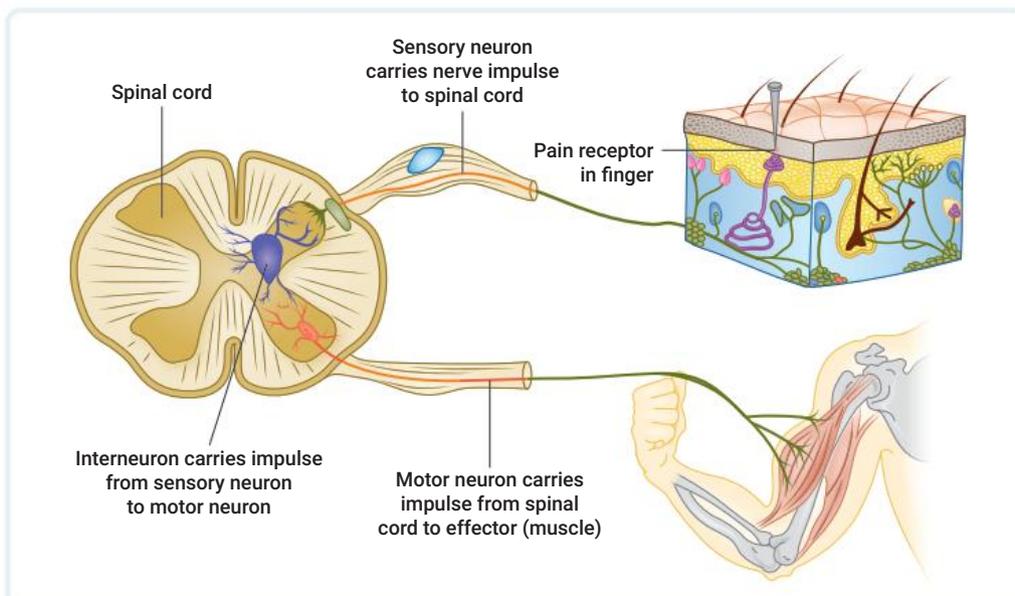


FIGURE 7.3.4 Sensory neurons detect changes in the internal and external environments. Interneurons connect sensory neurons to motor neurons. Motor neurons transmit messages directly to effectors.

LEARNING CHECK 7.3

DESCRIBING

- 1 **Identify** the three different types of neurons.
- 2 State the functions of each of the three different types of neurons.

APPLYING

- 3 **Explain** the likely outcome of damaging interneurons.

ANALYSING

- 4 **Compare** sensory neurons, interneurons and motor neurons.

7.4 Passage of a nerve impulse

Many stimuli can initiate a nerve impulse. Stimulation can come from an external receptor organ, certain chemicals or even physical stimulation, such as a pinch. In all cases, the message is initiated by the opening of ion channels in the cell membrane of the dendrites of the sensory neuron. This allows the movement of sodium (Na^+) and potassium (K^+) ions across the membrane. This influx of positive ions changes the net charge inside the neuron, starting a cascade of electrical activity down the axon.

Transmission within the neuron

Initially, the cell membrane of an axon is polarised (i.e. there is a potential difference in charge between the inside and the outside of the cell). This does not mean that one side is positive and the other is negative, although there are many diagrams that depict it as such. Instead, both sides are positive, but one is more positive than the other.

Resting potential

An axon that is at rest (not transmitting an impulse) is slightly positive on the inside and very positive on the outside. This is called the **resting potential**, when the outside is more positive. In this state, **sodium–potassium pumps** in the cell membrane actively pump three sodium ions out of the cell for every two potassium ions they pump into the cell. Consequently, there is an accumulation of sodium ions outside the cell and potassium ions inside. Although both sodium and potassium ions are equally positive, the ‘three out vs two in’ mechanism results in more positive ions outside than inside.

Action potential

When an impulse is triggered, the influx of positive ions causes the membrane to become permeable to sodium ions. Sodium ions are actively pumped outside the cell, and they are about 10 times more concentrated on the outside than the inside, so they diffuse in rapidly. Because the membrane is not permeable to potassium ions, most of them are trapped inside while the sodium continues to flood in. This leads to a large positive charge inside the cell and only a small positive charge outside. As this is the reverse of the resting potential polarity, the process is called **depolarisation** of the membrane and results in an **action potential**. The whole process takes place in a millisecond (**Figure 7.4.1**).

resting potential the state of a neural cell membrane at rest, when outside the cell is more positive than inside

sodium–potassium pump a membrane protein that uses energy to transport sodium ions out of, and potassium ions into, cells against their concentration gradients

depolarisation a change in a cell's membrane potential so that the inside of the membrane is less negative than the outside

action potential the state of a neural cell membrane in active transmission, when inside the cell is more positive than outside

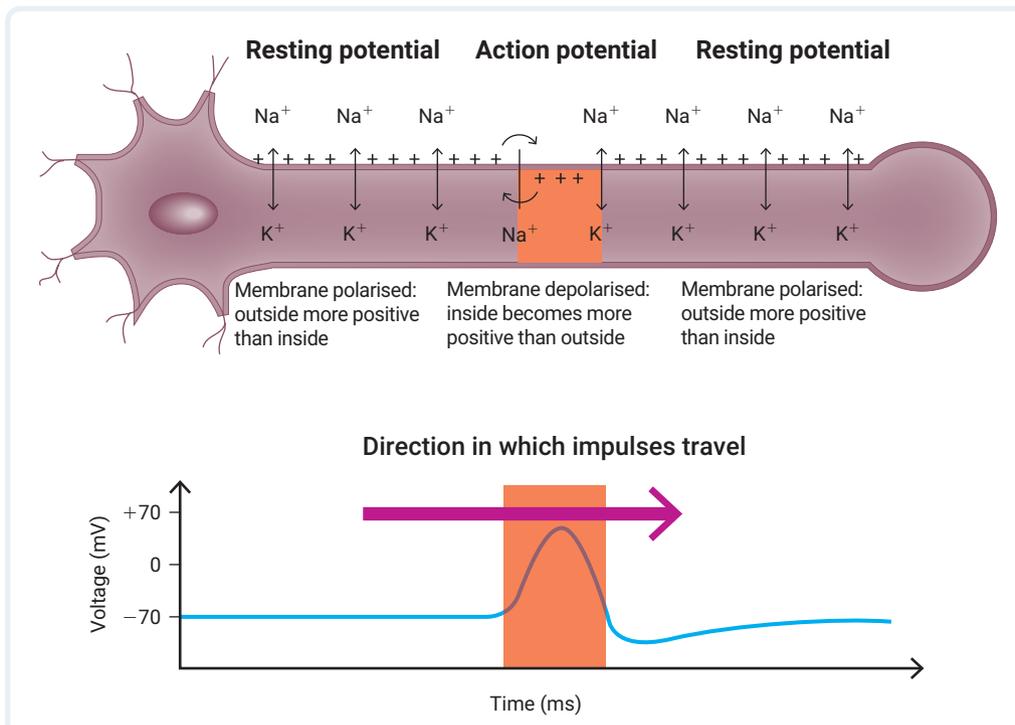


FIGURE 7.4.1 The transmission of an impulse along the axon requires most of the axon membrane to be at rest while the small action potential travels like a ripple along it.

Restoration of resting potential

While the sodium ions diffuse into the axon, the potassium ions slowly begin to leave: this is the start of the recovery process. The membrane becomes impermeable to sodium once more and the sodium–potassium pumps restore polarisation by pumping out sodium ions. As a result, the axon returns to its resting potential.

Role of myelin

In order to switch between resting and action potentials, the axon membrane must be exposed to the extracellular environment from which it can access sodium and potassium ions. The myelin sheath insulates the axon and prevents this exposure, which serves two very important purposes.

First, the proximity of other neurons means that when the sodium ions flow into the axon to trigger the action potential, it would also trigger the action potential in neighbouring exposed axons. Myelin ensures that only one axon is exposed in any particular area, insulating the rest.

Second, the ripple of action potential is quite slow, particularly when the axon is metres long. By insulating most of the axon, the action potential must jump from one exposed node to the next, accelerating the transmission speed. This results in faster reaction times – a distinct advantage for a multicellular organism.

Transmission between neurons

Once the action potential has reached the axon terminal, it is necessary to use a different method to transfer the signal across the terminal membrane to the next cell. There is a tiny space (about 20 nm) between the axon terminal and its target, called the **synapse** or **synaptic cleft** (Figure 7.4.2). The terms **presynaptic neuron** and **postsynaptic neuron** differentiate between the neuron sending the signal and the neuron receiving it.



Worksheet
Nerve impulses

Weblink
Nerve impulses

synapse (synaptic cleft)
the tiny space between an axon terminal and its target (neuron, muscle or gland)

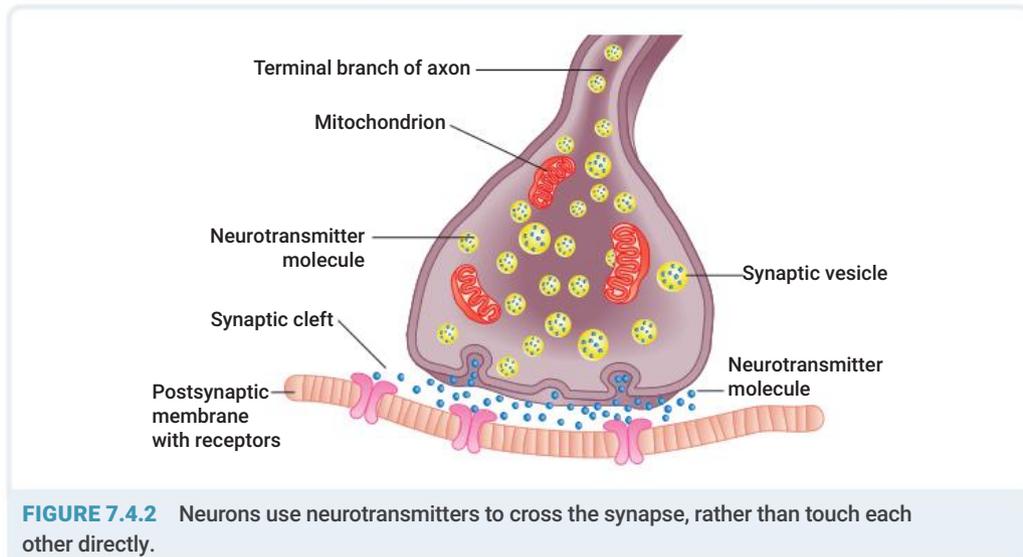
presynaptic neuron
the neuron sending the signal across the synapse

postsynaptic neuron
the neuron receiving the signal from the synapse



Weblink

Action potentials and synapses



Neurotransmitters

exocytosis the movement of solids or liquids from a cell to the environment via vesicle formation

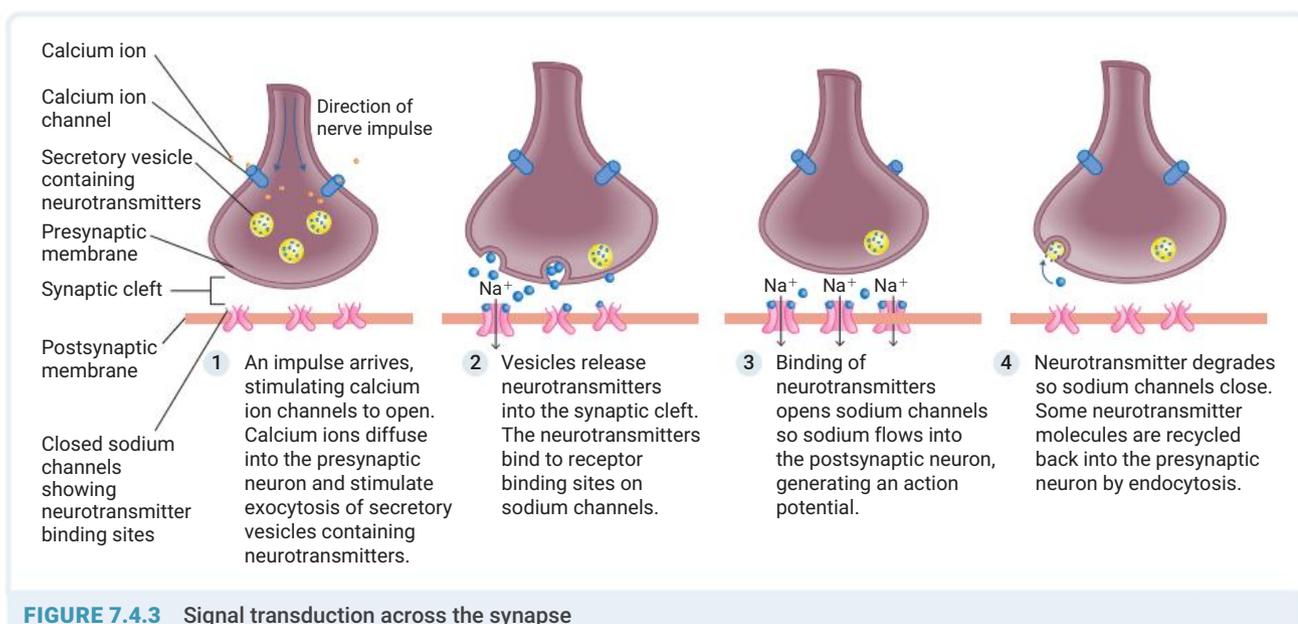
vesicle a small, membrane-bound sac in the cytoplasm that transports, stores or digests substances

neurotransmitter a chemical (protein) that is used by neurons to carry a signal across the synapse

When the electrical impulse arrives at the axon terminal, it causes calcium ion channels in the cell membrane to open, resulting in an influx of calcium ions. These stimulate **exocytosis**, in which the **vesicles** fuse to the presynaptic membrane and release their neurotransmitters into the synapse. **Neurotransmitters** are chemical messengers, protein molecules that cross the synapse. Some hormones can act as neurotransmitters (e.g. dopamine).

The neurotransmitters diffuse across the synapse to bind with specific receptors in the postsynaptic membrane. This causes ion channels to open there, allowing sodium ions to move from the synapse into the postsynaptic neuron. If sufficient channels are opened to cause depolarisation, an action potential is triggered.

Once the neurotransmitters have activated the channels, it is important that they do not continue their stimulation. Thus, excess neurotransmitters in the synaptic cleft are deactivated by enzymes and recycled back into the presynaptic neuron (**Figure 7.4.3**).



What has occurred within the presynaptic and postsynaptic neurons is signal transduction. **Signal transduction** is the process by which a signal (either chemical or electrical) is converted into another type of signal in the cell. In the example of a neuron, the action potential (electrical) begins at the dendritic end, passes along the axon as electrical energy and results in the production of neurotransmitters (chemical) at the axon terminal.

signal transduction the process of converting a signal into another type of signal in a cell (e.g. electrical to chemical)

PRACTICAL ACTIVITY 7.4.1

CHICKEN NERVE DISSECTION

Introduction

Axons are extremely thin and can only be seen through an electron microscope. However, larger nerve fibres are often visible inside the main nerves of the body. Chickens have similar nerve patterning to humans, including ganglia and nerve fibres.

Research question

How does the location of the nerve affect its structure?

Aim

- To use dissecting equipment safely
- To visualise nerves and neurons

Materials

- chicken leg (including thigh)
- light microscope
- microscope slides
- coverslips
- tweezers
- water dropper
- dissecting needle
- dissecting board or tray
- dissecting pins
- scalpel
- gloves
- lab coat



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Coverslips can break easily and can cut.	Take care with coverslips and do not push hard when placing them.
Scalpels and dissecting needles are sharp and can cut easily and deeply.	Take care with sharp objects and always use tweezers to hold the chicken while dissecting.
Raw chicken meat may contain pathogens.	Always wear gloves and a lab coat when handling the chicken. Wash your hands thoroughly at the end of the practical activity.

Procedure

Part A: Dissection

- Put on your gloves and lab coat.
- Rinse and pat the chicken leg dry and arrange it and your dissecting tools on the board or tray.
- Using the scalpel and tweezers, cut the skin and peel it away from the muscle. You may need to cut the connective tissue in some places (**Figure 7.4.4**).
- Insert your finger into an indentation between the muscle bundles in the lower leg (you may need to be quite firm to break the fascia (slimy clear lining)) and pull gently to separate them from each other but don't tear them from the bone (**Figure 7.4.5**).

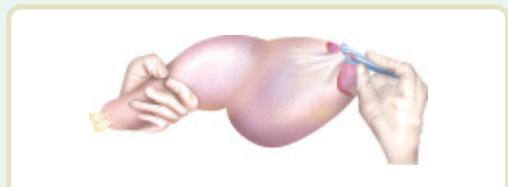


FIGURE 7.4.4 Removing the skin from the chicken leg



FIGURE 7.4.5 Separating the muscle bundles

- 5 Observe the muscle bundles and the strong white tendons holding each end of the muscle to the bone. Carefully cut the tendons of one muscle bundle and lift it away from the bone.
- 6 Between the bone and muscle, you should find a thinner, white nerve. If you cannot find it, choose a different muscle and try again. The nerves in the thigh should be thicker and easier to find.

Part B: Wet mount

- 7 Using the scalpel and tweezers, carefully remove a nerve from the chicken leg. Slice a small cross-section from one end.
- 8 Put the section of tissue onto a microscope slide. Try to avoid getting folds in it. Add one or two drops of water and, using the dissecting needle, carefully lower the coverslip.
- 9 Examine the slide under low power, moving to higher magnifications.
- 10 Repeat steps 9 and 10 with a longitudinal section of the nerve.

Results

- 1 For Part A, make a labelled scientific drawing.
- 2 For Part B, make detailed scientific drawings of a high-power cross-section and a longitudinal section of the nerve. Make sure features are labelled and magnifications are recorded.

Interpretation

- 1 Explain why the nerves in the thigh are thick and easy to see.
- 2 Discuss why the nerves are generally located between the muscle and bone.
- 3 Relate the location and appearance of the nerve tissue to its function in the body.

LEARNING CHECK 7.4

DESCRIBING

- 1 **Describe** the structure of an axon terminal in a presynaptic neuron.
- 2 **Describe** the function of myelin sheath.

APPLYING

- 3 **Summarise** what happens to sodium ions and potassium ions during the rising and falling phases of an action potential.
- 4 **Explain** how sodium deficiency could be life-threatening.

ANALYSING

- 5 **Compare** signal transmission with signal transduction.
- 6 **Identify** the relationships between the following by creating a flow chart to show:
- a transmission along the axon
 - b transduction across the synapse.

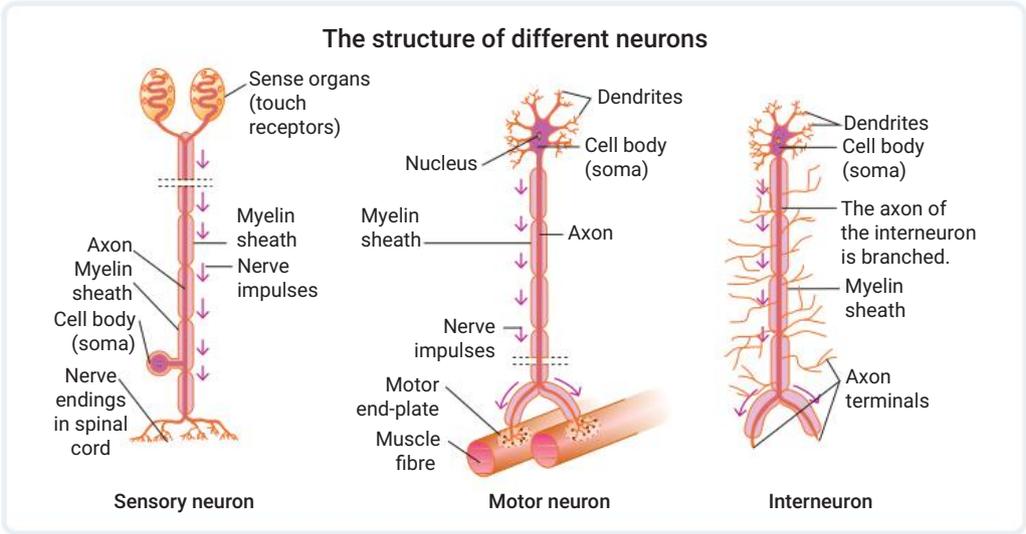
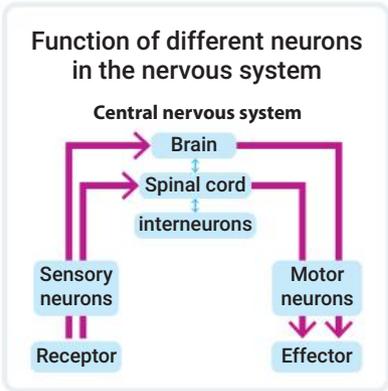
Types of receptors

- There are five types of receptors, each sensitive to particular stimuli. Exteroceptors receive stimuli from the external environment; interoceptors receive stimuli from the internal environment.

Type of receptor	Exteroceptor stimuli	Interoceptor stimuli
Chemoreceptor	Smells and tastes in nose and mouth	Oxygen and ion levels in blood vessels
Mechanoreceptor	Pressure, touch, sound vibrations	Pressure, vibrations, balance
Photoreceptor	Light in the eyes and on the body surfaces of some invertebrates	None
Thermoreceptor	Air temperature on skin	Internal temperature in hypothalamus
Nociceptor	Painful heat, cold, pressure, light	Painful pressure, tension

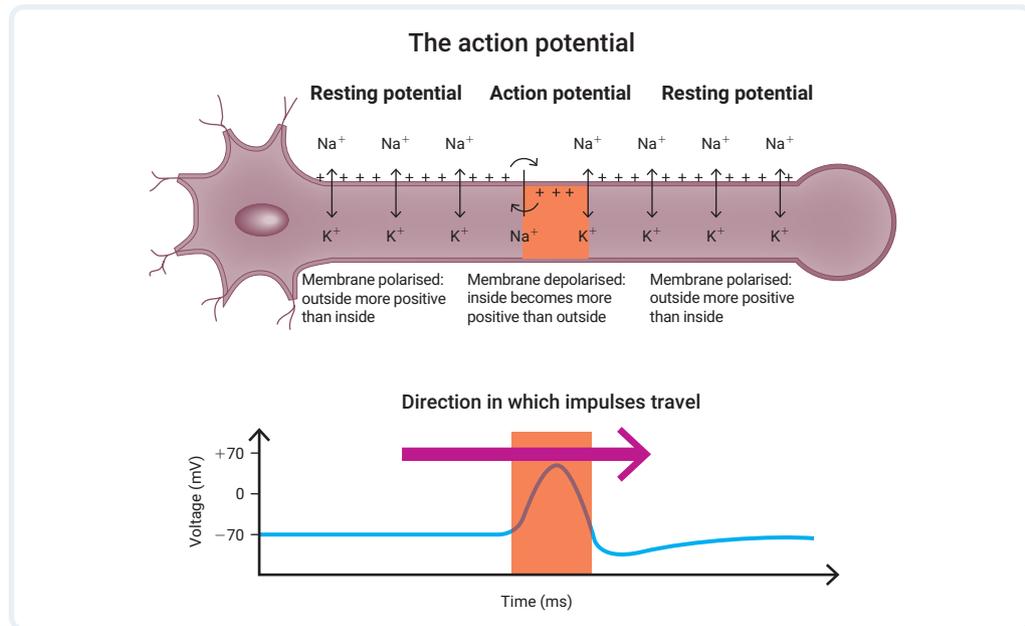
Types of neurons in the nervous system

- There are three types of neurons:
 - sensory neurons transmit nerve impulses from the receptor to the CNS
 - interneurons occur in the CNS and link the sensory and motor neurons
 - motor neurons transmit nerve impulses from the CNS to the effector.
- The structure of each neuron type is directly related to its function.



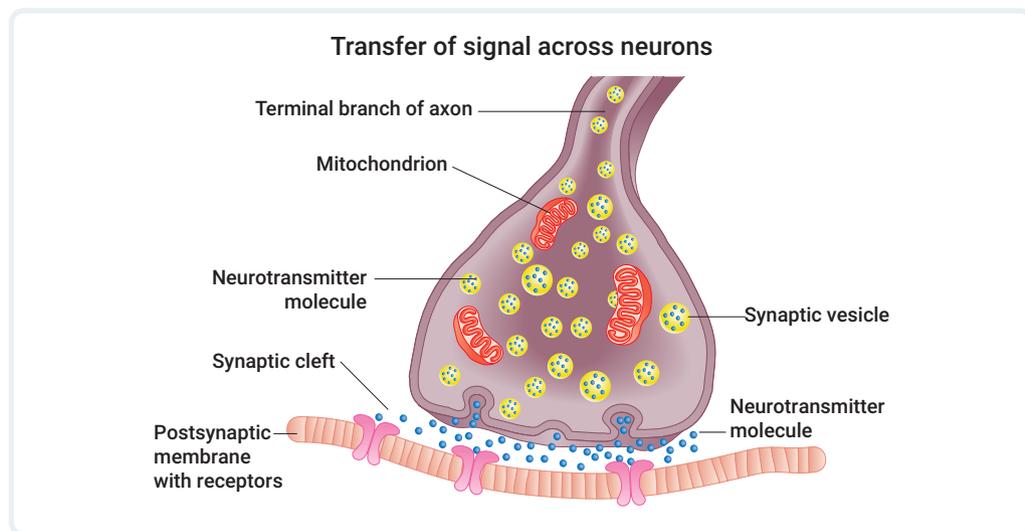
The nerve impulse

- The movement of an action potential along the length of an axon is caused by the movement of positive ions.
- A cell at rest is slightly positive on the inside and more positive on the outside
- An action potential is when the cell is more positive on the inside than the outside; return to resting potential.



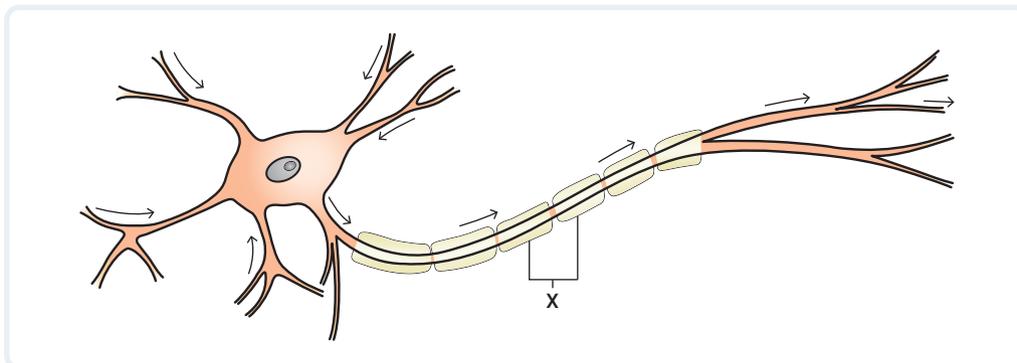
Signal transduction

- Neurons do not touch each other directly; rather, neurotransmitters cross the synapse between presynaptic and postsynaptic neurons.
- The conversion of an electrical impulse into a chemical signal is known as signal transduction.



MULTIPLE CHOICE

- There are five categories of sensory receptors in the human body. Which alternative is a correct statement about these receptors?
 - Photoreceptors detect changes in temperature.
 - Nociceptors detect blood glucose concentration.
 - Mechanoreceptors detect sound vibration.
 - Chemoreceptors detect intense pain.
- Snakes can detect infrared radiation, enabling them to create a thermal image of their prey. Humans cannot detect infrared radiation. Why is this?
 - Humans have a sense organ for detecting infrared radiation but it is not functional.
 - Humans do not have a sense organ for detecting infrared radiation.
 - Snakes mostly move about in the dark so have learnt how to detect infrared radiation.
 - The human infrared sense organ has evolved into chemoreceptors.
- Which one of the following is an example of an exteroceptor?
 - Pancreas
 - Hair
 - Heart
 - Eye
- In the following diagram, identify X.



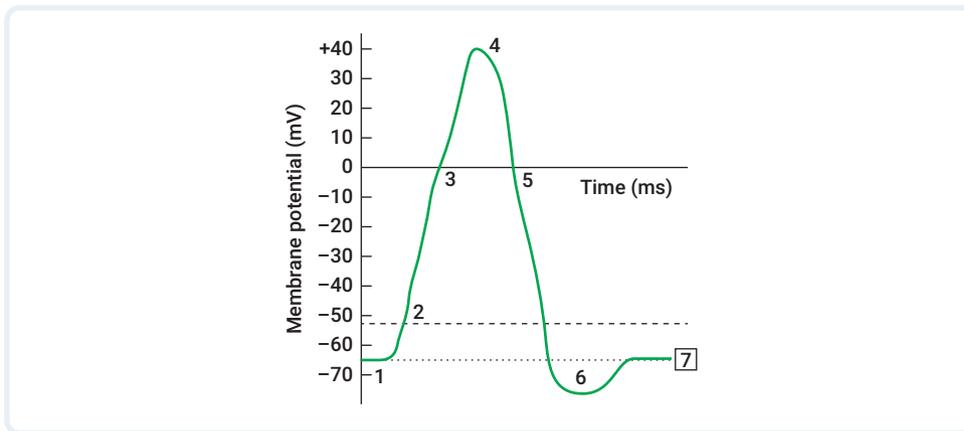
- Dendrite
 - Myelin sheath
 - Nodes of Ranvier
 - Axon
- Which of the following statements applies to the transmission of nerve impulses in vertebrates?
 - Myelinated nerve fibres usually transmit an impulse more slowly because the myelin interferes with the movement of ions across the membrane.
 - Neurons make direct contact with other neurons, creating a pathway for electrical signals.
 - Schwann cells create myelin and are found around the dendrites of a neuron.
 - Interneurons relay the electrical impulses from sensory neurons to motor neurons.

6. In sensory neurons, the soma is:
- A the branching appendages on the cell body.
 - B a cell body at the end of the axon.
 - C a side bulge along the length of the axon.
 - D the tightly wrapped cells shielding the axon.
7. When a neuron is in resting potential, its axon is:
- A very negative on the inside and slightly positive on the outside.
 - B equally positive and negative on the inside and outside.
 - C slightly positive on the inside and very positive on the outside.
 - D slightly negative on the inside and very negative on the outside.
8. Which one of the following statements is correct in relation to transferring signals between neurons?
- A The presynaptic neuron is the neuron sending the signal across the synapse.
 - B The postsynaptic neuron is the neuron sending the signal across the synapse.
 - C The presynaptic neuron is the neuron sending the signal across the terminal.
 - D The postsynaptic neuron is the neuron sending the signal across the terminal.
9. Signal transduction is when:
- A an action potential travels along the axon.
 - B the electrical action potential is converted into chemical neurotransmitters.
 - C resting potential changes into action potential.
 - D the sodium–potassium pump transports sodium ions out of the neuron.
10. Opioids are painkillers that act to reduce the severity of pain by:
- A reducing the production of some neurotransmitters.
 - B shutting down the sodium–potassium pump.
 - C reversing the direction of impulse in neurons.
 - D preventing interneurons from relaying messages to motor neurons.

SHORT RESPONSE

11. Imagine removing a roast chicken from the oven and you accidentally touch your arm on the oven door. You immediately remove your arm away from the hot door. **Create** a flow chart that explains the processes that occurred in your nervous system to bring this action about.

12. Using your knowledge of the stages of an action potential, copy and complete the following table by matching each number on the graph to its description.



Number	Description of what is happening
	Sodium ions flood the membrane – depolarisation
	Potassium ions begin to flow in past resting potential
	Resting potential restored
	Resting potential
	Potassium ions slowly begin to leave the cell – repolarisation
	Peak action potential
	Sodium ion channels open

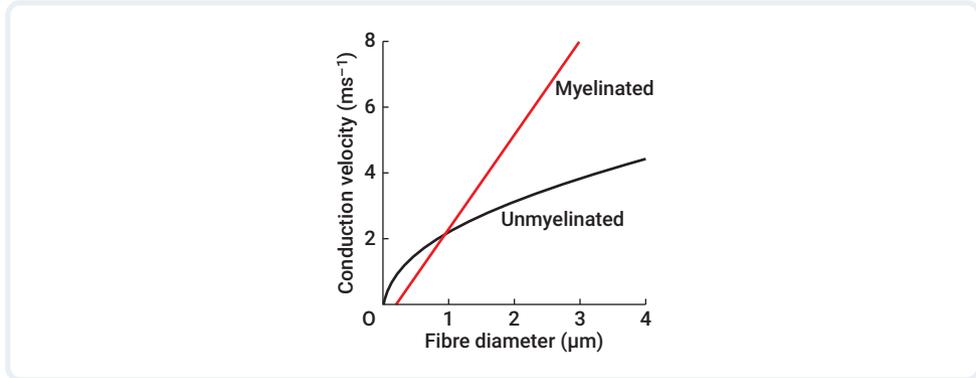
CROSS-CHAPTER QUESTION

13. Neurotransmitters are produced in the presynaptic neuron. They are packaged into vesicles and released from the axon terminal by exocytosis.
- Explain** what is meant by exocytosis.
 - Axon terminals contain a large number of mitochondria. **Explain** why this might be.
 - Neurotransmitters move across the synaptic cleft by diffusion. **Explain** what this means.
 - Explain** what happens to the neurotransmitter once it has relayed its message to the postsynaptic neuron. Provide one reason why this occurs.

DATA ANALYSIS

14. Analyse evidence

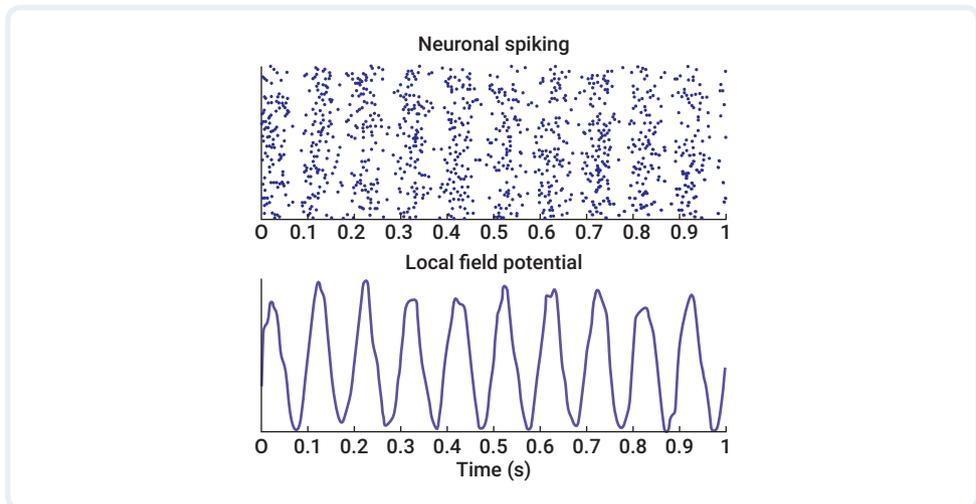
The graph shows the conduction velocity (m s^{-1}) against nerve fibre diameter (μm) for myelinated and unmyelinated nerve fibres.



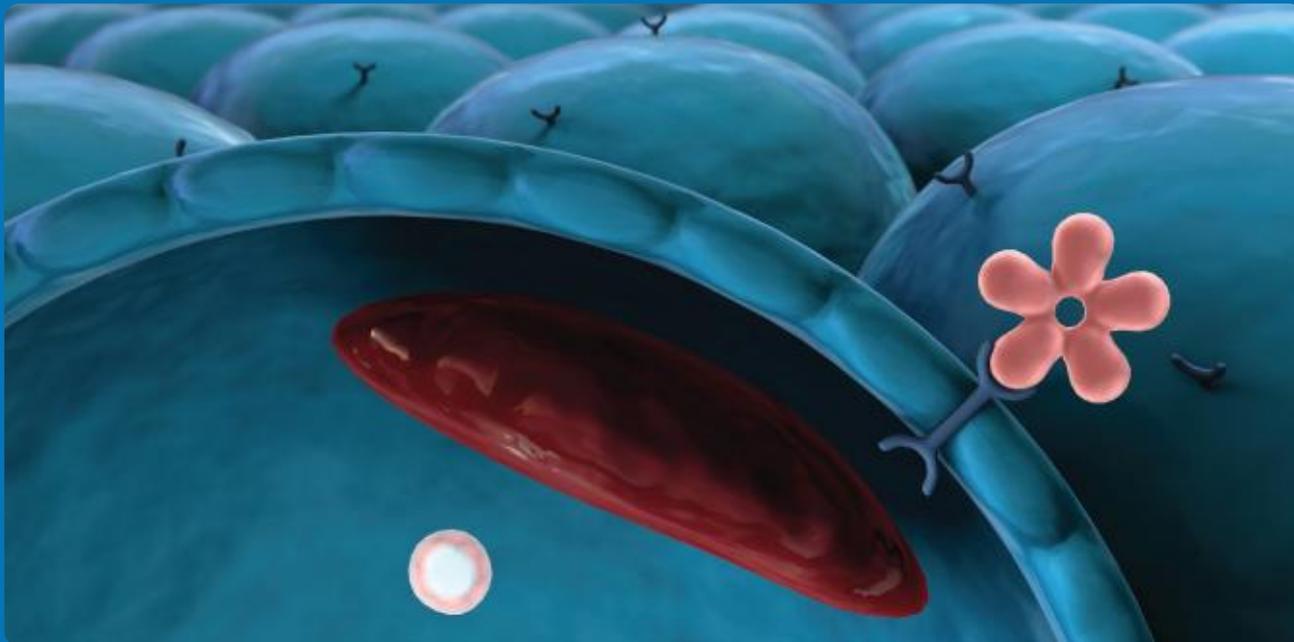
Identify a pattern that is shown between myelinated and unmyelinated nerve fibres.

15. Interpret evidence

The following graph shows neuronal spiking demonstrating action potentials in individual neurons in a human brain. Underneath shows their summed activity. Use the information presented in this data and your knowledge of neurons to answer the questions below.



- a Deduce** what is happening within the neuron at:
- 0.22 s
 - 0.37 s
- Provide a reason.
- b** Neuronal spikes are said to be *all-or-nothing*. **Determine** whether the graph supports this statement.



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SYLLABUS
DOT POINTS**SCIENCE UNDERSTANDING**

- Describe how hormones relay messages to cells displaying specific receptors via the circulatory or lymphatic system.
- Explain how receptor binding alters cellular activity, recognising that a cell's sensitivity to a specific hormone is directly related to the number of receptors it displays for that hormone.

SCIENCE INQUIRY

- Investigate the use of hormones in agriculture.

Biology 2025 v1.1 General Senior Syllabus © QCAA 2024

Introduction

Moving a hand away from a hot stovetop requires an immediate response. This stimulus and response is controlled by the nervous system. Some responses need to affect almost all of the body (e.g. growth) or take time (e.g. storage of excess glucose as glycogen in our liver and muscles). Nerve impulses are both too fast and too localised to be effective in these cases. The body uses a second, slower pathway to produce a slower response – the endocrine system. Endocrine glands, part of the endocrine system, receive the response signal from the central nervous system. They release their hormones directly into the bloodstream which then travel around the body to the specific receptor sites.

Worksheets

- Hormones
- Receptor binding

 Nelson MindTap

To access resources above, visit
[cengage.com.au/nelsonmindtap](https://www.cengage.com.au/nelsonmindtap)



ASSUMED KNOWLEDGE

- ✓ The circulatory system is made up of different organs and tissues whose main function is to transport nutrients and waste products throughout the body.
- ✓ Different sensory receptors detect different stimuli.
- ✓ The composition of the cell membrane means that not all molecules can pass through and enter the cell.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ identify what hormones are made of
- ✓ describe the function of hormones as chemical messengers
- ✓ describe how hormones travel through the body
- ✓ describe the specificity of hormone function and how it affects cellular activity
- ✓ identify the relationship between the number of cell receptors and hormone sensitivity
- ✓ explain how the number of receptors on the cell surface for a particular hormone affects that cell's sensitivity to that hormone.

8.1 Hormones as chemical messengers

hormone an organic compound produced by one part of the body and transported in the circulatory or lymphatic systems to another part of the body to prompt a response from specific cells

lymphatic system a drainage system in the body that helps maintain a balanced fluid level

signalling molecule a molecule that is released by one type of cell and binds to another type of cell and causes an effect

Hormones are organic compounds. They are produced by one part of the body and transported in the circulatory or **lymphatic systems** to another part of the body where they prompt a response from specific cells. They are a type of **signalling molecule** in that they transmit information between cells and cause a response.

The human body produces more than 50 different hormones that control many different bodily functions, including growth, development, the sleep–wake cycle, mood and homeostasis. Each hormone targets and activates a particular cell and causes a particular response. Some hormones and the responses they produce are shown in **Table 8.1.1**.

TABLE 8.1.1 Examples of human endocrine glands, the hormones they produce and secrete, and the homeostatic responses they cause in another part of the body

Endocrine gland	Hormone secreted	Target tissue/organ	Homeostatic response
Posterior pituitary	Antidiuretic hormone	Kidney	Stimulates reabsorption of water
Adrenal	Adrenaline	Kidneys, liver, blood vessels	Causes constriction of blood vessels in kidney and liver; stimulates liver to release more glucose; prepares for 'fight or flight'
	Cortisol	Many tissues	Prevents excessive immune response
Thyroid	Thyroxine	Nearly all tissues	Increases metabolic rate; therefore, increases oxygen consumption and release of heat
Pancreatic beta cells	Insulin	Most body cells	Lowers blood sugar level, increases glycogen storage by liver, stimulates protein synthesis
Pancreatic alpha cells	Glucagon	Liver	Stimulates conversion of glycogen to glucose and the release of glucose

Hormones are produced in **endocrine glands**, part of the **endocrine system**. Although only minute quantities of a hormone are produced, they have considerable impact. Some effects are temporary, such as when adrenaline signals the release of glucose and increased heartbeat in the fight or flight response. Regulatory mechanisms such as those in foetal development can have a longer effect.

Coordination of activities associated with the endocrine system (**Figure 8.1.1**) is often connected to the pituitary **gland** in the brain. The pituitary gland is known as the master gland because it produces many hormones that affect hormone production by other endocrine glands.

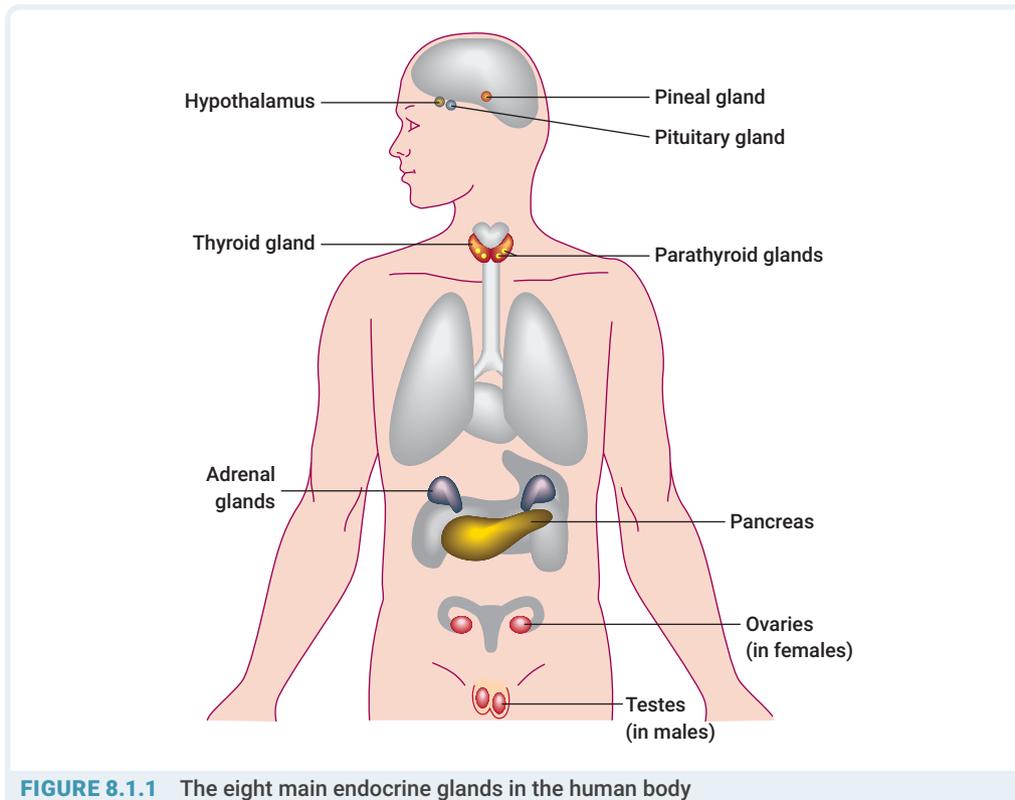


FIGURE 8.1.1 The eight main endocrine glands in the human body

Hormones and hormone-like substances occur in other organisms, including plants, and are essential to the regulation of a variety of activities. Female ring doves coo during courtship to stimulate the release of hormones that result in egg development. In plants, the light-sensitive hormone auxin is responsible for plant growth towards light (phototropism) to maximise photosynthesis.

Types of hormones

Hormones are generally divided into two categories, water-soluble and fat-soluble. Water-soluble hormones (called **hydrophilic hormones**) are polar molecules (a molecule with one slightly positive end and one slightly negative end) derived from amino acids. They cannot pass through the cell membrane without assistance and usually bind to **cell receptors** on the outside of the cell (**Figure 8.1.2**). Fat-soluble hormones (called **hydrophobic hormones**) are non-polar molecules derived mostly from cholesterol (e.g. **steroids**). These hormones need a companion molecule to travel through the blood but can detach and pass through the cell membrane by themselves. They usually bind to receptors inside the nucleus of the cell (**Figure 8.1.2**).

endocrine gland a ductless gland that produces hormones

endocrine system the collection of ductless glands that produce hormones and secrete them directly into the bloodstream

gland an organ that produces and secretes chemicals or proteins within the body or externally



Weblinks

Types of hormones

How do your hormones work?

hydrophilic hormone a hormone that is soluble in water and binds to extracellular receptors to initiate a response in that cell (e.g. peptide and some amine hormones)

cell receptor a protein that binds hormones to form a hormone-receptor complex

hydrophobic hormone a hormone that is insoluble in water and binds to intracellular receptors (e.g. steroid and thyroid hormones)

steroid a hydrophobic signal molecule produced from cholesterol

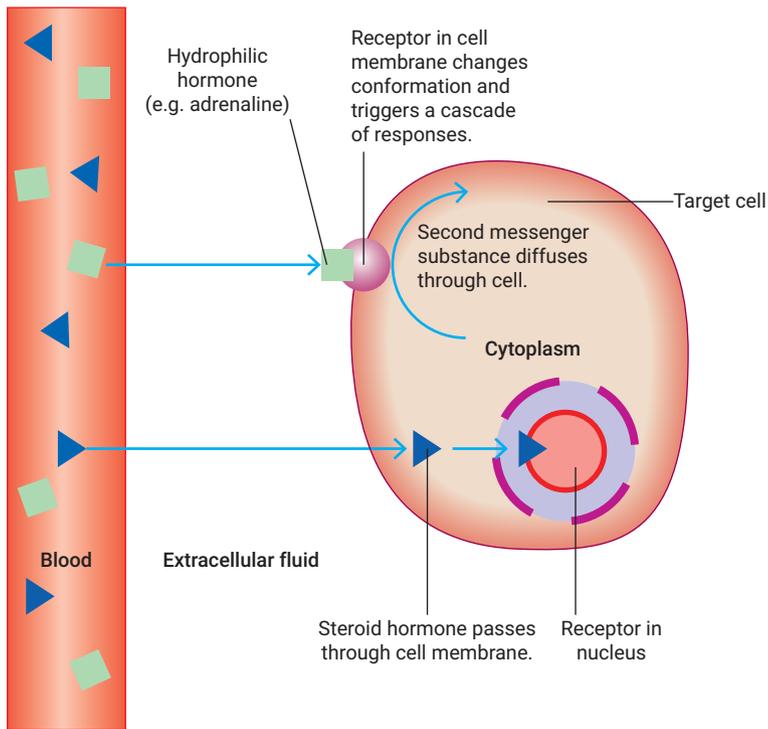


FIGURE 8.1.2 Water-soluble hydrophilic hormones bind to extracellular receptors to trigger a cascade of events inside the cell, resulting in a cellular response. Fat-soluble steroid hormones pass through the cell membrane to bind to intracellular receptors, leading to a change in gene expression.

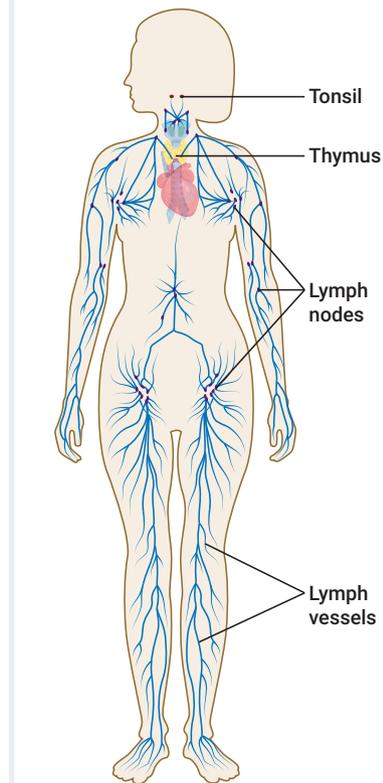


FIGURE 8.1.3 The lymphatic system

Transporting hormones

Endocrine glands are ductless glands. This means they secrete hormones directly into the bloodstream or lymphatic system. Once secreted, the hormone is carried around the body, but it will only exert its effect on those cells that have a specific receptor for that hormone.

The lymphatic system is made up of thin-walled, open-ended vessels that originate in the cells, tissues and organs. Its role is to absorb excess extracellular fluid (**lymph**) and return it to the circulatory system through the subclavian veins situated near the neck. This is an important homeostatic function to maintain stable fluid levels in the blood and the tissues. Unlike the circulatory system, the lymphatic system is one-directional, towards the heart. The lymphatic system also contains lymph organs, such as the tonsils and adenoids, and lymph nodes that contain white blood cells, and has an important role in fighting disease (**Figure 8.1.3**).

Targeting specific cells

Only the cells in the body that express receptors for a particular hormone respond to it (**Figure 8.1.4**). Without a receptor to bind to, the hormone drifts by the cells without any effect. In this way, a hormone such as ADH (antidiuretic hormone) can be secreted from the pituitary gland in the brain and travel the entire body without triggering its message for water-reabsorption effect until it reaches the collecting duct cells in the kidney nephron, where it can finally find its receptor.

lymph the extracellular fluid collected by the lymphatic system

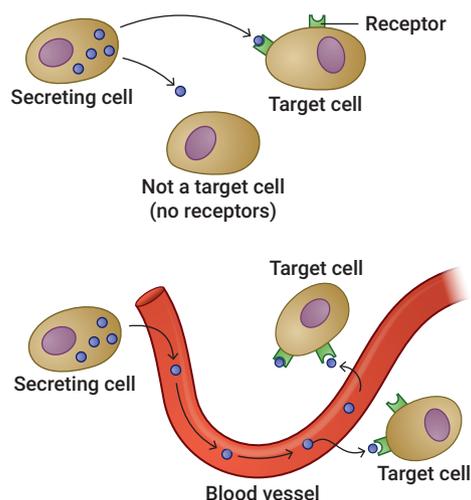


FIGURE 8.1.4 Hormones only bind to their specific receptor and, thus, only affect cells that express their specific receptor.

LEARNING CHECK 8.1

DESCRIBING

- 1 State a definition for:
 - a hormone
 - an endocrine gland
 - a receptor.
- 2 State two examples of a hormone, the gland that produces it and the target cells that it affects.
- 3 **Identify** the two body systems that can transport hormones around the body.

APPLYING

- 4 **Explain** why signalling molecules only have an effect on their target cells.
- 5 When taking hormones for medical reasons, fat-soluble hormones are more dangerous in high doses than water-soluble hormones. **Explain** why water-soluble hormones are less likely to cause overdose.

ANALYSING

- 6 **Compare** water-soluble and fat-soluble hormones.

8.2 Receptor binding

A cell's ability to carry out hormone-controlled cellular processes such as growth, reproduction and metabolism, depends on how well it binds to hormones and responds to signals. For example, a cell in a high-turnover tissue where cells are continually being removed and replaced, such as the lining of the mouth, needs to be very sensitive to the hormones responsible for cell division. A cell in a low-turnover tissue such as skeletal muscle needs to be less sensitive to this and more sensitive to hormones responsible for cell metabolism.

Cell sensitivity

A cell's sensitivity to any particular hormone is determined by the number of receptors that it expresses for that hormone. More receptors make a cell more sensitive and responsive than fewer receptors. However, a cell needs to produce receptors for many hormones, so most cells permanently express only a small number of each type of receptor.

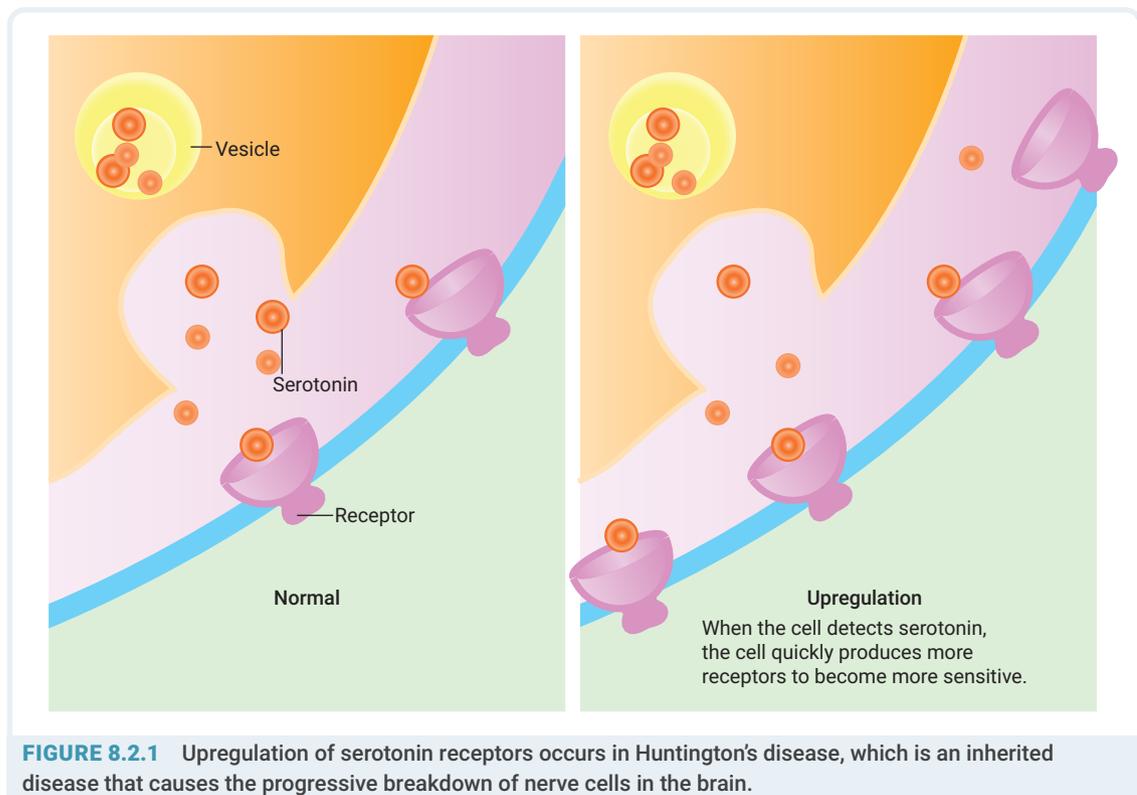
The quantity of hormone secreted is usually related to the degree of response that is required. A small hormone demand requires a small response, while a large quantity of hormone requires a large response. Without an adequate number of receptors, the target cell cannot tell how large the hormone demand is, but it is too expensive in terms of energy and resources to maintain a large number of receptors permanently on the cell surface.

To adequately respond to the hormone demand, the receptor actually activates two pathways. The first triggers the **upregulation** of the receptor itself, so that more receptors are quickly produced and the cell becomes more sensitive to the hormone (**Figure 8.2.1**). This allows the cell to accurately respond to the hormone demand. The second triggers the hormone's effector pathway that it is signalling for, producing the desired response in the cell.

After responding, **downregulation** occurs to reduce the number of receptors on the cell surface.

upregulation when a cell is prompted to produce more of a particular cellular component, such as receptors

downregulation when a cell is prompted to produce less of a particular cellular component, such as receptors

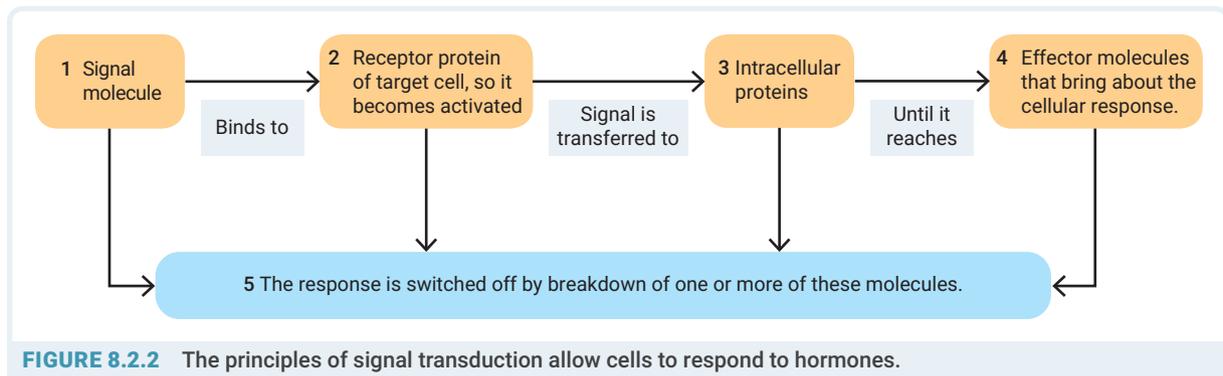


When a hormone binds to its receptor protein, the receptor changes shape and becomes activated. The activated receptor alters the activity of intracellular proteins, setting off an intracellular signalling cascade that transmits the message through the cell to effector proteins, which are stimulated to produce a response. This process is called **signal transduction** (**Figure 8.2.2**).

When the hormone is bound to the correct receptor and signal transduction has occurred, the response changes the cell's activity, typically resulting in an increase or a decrease of body processes. These responses may include:

- increased or decreased rates of mitosis and cell growth
- activation or deactivation of enzymes

signal transduction the process of converting a signal into another type of signal in a cell (e.g. electrical to chemical)



- changed membrane permeability
- a change in the level of protein synthesis occurring
- increased or decreased secretion of cell products.

The changes to cellular activity may occur immediately or be delayed. They may also be short lived or continue for a longer time.

One hormone, many effects – cortisol as an example

Cortisol, a steroid hormone, is produced and released by the adrenal glands, part of the endocrine system. It is often referred to as the ‘stress hormone’ because it is produced in response to stressful situations, such as during starvation. Although its primary role appears to be in protein and fat metabolism, it has a wide range of effects in a wide range of target cells, including maintenance of blood pressure and coordination of immune responses. A single hormone can have a diverse range of effects because of the wide variety of receptors it can bind to in the cell.

In liver cells, cortisol binds to a transcription factor that regulates the expression of genes coding for enzymes that control biochemical pathways for building glucose from amino acids and glycerol. Binding changes the **conformation** of the transcription factor, so that it can bind to its specific DNA region and switch on gene expression. The appropriate enzymes are then produced and the pathway is upregulated.

Although cortisol switches on one particular set of genes in the liver, it binds to different transcription factors in adipose (fat) tissue. Therefore, a different set of genes is switched on, a different set of enzymes is made and a different biochemical pathway is upregulated. As a result, the response of adipose cells is different from the response of liver cells, even though the two types of cell accept the same hormone.

The body continuously monitors the level of cortisol in the blood to maintain an optimal level. This is a homeostatic mechanism to ensure body health.



Weblink
Signal transduction

Worksheet
Receptor binding

conformation the shape of a molecule that is determined by the three-dimensional arrangement of its atoms and bonds; important for molecular functioning

LEARNING CHECK 8.2

DESCRIBING

- 1 Describe** the difference between upregulation and downregulation.
- State examples of cellular activity that can be altered by hormones binding to the correct receptor.

APPLYING

- 3 Explain** what is meant by cell sensitivity.
- 4 Explain** why fat-soluble hormones do not require signal transduction.
- 5 Explain** how hormones can have different effects in different cells.

CHAPTER SUMMARY

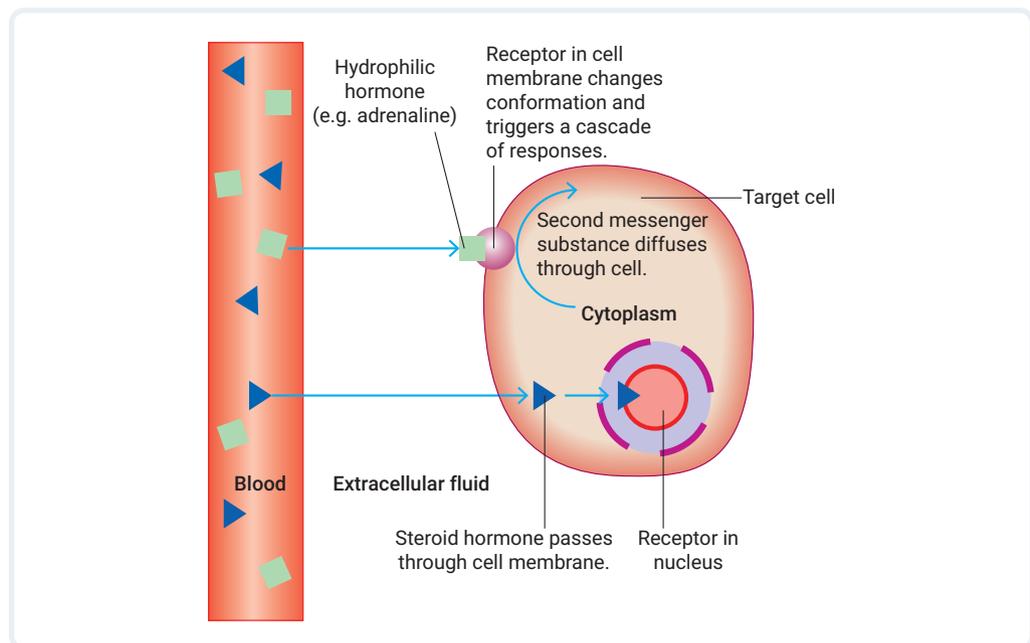
Hormone production

- Hormones are signalling molecules that are produced in one part of the body and travel in the circulatory or lymphatic systems to another part of the body to produce a response.
- Hormones are produced in endocrine (ductless) glands.

Endocrine gland	Hormone secreted	Target tissue/organ	Homeostatic response
Posterior pituitary	Antidiuretic hormone	Kidney	Stimulates reabsorption of water
Adrenal	Adrenaline	Kidneys, liver, blood vessels	Causes constriction of blood vessels in kidney and liver; stimulates liver to release more glucose; prepares for 'fight or flight'
	Cortisol	Many tissues	Prevents excessive immune response
Thyroid	Thyroxine	Nearly all tissues	Increases metabolic rate; therefore, increases oxygen consumption and release of heat
Pancreatic beta cells	Insulin	Most body cells	Lowers blood sugar level, increases glycogen storage by liver, stimulates protein synthesis
Pancreatic alpha cells	Glucagon	Liver	Stimulates conversion of glycogen to glucose and the release of glucose

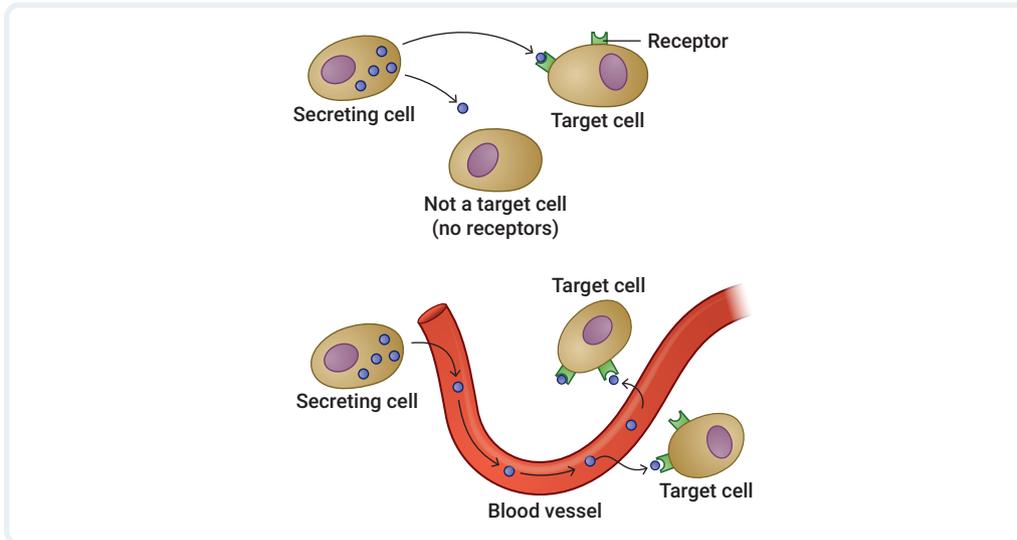
Characteristics of hormones

- Hormones are either hydrophilic (derived from amino acids) or hydrophobic (derived from cholesterol or amine-based).
- Hydrophilic hormones bind to external cellular receptors, whereas hydrophobic hormones bind to intracellular receptors.



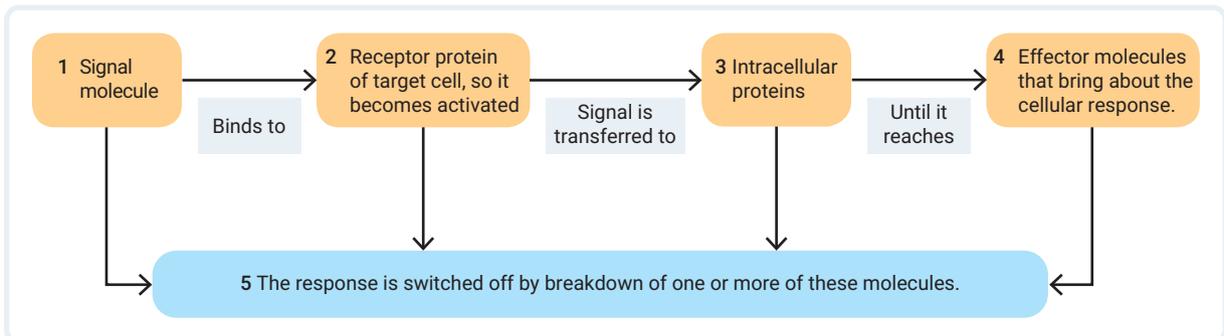
Targeting cells

- Hormones pass by cells without specific receptors and only bind to cells that express specific receptors.



Signalling cascade

- Once the hormone binds to the receptor, it sets off an intracellular signalling cascade that transmits the message through the cell.

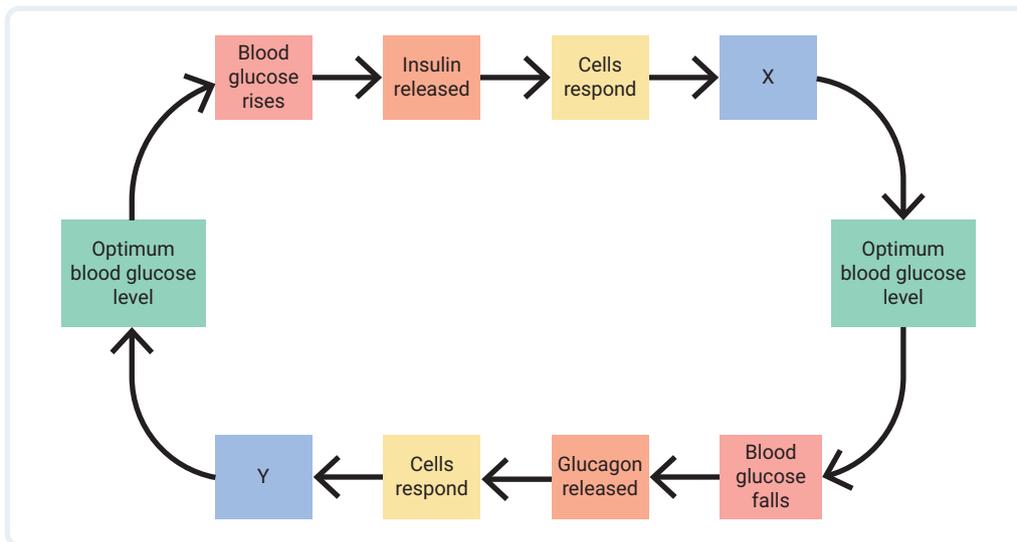


CHAPTER EXAM

MULTIPLE CHOICE

1. Antidiuretic hormone is produced in the pituitary gland in the brain. The hormone is secreted into the circulatory system. The receptors for this hormone are located in the:
A liver.
B kidneys.
C nearly all tissues.
D lining of the blood vessels.
2. Which gland is known as the master gland?
A Hypothalamus
B Pituitary
C Pineal
D Thyroid
3. A new hormone has been recently discovered. It binds to receptors on the cell membrane. This hormone is most likely to be:
A non-polar and hydrophilic.
B non-polar and hydrophobic.
C polar and hydrophilic.
D polar and hydrophobic.
4. Upregulation of a receptor is:
A starting to degrade it.
B it binding to a hormone.
C releasing it from a hormone.
D an increase in its production.
5. The major role of the lymphatic system is to:
A carry hormones.
B carry blood cells and plasma.
C circulate lymph to all body tissues.
D return extracellular fluid to the bloodstream.
6. Which one of the following cells would you expect to constantly exhibit upregulation of the hormone receptors for cell division?
A Skeletal cells
B Cells in the brain
C Cells in fingernails
D Cells lining the small intestine
7. The binding of a hormone to its receptors sets off a series of cascading events within a cell, resulting in a cellular response. This is called:
A homeostasis.
B signal transduction.
C negative feedback.
D second messenger.
8. The hormone glucagon is produced in the pancreas and travels in the bloodstream to the liver. Once it meets its target cells in the liver, you would expect:
A upregulation to occur.
B downregulation to occur.
C a decrease in metabolic rate.
D an increase in metabolic rate.

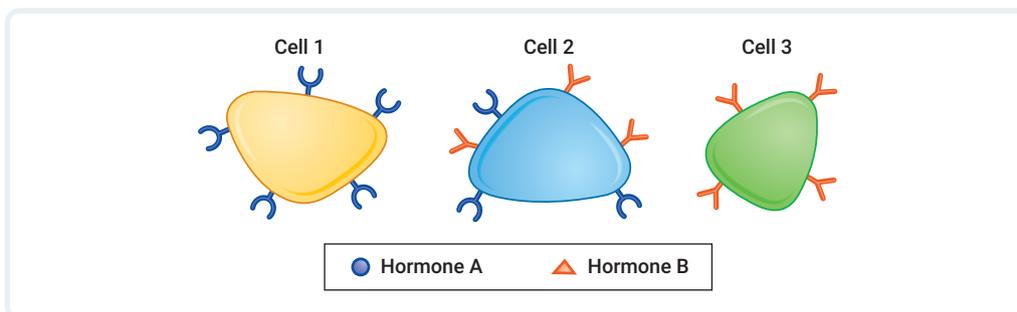
9. Antidiuretic hormone (ADH) is a hydrophilic hormone. Which one of the following would not occur when ADH reaches its target cells?
- Signal amplification
 - Signal transduction pathway
 - Intracellular binding with the receptor
 - Extracellular binding with the receptor
10. Consider the feedback-control diagram below.



It would be reasonable to expect the missing labels to be:

- X = blood glucose rises; Y = blood glucose rises
- X = blood glucose falls; Y = blood glucose rises
- X = blood glucose rises; Y = blood glucose falls
- X = blood glucose falls; Y = blood glucose falls

SHORT RESPONSE



11. The diagram shows two different types of hormones, A and B. Also shown are three different target cells and their hormone receptors.
- Identify** the cell(s) that display receptors for hormone A.
 - Identify** the cell(s) that display receptors for hormone B.
 - Explain** one situation that would cause the development of more receptors on cell 3.

12. **Explain** how upregulation and downregulation control the sensitivity to hormones circulating in your body.

CROSS-CHAPTER QUESTION

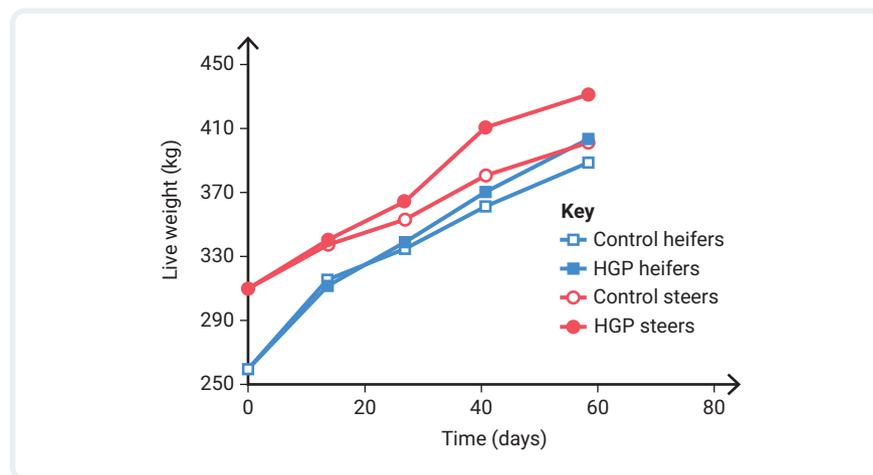
13. **Identify** and **explain** which organelles would be most active in a cell that is producing and transporting high levels of the reproductive hormone progesterone.

DATA ANALYSIS

14. **Interpret evidence**

Hormonal growth promotants (HGPs) are implants that are inserted under the skin of an animal. They contain naturally occurring hormones to promote growth in beef cattle. Researchers studied the effects of HGPs on the growth of heifers (female calves) and steers (male calves). Their results are shown in the graph. Use the information contained within this graph, and your knowledge, to answer the questions.

- a **Determine** whether the heifers or steers showed the greatest gain in liveweight at the end of the study. **Justify** your answer.
- b **Determine** whether the HGP made an overall difference to the liveweight of the steers and heifers. **Justify** your answer.



Thompson, J., McIntyre, B.M., Tudor, G.D., Pethick, D.W., Polkinghorne, R. & Watson, R. (2008). Effects of hormonal growth promotants (HGP) on growth, carcass characteristics, the palatability of different muscles in the beef carcass and their interaction with aging. *Animal Production Science*, 48, 1405–1414.

15. Apply understanding

To be healthy it is important that your hormones are in balance. Imbalances of hormones, even small, can cause serious and life-altering symptoms. The following table shows patient X's results from a test for the class of hormones known as androgens. Androgens are sex hormones that bring on puberty. Ketosteroids are formed when androgens break down. The results were gained from the analysis of a urine sample.

Androgens		Reference range (μ mol/24 h)
Ketosteroids		
DHEA	0.10	0.20–0.90
Androsterone	3.69	0.60–5.50
Etiocholanolone	1.48	1.20–6.10
11-Keto-androsterone	0.20	0.30–1.90
11-Keto-etiocholanolone	0.34	0.30–1.60
11-Hydroxy-androsterone	3.17	1.30–4.10
11-Hydroxy-etiocholanolone	0.31	0.50–2.60
17-Ketosteroids, Total		6.0–22.2

<https://biobalanceinstitute.com/the-tests/hormone-imbalances>

- Identify** the ketosteroids that are within the normal level for this patient.
- Identify** the three ketosteroids that the doctor would be most concerned about for this patient.
- Calculate** the total ketosteroids for this patient.

Homeostatic regulation – systems working together



Shutterstock/Alexander Penyushkin

SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- Explain how the nervous and endocrine systems use negative feedback to coordinate responses to internal/external stimuli and maintain homeostasis (stimulus–response model).
- Analyse feedback–control diagrams to identify the stimulus, receptor/s, control centre, effector/s and communication pathway/s in different scenarios.
- Explain thermoregulatory mechanisms of endotherms, including:
 - structural features: brown adipose tissue, insulation
 - behavioural responses: kleptothermy, hibernation, aestivation and torpor
 - physiological mechanisms: evaporative heat loss, thermogenesis and vasomotor control.
- Explain thermoregulation in humans, including the role of sweating, shivering, vasodilation and vasoconstriction using feedback control diagrams.
- Explain osmoregulation in humans, including the role of antidiuretic hormone (ADH) and the kidney using feedback control diagrams.





SCIENCE INQUIRY

- Investigate structural, behavioural, physiological and/or homeostatic mechanisms used by different species to control heat exchange/metabolic activity/water balance.

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Introduction

In 1988, Mark Dorrity went on an 8 km run in extreme heat in New South Wales. During the run, he neglected to drink water to stay hydrated and his muscles generated more heat than could be lost from his body. As a result, Mark's body overheated to 42.8°C and he suffered a rare condition known as rhabdomyolysis. His thigh muscles liquefied and released excess proteins into his blood. This caused Mark's kidneys and other organs to fail. Dehydration also caused Mark's blood to thicken so that it could not flow freely in some parts of his body, causing gangrene in his extremities. Every organ in his body was affected; he became delirious, brain damage occurred, his lungs barely functioned, and his heart stopped at least once. Within an hour, he had collapsed into a coma, was on dialysis and had to have a leg amputated.

Fortunately, few people engage in the kind of activity that Mark did under such extreme conditions, although for many organisms these conditions are a feature of their daily lives. Mark pushed his body beyond tolerable limits and severely disrupted the biochemical processes that normally work to keep internal conditions relatively stable.

Practical

- The skin and temperature control

Worksheets

- Homeostasis
- Homeostatic loops
- Thermoregulation
- Osmoregulation

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ The body has mechanisms that allow it to detect and respond to different stimuli.
- ✓ Negative feedback systems function to reduce/reverse the initial change.
- ✓ Hormones help to control different processes in the body, including metabolism and growth and development.
- ✓ Nerves transmit electrical signals that allows for different areas of the body to communicate with each other.
- ✓ Homeostasis is the maintenance of a relatively constant internal environment.
- ✓ The circulatory system is made up of different organs and tissues whose main function is to transport nutrients and waste products throughout the body.
- ✓ Heat can be lost or gained by convection, conduction and radiation.
- ✓ Matter can change state depending on the energy (heat) applied.
- ✓ The kidney is an organ that excretes the urea dissolved in blood out of the body.
- ✓ G proteins relay signals from a cell membrane G protein-coupled receptor to other signal transduction proteins inside the cell.
- ✓ Osmosis is the movement of water across a selectively permeable membrane from a region of low solute concentration to a region of high solute concentration.

stimulus–response model a model that shows how organisms respond to stimuli

impulse the movement of an action potential along a nerve fibre in response to a stimulus; a signal sent along a nerve

processing centre the organ or organ system, usually the central nervous system, that receives signals from receptors and sends appropriate responses to effectors

effector an organ, muscle, gland, cell or protein that acts in response to a stimulus

response the action resulting from a stimulus

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ explain how the stimulus–response model represents the workings of the endocrine and nervous systems
- ✓ identify the role of the endocrine and nervous systems in homeostasis
- ✓ examine feedback–control diagrams to identify factors involved in the processes that occur for the body to maintain homeostasis
- ✓ identify structural characteristics and behaviours that help endotherms regulate internal temperatures
- ✓ explain how the features contribute to thermoregulation
- ✓ explain the role of negative feedback on thermoregulation in endotherms
- ✓ explain osmoregulation in humans
- ✓ explain the role of antidiuretic hormone and kidneys in the regulation of water levels in the human body.



Weblink
Stimulus–response

9.1 Stimulus–response model

Bodies are constantly responding to not only external, but also internal, environmental changes. The **stimulus–response model**, shown in **Figure 9.1.1**, provides a useful way of understanding how the cells and organs of the body detect and respond to these changes.

A stimulus is detected by a receptor that is specific for that stimulus. The **impulse** from the receptor is relayed to a **processing centre**, which could be the brain or spinal cord (CNS), and a responding impulse is delivered by nerves or hormones to an **effector**. An effector is usually a muscle or gland that carries out the **response**.

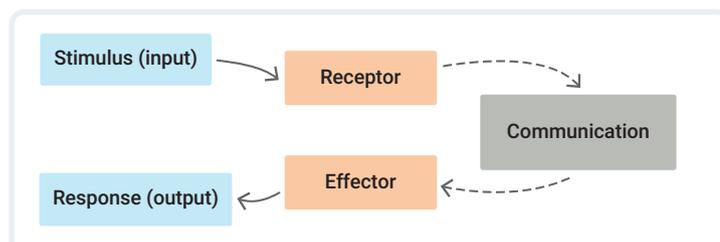


FIGURE 9.1.1 The stimulus–response model relies on the transfer of information between the receptor and effector.

For example, at the starting line for a 200 m race, the stimulus is the noise made by the starter's gun that is detected by ears (receptor). This impulse is sent to the brain (processing centre), which sends a responding impulse to the leg muscles (effector) to start running (response).

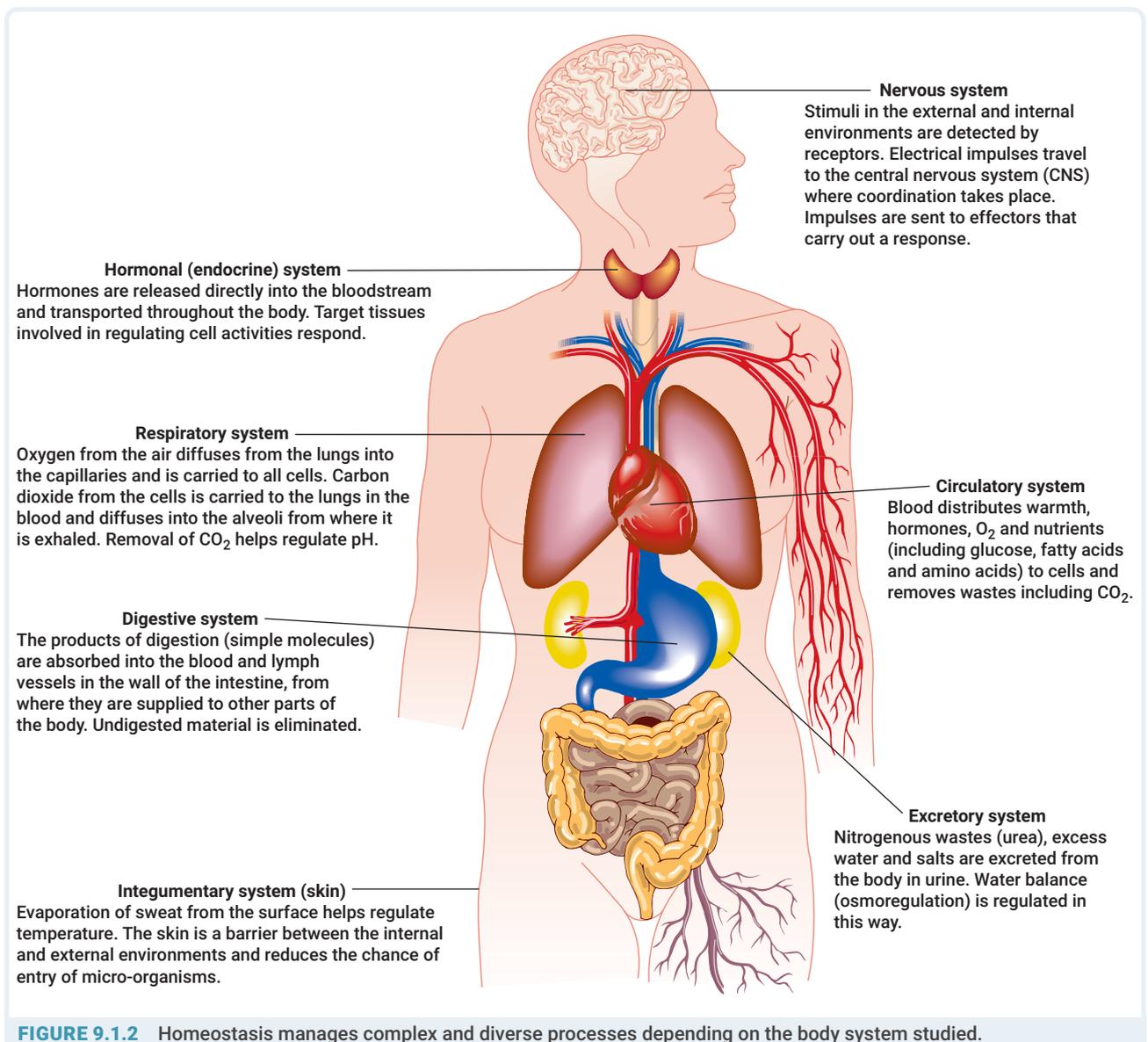
Feedback

As well as responding to external changes in the environment, bodies require very specific internal conditions to operate effectively, such as temperature and levels of water, salts, glucose oxygen and carbon dioxide. **Homeostasis** is the term used to describe the maintenance of a relatively constant internal environment, and although it is often used to refer to balance across the entire organism, homeostasis involves managing a complex and diverse set of homeostatic processes in each body system. **Figure 9.1.2** shows how both the nervous and endocrine systems are involved in homeostasis in the human body.

To maintain a constant internal environment, the body is always making adjustments. In many cases, the response counteracts the stimulus so that conditions within the body stay at optimum levels. This **feedback mechanism** (**Figure 9.1.3**) is a more complex stimulus–response relationship.

homeostasis the maintenance of a relatively constant internal environment within small tolerance limits, despite changes in the external environment

feedback mechanism a physiological process that works to return the condition to its optimal state

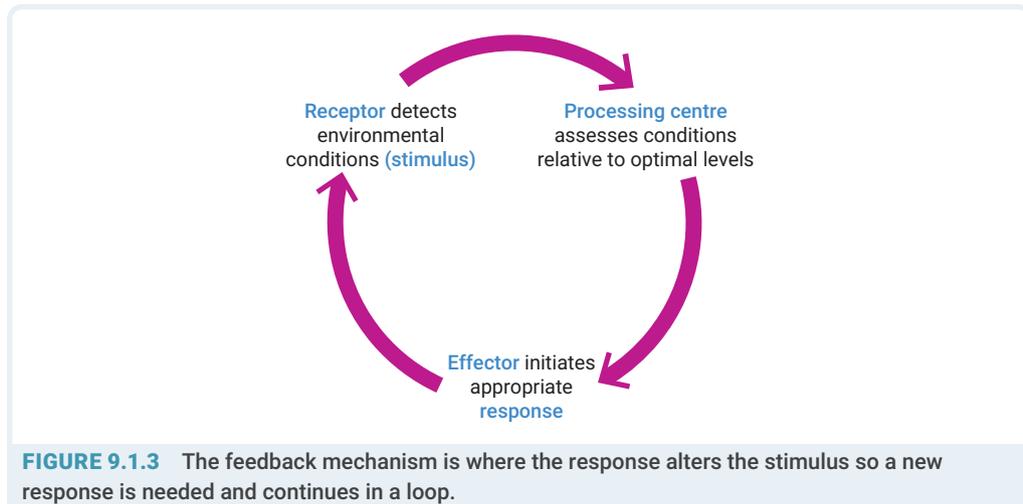




Weblinks

Feedback loops

Negative feedback



negative feedback a cyclic process where responses counteract disturbances to keep concentrations of substances within narrow limits for optimal cellular function

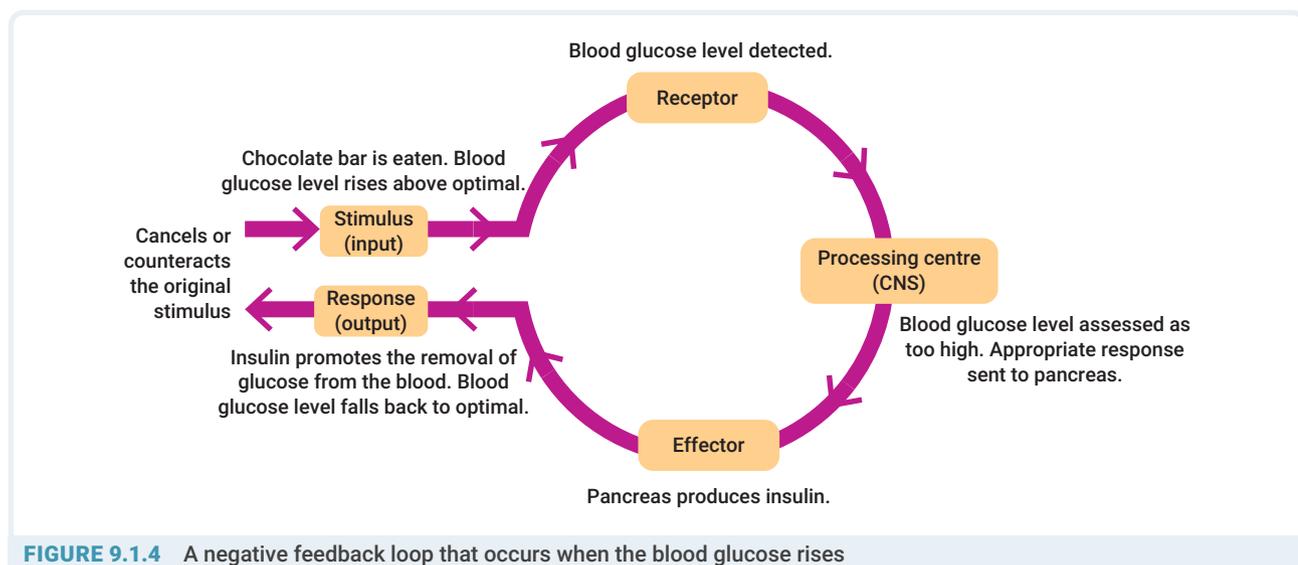
positive feedback a cyclic process where responses reinforce and strengthen disturbances to normal cellular function

optimal level the most favourable condition for effective functioning

Responses that counteract the disturbance are called **negative feedback**, whereas responses that reinforce the disturbance are called **positive feedback**. Homeostasis is, by its nature, a stabilising process that employs mainly negative feedback. Positive feedback, while necessary for some life processes, such as childbirth, is not homeostatic.

Negative feedback

Consider what happens when a bar of chocolate is eaten. Once the chocolate is digested, blood glucose levels rise rapidly above the **optimal level**. The body's response is to lower the blood glucose level to optimal level by removing glucose from the blood and converting it to glycogen for storage in the liver. The level of glucose in the blood drops as the glycogen is stored. If this was allowed to continue, the blood glucose level would drop below optimal level. The body responds to this altered stimulus by breaking down glycogen stores in the liver and returning glucose levels in the blood to optimal level. This is an example of negative feedback because the original stimulus (high blood glucose level) was reduced or cancelled, and an altered or new stimulus (low blood glucose level) comes into effect.





As seen in **Figure 9.1.4**, this interaction between the nervous and endocrine systems can be shown as a diagram. The glucose level in the bloodstream (stimulus) is detected by specialised cells in the pancreas (receptor). The hypothalamus in the brain (processing centre) coordinates this information and directs changes in glucose uptake and output. Glucose levels are stabilised by the pancreas (effector) through the production of hormones, in this case glucagon (if levels are too low) or insulin (if levels are too high), to bring about a response.

Continual maintenance

As conditions within the body are constantly fluctuating, negative feedback is constantly working to support homeostasis. The receptors continually scan the internal environment to ensure the narrow range of appropriate conditions is met. **Figure 9.1.5** shows the process of homeostasis as a continual readjustment of the body conditions to maintain them within set **tolerance limits**.

tolerance limit the most extreme point that internal and external conditions can reach for an organism still to function effectively

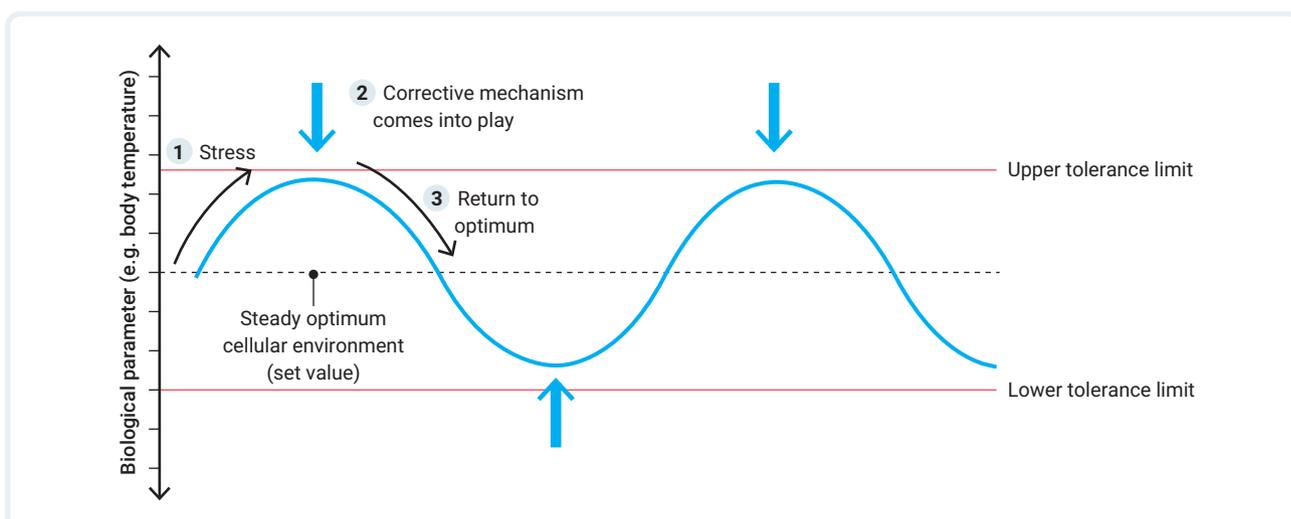


FIGURE 9.1.5 Optimum conditions within the tolerance limits are maintained through negative feedback.

LEARNING CHECK 9.1

DESCRIBING

- 1 State a definition for:
 - a stimulus
 - b receptor
 - c effector
 - d response.

APPLYING

- 2 **Create** a labelled diagram that explains the main components of the stimulus–response model.
- 3 **Explain** how maintenance of blood glucose levels in the human body is an example of negative feedback.
- 4 **Discuss** whether optimum conditions ever exist within our bodies.

ANALYSING

- 5 **Compare** stimulus–response to negative feedback.

9.2 Feedback–control diagrams



Syllabus link
Chapter 8 discusses the role of hormones in homeostatic control pathways.

The negative feedback model can also be displayed in a feedback–control diagram. This is a more complex version of the general stimulus–response model and can contain multiple pathways, receptors and effectors. These diagrams are loops, with the response circling back to the receptor. **Figure 9.2.1** is a feedback–control diagram. It shows what happens in the body after a meal of carbohydrates and blood glucose levels rise.

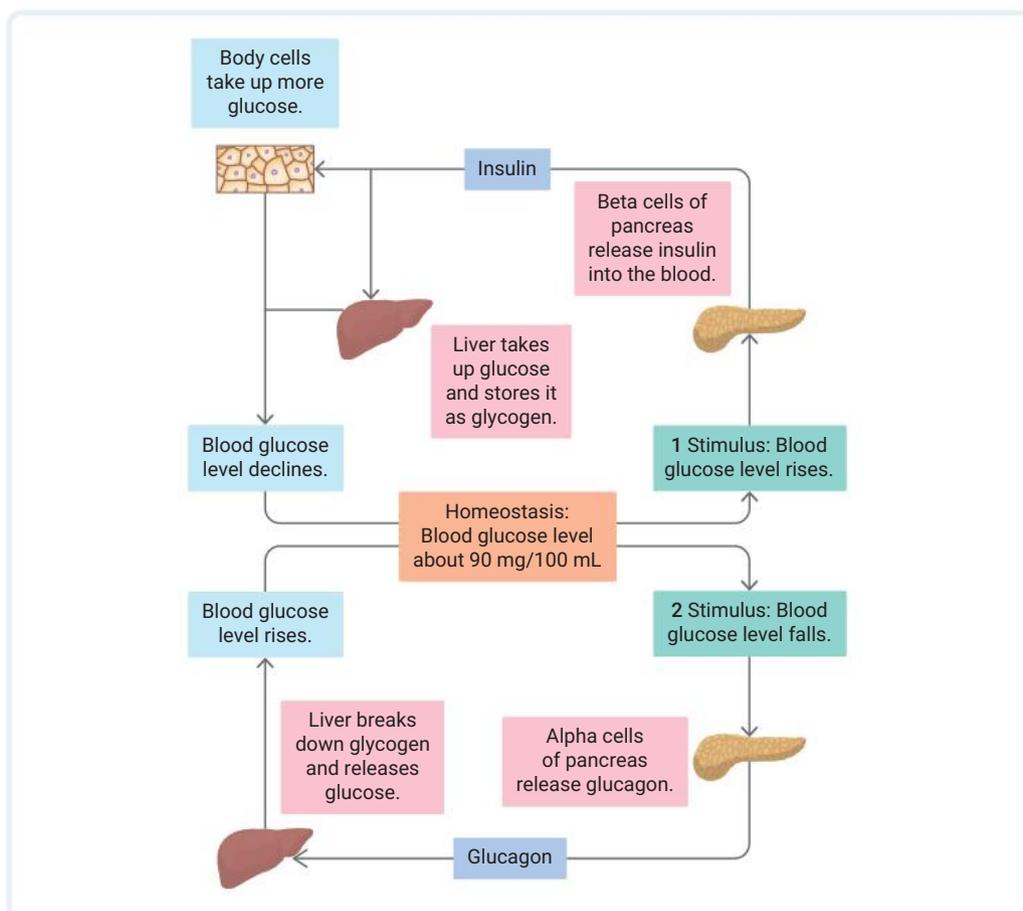


FIGURE 9.2.1 Feedback–control diagrams attempt to incorporate all the physiological responses to a particular stimulus.

Figure 9.2.1 has two parts set out as a figure 8. This is because the response in one half alters the stimulus in the other direction and initiates a different response.

LEARNING CHECK 9.2

DESCRIBING

- 1 **Identify** the stimuli, receptor, processing centre, effector and responses in Figure 9.2.1.
- 2 **Outline** the role of the arrows in feedback–control diagrams.



APPLYING

- 3 Explain** why the pancreas can act as a receptor as well as an effector in the maintenance of blood sugar concentration.
- 4 Explain** the effect on the body's homeostatic processes of removing the pancreas.

9.3 Thermoregulation

Thermoregulation is the process by which **endothermic** animals maintain their body temperature within a normal range. The principle of thermoregulation is maintaining a rate of heat gain that equals the rate of heat loss.

Table 9.3.1 shows various mechanisms an endothermic animal may use to maintain its heat balance.

TABLE 9.3.1 Mammalian mechanisms of controlling body temperature

Structural features	Behavioural responses	Physiological mechanisms
Insulation Brown adipose tissue Shape and size	Kleptothermy (huddling) Torpor Hibernation Aestivation	Vasomotor control Evaporative heat loss Thermogenesis

thermoregulation
the process by which animals maintain their body temperature within a normal range

endotherm an animal that retains heat generated by metabolic activity



Weblinks
Thermoregulation
Hypothermia and hyperthermia

Structural features of endotherms

Structural features refer to how an organism is built and can be external (e.g. wings and feathers) or internal (e.g. size of heart and length of blood vessels).

Insulation

Endotherms that live in very cold environments have evolved structural features to insulate their bodies.

Air is a good insulating material because it is a gas with spread-out particles that do not conduct heat well. Feathers and fur help thermoregulation by trapping an insulating layer of air close to the skin. A polar bear is so well insulated that virtually no heat escapes to the environment (**Figure 9.3.1**).

In hot climates, fur can also act as an insulating material for animals, trapping air and protecting them from radiant heat or hot air around them.

Brown adipose tissue

Unlike regular white adipose tissue, which is used for fat storage, brown adipose tissue is a structural adaptation for generating metabolic heat (**Figure 9.3.2**). Brown adipose tissue contains many blood vessels and a high number of mitochondria per cell, which gives brown fat its characteristic colour and increased heat output. The controlled flow of hydrogen ions in the mitochondria is used to generate heat, instead of adenosine triphosphate (ATP).



FIGURE 9.3.1 The double-layered fur of polar bears is made of hollow hairs; the trapped air helps insulate them against Arctic temperatures.

michaklootwijk/Adobe Stock Photos

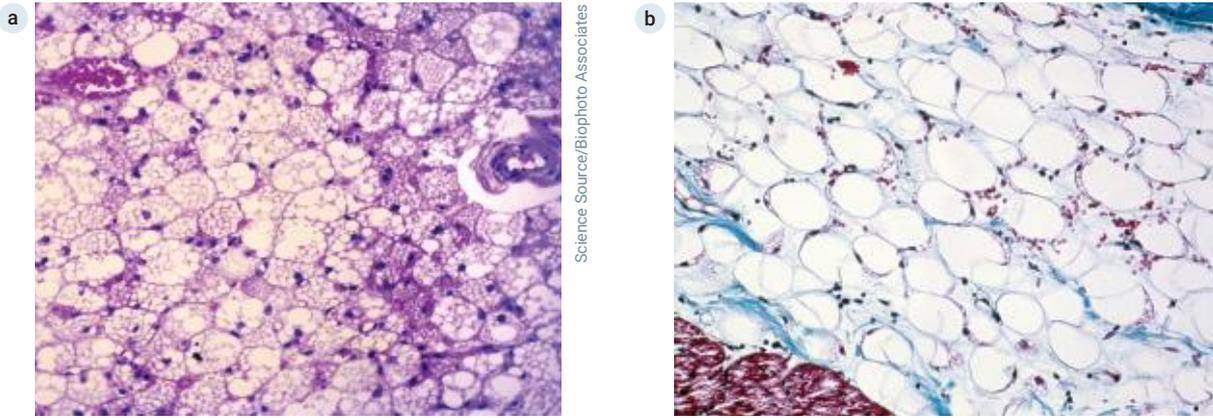


FIGURE 9.3.2 (a) Brown adipose tissue has more mitochondria per cell than (b) white adipose tissue, mostly used for storage of lipids.

Hibernating mammals have high levels of brown fat, and some mammals also have brown adipose tissue in their neck and between their shoulders. In human infants, brown adipose tissue makes up about 5% of their total body weight and gradually reduces with age. Since newborns have a large surface area for their small volume, they are prone to heat loss and brown adipose tissue is a valuable adaptation that generates heat when babies are cold.

Shape and size

The shape of an organism helps to maintain homeostasis and internal temperature. Adaptations that reduce the surface area-to-volume ratio (SA:V) reduce heat loss.

The Arctic fox lives north of the Arctic Circle. The ears and limbs of Arctic foxes are more rounded than those of their relatives the red fox, which was introduced into Australia from Europe, and the fennec fox, which is native to the deserts of North Africa (**Figure 9.3.3**).



FIGURE 9.3.3 Limb and ear shape and size differ between (a) the Arctic fox and its relatives (b) the red fox and (c) the fennec fox.

Thinkstock/MikelLane45; Shutterstock.com/
Volodymyr Burdiak; iStock.com

Behavioural responses

Behavioural responses can also assist endotherms to regulate their internal temperature. To reduce heat gain, dingoes, birds and rock wallabies are diurnal; they shelter from high temperatures, and only emerge to feed in the relative cool of dusk and dawn. Various wallabies and kangaroos also lick their wrists, where the blood vessels form a dense network close to the surface.

Kleptothermy

In 2009, François Brischox and colleagues from Australia used the term **kleptothermy** to describe the form of thermoregulation in which an animal shares the warmth of another animal, such as in huddling. In endotherms, the body heat of one animal in a cool environment is used to maintain the body temperature of another animal. In this way the body heat of both animals can be maintained at a higher and more stable level than would be possible than if they had acted individually.

Emperor penguins survive in the freezing Antarctic temperatures, sometimes as low as -60°C , with this behaviour (Figure 9.3.4). Huddling reduces the group's overall surface area-to-volume ratio exposed to the cold. The centre of the huddle can sometimes get to about 37°C so the central penguins move to the outside to prevent overheating and to share their heat with the colder outside penguins.



FIGURE 9.3.4 Emperor penguins (*Aptenodytes forsteri*) have physiological and behavioural adaptations to survive in the freezing Antarctic temperatures.

Nature Picture Library/Alamy Stock Photo



Weblinks

Temperature regulation strategies

Kleptothermy

torpor a state of decreased physiological activity, usually by a reduced body temperature and metabolic rate

hibernate a period of very low metabolic activity over long periods of cold conditions

aestivation very low metabolic activity in some animals during periods of drought

Shutting down in extreme conditions

Some animals respond to environmental conditions by entering **torpor**. Torpor is a state of decreased activity and metabolism that allows animals to survive unfavourable conditions and/or conserve energy. Torpor results in reduction of body temperature, breathing rate, heart rate, metabolic rate and level of activity and typically lasts a few hours. Many Australian carnivorous marsupials undergo daily torpor, such as the kowari (*Dasyuroides byrnei*) (Figure 9.3.5).

Under extended very cold conditions, torpor may be insufficient to maintain body temperature within tolerance limits. Many animals in these situations **hibernate**, a longer-term version of torpor where the metabolic rate falls to a level that just sustains life (Figure 9.3.6).

Under extended, extremely hot conditions, some animals survive by entering a kind of seasonal dormancy known as **aestivation**. It is similar to hibernation because it involves long-term inactivity and reduced metabolic rate.



FIGURE 9.3.5 A kowari (*Dasyuroides byrnei*)

iStock.com/slowmotionji

In general, aestivation appears to be a fairly 'light' dormancy involving only physiological changes that can be very rapidly reversed. The garden snail moves into the shade, retreats into its shell and seals itself off with a mucus secretion to prevent water loss. Some earthworms coil into balls wrapped in mucus that dries out. Lungfish burrow in mud that hardens, and they remain there until the next rainy season some months later.

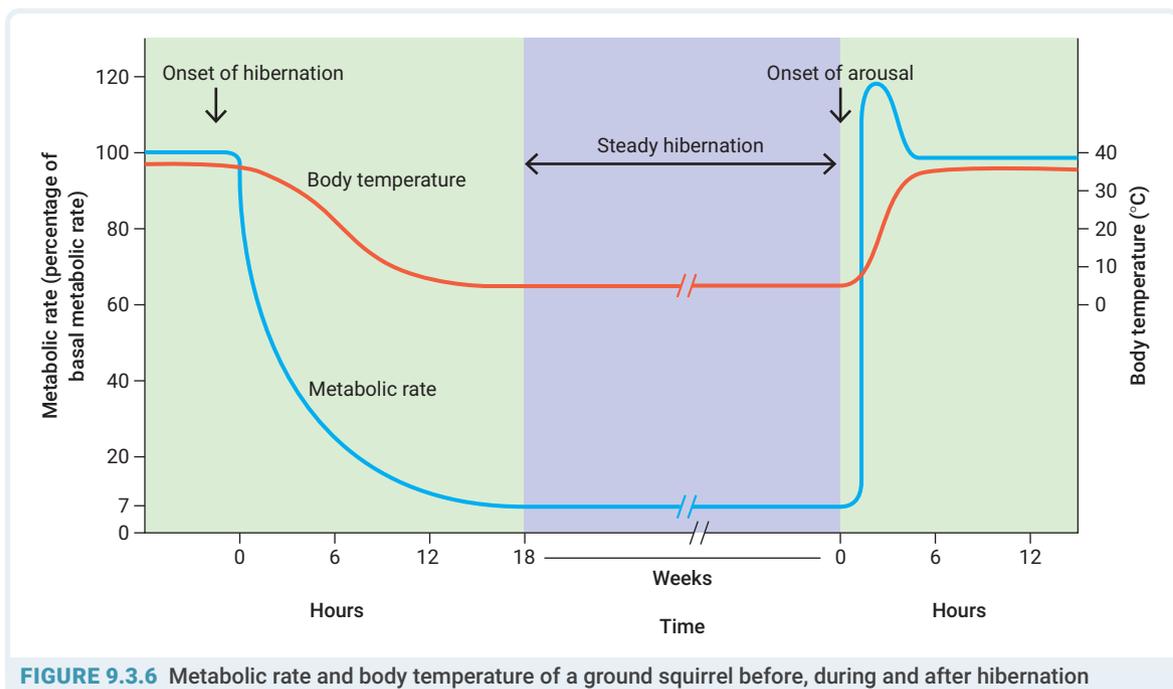


FIGURE 9.3.6 Metabolic rate and body temperature of a ground squirrel before, during and after hibernation

Physiological mechanisms

Thermoregulation can also be achieved by physiological mechanisms, where body systems alter their functioning in response to internal body temperature.

Vasomotor control

Blood that flows close to the surface of the body loses heat to the external environment. In response to a rise in internal core temperature, nerve impulses stimulate the smooth muscles surrounding the arterioles near the skin surface to relax and dilate (**vasodilation**). This dilation allows a lot of blood to flow close to the skin's surface, letting heat escape by radiation. As a consequence of increased blood flow near the body surface, the skin looks redder and feels warm.

The reverse response happens under cold conditions. Nerve impulses cause the smooth muscles surrounding the arterioles near the skin to constrict. This process of **vasoconstriction** decreases the diameter of the blood vessels so blood and heat transfer decrease. **Figure 9.3.7** shows the effect of these two processes on the diameter of a blood vessel.

vasodilation dilation (widening) of blood vessels, particularly arterioles

vasoconstriction the constriction of blood vessels by the surrounding smooth muscle cells, which increases blood pressure and redirects blood flow away from the constricted vessel



Weblink

Thermoregulation mechanisms and the skin



FIGURE 9.3.7 Vasoconstriction and vasodilation is the narrowing or widening of the artery to assist in the maintenance of a stable core body temperature.

Evaporative heat loss

On hot days, sweat glands open to release water and salt onto the skin. Water absorbs considerable heat energy when it changes from a liquid state to a gaseous state in the process of evaporation. Evaporation of water from the skin cools the blood as it flows through capillaries near the surface. Sweating is most effective when the external environment increases evaporation, such as hot, dry, windy conditions. Humid or stuffy conditions reduce the effectiveness of sweating as a thermoregulatory mechanism.

Thermogenesis

While many responses to low temperatures conserve heat, some types of responses generate heat (**thermogenesis**). All metabolic processes produce heat as a by-product, so endotherms can become more active to increase the heat generated by their cells. Shivering – rhythmic tremors as muscles rapidly contract 10–20 times per second – dramatically increases cellular respiration in the muscles. However, it has a high energy cost so it is a short-term adaptation.

Thermoregulation in humans

In humans, the **hypothalamus** acts as a thermostat for internal core body temperature. The hypothalamus is sensitive to the temperature of the blood flowing through it, and, if the temperature varies from the set point (about 36.8°C), it responds by sending impulses to the appropriate effectors.

Figure 9.3.8 shows several human thermoregulatory mechanisms in a feedback-control diagram, including vasoconstriction and shivering when the body temperature drops below normal and vasodilation and sweating when it rises above normal.



Weblink

Control of body temperature

Worksheet

Thermoregulation

thermogenesis the process of heat production in organisms

hypothalamus a region of the forebrain that coordinates the endocrine and nervous systems; it secretes hormones and releasing factors that regulate the anterior pituitary gland, controlling body temperature, thirst, hunger and other homeostatic systems

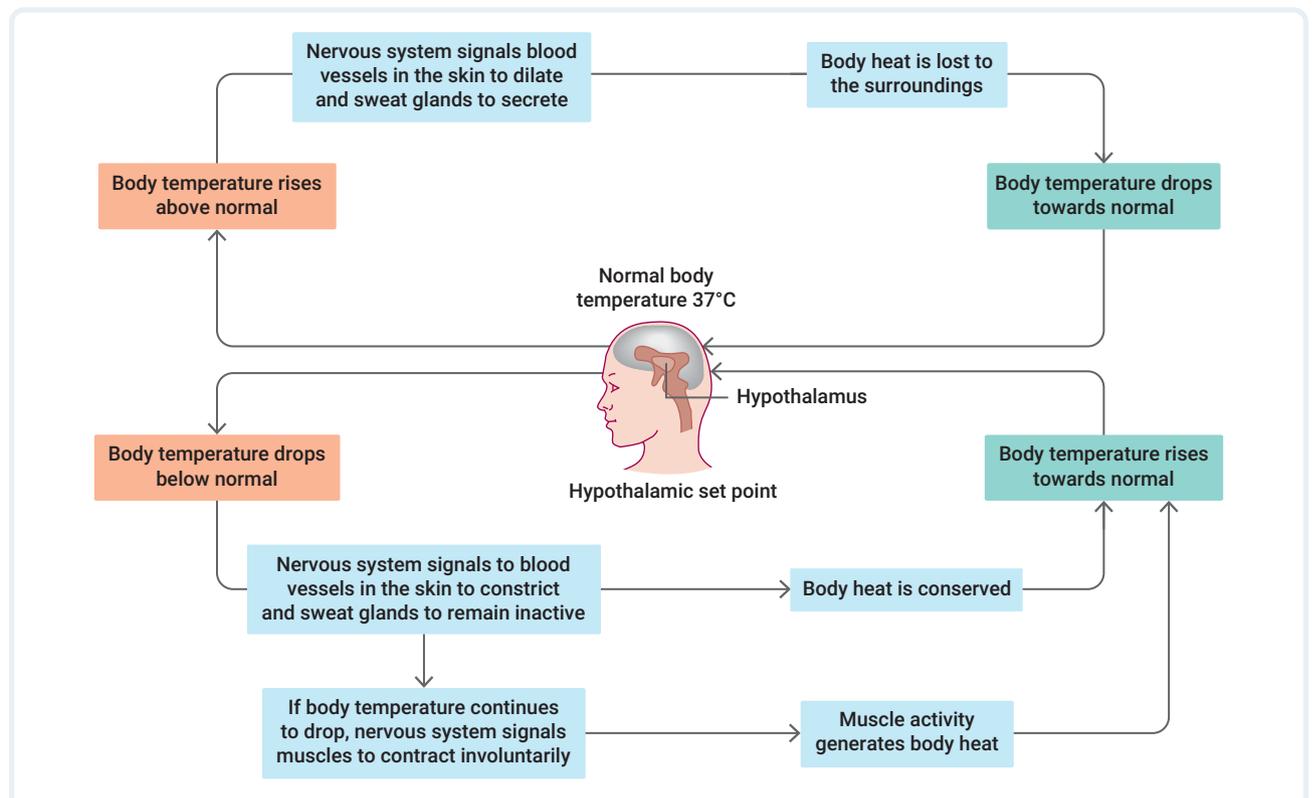


FIGURE 9.3.8 A feedback-control diagram showing thermoregulation in humans

PRACTICAL ACTIVITY 9.3.1

THE SKIN AND TEMPERATURE CONTROL

Introduction

Mammalian body temperature varies little. This practical activity will enable you to explore some of the adaptations that help mammals maintain a fairly constant body temperature.

Research question

How do insulation (IV) and moisture (IV) affect heat lost from an exposed surface in $^{\circ}\text{C min}^{-1}$ (DV)?

Aim

To model and investigate heat loss from an exposed surface

Materials

- 4 test tubes
- 4 thermometers
- 4 beakers
- funnel
- measuring cylinders
- cotton wool (or other insulating material)
- cardboard cylinder (such as from a toilet roll)
- timer
- fan
- spray bottle of warm water



What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Hot water can burn.	Use a funnel and fill test tubes carefully.
Glass can cut if broken.	Alert your teacher if there is any breakage of glass.

Procedure

Part A: Effect of insulation on heat loss

- 1 Label three test tubes A, B and C, and place each test tube into a separate beaker.
- 2 Surround test tube A with cotton wool or another insulating material.
- 3 Place test tube B in a cardboard cylinder. Wrap the outside of the cylinder with the same amount of insulating material as you used for tube A, so that there is a layer of air between the test tube and the insulation.
- 4 Cover the top of the cylinder so the air is trapped.
- 5 Leave test tube C with no insulating material around it.
- 6 Fill each of the three test tubes with 20 mL water at 80°C .
- 7 Insert a thermometer in each test tube and record the temperature as soon as possible after the water is added. In a table, record the temperature every minute for 10 minutes.
- 8 Graph the results.

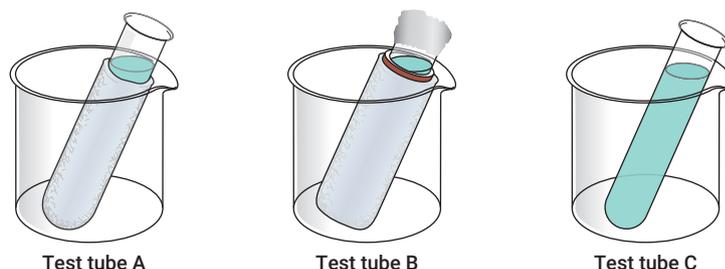


FIGURE 9.3.9 The experimental set-up to investigate the effect of insulation on heat loss

Part B: Effect of moisture on heat loss

- 1 Place four test tubes that have been wrapped in cotton wool in separate beakers. Label them 1, 2, 3 and 4.
- 2 Spray the outside of test tubes 1 and 3 with warm water.
- 3 Place test tubes 1 and 2 in front of a fan, and test tubes 3 and 4 in an area without air movement.
- 4 Fill each of the four test tubes with 20 mL water at 80°C.
- 5 Insert a thermometer in each test tube and record the temperature as soon as possible after the water is added. In a table, record the temperature every minute for 10 minutes.
- 6 Graph your results.

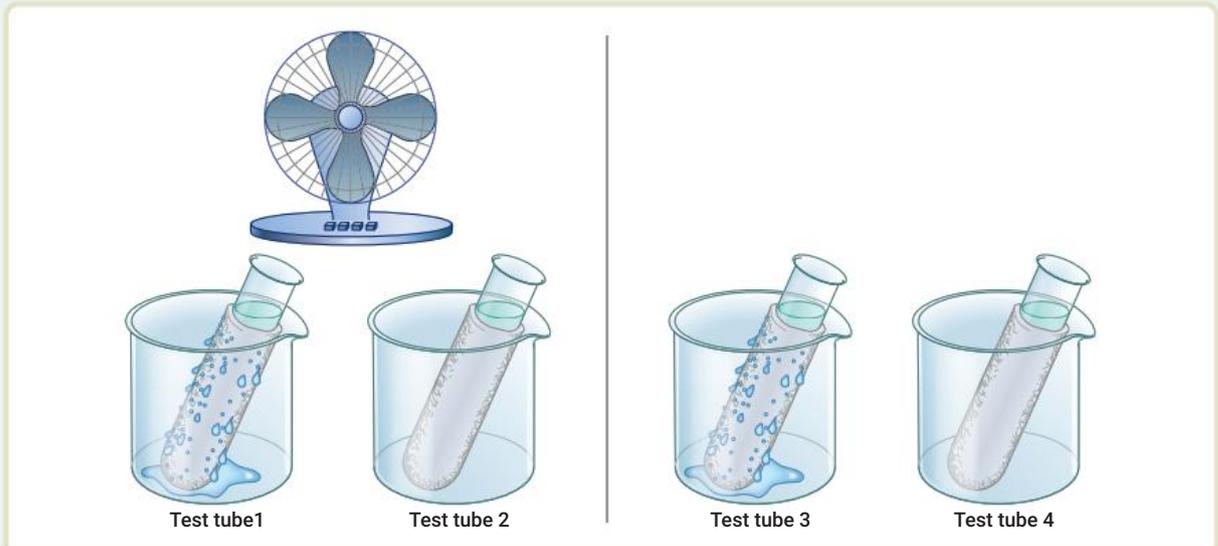


FIGURE 9.3.10 The effect of moisture on heat loss

Results

Record observations in tables.

Analysis of results

- 1 Construct a graph showing the effect of:
 - a insulation on temperature change
 - b moisture on temperature change.
- 2 Which test tube in Part A was the most effective at reducing heat loss? Suggest what makes this set-up most effective at reducing heat loss.
- 3 Which test tube in Part B was the most effective at increasing heat loss?
- 4 Identify any limitations of the data collected.

Interpretation

- 1 What structural feature of mammals is the cotton wool simulating?
- 2 How can an insulating layer of air be achieved in mammals?
- 3 How can the results from test tube B be used to explain the observation that a cat looks larger on colder days?
- 4 Based on the results, suggest why an individual feels cooler on a hot windy day than on a hot, still day.
- 5 Using the observations collected in this experiment, explain why panting in dogs is an effective way of losing body heat.
- 6 Why are animals such as frogs at greater risk of perishing on a hot windy day? Use the experimental results to support your answer.

Evaluation

- 1 Were any experimental controls used in Parts A and B of this experiment? If so, explain what they were and their importance.

Taking it further

- 1 Which part of the experiment modelled the role of perspiration in maintaining body temperature?
- 2 Draw a diagram of a negative feedback model, using the examples of thermoregulation investigated in this experiment. Are all components of a feedback model completely demonstrated in this experimental set-up? Explain your answer.
- 3 When body temperature in mammals starts to drop, several things happen. Describe some of these physiological and behavioural responses. Are any of these responses being modelled in this experimental set-up? Explain your answer.
- 4 When body temperature in mammals starts to increase, different physiological and behavioural responses occur. Describe these responses. Are any of these responses being modelled in this experimental set-up? Explain your answer.

LEARNING CHECK 9.3

APPLYING

- 1 **Explain** how feathers and fur insulate an animal against hot and cold environments.
- 2 **Explain** how huddling reduces heat loss.
- 3 **Explain** how vasodilation helps to maintain internal temperature.
- 4 You will often see a dog panting on a hot day. **Explain** how panting helps the dog maintain a constant internal body temperature.
- 5 Refer to Figure 9.3.8. **Identify** the stimuli, receptor, control centre, effectors and communication pathway.

ANALYSING

- 6 **Compare** the problems faced by endotherms living at high temperatures.
- 7 **Identify** the differences between torpor, hibernation and aestivation.

INTERPRETING

- 8 Refer to Figure 9.3.3. **Deduce** how the size and shape of the ears of different species of fox assist the survival of each species in its environment.



Syllabus link

Chapter 3 described the structure and function of the mammalian excretory system.

osmoregulation the processes by which internal water and solute concentration are maintained despite fluctuations in the external environment

extracellular fluid the fluid that bathes the outside of cells in multicellular organisms

9.4 Osmoregulation

The function of **osmoregulation** is to control solute concentration in cells. To do this, the body makes compensatory adjustments to the **extracellular fluid** to maintain its volume and composition. In vertebrates, an excretory system is important to balance the intakes and output of water and solutes.

Humans are osmoregulators who regulate water balance to be either higher or lower than our external environment so we can live in and move between different environments.

Water balance feedback mechanism

The feedback mechanism for the maintenance of water balance in humans is determined by the **osmotic pressure** of the blood. If there are high amounts of solutes in the blood, then the osmotic pressure is high. If there are low amounts of solutes in the blood, then osmotic pressure is low.

Osmoreceptors in the hypothalamus of the brain detect the rise in osmotic pressure of the blood. When the receptors are stimulated, the hypothalamus sends an impulse to the pituitary gland, which is situated in the brain below the hypothalamus. The pituitary gland releases **antidiuretic hormone (ADH)** (also called vasopressin) into the bloodstream.

The role of ADH

ADH is a water-soluble, or hydrophilic, hormone. Water-soluble hormones cannot pass across the cell membrane because of their charge and size. Instead, they bind to extracellular receptors that are embedded in the cell membrane. ADH receptors are located on the cell membranes of collecting duct cells in each nephron within the kidney (**Figure 9.4.1**). As it binds, the receptor changes its structure and releases a type of protein known as a G protein, which is attached to the receptors on the inside of the cell membrane. This activates proteins inside the cell, setting off a cascade of intracellular signalling that transmits the message through the cell to effector proteins, which are stimulated to elicit a response.

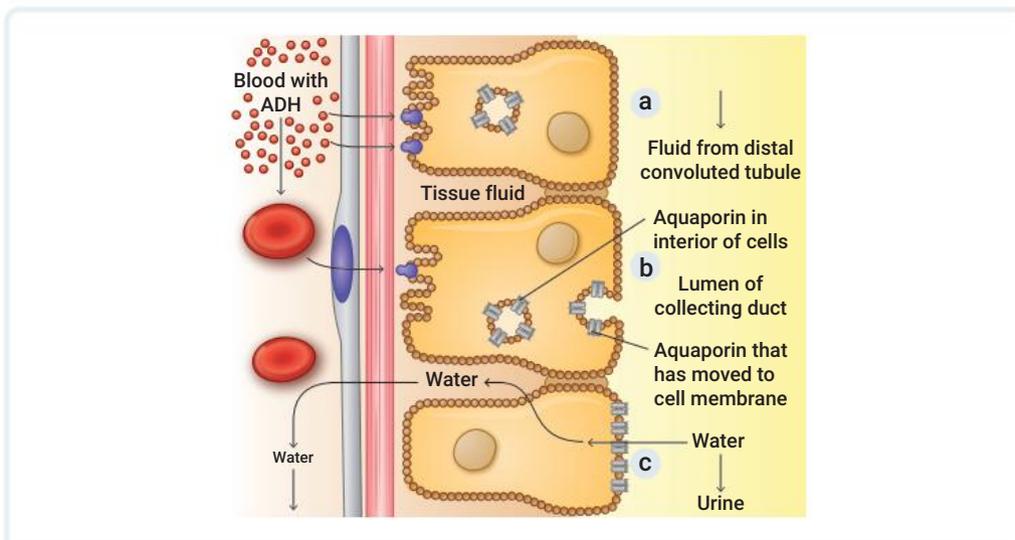


FIGURE 9.4.1 (a) ADH binds with the receptors on the cell membrane of collecting duct cells. (b) It causes aquaporins to move from inside the cell to the cell membrane. (c) Water can now be reabsorbed from inside the collecting duct, passing through the cell and back into the bloodstream.

The response is to move water channels (aquaporins) attached to vesicles in the interior of the cells to the cell membrane to increase the number of aquaporins in the cell membrane. When there are more aquaporins on the surface of the cell membrane, the cell is much more permeable to water. Water flows from the fluid in the adjacent collecting duct, through the open aquaporins and into the cell. The water then diffuses by osmosis into the adjacent bloodstream, increasing the amount of water in the blood. When fluid is removed from the fluid in the collecting duct, more concentrated urine is produced.

osmotic pressure the concentration of solutes in the blood



Weblink
Importance of osmoregulation in humans

antidiuretic hormone (ADH) a hormone responsible for increased permeability of the distal tubules of the kidney, increasing water reabsorption and reducing urine volume



Worksheet
Osmoregulation

Increasing reabsorption of water with ADH is only a temporary measure though, because water is still continually used by cellular respiration. Another physiological response to high osmotic pressure is feeling thirsty, which continues to increase in urgency until the osmoregulator drinks.

Drinking a large volume of water results in the osmotic pressure of the blood falling below its normal value, reducing stimulation of the osmoreceptors in the hypothalamus. As a result, negative feedback decreases the release of ADH from the pituitary gland, so less water is reabsorbed by the kidney. This results in the production of greater volumes of urine, which is more dilute. **Figure 9.4.2** shows how osmoregulation works in humans.

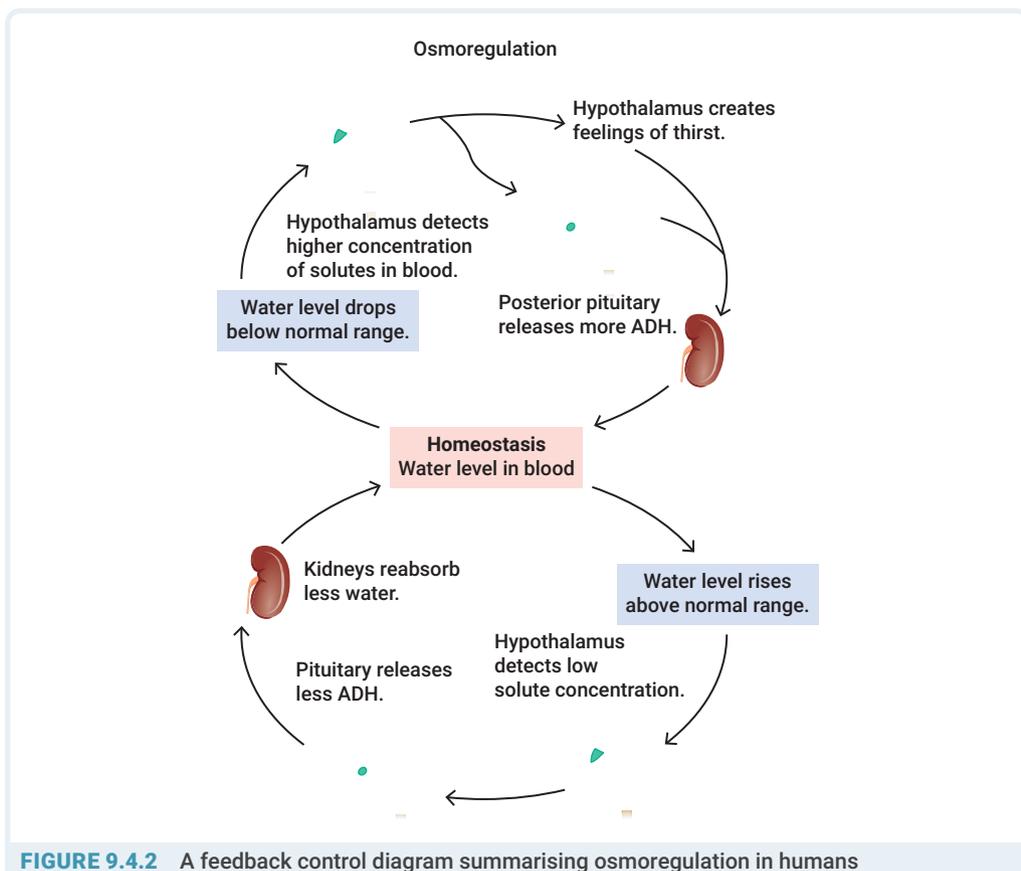


FIGURE 9.4.2 A feedback control diagram summarising osmoregulation in humans

LEARNING CHECK 9.4

DESCRIBING

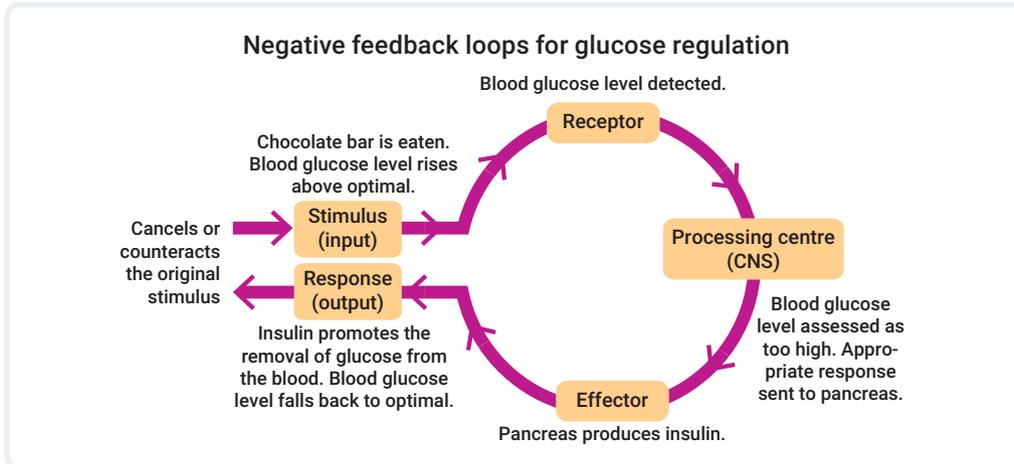
- 1 **Describe** the function of osmoregulation.
- 2 **State** where ADH is produced.

APPLYING

- 3 **Explain** the effect of ADH on the cells lining the collecting duct in the nephrons.
- 4 Refer to Figure 9.4.2. When the osmotic pressure of the blood rises, **identify** the receptor, effector and response.

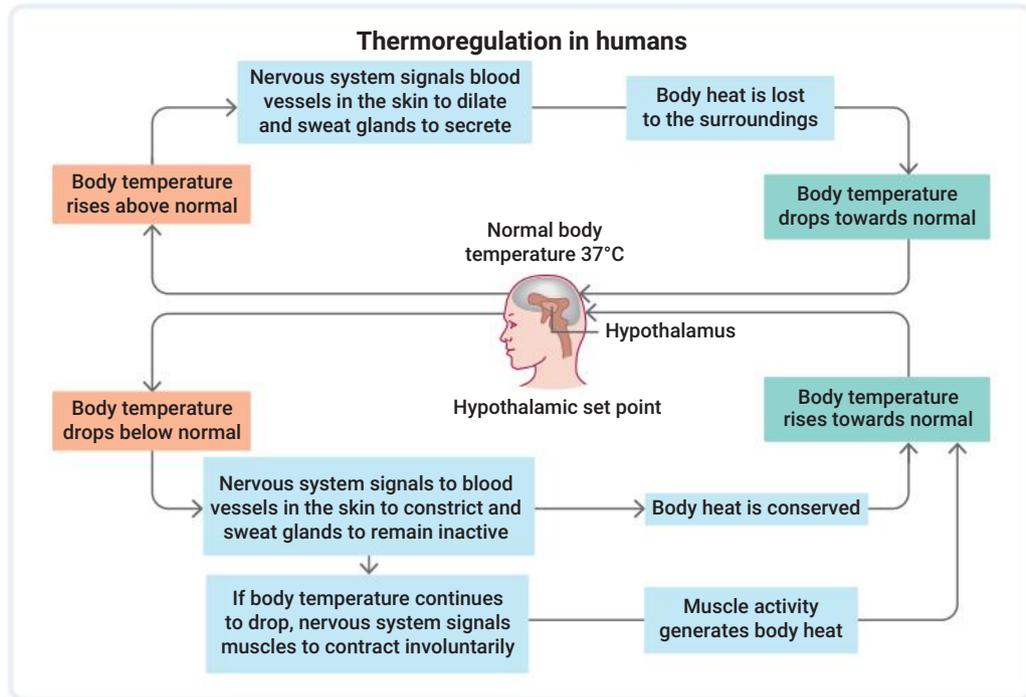
Negative feedback

- The nervous and endocrine systems use **negative feedback**, where the response counteracts the stimulus, to maintain homeostasis.

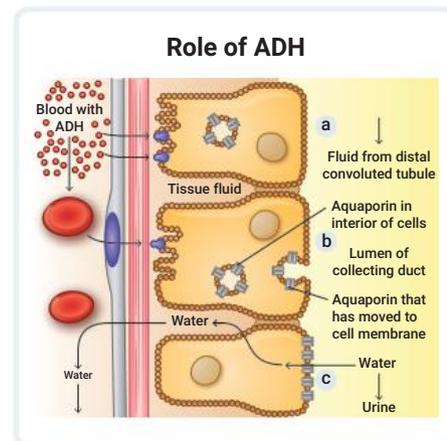
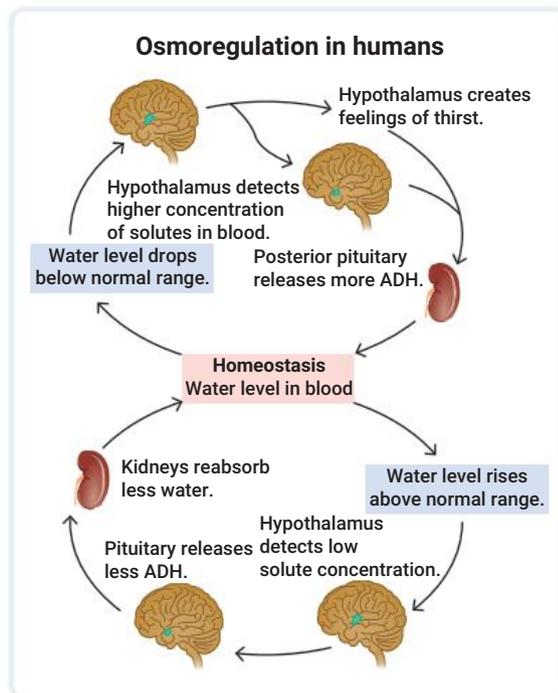


Thermoregulation

Structural features	
Insulation	Fur or feathers to trap a layer of air against the skin
Brown adipose tissue	Many mitochondria to conduct cellular respiration to generate heat
Size and shape	Larger, rounder bodies to conserve heat by reducing surface area-to-volume ratio
Behavioural responses	
Kleptothermy	Huddling with other individuals to heat each other
Torpor	State of low metabolic activity for a few hours
Hibernation	State of very low metabolic activity for several months
Aestivation	State of very low metabolic activity for variable duration
Physiological mechanisms	
Vasomotor control	Dilation or constriction of surface blood vessels to increase or decrease heat loss by radiation
Evaporative heat loss	Sweating to allow evaporation of water to remove heat from skin
Thermogenesis	Involuntary movement to increase cellular respiration to generate heat



Osmoregulation



- Antidiuretic hormone (ADH) is secreted by the pituitary gland in response to the detection of high osmotic pressure. It increases the number of aquaporins on the surface of the nephron's collecting duct, allowing more water to be reabsorbed into the bloodstream.

MULTIPLE CHOICE

- In a stimulus–response model the correct progression of events is:
 - stimulus, effector, processing centre, receptor, response.
 - stimulus, receptor, processing centre, effector, response.
 - stimulus, receptor, effector, response, processing centre.
 - response, receptor, processing centre, effector, stimulus.
- The two body systems that interact to maintain overall homeostasis in the human body are:
 - nervous and excretory.
 - nervous and endocrine.
 - endocrine and excretory.
 - endocrine and respiratory.
- Homeostasis is best described as the:
 - process that describes all the body’s functions.
 - maintenance of a relatively constant internal state.
 - maintenance of a fixed and unaltered internal state.
 - ability of the body to manipulate the external environment.
- In a negative feedback model, an effector:
 - detects a stimulus.
 - assesses the situation.
 - could be a muscle or gland.
 - causes a feedback loop to start.
- Which of the following is a behavioural response employed by endotherms in extremely cold environments to maintain a constant body temperature?
 - Aestivation
 - Thermogenesis
 - Kleptothermy
 - Vasomotor control
- A physiological response to an increase in body temperature is:
 - a person shivering.
 - a desert snail undergoing aestivation.
 - penguins huddling together.
 - an animal developing deposits of brown adipose tissue.
- The temperature control centre in mammals is in the:
 - skin.
 - thyroid gland.
 - pituitary gland.
 - hypothalamus.

8. It is essential that humans maintain their core body temperature at or about 36.8°C. If core body temperature increases above this, the receptor will send a signal to effectors to bring about a response to lower the core body temperature. In this case, the response would be:
- A vasodilation and sweating.
 - B vasoconstriction and sweating.
 - C vasodilation and stop sweating.
 - D vasoconstriction and stop sweating.
9. The function of osmoregulation is to control the:
- A solute concentration in cells.
 - B solvent concentration in cells.
 - C solution concentration in cells.
 - D water concentration in cells.
10. When the osmotic pressure of the blood falls, you would expect:
- A more ADH to be secreted into the blood.
 - B less ADH to be secreted into the blood.
 - C a feeling of thirst.
 - D the kidneys to reabsorb more water back into the bloodstream.

SHORT RESPONSE

11. An experimenter in a science laboratory rings a bell. This bell is heard by a dog, who then starts to salivate because it thinks it is going to get fed.
- a **Identify** the stimulus, receptor, processing centre, effector and response in this example.
 - b **Create** a stimulus–response diagram that illustrates this example.
 - c **Compare** a stimulus–response model to a negative feedback model.

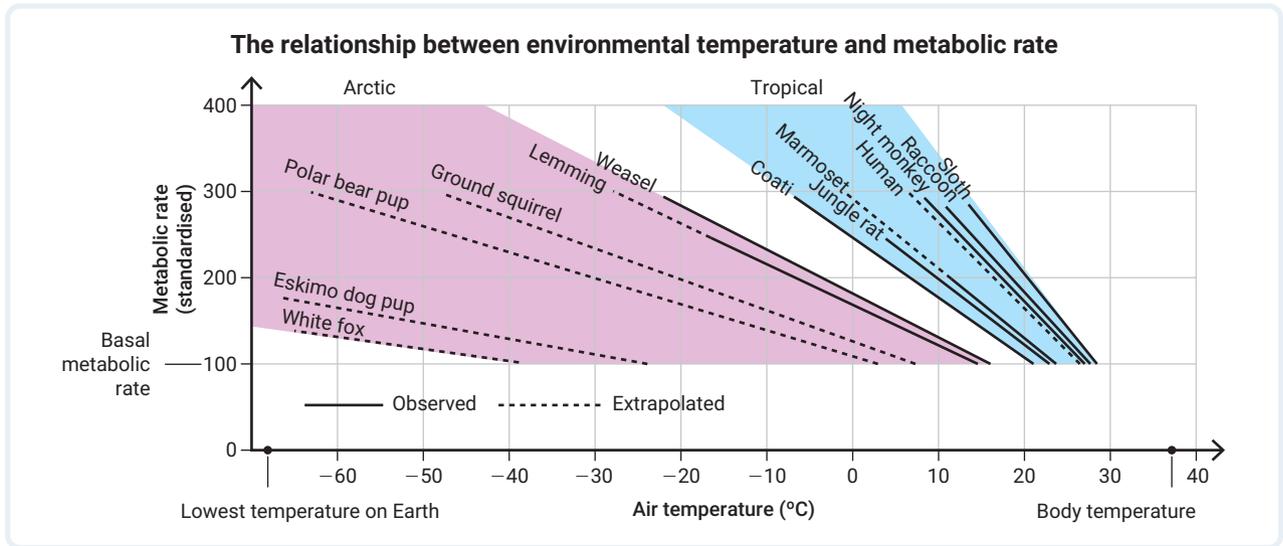
CROSS-CHAPTER QUESTION

12. Assume a person is at rest in a room at 23°C. **Predict** the effect on the quantity and composition of this person's urine after:
- a drinking a large amount of water
 - b eating a very salty meal.

DATA ANALYSIS

Questions 13 and 14 refer to the following information.

The figure below shows the relationship between environmental temperature and the metabolic rate of different animals. The basal metabolic rate for each animal is given a value of 100%. Any increase in metabolic rate is in relation to this value.



13. Analyse evidence

Compare the metabolic rate of the ground squirrel to the Eskimo dog pup.

14. Interpret evidence

Deduce, with appropriate reasoning, the likelihood of a jungle rat surviving at:

- a 0°C
- b -40°C

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

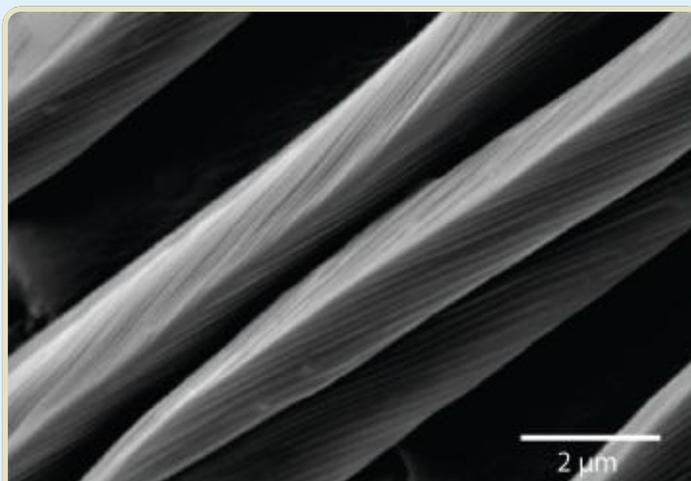
- Appreciate that understanding natural systems can lead to advances in technology and engineering.

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Wearable carbon nanotubes

If you have ever worked outside on a hot and humid day, you will know that it can quickly become uncomfortable. The textiles that make up your clothing trap infrared radiation (heat). Infrared radiation has a wavelength around $10\ \mu\text{m}$. This causes a layer of heat to build up near your skin. As your internal core temperature rises, your body kicks into thermoregulatory mode and your sweat glands open in an attempt to cool your body down. This only serves to saturate your clothing and make you feel more uncomfortable. Wearing natural fibres like linen, which have a more open weave than synthetic materials, can help by letting the heat escape from your body.

Inspired by Saharan silver ants that have triangular-shaped hairs (**Figure 1**) that reflect heat depending on the Sun's position, Xu Zhang and colleagues from the University of Maryland, USA, investigated the possibility of creating a fabric that could act in a similar way.



Willot Q, Simonis P, Vigneron J-P, Aron S (2016) Total Internal Reflection Accounts for the Bright Color of the Saharan Silver Ant. PLoS ONE 11(4): e0152325. <https://doi.org/10.1371/journal.pone.0152325>

FIGURE 1 Microscopic studies on the hair on Saharan silver ants revealed them to be triangular in shape.

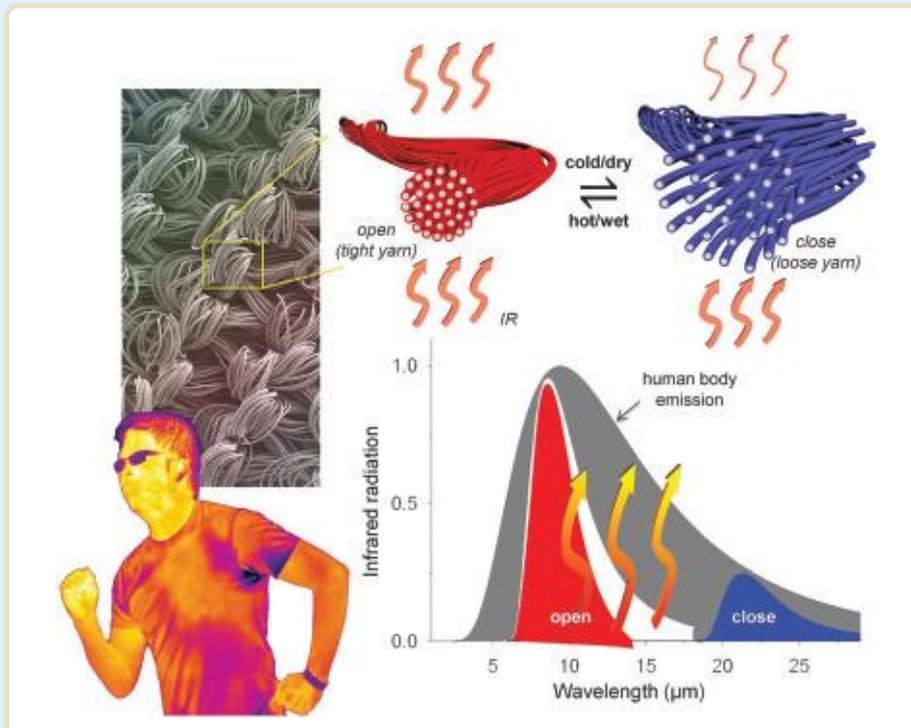
They set about to engineer an infrared-adaptive textile that could regulate thermal radiation to make the wearer feel more comfortable. They proposed that each textile yarn be composed of:

- a bundle of metafibres that have a conductive element added in controlled quantities to the polymer textile fibres
- an actuation mechanism (to get the process to start) that responds directly to changes in temperature and/or relative humidity of the skin.

To meet the first requirement, the scientists created a textile composed of polymer fibres coated with carbon nanotubes. Carbon nanotubes have excellent thermal conductivity, and are chemically stable, mechanically flexible and lightweight.

To meet the second requirement, they used a hydrophobic ('water-hating') triacetate and a hydrophilic ('water-loving') cellulose. Upon meeting water, as in sweat, the hydrophilic cellulose absorbs more water and swells. The hydrophobic triacetate repels the water and stays the same size. This acts to open up the spaces between the fibres.

This means it is possible to effectively open and close the fibres of the textile in response to environmental change (Figure 2). When the body is hot and sweaty, each yarn collapses into a tight bundle, making each yarn smaller and opening up the weave of the textile. This allows heat and moisture to escape. When the body is cold and dry, the yarn becomes loose, decreasing the size of the pores in the weave and trapping heat and moisture close to the body (Figure 2).



Zhang X. A., Yu S., Xu B., Li M., Peng Z., Wang Y., Deng S., Wu X., Wu Z., Ouyang M., & Wang Y. (2019). 'Dynamic gating of infrared radiation in a textile'. *Science*, 363(6427), 619–623. <https://doi.org/10.1126/science.aau1217>

FIGURE 2 The weave of the textile could be closed (blue) or open (red) depending on the temperature and humidity of the wearer.

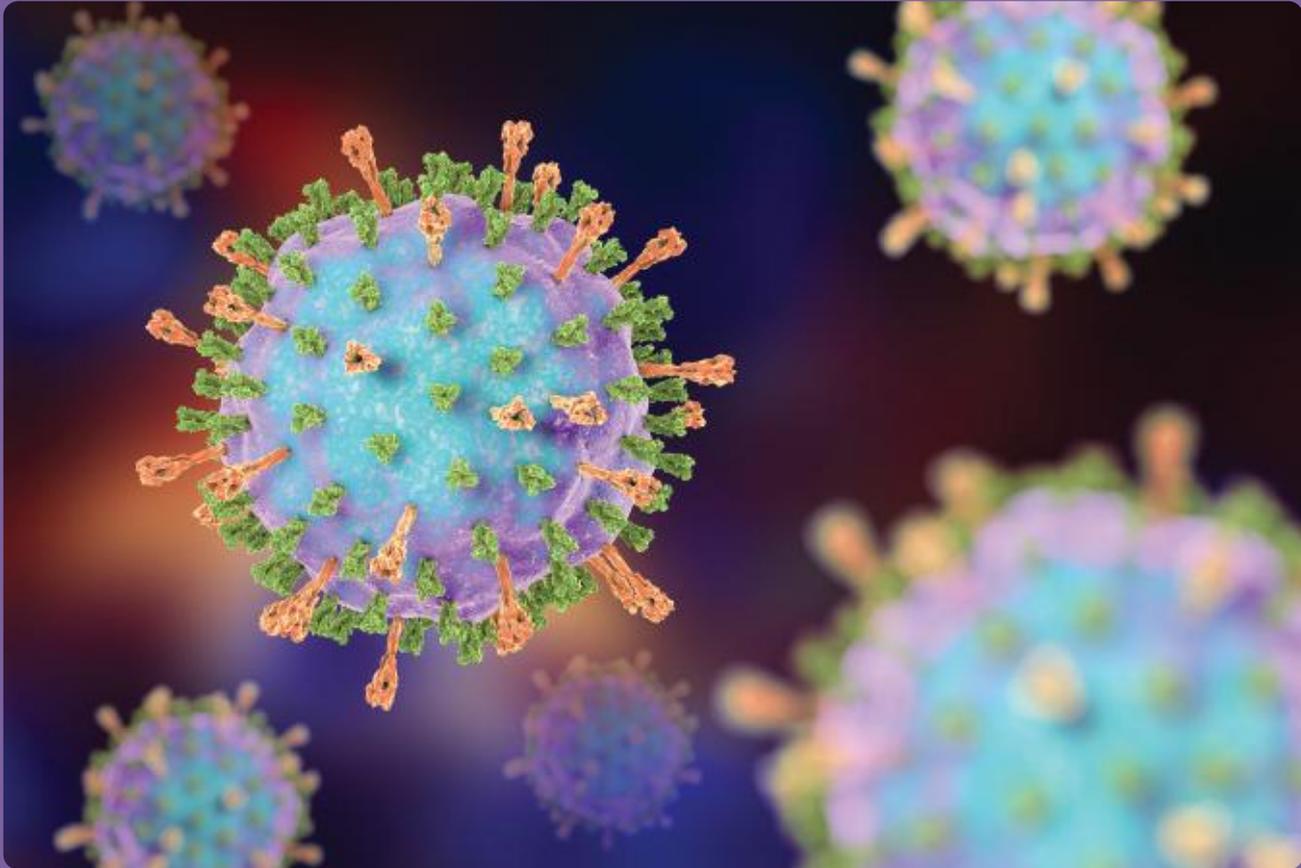
The knitted textile can be dyed and washed in a similar way to other fabrics, and could be used as wearable thermal-management clothing.

Reference

Zhang XA, Yu S, Xu B, Li M, Peng Z, Wang Y, Deng S, Wu X, Wu Z, Ouyang M, Wang Y. (2019). Dynamic gating of infrared radiation in a textile. *Science*, 363(6427): 619–623. <https://www.science.org/doi/10.1126/science.aau1217>

CHAPTER
10

Infectious disease



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**SYLLABUS
DOT POINTS**

SCIENCE UNDERSTANDING

- Distinguish between infectious and non-infectious disease.
- Identify key features of prions, viruses, bacteria, fungi, protists and parasites.
- Explain how adherence factors, invasion factors, capsules and toxins affect pathogenesis.
- Interpret data from an experiment investigating the effect of an antimicrobial agent on the growth of a microorganism.

SCIENCE INQUIRY

- Investigate the effect of an antimicrobial agent on the growth of a microorganism (via the measurement of zones of inhibition) in either a laboratory or virtual context.

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Introduction

History shows that diseases have repeatedly reduced human populations. Tuberculosis has been infecting humans for many thousands of years and evidence of its presence has been found in Egyptian mummies dating from 1000 BCE. Cholera and smallpox epidemics were rife for centuries and the plague threatened to wipe out most of Europe during the 14th century.

Infectious diseases are caused by different types of pathogens with highly specified mechanisms for survival and reproduction. Infections from a range of pathogens, including Zika virus, Ebola virus and COVID-19 continue to affect millions of people each year.

Practical

- Antimicrobial agents

Worksheets

- Getting to know tuberculosis
- Pathogens and their diseases

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Weblink
Infectious and
communicable diseases

infectious disease a disease caused by a pathogen that can be transmitted from one organism to another

pathogen a disease-causing agent

host an organism that is infected by a pathogen

non-infectious disease a disease that is not transmitted from one organism to another

communicable can be communicated (transmitted) from one organism to another

genetic disease a disease arising from DNA mutations inherited from parents

immune system a complex network of cells, tissues and organs in the body that detects differences between 'self' and foreign organisms, and mounts an immune response

autoimmune disease a condition where the immune system attacks the body's own tissues

ASSUMED KNOWLEDGE

- ✓ Prokaryotic and eukaryotic cells share similar structures but due to their specific function, also have cellular features that are different.
- ✓ Different organelles have different functions.
- ✓ Genetic information is contained within DNA.
- ✓ Protein structure is determined by DNA sequences.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ identify differences between infectious disease and non-infectious disease
- ✓ use information provided to classify diseases as infectious or non-infectious
- ✓ list the key characteristics of each type of pathogen
- ✓ give reasons why some factors make a particular disease more effective or able to survive for longer.

10.1 What is disease?

A disease is any condition that interferes with how an organism, or any structure within it, functions. Diseases can be grouped according to their cause.

Infectious diseases can be transmitted from one individual to another. An agent that causes an infectious disease is called a **pathogen**. The infected organism is the **host**. Infectious diseases such as COVID-19, salmonella or tinea are caused by pathogens that include prions, viruses, bacteria, fungi, protists and parasites.

Non-infectious (chronic) **diseases** are not **communicable** – they cannot be transmitted from one individual to another. They are the result of genetic, behavioural, physiological (metabolic) and/or environmental factors. The World Health Organization lists the main types of chronic diseases as cardiovascular disease, cancers, chronic respiratory diseases (e.g. asthma) and diabetes.

Genetic diseases or disorders are due to DNA mutations inherited from parents. They are numerous and include cystic fibrosis, phenylketonuria and haemophilia. Environmental factors include air pollution or radiation. Behavioural factors include exercise, diet or use of drugs/alcohol. Physiological factors include high blood pressure, obesity, high blood sugar levels or high blood lipid levels.

The **immune system** is responsible for detecting the difference between its own cells and those of other organisms. Sometimes a malfunction causes illness. When tissues are attacked by the body's own defence system, **autoimmune diseases** (*auto* meaning 'self') such as rheumatoid arthritis, multiple sclerosis and lupus can result.

LEARNING CHECK 10.1

DESCRIBING

- 1 State a definition for:
 - a disease
 - b pathogen
 - c communicable.

- 2 **Identify** the types of organisms that can cause disease.
- 3 **Describe** the relationship between a pathogen and its host.
- 4 Using examples, state differences between an infectious disease and a non-infectious disease.

10.2 Pathogens

Progress in understanding infectious disease was slow. This was in spite of physician Ignaz Semmelweis, in 1847, reducing mortality in maternity wards through pioneering handwashing by doctors and Florence Nightingale demonstrating the importance of hand hygiene during the Crimean War in 1853–1856. It was not until the end of that century that the work of Louis Pasteur and Robert Koch provided convincing evidence that infectious diseases were caused by pathogens.

Viruses

A **virus** is a non-cellular agent composed of a protein coat and nucleic acid (Figure 10.2.1), either DNA (Figure 10.2.2) or RNA, but never both.

When a virus infects an organism, it injects its nucleic acid into a host cell. Once inside, the viral nucleic acid takes over the host cell and instructs it to make multiple copies of the viral protein coat and nucleic acid. These then assemble into new viruses and are released when the host cell undergoes lysis (splits open). This releases many more viral particles, which can infect other cells within the host (Figure 10.2.3). Exposure to cold and wet conditions might lower a person's resistance to the virus but cold and wet conditions are not the cause of the disease.

virus a non-cellular agent composed of a protein coat and nucleic acid



Weblink
A virus attacks a cell

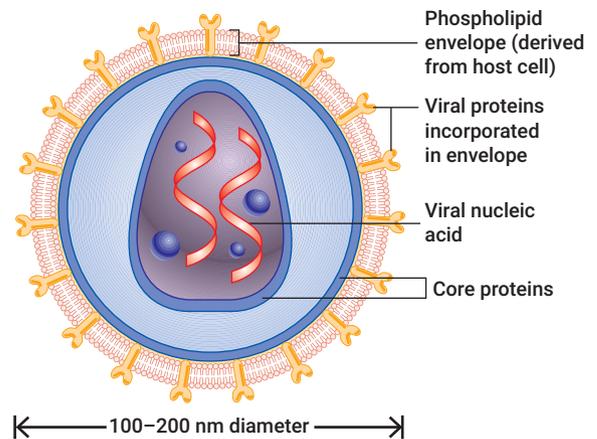


FIGURE 10.2.1 Viruses consist of a nucleic acid core surrounded by a protein coat.

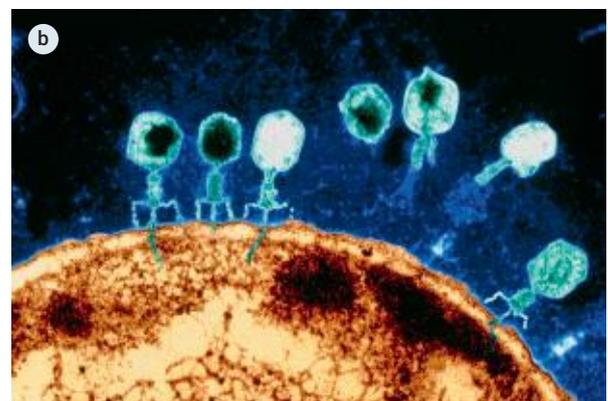
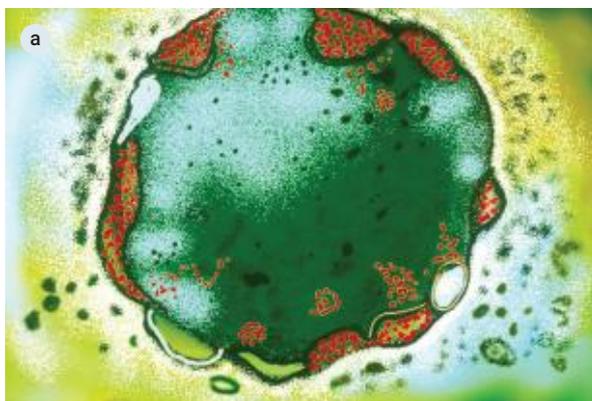


FIGURE 10.2.2 (a) The DNA virus that causes herpes in humans. (b) A coloured transmission electron micrograph of T-bacteriophage viruses attacking a bacterial cell of *Escherichia coli*. Seven virus particles are seen (blue), each with a head and a tail. Small blue tails of genetic material (DNA) are being injected into the bacterium.

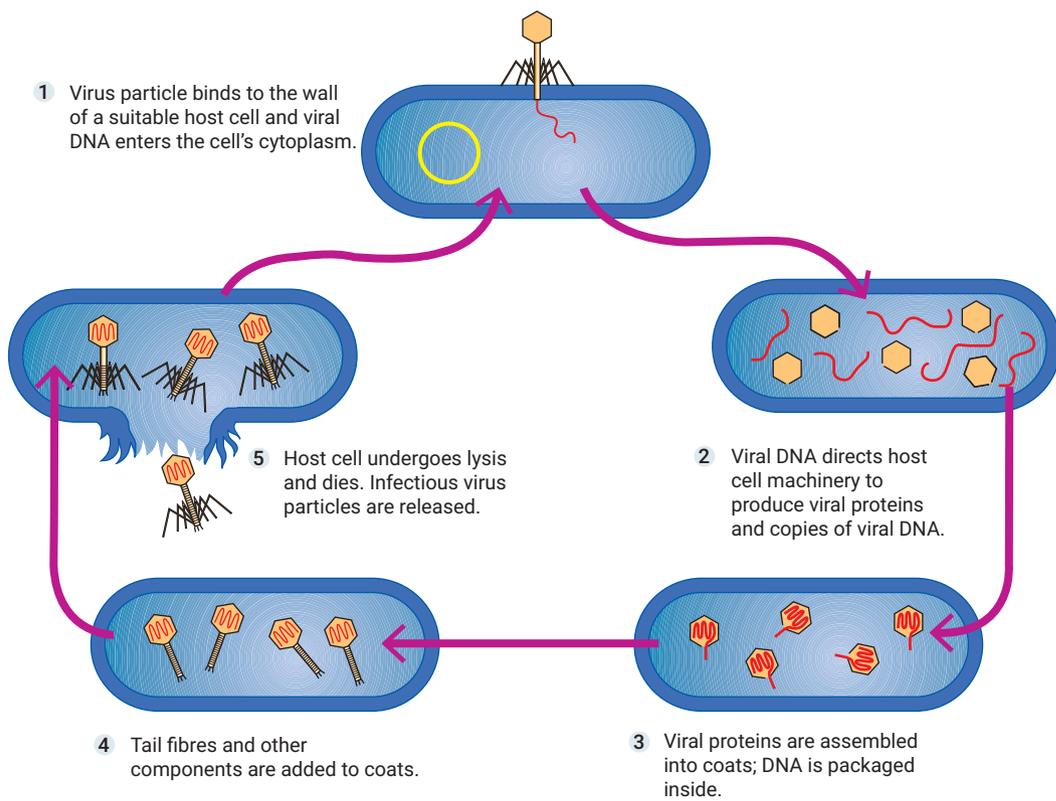


FIGURE 10.2.3 Viruses reproducing inside a live bacterial cell. New viruses are produced within the infected bacterium.



FIGURE 10.2.4 This apple tree is afflicted with the apple mosaic virus, one of the oldest known and most widespread apple viruses.

bacteriophage a virus that invades bacteria

All viruses cause disease, as they completely rely on host cells for their reproduction. Unlike bacteria, viruses cannot be grown and studied outside live cells. This puts limitations on viral research.

Each virus is usually highly specific to the host cell or organism it can infect. For example, an adenovirus specifically infects epithelial cells in the upper respiratory tract, causing respiratory infections. This is because the virus can recognise and bind to receptors that are expressed only on respiratory tract epithelium.

Virtually every type of organism on Earth is susceptible to viral infection (**Table 10.2.1**). Viruses are significant pathogens of many plants, sometimes resulting in the loss of crops such as potato, tobacco, corn and apples (**Figure 10.2.4**). Even bacteria have their own group of viral pathogens, known as **bacteriophages**.

TABLE 10.2.1 Some diseases caused by viruses

Virus	Disease	Symptoms
<i>Herpes simplex</i> type I	Cold sores	Recurring blisters on skin, usually around mouth
<i>Herpes simplex</i> type II	Genital herpes	Recurring blisters in genital area; affects both males and females
<i>Varicella zoster</i>	Chickenpox	Fever, pink spots that blister and burst
Hepatitis A virus (a retrovirus)	Hepatitis A	Inflammation of liver, kidney, spleen; jaundice, fatigue, aching limbs, headache
HIV (a retrovirus)	AIDS	Fatigue, loss of appetite and weight, immune system impaired so prone to many infections
Adenovirus	Respiratory infections	Sore throat, coughing, sneezing
SARS-CoV-2	COVID-19	Fever or chills, cough, shortness of breath, headache, fatigue, muscle aches
Flaviviruses	Yellow fever, dengue fever	Fever, chills, jaundice, severe muscle pain
Rhinoviruses	Common cold	Sore throat, sneezing, coughing, headache
Pox viruses	Smallpox, cowpox	Sores, fever

Prions

Prions (pronounced pree-ons) are non-cellular. A prion is a small infectious protein that brings about degeneration of the nervous system and ultimately death. Transmissible spongiform encephalopathies (TSEs) are a disease of humans and other mammals, such as sheep, cattle and cats.

In the United Kingdom in the late 1980s, there was an outbreak of ‘mad cow’ disease. The affected cattle became nervous and aggressive, lost coordination, and then fell into a coma (**Figure 10.2.5**). This had serious consequences for the British beef industry and resulted in the slaughter of more than 4 million cattle. Mad cow disease is also known as bovine spongiform encephalopathy (BSE). The name comes from *encephalo*, meaning ‘brain’, *pathy*, meaning ‘disease’, and *spongiform*, meaning ‘sponge-like’, because the degeneration of brain tissue makes it look like a sponge.

Consumption of cattle products infected with the prion protein that causes BSE has now been linked to the occurrence of a new variant of the human TSE, variant Creutzfeldt–Jakob disease (vCJD). This disease, like BSE, is characterised by gradual loss of motor coordination, dementia and paralysis, eventually leading to death. More than 200 deaths in Britain and Europe have been attributed to this disease.

Prions are unique among pathogenic agents because they do not possess any genetic material, neither DNA nor RNA. They are much smaller than viruses.

Prion proteins exist in bodies normally and play important roles in memory, learning and passing signals from cell to cell. They are often found at the surface of neurons. There are two forms: the normal prion protein cellular form and the disease-causing prion protein form. When a prion protein encounters a normal protein, it converts it to the harmful form, which in

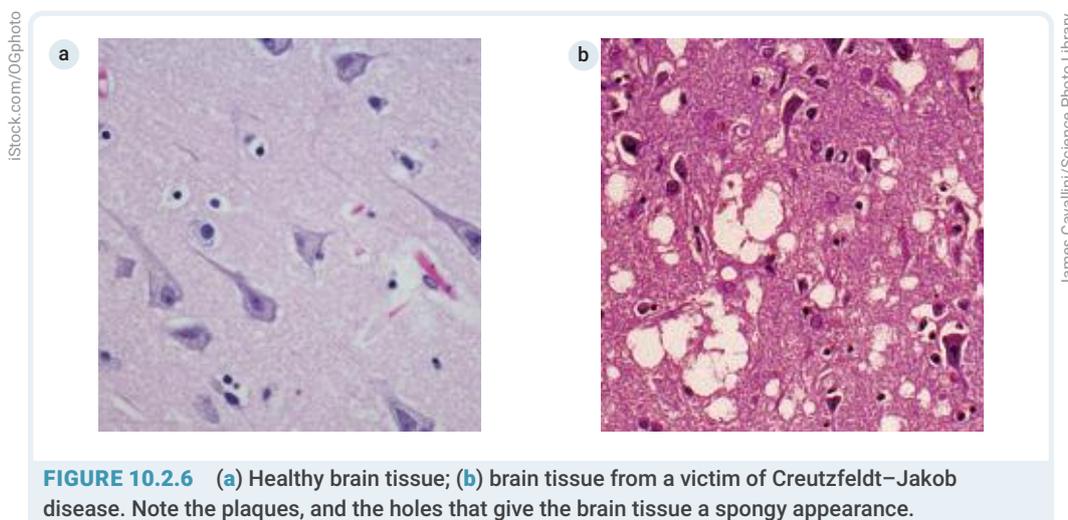
prion a small infectious protein



FIGURE 10.2.5 This cow is infected with mad cow disease, or BSE, which is caused by a prion.

CVL/Eurelios/Science Photo Library

turn converts other normal forms to harmful forms. When there are sufficient numbers of the pathogenic form, they aggregate into filaments. These fibres kill brain cells (Figure 10.2.6), consequently affecting muscle coordination and brain function.



The prion protein is very resistant to high temperatures, strong enzymes and ultraviolet radiation, and there is no effective treatment. The prion form of the protein can arise spontaneously, but it is usually transmitted by entering the body in infected food, most commonly brain tissue from an infected animal.

Bacteria

It is thought that bacteria were the first life form on Earth, and today they are still the most abundant and most diverse group of organisms. However, only a relatively small number of bacteria cause disease (Table 10.2.2). There are billions of bacteria living in and on human bodies, creating a helpful microbiome that supports digestion and overall health.



Weblink
How bacteria
invade the brain

TABLE 10.2.2 Some diseases caused by bacteria

Bacteria	Disease	Symptoms
<i>Clostridium tetani</i>	Tetanus	Sustained, severe muscle contractions due to blocking of nerve impulses by tetanus toxin
<i>Legionella pneumophila</i>	Legionnaire's disease	Fever, coughing, lung congestion
<i>Vibrio cholera</i>	Cholera	Severe dehydration, diarrhoea
<i>Yersinia pestis</i>	Bubonic plague	Swollen lymph nodes, fever, ulcers
<i>Corynebacterium diphtheriae</i>	Diphtheria	Headache, vomiting, spots on throat and tonsils
<i>Mycobacterium leprae</i>	Leprosy	Lesions on skin, loss of pigmentation, nerve damage that causes numbness – leads to muscle weakening and damage to affected areas due to lack of feeling
<i>Bacillus anthracis</i>	Anthrax (in cattle)	Boil-like lesions on skin, swelling of lymph glands, respiratory distress, fever, possibly death

Typically, bacteria are very small (1–10 μm long). They have a cell wall outside their cell membrane. Some species have an outer protective **capsule**; others have a whip-like **flagellum** for movement. Many bacteria can form tough, dormant structures called **endospores**, which are resistant to extreme temperatures, chemicals and drying out. An endospore consists of a bacterium's DNA, ribosomes and other cytoplasmic substances. This adaptation helps bacteria withstand unfavourable conditions and facilitates dispersal to new hosts.

Some bacteria reproduce by **binary fission** (Figure 10.2.7), in which one cell splits into two. Others reproduce by budding off spores. These asexual forms of reproduction allow bacteria to reproduce very rapidly when conditions are favourable. Some species can reproduce every 20 minutes; others take 12 hours to divide.

Bacteria can be studied in detail under a powerful electron microscope. However, useful information can be obtained by staining bacteria and using a light microscope. This reveals a variety of different shapes of bacteria, namely:

- spherical, known as coccus (plural: cocci) (Figure 10.2.8a)
- rod-shaped bacillus (plural: bacilli) (Figure 10.2.8b)
- spiral (plural: spirilli) (Figure 10.2.8c)
- vibrio, rather like a comma.

capsule a slimy layer sitting outside the cell wall of some species of bacteria

flagellum a whip-like appendage that helps bacteria move

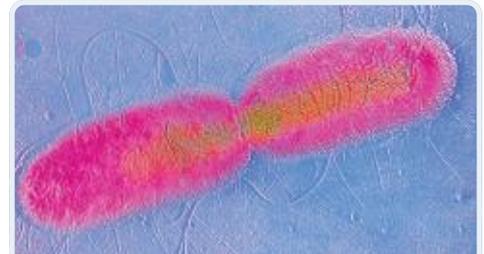


FIGURE 10.2.7 A transmission electron micrograph of *E. coli* dividing into two by binary fission

endospore a tough, dormant structure formed by many bacteria to help them resist unfavourable conditions and disperse to new hosts

binary fission the division of a cell into two without mitosis; a prokaryotic cell splits to form two daughter cells

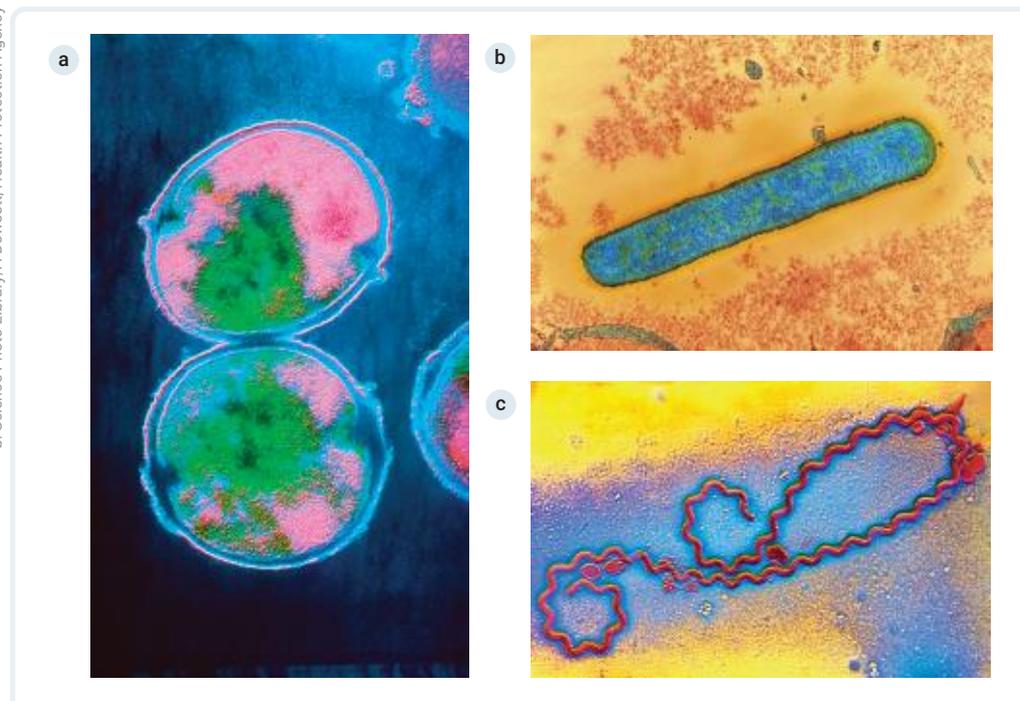


FIGURE 10.2.8 Transmission electron micrographs of (a) cocci-shaped bacteria, *Streptococcus pneumoniae* (magnification × 30 000); (b) a rod-shaped bacterium, *Bacillus anthracis*, which causes anthrax in sheep and cattle (magnification × 10 500); (c) a spiral-shaped bacterium, *Leptospira* (magnification × 4400)

Although it is difficult to distinguish visually between the different strains of each shape, bacterial reaction to stains can be used to classify them (Figure 10.2.9). Differences in the structure and composition of their cell walls cause them to take up different colours in the Gram stain technique.



Worksheet
Getting to know tuberculosis

fungi single-celled to complex multicellular eukaryotic organisms that have cell walls made of chitin and reproduce by spores

chitin a polysaccharide that is the main component of fungal cell walls and the exoskeletons of insects and other arthropods



Science Photo Library/CNR I

FIGURE 10.2.9 These bacteria have been stained by the Gram stain technique. The Gram-positive bacteria stain purple and the Gram-negative bacteria stain pink (magnification $\times 1000$).

Science Photo Library/CC Studio



FIGURE 10.2.10 Haemolytic bacterial pathogens infect blood cells, so they must be grown on agar plates that contain blood. Each small white bump is a colony of bacteria.

Science Photo Library/Dr. Jeremy Burgess



FIGURE 10.2.11 These grapes are infected with the fungus *Botrytis cinerea*.

Large numbers of bacteria can be grown by inoculating a small sample of a particular strain into a medium containing all their nutrient needs. This medium may be a liquid broth or a solid gel called agar (**Figure 10.2.10**). When one bacterium lands on a plate, it divides many times by binary fission to form a visible colony. The appearance of these colonies can differ in colour, texture and shape, depending on the particular strain. Individual strains can then be isolated and grown in pure culture. In this way, microbiologists can study the responses of different strains to antibiotics and chemicals.

Fungi

Fungi include large organisms, such as mushrooms and toadstools, as well as minute forms that can only be seen under a microscope. Microscopic fungi include unicellular yeasts and moulds. Fungi are eukaryotes that reproduce by spores and have cell walls made of **chitin**, rather than cellulose. Microscopic fungi are generally larger than bacteria. Some of them are pathogenic, causing disease in a wide range of organisms, including plants (**Figure 10.2.11**) and animals. Like bacteria, not all fungi cause disease.

Fungi secrete enzymes into their host, digest their food externally and absorb nutrients directly through their cell walls and membranes, also known as saprotrophic nutrition. Most fungal diseases in animals are external, where they irritate and inflame the skin. A common example is ringworm, a fungal skin infection of rabbits, dogs, cats, horses and humans (**Table 10.2.3**). Tinea, or athlete's foot, is another fungal skin disease of humans. Symptoms include a rash and itchy skin. If the spores the fungi release come into contact with damaged or broken skin, they may cause new infections elsewhere.

Fungal infections in plants can cause serious disease. For example, *Phytophthora cinnamomi*, the cinnamon fungus, is devastating jarrah forests in Western Australia and affecting susceptible native vegetation in Tasmania. Rusts, which infect crops such as wheat and barley, are significant pathogens. The hyphae of fungi, the underground branching filaments, penetrate the external surface of the plant and extend into its tissues, depriving it of valuable nutrients and reducing crop yield. The production and release of large quantities of spores effectively transmit these fungal pathogens to new hosts.

TABLE 10.2.3 Some diseases caused by fungal infections

Pathogen	Disease	Symptoms
<i>Candida albicans</i>	Thrush (candidiasis)	White patches in mouth, itchiness in vaginal area, inflamed skin
<i>Tinea pedis</i>	Tinea (athlete's foot)	Itching and blisters between toes, peeling and cracking skin; secondary bacterial infections in the cracks
<i>Trichophyton rubrum</i>	Ringworm	Red blisters on skin, often in a circular pattern
<i>Diplocarpon roseae</i>	Black spot in roses	Black spots on leaves, leading to leaf damage
<i>Botrytis cinerea</i>	Dieback in many plants	A grey mould that destroys plant tissues, causing parts of the plant to die back
<i>Puccinia graminis</i>	Rust in cereal crops, such as rye and wheat	Reduces photosynthesis and productivity
<i>Claviceps purpurea</i>	Fungus produces toxins in rye that cause ergotism	Once it infects plants, the ergot fungus replaces grains with a dark fungal body called 'sclerotium'. This reduces the yield and quality of the grain.

Protists

Protists are unicellular, eukaryotic organisms. They reproduce both sexually and asexually. Of the 65 000 known species of protists, fewer than 24 species cause diseases in humans, but these few infect hundreds of millions of people each year. This includes *Giardia* (Figure 10.2.12) and *Cryptosporidium*, both of which produce symptoms of fatigue, nausea and diarrhoea. These two species also produce environmentally resistant cyst stages that are passed in the faeces of a host and transmitted to a new host in drinking water. Amoebic dysentery is also caused by pathogenic protists transmitted in contaminated water.

Malaria has been plaguing humans for many thousands of years. It is caused by protists from the *Plasmodium* genus. These are transmitted to the host by the bite of a female *Anopheles* mosquito. *Plasmodium* has a complicated life cycle that includes both sexual and asexual reproduction and infection of the red blood cells. Symptoms include headaches, chills and a burning fever. Symptoms may eventually subside but can recur when infected red blood cells rupture and release more pathogen. Today, malaria is still one of the most serious diseases in tropical and subtropical countries.

Parasites

A **parasite** is an organism that lives on or in its host for all or part of its life, causing harm and gaining nutrition from the host. Because parasitism is a relationship between organisms in which one organism, the parasite, benefits at the expense of the other organism, the host, by definition all parasites are pathogens. The examples given here refer to multicellular parasites.



FIGURE 10.2.12 A scanning electron micrograph of *Giardia lamblia* (yellow) in the human small intestine. This flagellated protist contaminates drinking water, causing intestinal upsets.

Science Photo Library/Dr Tony Brain



Weblink

Pathogens and human infectious disease

Worksheet

Pathogens and their diseases

parasite an organism that lives on or in its host for all or part of its life, causing harm and gaining nutrition from the host

endoparasite a parasite that lives inside another organism

intermediate host an organism in which a pathogen or parasite undergoes development and spends a small portion of its life cycle

encyst when organisms produce a covering around themselves and enter a resting stage

definitive host a host in which the adult phase of a parasite produces gametes

Endoparasites

Multicellular internal parasites (**endoparasites**), such as tapeworms, roundworms and flukes, generally live inside our intestines, where they consume nutrients, reproduce and release huge quantities of eggs, which leave the body in the faeces. Often, they cause significant illness and blood loss. For example, hookworms (**Figure 10.2.13**) parasitise more than 900 million people worldwide, causing daily combined blood loss of 7 million litres.

Some tapeworms that parasitise humans use other animals as **intermediate hosts**, such as pigs, freshwater fish, and cattle. There they undergo development, but do not reach sexual maturity. After the eggs hatch, juvenile larval stages migrate to the intermediate host tissues to **encyst**. Humans can become infected when they eat contaminated pork, fish or beef

that is raw or improperly cooked. Once the parasites reach the human intestine, they mature and excrete fertilised eggs, which leave the body in the faeces. Humans are called the **definitive host** because the adult phase of the parasite produces eggs (gametes) in us. When eggs are eaten by grazing animals, they become intermediate hosts, completing the life cycle.

Science Photo Library/David Scharf



FIGURE 10.2.13 Hookworms are so-called because of their 'hooks' – tooth-like structures that enable them to cling to the host's bowel.

Ectoparasites

ectoparasite a parasite that lives on the surface of another organism

Ectoparasites are parasites that live on the surface of another organism. The most common are fleas, ticks (**Figure 10.2.14**) and lice, which belong to the arthropod group. While their biting may cause discomfort at times, most ectoparasites only produce minor symptoms that can be easily treated. Ectoparasites often act as carriers for the real villains; for example, the bacteria that cause the plague and Lyme disease.



FIGURE 10.2.14 A tick feeding on a dog. Ticks and fleas usually cause only minor skin irritations, but they may also transmit dangerous pathogens.

Science Source/Dr P. Marazzi

LEARNING CHECK 10.2

DESCRIBING

- 1 **Identify** two diseases caused by bacteria.
- 2 **Describe** the way in which fungi obtain nutrients.
- 3 **Describe** two fungal diseases of plants.
- 4 **Describe** both the route of infection and symptoms caused by *Giardia lamblia*.
- 5 **Describe** the unique feature of a prion that distinguishes it from other non-cellular infectious agents.
- 6 **Describe** two methods by which different strains of bacteria can be identified.
- 7 **Describe** the difference between malaria and *Plasmodium*.

APPLYING

- 8 **Explain** how altered prion proteins affect the brain.

ANALYSING

- 9 **Compare** ectoparasites and endoparasites. Give two examples of each.

INTERPRETING

- 10 **Justify** this statement: 'All viruses are pathogens'.
- 11 Viruses infect only specific host cells. **Explain** how this specificity comes about.



Weblink

What are parasites and how do they make us sick?

10.3 Pathogenesis

Pathogenesis describes the process by which a disease arises then persists or is resolved, thus determining how an individual develops an illness.

Susceptibility

Individuals vary in their **susceptibility** to a pathogen; some have greater **resistance** than others. For example, if a cold is spreading through family and friends, every person does not necessarily become ill. Those in contact with the sufferer will have contact with the cold virus, but not everyone will develop cold symptoms. An individual's ability to avoid infection by a pathogen depends on factors such as their age, state of health and their natural resistance to that particular pathogen.

Symptoms are the effects of the pathogen on the host. For example, the measles virus causes a high temperature and a rash, and the early signs of a tuberculosis infection are an annoying cough and sore throat. Diseases usually have characteristic symptoms, which aid diagnosis.

For many infections, symptoms do not appear immediately. The time between infection and the onset of symptoms is known as the **incubation period**. This time lag (**Figure 10.3.1**) may occur for a number of reasons. Some pathogens may take time to reach the target tissues; others must reproduce to reach the number needed to cause disease. Toxins produced by bacteria may need to accumulate to a level that affects the host. Diseases are often communicable before the onset of symptoms, allowing the pathogen to be transmitted before the host is incapacitated by symptoms.

susceptibility the likelihood of an organism being infected by a pathogen

resistance the extent to which an organism is or is not affected by an agent such as a pathogen or chemical toxin

symptom a characteristic effect of a pathogen on the body

incubation period the time between infection and the onset of symptoms

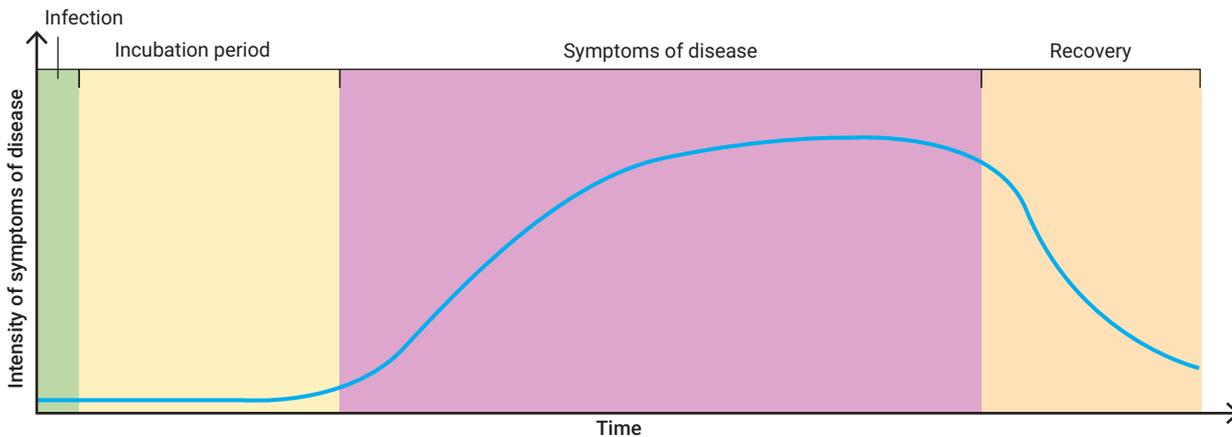


FIGURE 10.3.1 The various phases of an infection. Note the time lag between the time of infection and the onset of symptoms. This is known as the incubation period.

pathogenicity the capacity of a pathogen to cause disease

virulence a measure of a pathogen's ability to cause disease within its host

virulence factor a characteristic that helps bacteria to invade the host, cause disease and evade host defences

In most cases, the defence mechanisms of the host organism fight off the pathogen and the host recovers. If this does not happen, disability or death may occur.

Pathogens differ in their disease-causing capacity, or **pathogenicity**. **Virulence** is the measure of the pathogenicity of an organism. It can be thought of as the intensity of the effect of the pathogen on the host. A micro-organism is pathogenic as a result of special characteristics of the organism. This includes the ability to stick to or invade a particular cell type, produce toxins, or cope with or avoid the host immune system. These characteristics that promote the establishment and maintenance of disease are called **virulence factors**. It is largely these virulence factors that bring about the disturbances in body function that is known as disease.

Adherence factors

When a pathogen colonises a new host, it first must bind or adhere to host cell surfaces. Virulence factors that facilitate adherence are known as **adhesins**. As adhesins bind to specific epithelium receptors in the host, they ensure that the pathogen attaches to the tissue type in which it can survive.

Bacteria have evolved a variety of attachment mechanisms. Many pathogenic bacteria recognise and attach to epithelial surfaces by using pili (singular: **pilus**). Pili, also called fimbriae, are fine filaments of protein, up to several micrometres in length. Under an electron microscope, they resemble fine hairs distributed all over the surface of the bacterial cell (**Figure 10.3.2**). In some cases, the actual adhesin is a minor subunit protein at the tip of the pili.

adhesin a protein that helps bacteria to bind to host cell surfaces

pilus a surface appendage in some bacteria that functions in adherence

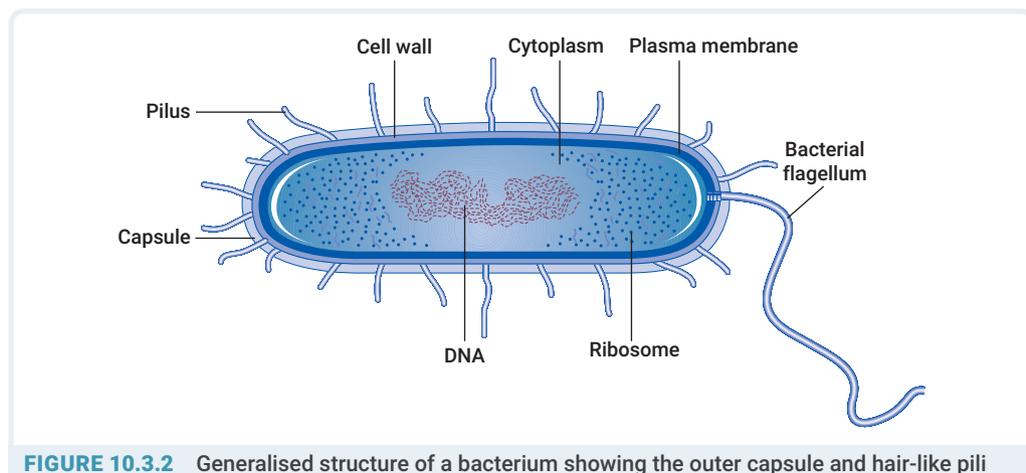


FIGURE 10.3.2 Generalised structure of a bacterium showing the outer capsule and hair-like pili

Adhesins also include a wide variety of other surface proteins, as well as bacterial cell walls and bacterial capsules. Adhesins can potentially be used in vaccines because they are often essential to infection and are surface-located, making them readily accessible to antibodies.

Invasion factors

Invasion factors are virulence factors that facilitate bacterial invasion of a host. They play a role in enabling entry into the cells and tissues of the host in order to ensure its colonisation.

Invasion factors are often enzymes secreted by bacteria. In animals, the extracellular matrix forms a scaffold in which the body cells reside. Certain enzymes released by bacteria degrade and destroy the extracellular matrix. This brings about tissue destruction, thereby promoting the spread of the pathogen. The action of another invasion factor, also an enzyme, degrades a structural component of blood clots, which facilitates bacterial transport across epithelial layers and penetration into the surrounding tissues.

A successful invasion by **intracellular pathogens** means penetrating host cell membranes. Surface proteins on some bacteria allow them to invade mammalian cells via trans-membrane proteins.

Capsules

The capsule is a large, well-organised layer made of thick polysaccharide gel that forms part of the outer structure of many bacterial cells. Not all species produce capsules. Encapsulated strains of bacteria have been shown to be more virulent than non-encapsulated strains. Research has shown that capsules inhibit phagocytosis by host immune cells, thereby protecting bacteria against host defences.

Toxins

Toxins were the first bacterial virulence factors to be identified. Toxins are poisonous substances formed during the metabolism and growth of certain micro-organisms, which cause disease when introduced into the host body tissues.

Endotoxins

An **endotoxin** is a molecular complex of lipid and polysaccharide called a **lipopolysaccharide**. It is attached to the outer membrane of certain bacteria and is usually released upon lysis of the bacterial cell. The lipid component is the main toxin, causing fever, changes in blood pressure, inflammation, lethal shock and many other toxic events. These events can culminate in sepsis and may lead to death.

Endotoxins do not always have negative effects on the host. Some potentially beneficial responses include activation of the immune system and stimulating division of white blood cells.

Exotoxins

Exotoxins are more toxic than endotoxins. They may act locally or in tissues some distance from the site of bacterial growth. Their action is often confined to particular cell types or specific cell receptors. Exotoxins are protein toxins and enzymes actively secreted by pathogenic bacteria into their surroundings. They are among the most toxic of all substances and have a wide range of effects in the host. Major categories include **cytotoxins**, **neurotoxins** and **enterotoxins**.



Weblink
Virulence factors

invasion factor a characteristic that helps pathogens to invade the host

intracellular pathogen an organism that lives inside host cells

toxin a naturally occurring poison produced by the metabolic action of a living organism

endotoxin a poisonous molecule attached to the outer membrane of certain bacteria that is usually released upon lysis of the bacterial cell

lipopolysaccharide a lipid-sugar compound that forms the outer surface of some types of bacteria

exotoxin a protein toxin or enzyme actively secreted by pathogenic bacteria into their surroundings

cytotoxin a toxin that disrupts or kills cells

neurotoxin a toxin that disrupts the functioning of nerves

enterotoxin a toxin that disrupts intestinal function

The most toxic substance known is an extremely potent neurotoxin, the botulinum toxin, secreted by *Clostridium botulinum*. This bacterium may infect wounds or occur after improper heating during the canning of foods. The botulinum toxin blocks nerve function. This prevents muscle contraction and leads to paralysis. Death is usually caused by respiratory failure, but heart failure can also be the primary cause. The toxin is used to treat a variety of conditions (e.g. migraine headaches) by taking advantage of its effect as a specific muscle relaxant. It is the active ingredient in Botox, which reduces wrinkles by paralysing facial muscles.

Cytotoxins lead to cell death by splitting open the host cells with enzymes such as phospholipases that break down the phospholipids of the cell membrane. Cholera bacteria cause disease after attaching to the lining of the small intestine and secreting exotoxins. These toxins stimulate secretion of Na^+ and HCO_3^- ions from the intestinal epithelium, causing massive water loss by osmosis. The resulting diarrhoea may be fatal, especially if water and electrolytes are not replaced.

mast ring a ring of paper with small circular 'offshoots' impregnated with different antibiotics

PRACTICAL ACTIVITY 10.3.1

ANTIMICROBIAL AGENTS

Introduction

Antibiotics are killer molecules produced by bacteria and fungi to defend themselves from other microbes. Antibiotics are used to treat bacterial disease, but not all antibiotics are effective against all bacteria. To select the best treatment for a given disease, we need to know which bacteria are susceptible to which antibiotics. If bacteria are grown on agar plates, they produce a bacterial 'lawn', a cloudy film of millions of bacterial colonies. When paper discs containing antibiotics (**mast rings**) are placed on the agar before the bacteria have had a chance to grow, clear areas where the antibiotic has killed the bacteria (zone of inhibition) develop.

Research question

Do a variety of antibiotics (independent variable) affect the growth of two species of bacteria (*E. coli* and *S. epidermis*) indicated by a change in the zone of exclusion (mm) (dependent variable)?

Materials

- broth cultures of *Escherichia coli* and *Staphylococcus epidermidis*
- incubator set to 25°C
- 2 nutrient agar plates
- 2 antibiotic mast rings or a selection of antibiotic paper discs
- 2 sterile 5 mL pipettes
- forceps
- glass spreader
- Bunsen burner
- sticky tape
- ruler
- disinfectant solution (e.g. bleach)
- lab coats
- safety glasses
- gloves



What risks are there in doing this experiment?	How can you manage these risks to stay safe?
Bacteria may cause disease; assume they are pathogenic.	Wear lab coats, gloves and safety glasses; wash hands thoroughly at the end. Decontaminate benches before and after the activity. Flood spills with bleach. Avoid contamination by not touching your hands to your mouth or face.
Micro-organisms will grow on the agar plates.	Do not open plates once they are securely taped. Dispose of plates appropriately in autoclave or pressure cooker.
Bleach may leave a corrosive residue and discolour clothes.	Wear lab coats and gloves. Wipe the bleach off the bench after decontamination.

Procedure

- 1 Work in groups. Before starting, ensure the bench is swabbed down with bleach to minimise contamination.
- 2 Label the bases of plates with the date, name of your group and the type of bacteria.
- 3 Remove 0.1 mL of *E. coli* culture with the pipette, lift the lid off the labelled plate and transfer the bacteria to the surface of the agar.
- 4 Either replace the lid quickly and spread the liquid evenly by swirling, or spread the liquid evenly with the glass spreader, then replace the lid. Leave the plate on the bench for 2 minutes to allow the bacteria to penetrate agar.
- 5 Repeat steps 3 and 4 with the *S. epidermidis* culture on the second plate.
- 6 Sterilise the forceps in the flame of the Bunsen burner, allow them to cool and then use them to place a mast ring on the surface of each of the plates. Each lobe of the mast ring is impregnated with a different antibiotic, as shown by the code on the packet.
- 7 Replace the lid and seal both plates with sticky tape and incubate them at 25°C for 24 hours.
- 8 Ensure the bench is swabbed down with bleach and wash your hands thoroughly.
- 9 The next day, observe for the presence or absence of growth near the discs.
- 10 Carefully avoiding contamination, measure the diameter of zone of inhibition: the clear area around each disc. This shows the degree of sensitivity of the bacteria to each antibiotic.

Results

Copy and complete [Table 10.3.1](#), adding as many rows as needed.

TABLE 10.3.1 Results table

Antibiotic	Diameter of zone of inhibition (mm)	
	<i>Escherichia coli</i>	<i>Staphylococcus epidermidis</i>

Analysis of results

- 1 Construct a bar chart with zone of inhibition (*y*-axis) and antibiotic used (*x*-axis). Include a bar for each of the bacterial species.
- 2 Identify the patterns or relationships in the results, then compare the effects of each antibiotic on the two different species of bacteria.

Interpretation

- 3 Explain which antibiotic would be most suitable to treat an infection by *S. epidermidis*.
- 4 Decide which antibiotic would be best to use if the pathogen causing an infection is unknown. Provide reasoning.

Evaluation

- 5 Explain why a control was not used in this experiment. How would a control improve this method?
- 6 State four variables that were kept constant in this experiment and describe how they were controlled.
- 7 Explain the benefit of pooling data from different class groups and finding average areas of inhibition for each antibiotic.

Extension

- 8 Why have antibiotics become a less effective treatment for infection in recent years?

LEARNING CHECK 10.3

DESCRIBING

- 1 State three factors that determine the pathogenicity of an organism.
- 2 State a definition for each of these terms:
 - a virulence factor, and provide two examples
 - b susceptibility
 - c incubation period.
- 3 **Describe** the role of an adherence factor.

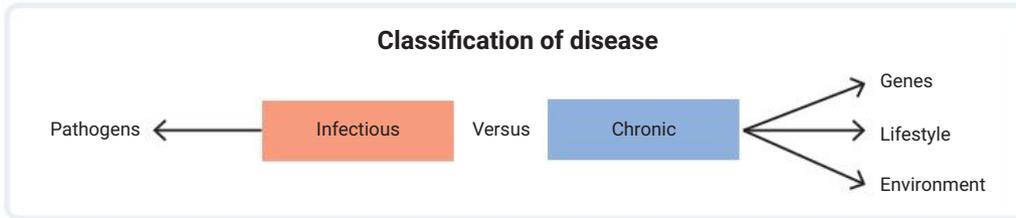
APPLYING

- 4 **Explain** the difference between pathogenicity and virulence.
- 5 **Explain** the role of invasion factors in pathogenicity.

ANALYSING

- 6 **Compare** endotoxins and exotoxins.

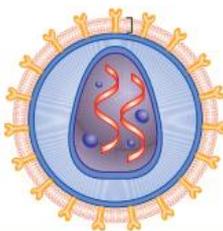
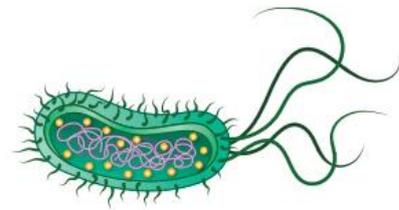
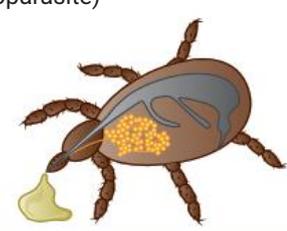
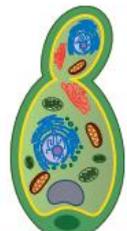
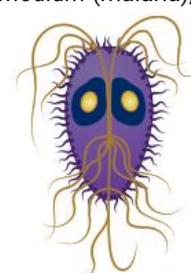
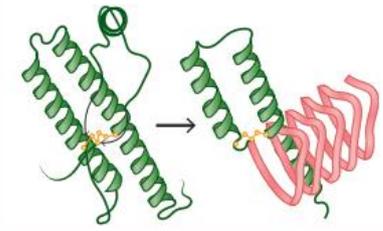
Disease: how is it classified?



Pathogens: what types of pathogens are there?

- A pathogen is any agent that causes disease.
- A pathogen is capable of producing infection, depending on virulence factors.

Examples of pathogens

Viruses	Bacteria	Parasites
<p>Consist of nucleic acids and can only reproduce inside a cell. e.g. hepatovirus, SARS-CoV-1, HIV, influenza A</p> 	<p>Tiny single-celled prokaryotes. Can live inside or outside the body. e.g. <i>Mycobacterium tuberculosis</i></p> 	<p>Multicellular eukaryotic organisms. Can live inside or outside organism. e.g. tapeworm (endoparasite), tick (ectoparasite)</p> 
Fungi	Protists	Prions
<p>Single-celled or multicellular organisms with saprotrophic nutrition. e.g. ringworm, candidiasis</p> 	<p>Single-celled eukaryotic organisms. e.g. <i>Plasmodium</i> (malaria), <i>Giardia</i></p> 	<p>Made of protein. e.g. BSE (mad cow disease), variant Creutzfeldt–Jakob disease</p> 

Pathogenesis

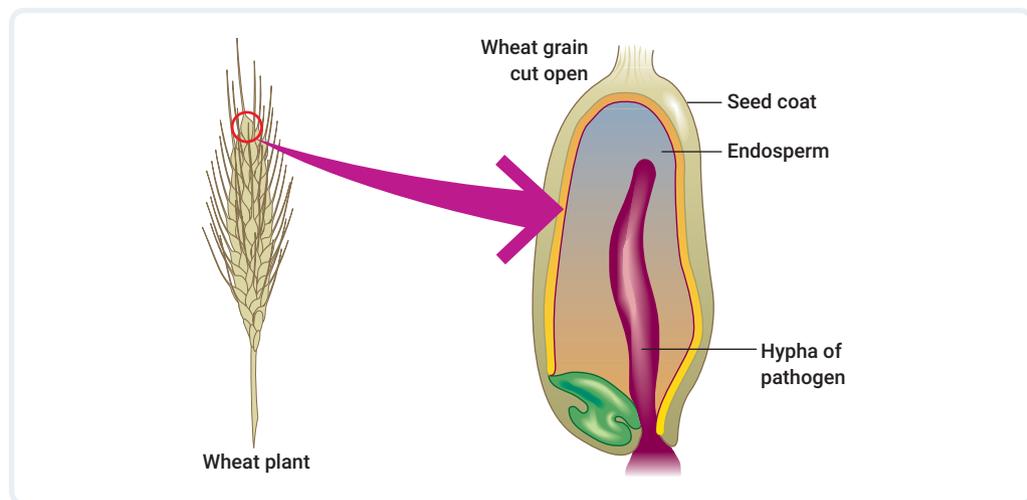
- Virulence factors that help the pathogen cause disease: adherence factors (enabling a pathogen to attach to host cells), invasion factors (enabling a pathogen to invade host cells), capsules (protecting pathogens from immune recognition), toxins (endotoxins and exotoxins).

Pathogenesis: exposure (contact) → adhesion → invasion → infection

CHAPTER EXAM

MULTIPLE-CHOICE QUESTIONS

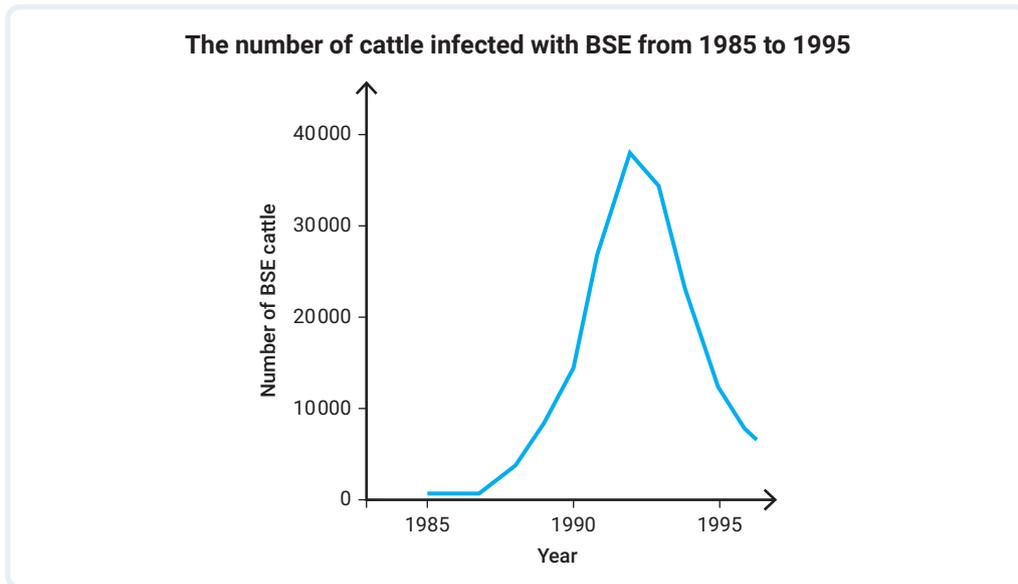
- The reason for keeping cold food below 5°C and hot food above 60°C is to:
 - stop denaturation of the food.
 - prevent binary fission of bacteria.
 - prevent the reproduction of viruses on the food.
 - inhibit conversion of normal proteins to prion proteins.
- Which of the following correctly identifies a pathogen and the disease it causes?
 - Amoebic dysentery is caused by a protist.
 - Food poisoning is caused by fungi.
 - Influenza is caused by a bacterium.
 - Mad cow disease is caused by a virus.
- The following diagram shows infection by a pathogen responsible for rust in wheat and rye. It shows a wheat plant and magnified cut wheat grain, showing infection by a pathogen. The group to which this pathogen belongs is:
 - bacteria.
 - fungi.
 - protist.
 - virus.



- The time between infection and the onset of symptoms of a disease is called:
 - incubation.
 - infection.
 - susceptibility.
 - virulence.
- Non-infectious diseases:
 - can be treated using antibiotics.
 - are easily passed from person to person.
 - cannot be passed from person to person.
 - are transmitted by pathogens in all circumstances.

Questions 6–9 refer to the following information.

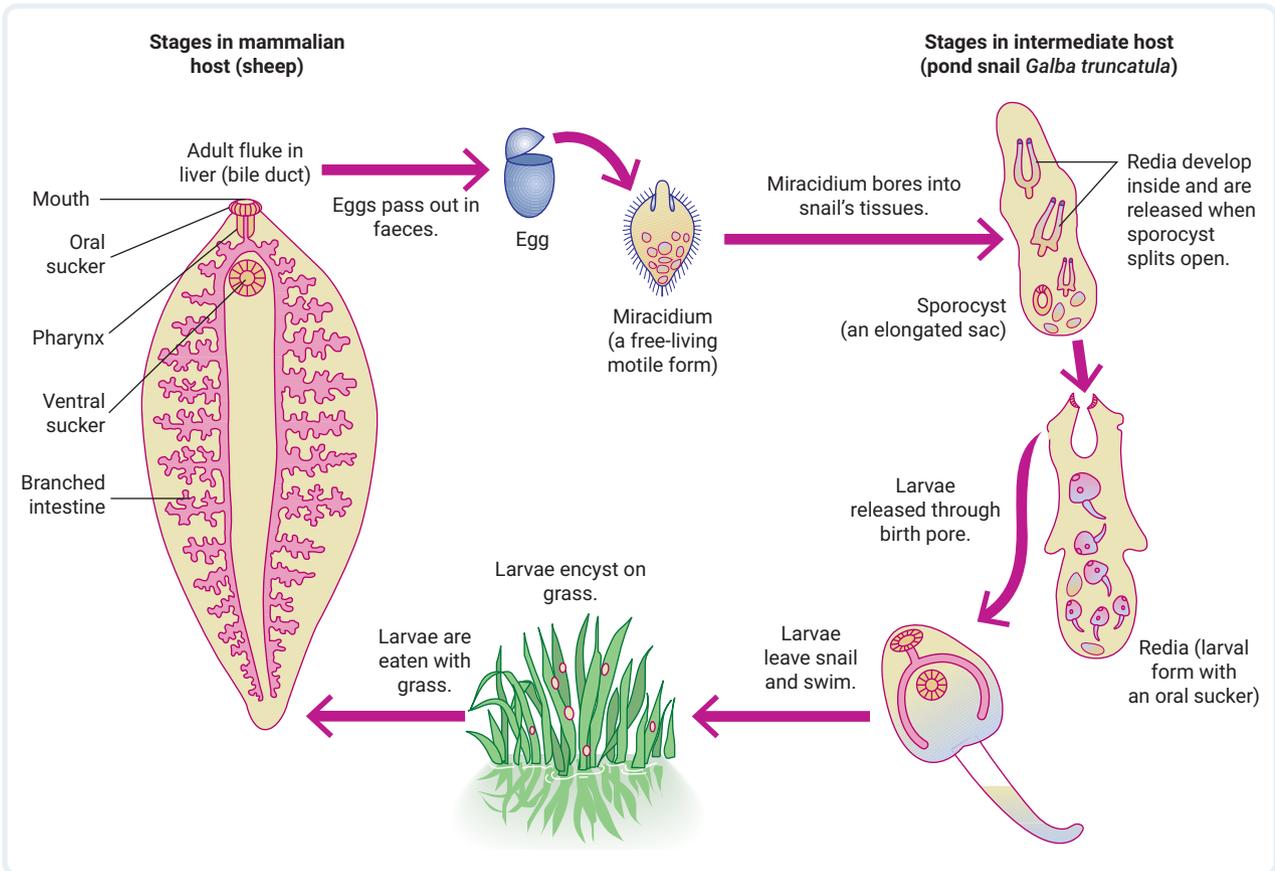
The following graph shows the number of cattle infected with BSE in Britain for the years 1985–95. Feedstock containing meat and bone meal was subsequently banned.



6. The number of cattle with BSE peaked around:
 - A 1985.
 - B 1990.
 - C 1992.
 - D 1995.
7. A trend shown in this data is that:
 - A between 1985 and 1995, the number of cattle with BSE increased.
 - B between 1985 and 1995, the number of cattle with BSE decreased.
 - C between 1985 and 1995, the number of cattle with BSE remained constant.
 - D between 1985 and 1992, the number of cattle with BSE increased then decreased between 1992 and 1995.
8. The disease BSE is caused by a:
 - A bacteria.
 - B parasite.
 - C prion.
 - D virus.
9. A possible reason for the reduction in BSE numbers is that cattle:
 - A became immune to BSE.
 - B were treated with an antibiotic.
 - C were no longer given feedstuff containing meat and bone meal.
 - D were provided with a vaccine to reduce the risk of infection.
10. Identify the vector of *Plasmodium*.
 - A Bacteria
 - B Malaria
 - C Mosquito
 - D Prion

SHORT RESPONSE

11. The following diagram shows the life cycle of the liver fluke, *Fasciola hepatica*.
- Determine** the group of organisms that this pathogen would be classified in.
 - Identify** the definitive host of *Fasciola hepatica*.
 - Explain** how the liver fluke enters its definitive host.
 - The adult liver fluke is hermaphroditic; that is, it has both male and female reproductive organs. **Describe** the advantage of this feature for the parasite.
 - Describe** the advantages for the liver fluke in having an intermediate host.



12. **Describe** the effect of virulence factors on host functioning.

CROSS-CHAPTER QUESTION

13. **Explain** how virulence factors are linked to cell membrane structure.

DATA ANALYSIS

Questions 14 and 15 refer to the following information.

The following table shows the leading causes of death in the world in 2002.

The 10 leading causes of death in the world in 2002

Rank	Cause	Death (millions)	Per cent of total deaths
1	Ischaemic heart disease	7.21	12.6
2	Cerebrovascular disease	5.51	9.7
3	Lower respiratory infections	3.88	6.8
4	HIV/AIDS	2.78	4.9
5	Chronic obstructive pulmonary disease	2.75	4.8
6	Perinatal conditions	2.46	4.3
7	Diarrhoeal diseases	1.80	3.2
8	Tuberculosis	1.57	2.7
9	Malaria	1.27	2.2
10	Trachea, bronchus, lung cancers	1.24	2.2

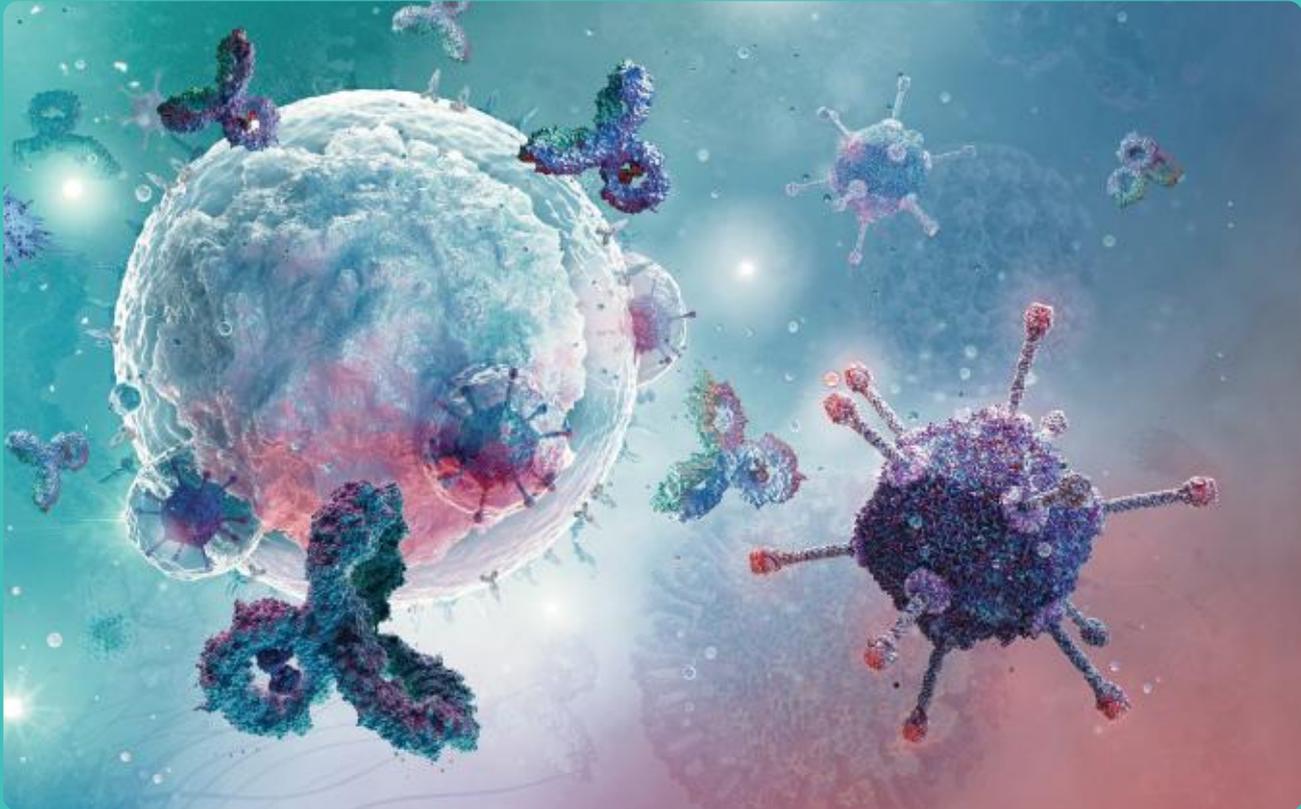
Mathers, C.D., Ezzati, M., & Lopez, A.D. (2007). Measuring the burden of neglected tropical diseases: The Global Burden of Disease Framework. *PLoS Negl. Trop. Dis.* 1(2): e114. doi:10.1371/journal.pntd.0000114 https://www.researchgate.net/figure/The-20-Leading-Causes-of-Deaths-and-Burden-of-Disease-for-the-World-2002_fig6_5788295

14. Analyse evidence

Classify each of the top 10 leading causes of death as *infectious*, *chronic* or *other*.

15. Apply understanding

Calculate the total deaths (millions) due to infectious diseases.



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**SYLLABUS
DOT POINTS**
SCIENCE UNDERSTANDING

- Explain how host cells recognise self from non-self.
- Identify the three lines of defence in vertebrates
 - the innate immune response: skin and mucous membranes (non-specific)
 - inflammatory response and complement system (non-specific)
 - adaptive immune response (specific).
- Describe the inflammatory response, including the roles of
 - prostaglandins and vasodilation
 - neutrophils and macrophages
 - natural killer cells.





- Compare active and passive immunity, both naturally acquired and artificially acquired.
- Explain the adaptive immune response, including the
 - humoral response (B lymphocytes, antibodies)
 - cell-mediated response (T lymphocytes)
 - role of memory cells.
- Describe the innate immune responses in plants, including
 - physical defence strategies: barriers and leaf structures
 - chemical defence strategies: plant defensins and production of toxins.

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Introduction

In this chapter, the multilayered system of defence used by complex multicellular organisms, such as vertebrates (including humans), to detect and respond to attack by pathogens is discussed.

Two distinct and important types of immunity exist to provide protection from pathogens: active immunity and passive immunity. Both natural and artificial forms exist for each. Both natural and artificial active immunity lead to relatively long-term protection from associated pathogens.

Passive immunity typically involves exposure to antibodies that are specific to an antigen. This can occur naturally when antibodies are transferred from mother to baby during pregnancy and breastfeeding or artificially through vaccination with isolated antibodies. Because the exposed individual does not produce their own 'memory' of exposure, the effect is relatively short-lived.

Like animals, plants are prone to attack by parasites, pests and disease and they also have innate immune responses.

Worksheets

- The first line of defence in the immune system
- Cells of the adaptive immune system
- Immunity
- Vaccinating tomato plants to repel pathogens

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ In contrast to eukaryotic cells, prokaryotic cells lack a defined nucleus and have no membrane-enclosed organelles.
- ✓ In multicellular eukaryotic organisms, each body system contains specialised cells and tissues that are structurally suited to their function. These specialised cells are produced through differentiation of stem cells.
- ✓ The body is able to respond to external and internal stimuli, including the presence of pathogens – disease-causing agents.
- ✓ In vertebrates there are three lines of defence.
- ✓ Stomata, controlled by guard cells, are openings on the leaf surface that facilitate gas exchange and transpiration.
- ✓ Plants, like animals, are able to distinguish self from non-self.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ identify and explain the process that host cells use to distinguish between self and non-self
- ✓ identify that the innate first line of defence in vertebrates, including skin and mucous membranes, is non-specific and focused on preventing the entry of pathogens
- ✓ identify that the innate second line of defence in vertebrates, including the inflammatory response and complement system, is also non-specific and crucial to destroying pathogens that breach the first line of defence
- ✓ describe the role of prostaglandins and vasodilation, neutrophils and macrophages, and natural killer (NK) cells in the inflammatory response
- ✓ identify that the adaptive response, or third line of defence, is specific and involves the activation of B and T lymphocytes and antibodies
- ✓ explain the adaptive immune response in terms of the humoral response (B lymphocytes, antibodies), the cell-mediated response (T lymphocytes) and the role of memory cells
- ✓ compare the outcomes of active and passive immunity: passive immunity is rapid but temporary whereas active immunity is slower but longer lasting
- ✓ identify natural examples of passive immunity (e.g. antibodies from mothers' milk)
- ✓ identify artificial examples of passive immunity (e.g. antibodies from vaccination)
- ✓ identify natural examples of active immunity (e.g. exposure to pathogens)
- ✓ identify artificial examples of active immunity (e.g. vaccination with weakened form of pathogen)
- ✓ describe physical barriers, such as the waxy cuticle, bark and cellulose of cell walls, that plants use to prevent pathogen entry
- ✓ describe chemical barriers, such as defensins and toxins, that plants use to prevent pathogen entry.

self an agent (e.g. cell, organism, substance) that is recognised by the immune system of an organism as being part of that organism

non-self an agent (e.g. cell, organism, substance) that is not recognised by the immune system as being part of the organism itself; it is foreign

11.1 Stimulating an immune response

To be able to defend itself from invasion by pathogens, an organism must be able to distinguish between what belongs in that organism and what is foreign. It must be able to distinguish between **self** and **non-self**. If a substance is identified as 'non-self', it is likely to stimulate an immune response.

Any substance that triggers an immune response is called an **antigen**. Both plants and animals are alerted to the invasion of bacteria and viruses by physical and chemical changes that occur in their cells or tissues. Antigens are generally protein or polysaccharide molecules foreign to the host. Their presence, either on the outer surface of the pathogens or in the **toxins** and enzymes they secrete, stimulates host immune responses that usually lead to the destruction and removal of the pathogen.

Pattern recognition receptors (PRRs) are proteins used by nearly all organisms to identify molecules associated with pathogens. These receptors are commonly found on the surface and in the cytoplasm of host body cells. They recognise specific substances and molecular patterns that are characteristic of a wide variety of pathogens, but not found on host cells. These molecules are called pathogen-associated molecular patterns (PAMPs) and include lipopolysaccharides, peptidoglycans, chitin, some glycoproteins and particular protein sequences on the surfaces of invaders (**Figure 11.1.1**). Knowledge about PRRs and PAMPs is not required as part of the syllabus.

A particular receptor can recognise a variety of pathogens if all of them display the same molecular pattern. For example, the material that makes up bacterial flagella, called flagellin, occurs in a wide variety of bacteria. This enables a flagellin receptor to recognise many different types of bacteria as invaders.

Host cells have evolved to recognise these broadly shared molecules because they are unique to pathogens and have remained largely unchanged during evolution. This system of recognition has the advantage of activating a rapid response to invaders, but it lacks a high degree of specificity.

The recognition of self from non-self is a critical aspect of the immune system's function, ensuring that the body's defence mechanisms selectively target foreign cells only. The **major histocompatibility complex (MHC)** is a group of proteins expressed on the surface of almost all nucleated cells that present fragments of self or non-self antigens to white blood cells that possess receptors that can distinguish between self and non-self antigens. Cells that respond to MHC–antigen complexes include T lymphocytes, macrophages, neutrophils and dendritic cells. Their specific action and roles are discussed in more detail in the next sections.

The **innate immune response** can be broadly divided into two categories:

- The first line of defence includes the physical and chemical barriers that prevent the entry of pathogens into the body (e.g. skin and mucous membranes).
- The second line of defence consists of the cellular and chemical responses that occur if a pathogen breaches these barriers and enters the body (e.g. phagocytosis, inflammatory response and complement system).

Both the first and second lines of defence are **non-specific**.

When the immune system detects a pathogen, it responds in a variety of ways (**Figure 11.1.2**). The third line of defence is activated when antigen molecules on the surface of the microbes are recognised by the host as being 'non-self'. This in turn initiates the **specific adaptive immune response** (the third line of defence) as required (e.g. the production of B and T lymphocytes and antibodies).

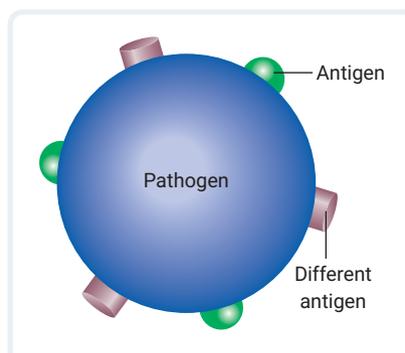


FIGURE 11.1.1 Molecules that act as antigens on the cell surface of a pathogen

antigen a large molecule, usually a protein or polysaccharide, that generates an immune response

toxin a naturally occurring poison produced by the metabolic action of a living organism

major histocompatibility complex (MHC) a group of proteins that present antigens to specific white blood cells to distinguish between self and non-self cells; there are two forms: MHC class I and MHC class II

innate immune response a non-specific response to pathogens that is not learnt and does not have memory

non-specific when the response is the same regardless of the type of pathogen

specific when the response is directed against a particular pathogen

adaptive immune response an acquired immune response; after an initial response to a pathogen, the immune system creates a 'memory' that leads to an enhanced response to subsequent encounters with the same pathogen



Weblink

Innate and adaptive immune systems

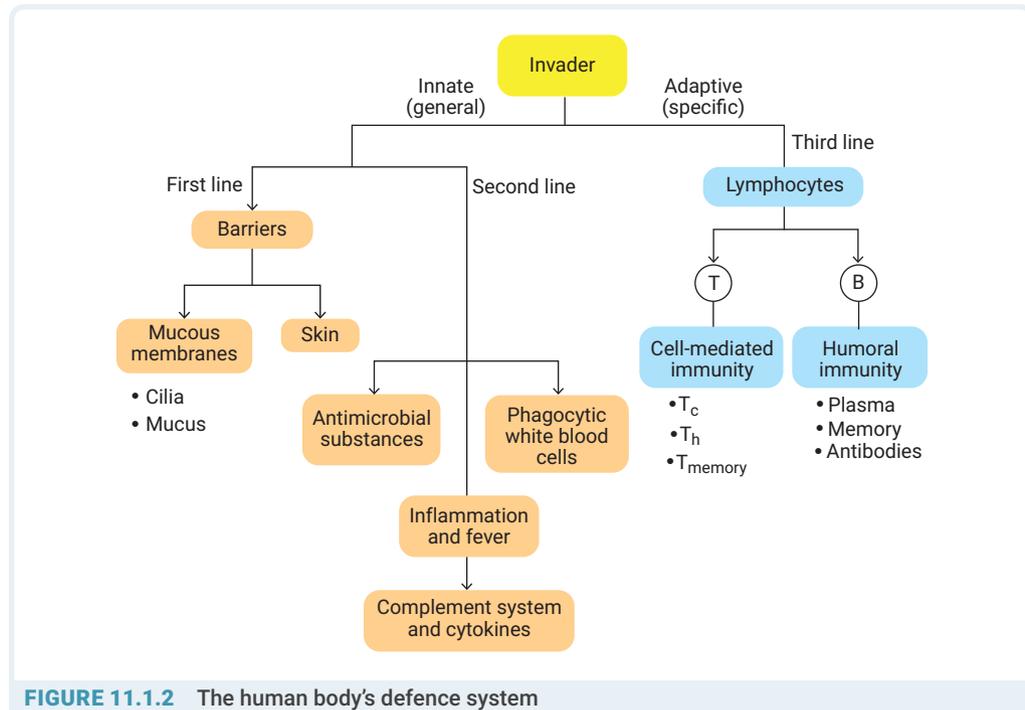


FIGURE 11.1.2 The human body's defence system

LEARNING CHECK 11.1

DESCRIBING

- 1 Define 'antigen'.
- 2 Provide two examples of molecules that can act as antigens.

APPLYING

- 3 Explain the importance of an organism being able to distinguish between self and non-self.
- 4 Explain the role of the major histocompatibility complex (MHC) in distinguishing self from non-self.

11.2 Innate immune response in vertebrates

epithelial cell a cell in a sheet of cells covering any external or internal surface in a multicellular organism

keratinised a process by which keratin is deposited in skin cells; the surface becomes tough and waterproof

keratin a strong, stable structural protein in skin, hair, horns and nails

The most effective way of preventing the colonisation of an organism by pathogens is to keep them out of the body in the first place. The skin of vertebrates provides various physical, chemical and biological barriers that stop the entry of pathogens and other foreign substances.

Physical barrier

As the largest organ in humans, the skin acts as a tough physical barrier between the body and the outside world. Like all the inner and outer linings of vertebrates, the skin is made from **epithelial cells**. After becoming **keratinised**, a process in which the structural protein **keratin** is deposited, the epithelial cells form a hard outer layer of the skin that is impervious to water and pathogens.

Cuts and abrasions that damage skin can allow the entry of pathogens and become ideal sites for infection. When the skin is wounded, blood vessels are damaged and cell fragments in the

blood, called **platelets**, are quickly attracted to the site. They stick to the damaged tissue, sending out chemical messages that trigger the formation of a web-like mesh of **fibrin** protein. The mesh stabilises the aggregation of platelets and traps red blood cells to form a clot. This plugs the break in the vessel wall, forming a scab that seals the wound and keeps out pathogens while the skin is healing.

platelet a cell fragment in blood that helps blood to clot

fibrin an insoluble, fibrous protein mesh that impedes the flow of blood during clotting

Chemical barrier

As well as being a physical barrier to infection, the skin produces chemical substances that destroy or inhibit the growth of micro-organisms. Glands in the skin (**Figure 11.2.1**) produce secretions such as sweat and oil. This gives the skin an average pH below 5, which is acidic enough to prevent colonisation by many pathogenic species. The skin is also protected by small **defensins** similar to those in plants. They are powerful natural antibiotics with antimicrobial, antiviral and antitoxic properties.

defensin a small peptide that plays an important role in antimicrobial activity of phagocytes, the skin and mucous membranes; secreted by virtually all animals and plants

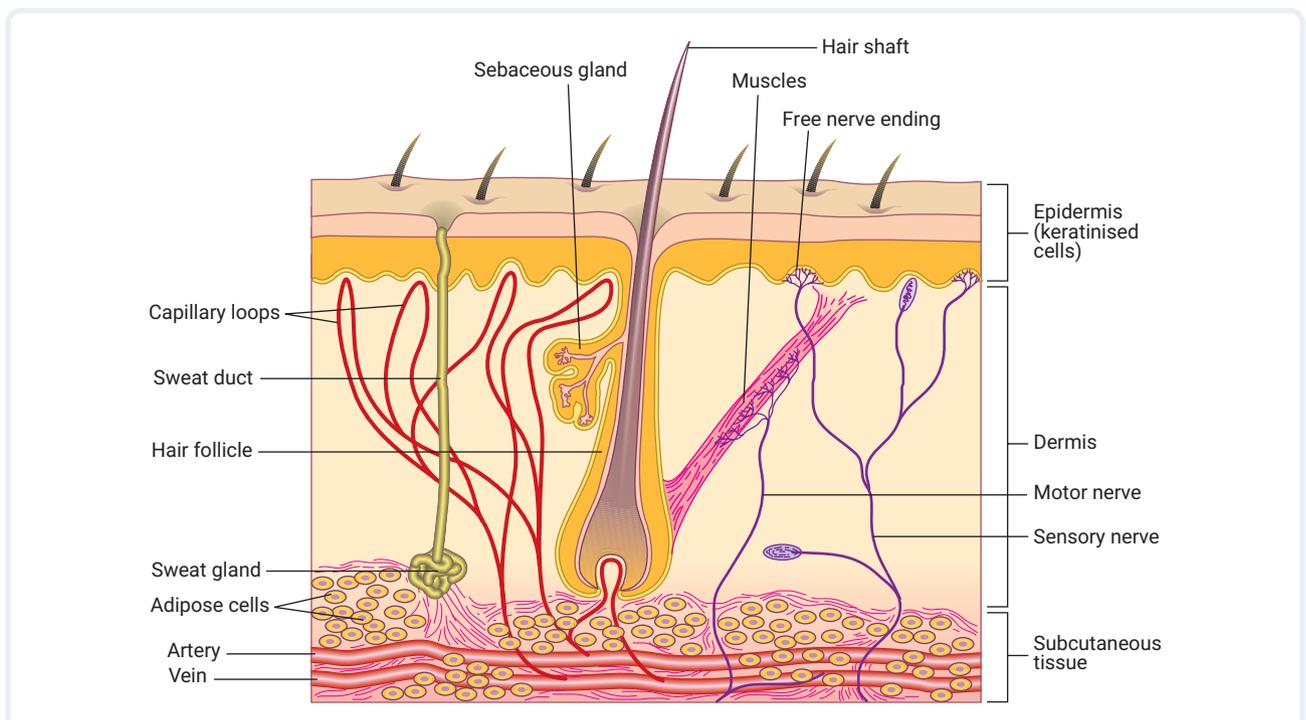


FIGURE 11.2.1 A cross-section of human skin; note the sweat gland and sebaceous gland

Biological barrier

During birth, a baby acquires various micro-organisms that will become permanently associated with it. These **symbiotic** micro-organisms become the normal **microflora** that live on and in the body, but do not cause disease (**Figure 11.2.2**). By taking up space and using nutrients, the microflora prevent colonisation by other pathogenic micro-organisms. Their importance should not be underestimated – about 100 trillion micro-organisms live on the skin surface and mucous membranes; that is ten microbial cells for every human cell.

symbiotic a type of relationship between two organisms where at least one organism benefits

microflora a community of micro-organisms, including fungi and bacteria, that live in or on another living organism

Mucous membranes and cilia

As long as it remains unbroken, tough waterproof skin is an effective barrier against invaders. However, the external openings of the respiratory, digestive, excretory and reproductive systems provide ideal entry points into any organism. Various mechanisms exist to physically trap and expel invading micro-organisms and other foreign particles before they become pathogenic.

The vertebrate respiratory, gastrointestinal and reproductive tracts are lined with mucous membranes that secrete mucus and defensins. The thick, sticky mucus traps invading microbes and prevents them from entering the tissues and gaining a foothold. Coughing and sneezing is one way that mucus containing potentially harmful micro-organisms and foreign substances can be removed from the nasal passages and upper respiratory tract. Another way to remove mucus is by the beating of slender hair-like structures called cilia that line the respiratory tract (Figure 11.2.3). This beating action pushes mucus up to the throat, where it can be coughed out or swallowed.

Passing urine and the flow of tears also help to flush out micro-organisms (Figure 11.2.4). **Lysozyme**, which is an enzyme in tears, saliva and mucus, acts as an antimicrobial agent, breaking down the cell wall of certain types of bacteria and causing them to burst (**lyse**).

lysozyme an antibacterial enzyme in tears, saliva and other body fluids

lyse to burst



Worksheet

The first line of defence in the immune system

Science Photo Library/Alamy Stock Photo

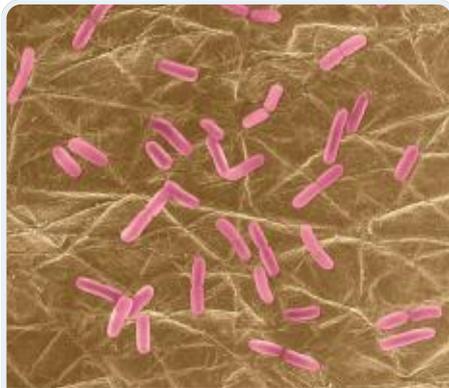


FIGURE 11.2.2 Bacteria living on the surface of the skin



FIGURE 11.2.3 A light micrograph of a mammalian trachea, showing, in vertical section, the cilia lining the wall. Cilia help to trap pathogens and move them up and out of the body.

Biology Pics/Science Source

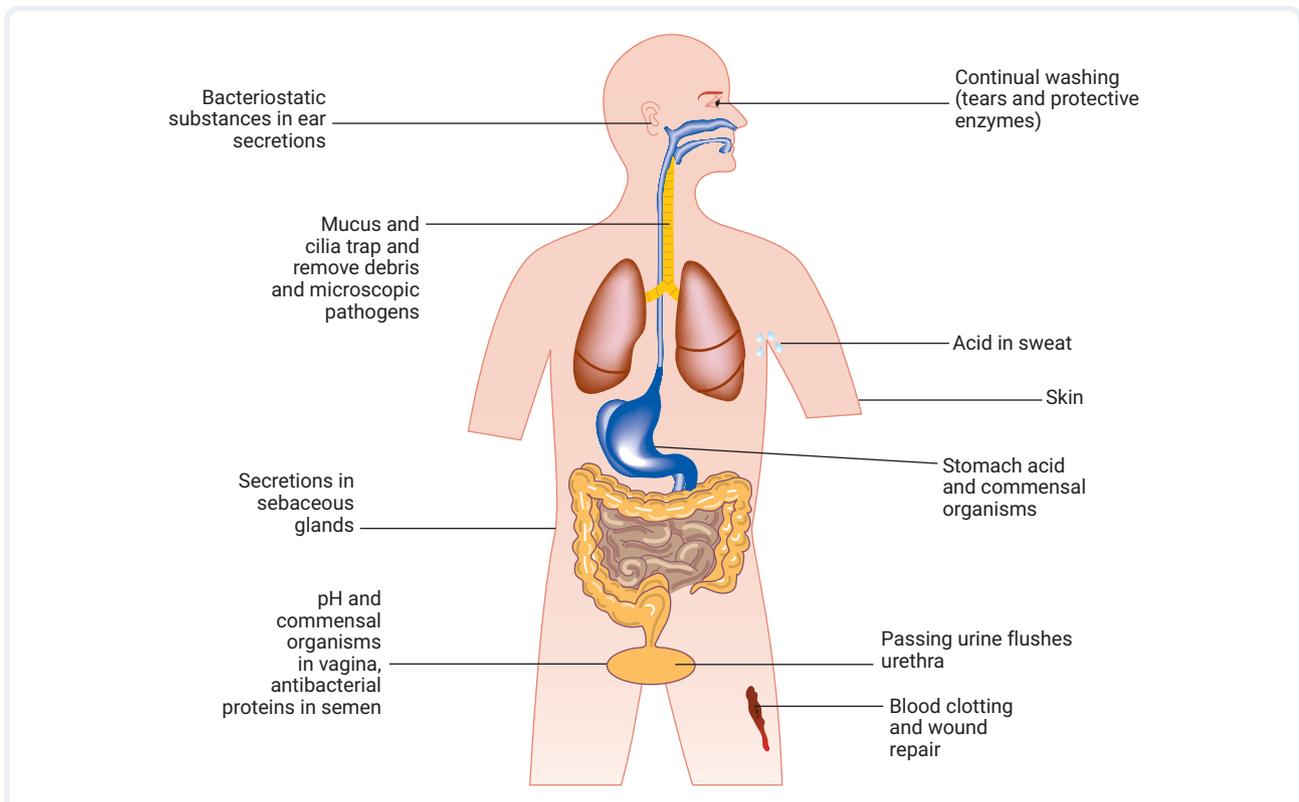


FIGURE 11.2.4 A summary of the physical and chemical barriers to pathogenic infections in a human

LEARNING CHECK 11.2

DESCRIBING

- 1 State the three types of barriers provided by the skin.
- 2 **Identify** two types of chemicals produced by the skin to prevent microbe colonisation.
- 3 **Identify** the enzyme in tears and saliva that has antimicrobial properties.
- 4 **Describe** the role of skin microflora in preventing colonisation with harmful microbes.

APPLYING

- 5 **Explain** how host cells are able to recognise an invading cell.
- 6 **Explain** the role of platelets in the innate immune response when the skin is wounded.
- 7 **Explain** how mucous membranes and cilia contribute to the defence against invading pathogens in the respiratory tract.

11.3 Inflammatory response

When cells are killed or damaged by invading pathogens, inflammation and the complement system are key weapons in the innate immune response. They are rapid, non-specific responses, occurring in the same way every time a pathogen invades the body.

Prostaglandins and vasodilation

Inflammation is characterised by swelling, redness, heat and pain. It is triggered when invading pathogens are encountered by **macrophages** that are strategically distributed in all body tissues. Macrophages detect pathogens and switch on inflammation in other immune cells by producing a range of cell signalling molecules called **cytokines**.

Mast cells are also located in the connective tissues and their cytoplasm is packed with intracellular granules containing **histamine** and **prostaglandins**, both powerful defensive chemicals important in inflammation. Histamine induces **vasodilation**, while prostaglandins are lipid-based molecules produced in response to tissue injury or infection. The release of prostaglandins causes vasodilation, fever and pain and a subsequent increase in blood flow and delivery of immune cells, including neutrophils and macrophages, to the infected area.

Vasodilation is widening of blood vessels, specifically **arterioles**, allowing increased blood flow to the area and leading to redness, swelling and increased heat. Histamine also increases the permeability of capillaries in the inflamed area, making it easier for white blood cells (leukocytes), blood plasma and blood proteins to squeeze out through the walls and into affected tissue. This further enhances swelling and causes some pain. Pain is important because it reduces voluntary movement in that area, thus speeding up the repair process.

Chemotaxis is an important way that immune cells in blood are directed to sites of infection or tissue damage. White blood cells move towards increasing concentrations of **chemokines**, which are molecules that are released by micro-organisms, activated macrophages and other immune cells (**Figure 11.3.1**).

inflammation an innate response to infection or damage that causes swelling, pain and redness

macrophage a large white blood cell in tissues that phagocytoses (ingests) pathogens

cytokine a small signalling molecule that coordinates inflammation and immune responses, and that leukocytes use to communicate with one another; includes interleukins and interferons

mast cell a cell located in the tissues, which when activated releases granules containing histamine

histamine a chemical released by mast cells that increases blood flow and the permeability of capillaries

prostaglandins a group of lipid-based molecules produced in response to tissue injury or infection and cause vasodilation, fever and pain

vasodilation dilation (widening) of blood vessels, particularly arterioles

arteriole a small blood vessel that carries oxygenated blood to the tissues

chemotaxis the movement of an organism or cell along a chemical concentration gradient either towards (positive chemotaxis) or away from (negative chemotaxis) the chemical stimulus

chemokine a molecule that induces chemotaxis; some cytokines are chemokines

complement system a number of small proteins in the blood that, when activated, promote chemotaxis, cell lysis and phagocytosis

opsonisation a process in which a pathogen is coated with antibodies and marked for ingestion and destruction by phagocytes

phagocyte a cell that is capable of phagocytosis; includes macrophages and neutrophils

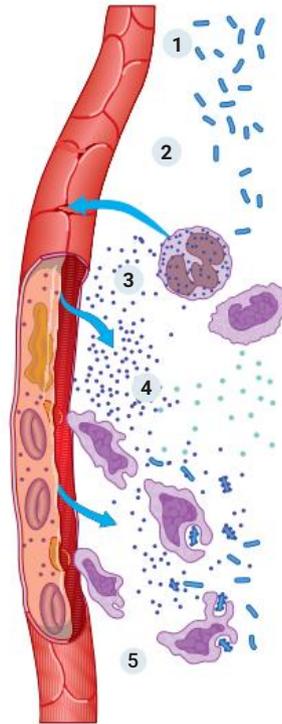
membrane attack complex a complex of complement proteins that form pores in the membranes of target cells, disrupting the phospholipid bilayer

lysis the breakdown of the cell membrane, resulting in the release of cell contents and subsequent death of the cell

monocyte a white blood cell that circulates in the blood and matures into a macrophage when it moves from the blood into the tissues

neutrophil a phagocytic leukocyte in blood and tissues

phagosome a membrane-bound vesicle formed around a particle during phagocytosis



- 1 Bacteria can invade cells or tissues where they can either kill the cells or release harmful by-products of metabolism.
- 2 Granulocytes in infected tissues secrete histamines, and phagocytes and other body cells secrete cytokines to recruit other immune cells.
- 3 Histamines can affect the permeability of small blood vessels so that plasma fluid and proteins can seep into surrounding tissue.
- 4 Cytokines cause phagocytes to move into the tissue and become activated.
- 5 Bacteria are engulfed by phagocytic white blood cells.

FIGURE 11.3.1 The steps that occur in acute inflammation after invasion by a bacterial pathogen

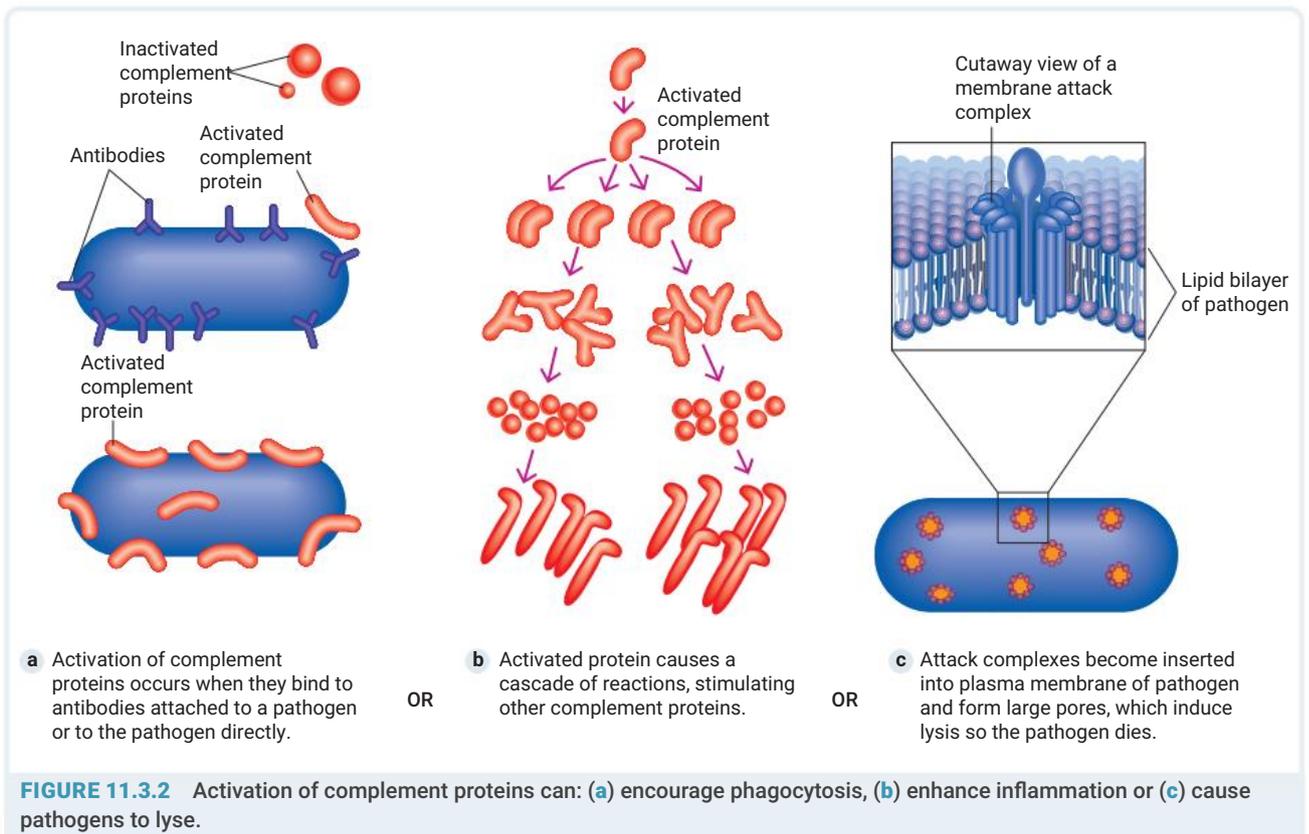
Complement system

The **complement system** consists of a number of small proteins with an important role in inflammation. Approximately 20 different kinds of complement proteins circulate in the blood as inactive precursors. These precursors become activated when they encounter a foreign body, such as an invading bacterium. Activation of one complement protein has a cascading effect, stimulating the activation of other complement proteins, which then activate other proteins in turn. These proteins produce a range of effects for defending the body (**Figure 11.3.2**).

In a process called **opsonisation**, complement proteins bind to the surface of pathogens, acting as a tag to facilitate detection and uptake of the pathogen by **phagocytes**. Complement proteins induce chemotaxis to the damaged or infected site. They also activate phagocytes, increasing their ability to ingest and destroy pathogens and stimulate mast cells to release histamine. An important product of the complement cascade is the **membrane attack complex** (MAC). The MAC forms pores in the membranes of target cells, disrupting the phospholipid bilayer. With membrane integrity destroyed, osmotic cell **lysis** and death follow.

Neutrophils and macrophages

In response to chemokines, two types of leukocytes – **monocytes** and **neutrophils** – squeeze out through the capillary walls into the tissues. Here, monocytes mature into macrophages. As both macrophages and neutrophils engulf invaders by phagocytosis, they are called phagocytes (**Figure 11.3.3**). The pathogen is taken in within a membrane-bound vesicle called a **phagosome**. A lysosome fuses with the phagosome to form a **phagolysosome**,



which becomes increasingly acidic. An array of digestive enzymes and antimicrobial compounds helps to destroy the invader (**Figure 11.3.4**). Macrophages also clear up dead body cells and damaged tissue. Neutrophils and macrophages also contribute to the adaptive immune response.

Natural killer cells

Natural killer (NK) cells are a type of lymphocyte (white blood cell) that do not require prior activation and therefore play a central role in the innate immune system. They continually patrol the body and can distinguish, via the major histocompatibility complex class I (MHC I) receptor pathway, between healthy cells and pathogen-infected cells.

NK cells have receptors on their surface that bind with the unique MHC I molecules of a host cell to prevent the destruction of the host's own cells. However, when 'activating', NK cell receptors bind with 'non-self' antigens (**ligands**) expressed on the surface of infected cells (**Figure 11.3.5**), the NK cell releases cytotoxic granules containing **perforin**, which leads to lysis of the target cell.

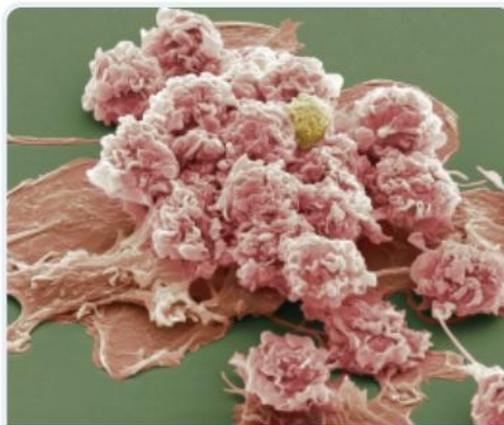


FIGURE 11.3.3 A scanning electron micrograph of a macrophage with cytoplasmic extensions. It uses these to engulf the foreign particle (yellow) that it encounters.

Science Source/Steve Gschmeissner



Weblink
Acute inflammation 3D animation

phagolysosome a membrane-bound vesicle formed from the fusion of a phagosome and lysosome

ligand a molecule that binds to a receptor

perforin a glycoprotein that creates pores in the cell membrane of target cells

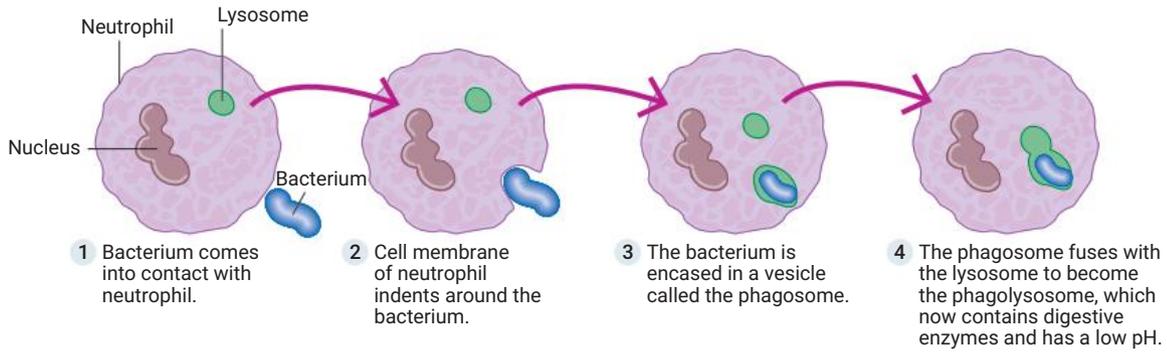


FIGURE 11.3.4 The stages of phagocytosis: a neutrophil ingesting a bacterium

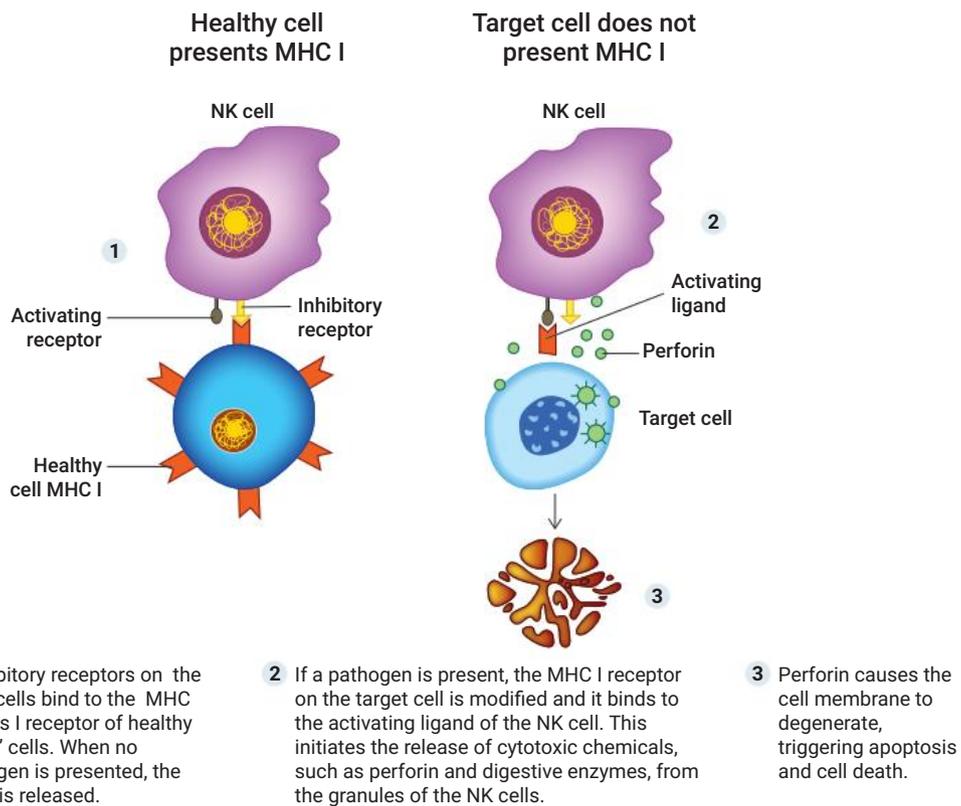


FIGURE 11.3.5 Natural killer cells recognise infected cells and induce apoptosis.

LEARNING CHECK 11.3

DESCRIBING

- 1 State four characteristics of inflammation.
- 2 **Describe** the role of mast cells in inflammation.
- 3 **Identify** two types of leucocytes that move through capillary walls at the site of infection.
- 4 **Describe** three effects that follow activation of complement.

APPLYING

- 5 **Explain** the importance of chemotaxis.
- 6 **Explain** why phagocytes, such as macrophages, typically contain large numbers of ribosomes and lysosomes.
- 7 **Explain** the importance of vasodilation.
- 8 **Discuss** the role of natural killer cells in the immune system.

ANALYSING

- 9 **Organise** the following points in order, to illustrate the sequence of events that would occur when a macrophage encounters a bacterium.
 - I Lysosome fuses with vacuole.
 - II Macrophage recognises bacterial surface molecules as 'non-self'.
 - III Powerful enzymes digest bacterium.
 - IV Vacuole forms around bacterium.
 - V Macrophage envelops bacterium with its cell membrane.

lymphocyte a type of leukocyte involved in adaptive immune responses

B cell (B lymphocyte) a class of lymphocytes; once activated, they are characterised by the production of antibodies

humoral an immune response brought about by antibodies that circulate freely in the bloodstream and can lead to the destruction of pathogens

T cell (T lymphocyte) a class of lymphocytes that mature in the thymus; differentiate into a number of different types of T cells

CD4 receptor a cell surface receptor expressed on T_h cells that binds to MHC class II receptors

CD8 receptor a cell surface receptor expressed on T_c cells that binds to MHC class I receptors

naive cell an immature cell that has not been activated

memory cell an immunological cell that 'remembers' a specific antigen

antigen presenting cell (APC) a phagocytic cell that expresses a foreign antigen on its surface and presents it to helper $T (T_h)$ cells via the MHC II molecule or to cytotoxic $T (T_c)$ cells via the MHC I molecule

cell-mediated immunity when cytotoxic T cells recognise and destroy virally infected and cancerous cells

cytotoxic T cell (T_c) a class of lymphocytes that destroys virally infected or cancerous cells by secreting proteins that cause cell death

11.4 Adaptive immune response in vertebrates

The adaptive immune system is specific and produces an immunological memory of antigens that have been encountered. Adaptive immunity offers a rapid and highly effective response to specific antigens that have been encountered previously.

There are two broad groups of **lymphocytes** involved in the adaptive immune system.

- **B cells** are produced and mature in the bone marrow (thus 'B' cell). They are responsible for the **humoral** (antibody-mediated) immune response.
- **T cells** mature in the thymus (thus 'T' cell). They are responsible for cell-mediated immunity. T cells possess either **CD4** or **CD8** cell surface receptors.

B and T cells can exist in three states.

- **Naive cells** have not been exposed to an antigen.
- Effector cells are activated T and B cells that respond to an antigen.
- **Memory cells** continue to circulate after the antigen has been eliminated. It is the memory cells that initiate a quick immune response if the antigen is encountered again.

The memory B and T cells of the adaptive immune response have the capacity to 'remember' a pathogen and initiate a faster, stronger response against it if exposure occurs again. These 'memory' cells are the basis of acquired immunity.

The adaptive immune response is triggered by a naive T cell binding to an **antigen presenting cell (APC)**.

Cell-mediated immunity

Cell-mediated immunity is required to target pathogens that have already infected host cells and involves the direct killing of infected cells, or cancerous cells, by **cytotoxic T cells (T_c cells)**. The cell-mediated response is activated when an APC presents a specific antigen via an MHC II molecule to a complementary T_h cell, which binds using a CD4 receptor. The T_h cells then release cytokines to activate the mass cloning of T_c cells.

cytotoxin a toxin that disrupts or kills cells

Once activated, effector T_c cells leave the lymph system and migrate to the site of infection, where they bind using a CD8 receptor to infected cells, presenting the antigen via their MHC I receptors. The T_c cells release powerful **cytotoxins** including perforin, which lyse the cell, killing any pathogens within it (**Figure 11.4.1**). T_c cells perform a similar function to NK cells, with one key difference: they require activation and, as such, form part of the adaptive immune response.

During this process, memory T cells with receptors specific to the antigen are formed.

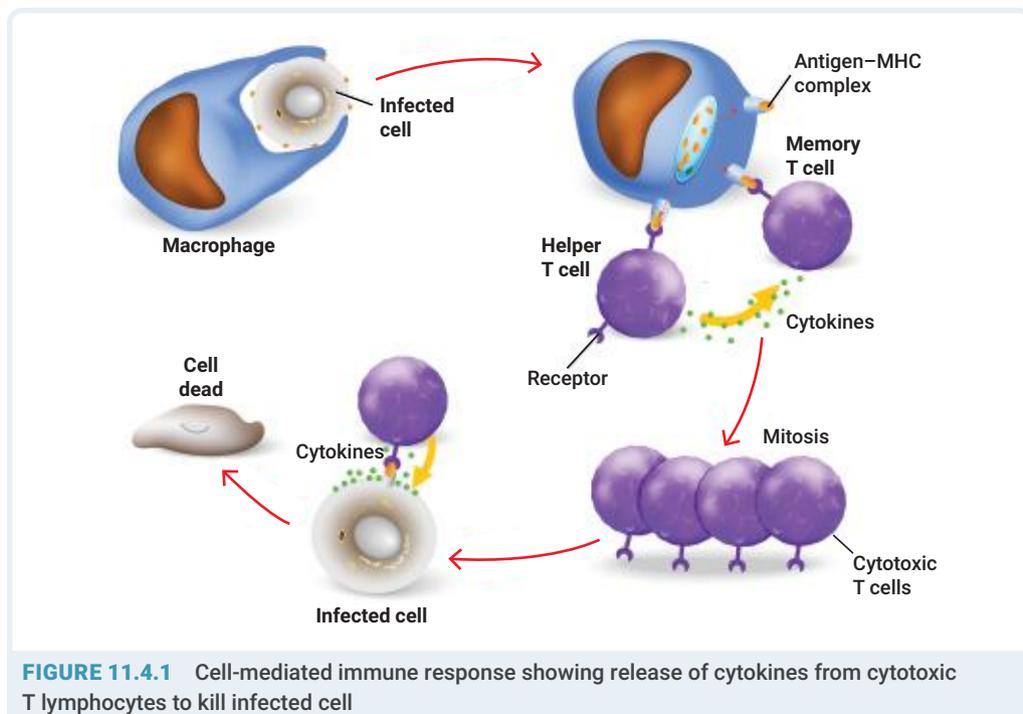


FIGURE 11.4.1 Cell-mediated immune response showing release of cytokines from cytotoxic T lymphocytes to kill infected cell

Humoral immunity

The humoral or antibody-mediated response is brought about by B lymphocytes (B cells) producing large numbers of different proteins called **antibodies**. The humoral immune response is activated when **helper T cells** (T_h cells) bind naive B cells. Along with the release of cytokines by the T_h cells, this promotes the activation and rapid **clonal expansion** (reproduction) of the B cell population that specifically targets the identified antigen. The activated B cells differentiate into **plasma cells**, which act as antibody factories (**Figure 11.4.2**) or memory B cells. The plasma cells secrete up to 10 000 molecules of specific antibody per second into the blood (**Figure 11.4.3**). Circulating antibodies bind directly with antigens to form an antibody-antigen complex, preventing them from causing further harm.

Australian Nobel laureate, Sir Macfarlane Burnet, published the first paper on clonal selection theory, which proposed that the human immune system produces cells that recognise one antigen only as a result of genetic processes during development. Once in contact with the antigen, the immune cells are induced to proliferate rapidly, subsequently producing high volumes of antibodies.

All antibodies have the same basic structure of two heavy chains and two light chains joined to form a Y-shaped molecule. Most of the heavy chain and the lower end of the light chain are conserved (the same) in all antibodies. In contrast, the ends of the heavy and light chains form variable regions that are unique to each antibody and act as the antigen-binding site (**Figure 11.4.4**). These binding sites can attach to complementary (matching) antigens with a specificity, similar to that of enzymes binding with their substrate (see Chapter 4).

antibody a protein produced by plasma cells that binds to a specific antigen; also called immunoglobulin

helper T (T_h) cells a type of T lymphocyte that, once activated by a specific antigen, stimulates the proliferation and differentiation of B cells and killer (cytotoxic) T (T_c) cells

clonal expansion rapid proliferation of clones

plasma cell an effector B cell that has differentiated to become highly specialised for producing antibodies

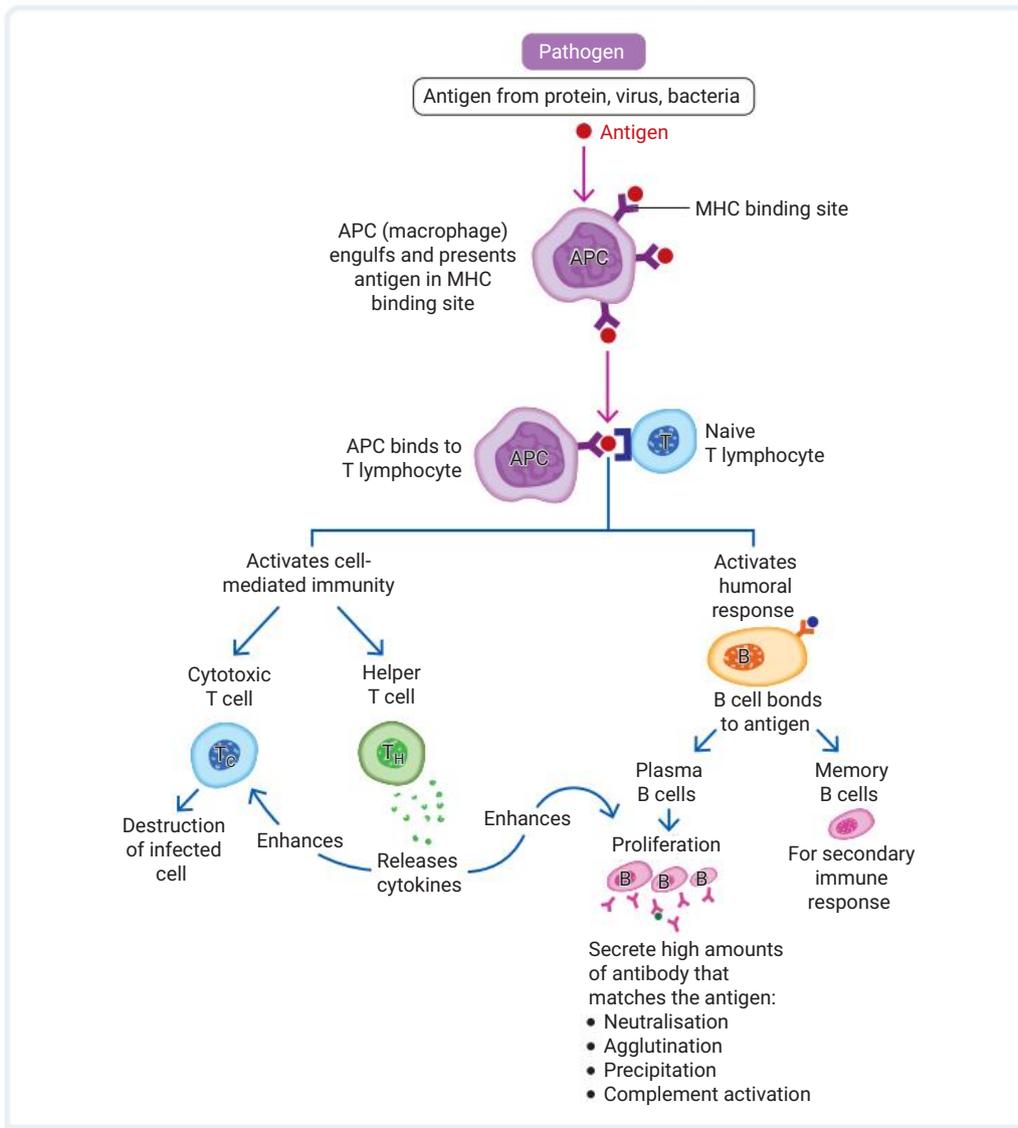


FIGURE 11.4.2 An example of an antibody-mediated immune response to a bacterial pathogen, summarising the steps of B lymphocyte activation

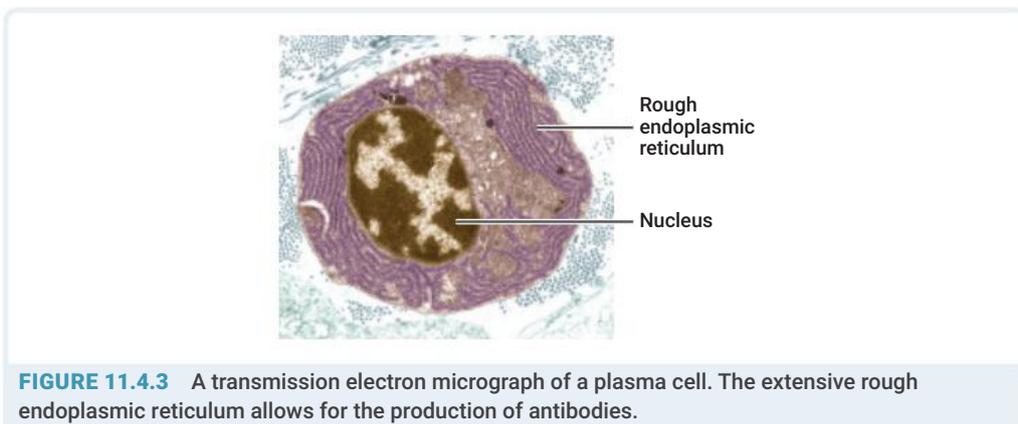


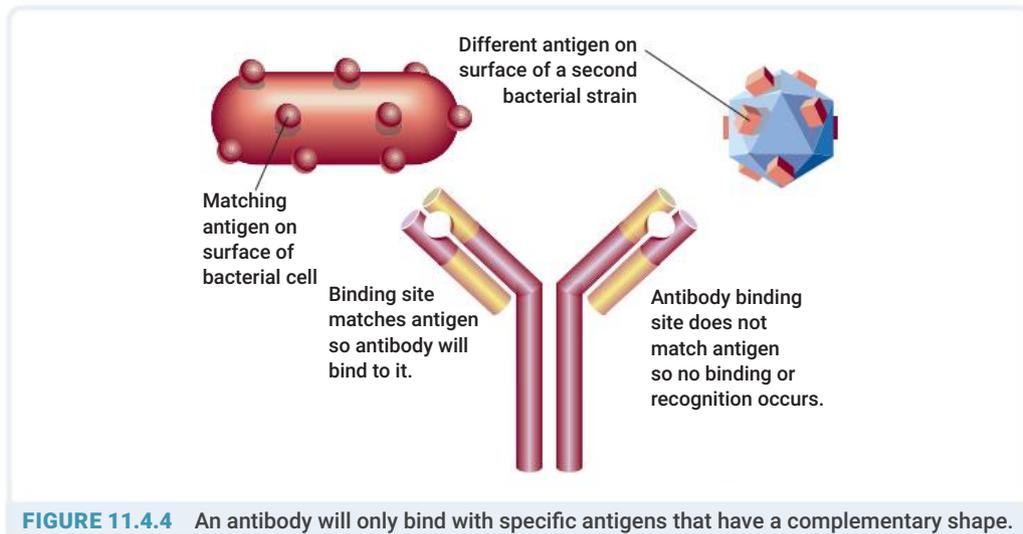
FIGURE 11.4.3 A transmission electron micrograph of a plasma cell. The extensive rough endoplasmic reticulum allows for the production of antibodies.

Steve Gschmeissner/Science Source

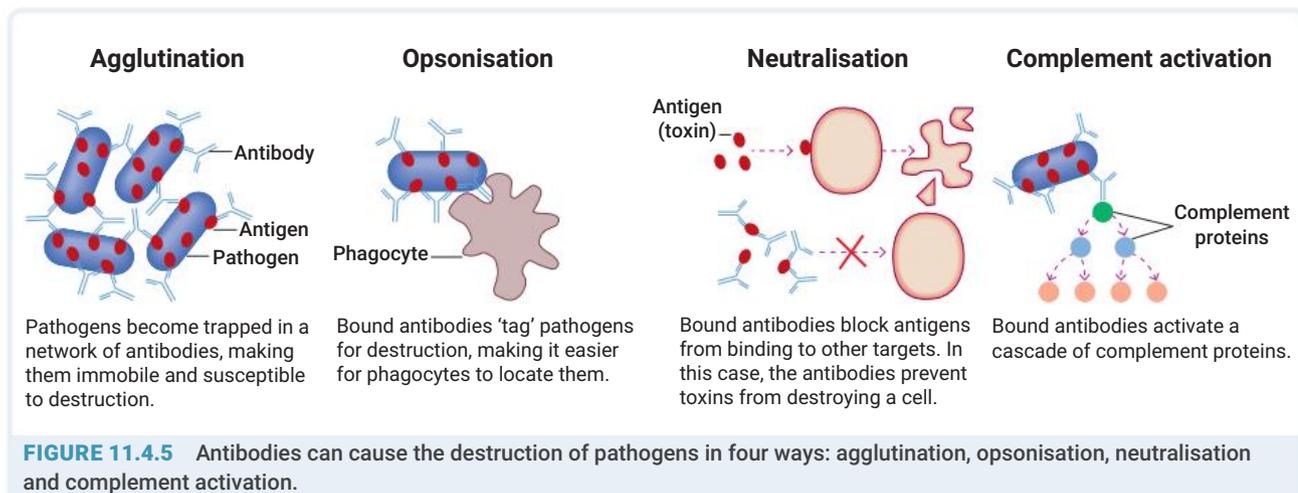


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The adaptive immune system animation
How antibodies work



Antibodies, once bound to an antigen, can lead to the destruction of pathogens in four ways, all of which may occur simultaneously (**Figure 11.4.5**). Complement activation occurs when antibodies that are bound to antigens activate the complement cascade. Opsonisation is the result of bound antibodies effectively ‘tagging’ pathogens for phagocytosis and destruction. Antibodies can neutralise antigens that act as toxins by preventing them from binding to their target. Agglutination occurs when the antigen and antibody become stuck together; therefore, the pathogens are immobile and cannot spread. Being clumped together in one spot also makes them more susceptible to destruction by phagocytosis.



Role of memory cells

Once an infection has been defeated, regulatory T (T_{reg}) cells are produced. T_{reg} cells release cytokines that prevent further production of T_c cells and B cells. Most circulating immune cells linked to the defeated pathogen die off, except for a population of memory T and B cells. These memory cells can remain circulating or accumulate in the spleen and lymph system, where they rapidly proliferate to very large numbers if they are exposed to an antigen they have encountered before. Acquired immunity has been achieved.

LEARNING CHECK 11.4

DESCRIBING

- 1 **Identify** what type of compound an antibody is.
- 2 **Identify** the three states in which B and T cells can exist.
- 3 **Identify** the two broad components of the adaptive immune response.
- 4 **Describe** how an antibody differs from an antigen.
- 5 **Describe** four ways in which an antibody can act to fight off a pathogen.

APPLYING

- 6 Plasma B lymphocytes have an extensive rough endoplasmic reticulum and many mitochondria. **Explain** the relationship between the structure of these cells and their function.
- 7 The adaptive immune system is often described as having memory. **Explain** what this means, using killer T cells as an example.
- 8 **Explain** the role of major histocompatibility complex molecules in the adaptive immune response.



Worksheet
Cells of the adaptive
immune system

11.5 Active versus passive immunity

Active immunity

After exposure to a pathogen, the adaptive immune response leads to the production of memory B and T cells as well as antibodies that are specific to the antigen associated with that pathogen. They lie in wait in the lymph nodes. If the same pathogen is encountered again, the immune response is more rapid – large numbers of plasma cells and T_c cells are produced that act specifically against the pathogen. The response is so effective that the host will often not even know they have been exposed to the pathogen. The individual has immunity to the disease – they have acquired immunity. This kind of immunity, stimulated by natural exposure to a pathogen, is an example of **active immunity** and generally lasts many years.

Unfortunately, it can often take some time for the combined forces of the natural adaptive immune system to locate an invading pathogen and mount a defence. Serious illness and even death may occur before a defence is mounted.

Vaccines

Vaccines have been developed that cause the immune system to respond as if it is being invaded by a pathogen. To do this, vaccines must contain some form of antigen. Once administered, this antigen stimulates the immune system so that memory B and T cells are formed. Vaccines may involve injecting a dead version of the pathogen or a weakened (attenuated) strain that produces only mild symptoms of the disease.

Vaccination gives an organism the experience of a particular pathogen's antigens without the host developing symptoms of the disease itself. It generates active immunity because both the innate and adaptive immune responses are stimulated. This kind of immunity generally lasts many years, although the immune system may need boosters periodically to enhance the number memory cells.

active immunity immunity that develops when the immune system is stimulated by an antigen and effector and memory cells are generated

vaccine a solution of antigens or pathogens that is designed to elicit a primary response and promote the formation of memory cells; can be administered through injection, ingestion or intranasally



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How do vaccines work?

passive immunity

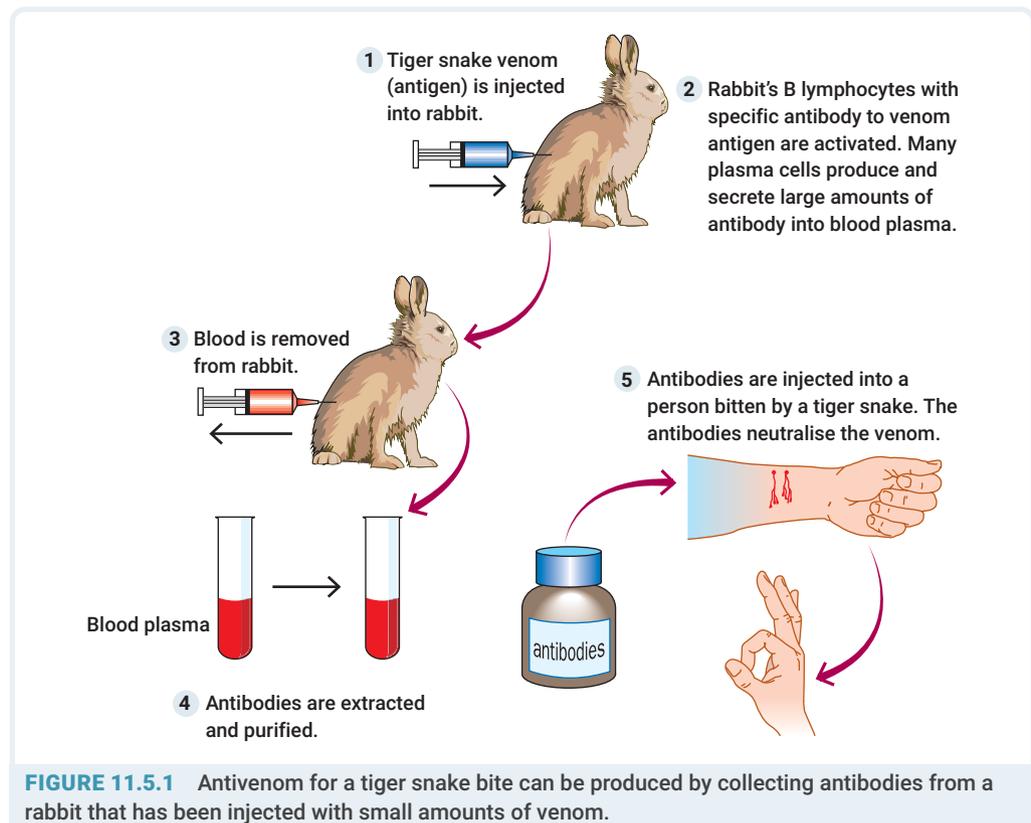
immunity characterised by the transfer of antibodies from one individual to another; this type of immunity does not show memory

Passive immunity

Passive immunity occurs when antibodies are transferred from an external source (**Table 11.5.1**). This provides protection from the pathogen, but only for as long as those antibodies last. Because there are no memory cells, if the person encounters the pathogen again, they will not be immune.

TABLE 11.5.1 Comparison of active and passive immunity

	Active	Passive
Naturally occurring	Exposure to a pathogen	Transfer of antibodies from mother to foetus via the placenta Transfer of antibodies from mother to baby via breast milk
Artificial	Vaccination	Antivenom (Figure 11.5.1) Antibodies against particular pathogens, e.g. rabies



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Active and passive immunity

Worksheet

Immunity

Comparing active and passive immunity

The two systems have some similarities and differences.

Similarities:

- Both can occur naturally or artificially.
- Both result in antibodies that attack the pathogen.

Differences:

- In active immunity, antigens stimulate the production of antibodies, whereas in passive immunity, antibodies are injected directly (**Figure 11.5.2**).

- In active immunity, memory cells are produced for long-term immunity, whereas in passive immunity, no memory cells are produced and immunity declines as antibodies are lost and not replaced.

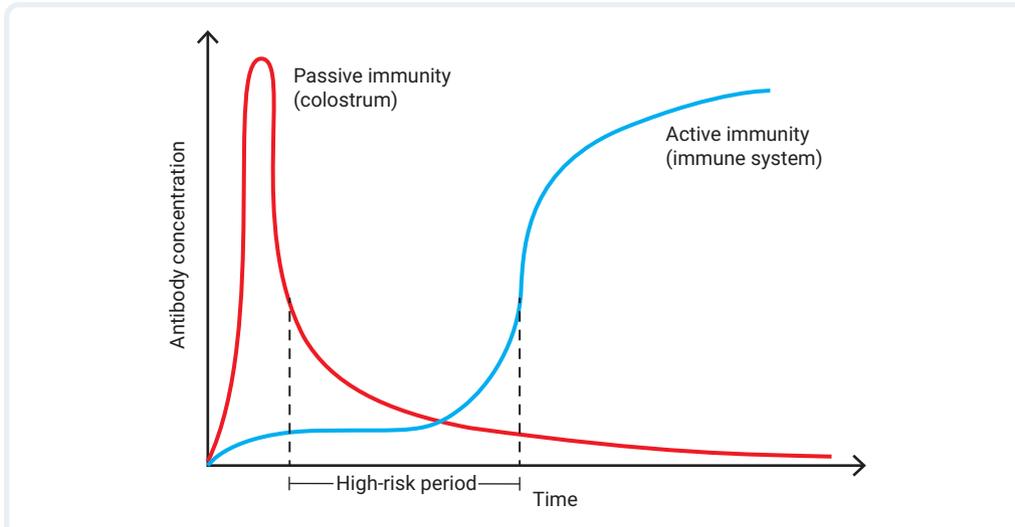


FIGURE 11.5.2 A comparison of antibody concentration in active and passive immunity

The differences between the two types of immunity can be summarised in **Figure 11.5.3**.

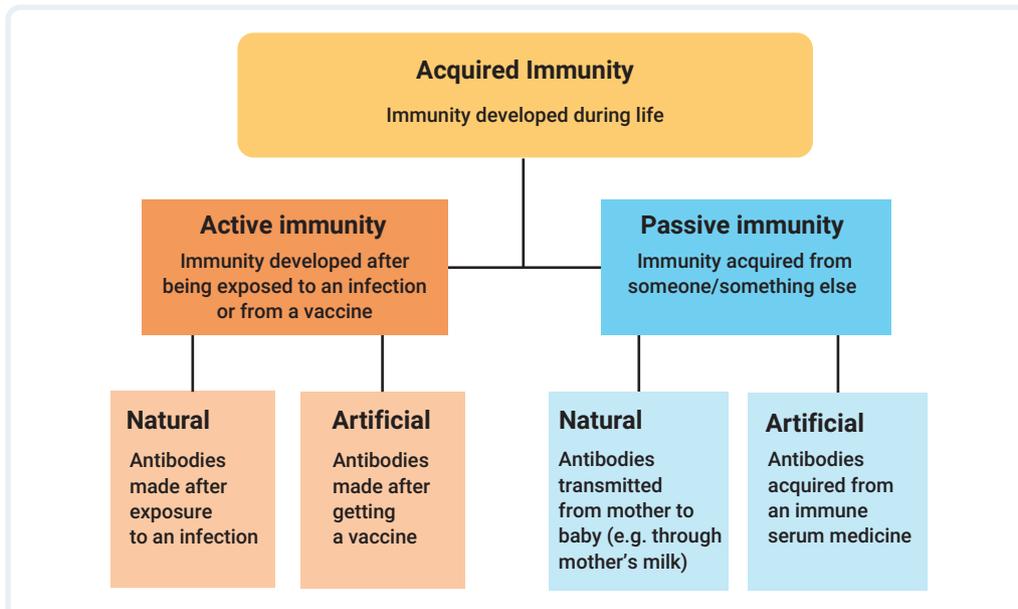


FIGURE 11.5.3 Summary of immunity differences

LEARNING CHECK 11.5

DESCRIBING

- 1 **Identify** two different materials that can be used in a vaccine.
- 2 State differences between passive and active immunity.
- 3 State differences between natural and artificial active immunity.



APPLYING

- 4 **Explain** why passive immunity only lasts for a relatively short time.
- 5 **Explain** the relationship between the adaptive immune system and acquired immunity.
- 6 **Explain** how a vaccination results in acquired immunity.

ANALYSING

- 7 **Compare** active and passive immunity by constructing two Venn diagrams:
 - a one for naturally acquired immunity
 - b one for artificially acquired immunity.

11.6 Innate immune responses in plants

Physical defence strategies

Although plants can be affected by all pathogen groups (**Figure 11.6.1**), the significant majority (nearly 90 per cent) of plant diseases are caused by fungal pathogens. Airborne fungal pathogens penetrate plant tissues via natural openings (stomata and lenticels), while soil-borne fungal pathogens enter via the plant's root system. Plants, like animals, have a range of **physical barriers** that protect against pathogen entry and slow the spread if entry is achieved. However, if these barriers are breached, the host plant will respond to minimise the harm caused.

physical barrier a structural obstruction that protects an organism against microbe entry



FIGURE 11.6.1 Leaves of a (a) healthy tobacco plant, *Nicotiana glauca*, and (b) plant infected with tobacco mosaic virus

Physical barriers

Some physical barriers function to deter herbivores from eating plants, such as thorns or spikes. Since pathogens are typically smaller, often just a single cell, the thick outer bark on stems and roots, which contains high amounts of waxy, water-resistant molecules, acts as the first line of defence, similar to skin in vertebrates.

The plant cell wall is another line of defence that responds to microbial attack by rapidly synthesising and depositing a polysaccharide called **callose** between the cell wall and cell membrane adjacent to the invading pathogen. This impedes cellular penetration at the site of infection. Several other mechanisms help stop the spread of infection through the plant. Unlike animals, plants can shed infected parts such as leaves and branches. Wounds caused by a pathogen can be quickly plugged by **resin** and cells can thicken and fortify their walls, thereby preventing the spread of pathogens into nearby cells.

callose a polysaccharide formed in plant cell walls in response to injury

resin a metabolic product secreted by plants in response to damage

Leaf structure provides several physical barriers to invaders (**Figure 11.6.2**). A thick waxy cuticle prevents entry of pathogens. Waxy cuticles and vertically hanging leaves also prevent the formation of moisture films on leaves. This inhibits bacteria and roundworms that require water for motility, and fungal spores that germinate only in water. Hairs and thorns may also deter vectors of pathogens. Stomatal openings are weak spots, offering an entry point. Many plants have hairs that guard these openings or have sunken stomata in the leaf that make access difficult.

If the physical barriers aimed at preventing pathogen entry are breached, a more active, targeted response is initiated.

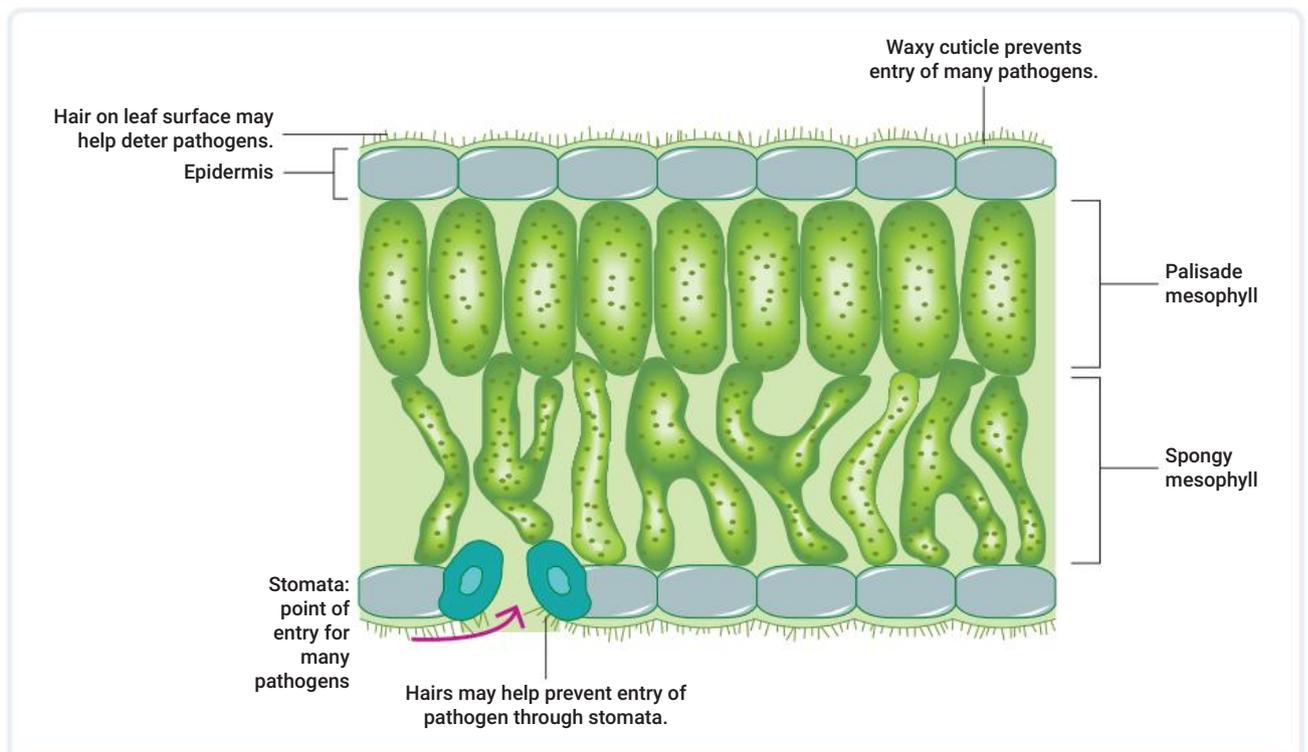


FIGURE 11.6.2 A cross-section of a typical dicotyledon leaf showing some barriers to pathogens found in plants

Chemical defence strategies

Plant defensins are small, stable peptides that can inhibit the development of fungi, as well as bacteria, viruses and insects. More than 300 defensin-like proteins have been identified in plants. Defensins may constitute up to 10 per cent of the total proteins in some types of seeds; they are also present in the cells of flowers, leaves, fruit, bark and tubers. Their antimicrobial action includes reducing membrane permeability and inhibiting the action of enzymes and ribosomes. Because defensins can stop insects feeding on plants, they also provide a defence against insect-transmitted viruses.

Some of the chemicals synthesised by plants can act as toxins against pathogens. Toxins may interfere with basic cellular and biochemical functions of the pathogen. For example, toxins may make it difficult for pathogens to extract essential nutrients from plant tissues, or delay insect



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The amazing ways plants defend themselves

Worksheet

Vaccinating tomato plants to repel pathogens

pathogenesis the nature and presentation of disease development

development. This effectively reduces plant damage. These substances may be released into the environment or retained within plant tissues and absorbed when the pathogen enters the tissue or is consumed by a herbivore. Asparagus plants and marigolds secrete chemicals into the soil that are toxic to nematodes. This makes them good companion plants for tomatoes, which are commonly attacked by these parasitic roundworms.

The bitter-tasting tannins that give tea its characteristic colour and taste are widespread throughout the plant kingdom and are toxic to insects. Caffeine, the alkaloid in plants such as coffee, tea and cocoa, is toxic to both insects and fungi, while pyrethrins are compounds produced by chrysanthemum flowers that act as insect neurotoxins.

Systemic acquired resistance is a non-specific, whole-plant response that occurs once the 'immune' response has been triggered. It results in plant tissues becoming highly resistant to a wide range of pathogens for an extended period. This systemic resistance is activated by the accumulation of salicylic acid, which initiates a signalling pathway to other parts of the plant, causing them to produce a range of broad-spectrum **pathogenesis**-related proteins (**Figure 11.6.3**). These prepare the plant for any pathogens that bypass the localised hypersensitive response.

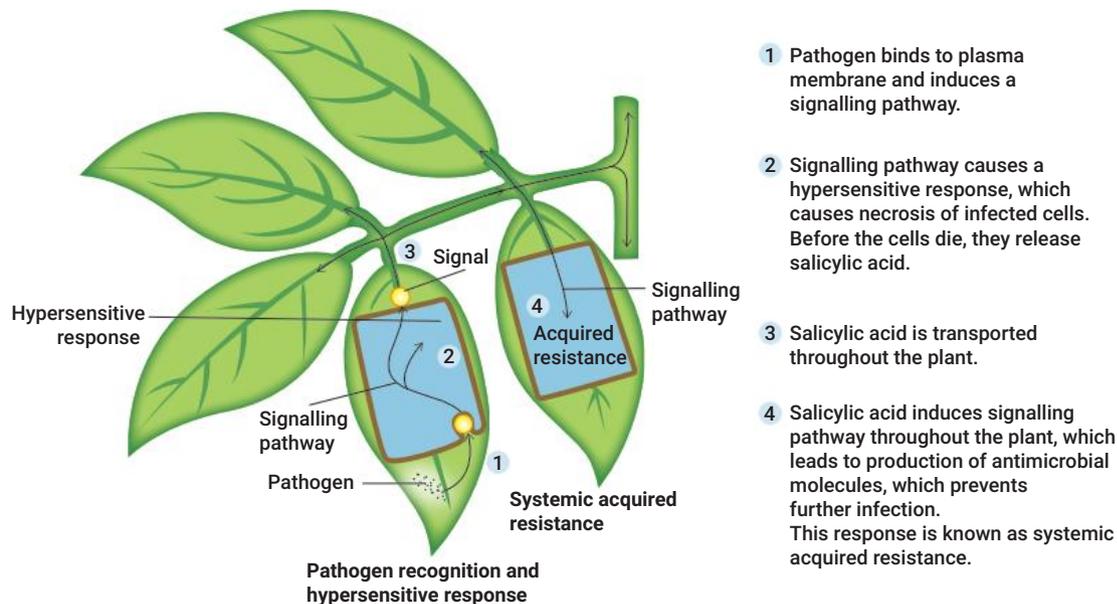


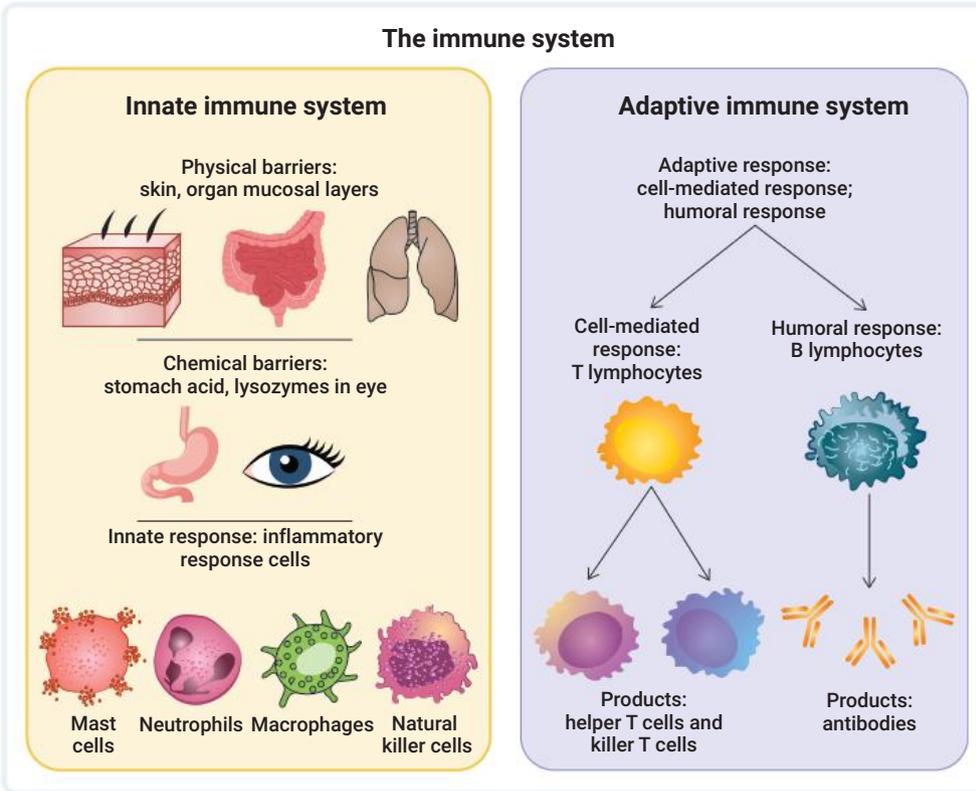
FIGURE 11.6.3 The hypersensitive response and systemic acquired resistance

LEARNING CHECK 11.6

DESCRIBING

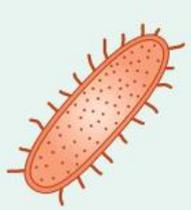
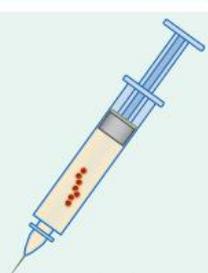
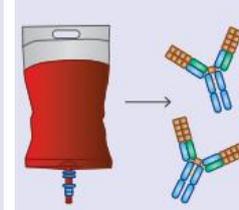
- 1 **Describe** the physical barriers plants possess to protect them from infection.
- 2 **Describe** the role of plant defensins in protecting plants from pathogens.

The immune system



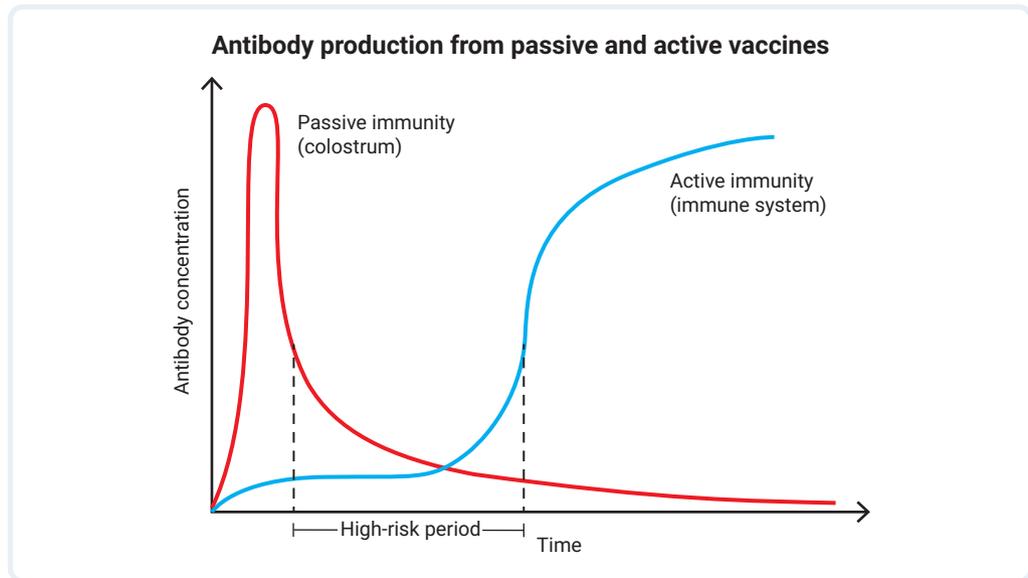
Healthy Immunity on Preventive Medicine for Combating COVID-19 Manna, Pulak R.; Gray, Zackery C.; Reddy, P. HemachandraNutrients, 01 Mar 2022, Vol. 14, Issue 5

Comparing active and passive immunity

Active immunity		Passive immunity	
Immunity developed after being exposed to an infection or getting a vaccine		Immunity acquired from someone or something else	
Natural	Artificial	Natural	Artificial
 Infection	 Vaccination	 Maternal antibodies	 Monoclonal antibodies
Antibodies made after exposure to an infection	Antibodies made after getting a vaccine	Antibodies transmitted from mother to baby (e.g. through mother's milk)	Antibodies acquired from an immune serum medicine

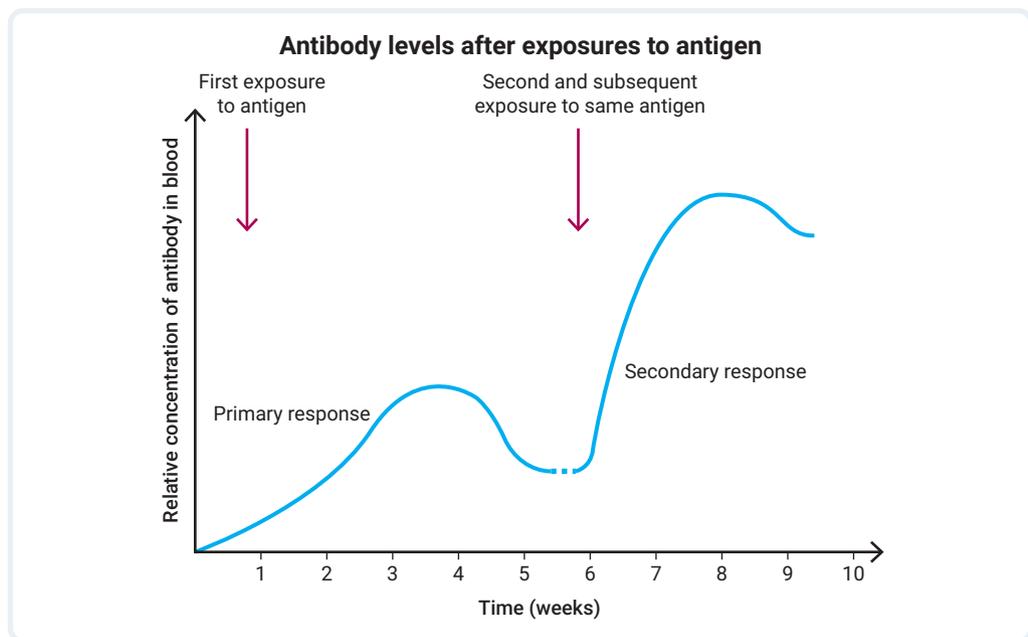
Vaccines and antibody production

- A comparison of antibody production from passive and active vaccines demonstrates the rapid and short-lived nature of passive immunity in contrast to active immunity.



Responses to antigen exposure

- The secondary response is faster, producing more antibodies at a sustained higher level for a longer period.
- This heightened secondary response is the result of acquired immunity where memory B and T cells are produced after the primary exposure.



Physical and chemical innate responses in plants

- Physical innate immune responses:
 - Physical barriers, including bark and cell walls, prevent pathogen entry, while waxy leaf cuticle, hairs and thorns deter pathogen vectors.
- Chemical innate immune responses:
 - Chemical defences inhibit microbial growth.
 - Defensins are small peptides that inhibit the growth and reproduction of fungal, bacterial and viral pathogens.
 - Defensins disrupt the cell membrane or inhibit a pathogen's enzymatic and ribosomal functions.
 - Plant toxins have antimicrobial properties and destroy the cell membrane or interfere with a pathogen's cellular processes.
 - Some plant toxins deter herbivores and insect vectors from eating the plant.

MULTIPLE CHOICE

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1. When human skin tissue is damaged by a sharp object, an inflammatory response is initiated.
Which one of the following is a correct statement about the inflammatory response?
- A Antibodies are released by macrophages that attach to pathogens in the area around the damaged skin tissue.
 - B Blood flow to the damaged area would decrease as blood vessels in the area vasoconstrict.
 - C Swelling around the damaged area is caused by an increase in the number of immune cells.
 - D Cytokines released by damaged cells attract neutrophils to the damaged area.

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2. In humans, an example of a chemical barrier that prevents the entry of pathogens into the internal environment is:
- A histamine.
 - B interferons.
 - C lysozymes.
 - D complement proteins.

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3. Some human cells produce proteins called cytokines.
A major function of cytokines is:
- A signalling immune cells in inflammatory responses.
 - B stimulating B cells to directly attack virally infected cells.
 - C diffusing across a synaptic gap to stimulate the adjacent cell.
 - D communicating very rapidly with a cell that is distant from the cytokine-producing cell.

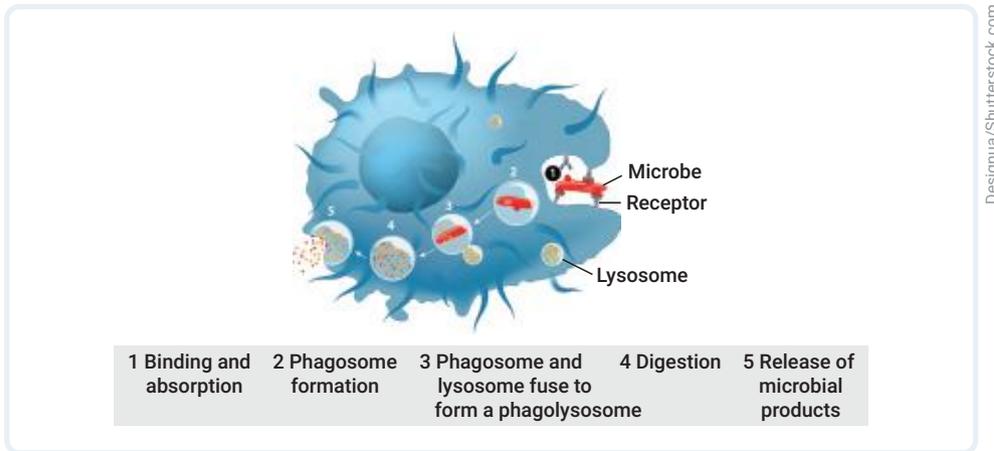
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4. Complement proteins and interferons are involved in a human immune response. Which one of the following is a correct statement about their role in a response?
- A Antibodies are produced in response to the release of both complement protein and interferons.
 - B Both complement proteins and interferons can be part of the innate immune response.
 - C Interferons are released in response to the presence of phagocytic cells.
 - D Complement proteins are released from activated mast cells.

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5. T helper cells encounter an antigen-presenting dendritic cell. The two types of cells will be able to bind if the:
- A receptor on the T helper cell is complementary in shape to the presented antigen.
 - B dendritic cell begins to divide after activation from the T helper cell.
 - C antigen matches the antibody found on the T helper cell.
 - D T helper cell receives a signal to form a plasma cell.

6. The diagram below shows the process of phagocytosis. This process is vital for immunity against extracellular infections.



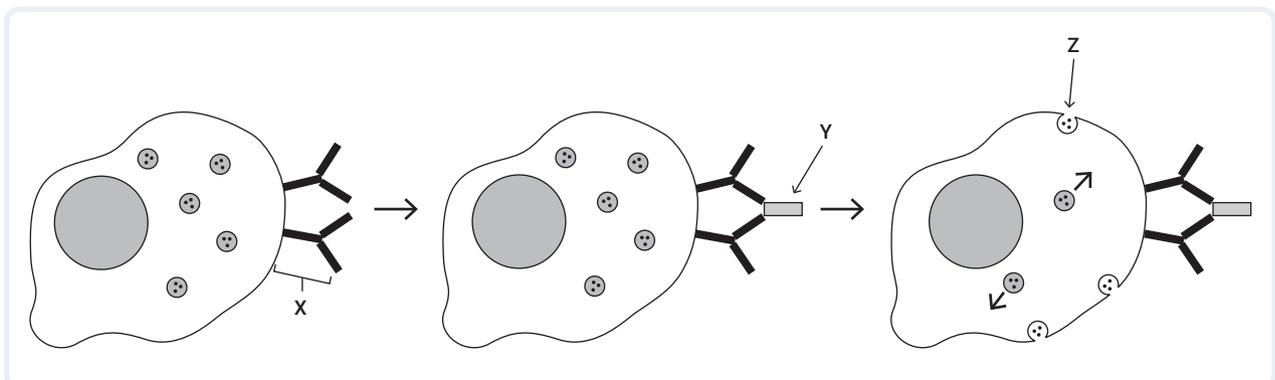
What is happening at position 3?

- A Enzymes that break down the micro-organism are released into the vesicle.
- B Antibodies are added to the vesicle to kill the micro-organism.
- C The cell is sampling the vesicle for antigen presentation.
- D Intracellular microbes are attacking the micro-organism.

7. Which one of the following describes a feature common to both T cells and B cells?
- A Having immunological memory
 - B Rapidly responding to pathogens on first exposure
 - C Providing a physical barrier to the entry of pathogens
 - D Being able to attach to both micro-organisms and viruses

Questions 8 and 9 refer to the following figure.

The diagram shows an immune cell responding to a substance. This process occurs during certain types of allergic reactions.



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8. Which type of immune cell is featured in the diagram?
- A Mast cell
 - B Neutrophil
 - C Macrophage
 - D Dendritic cell

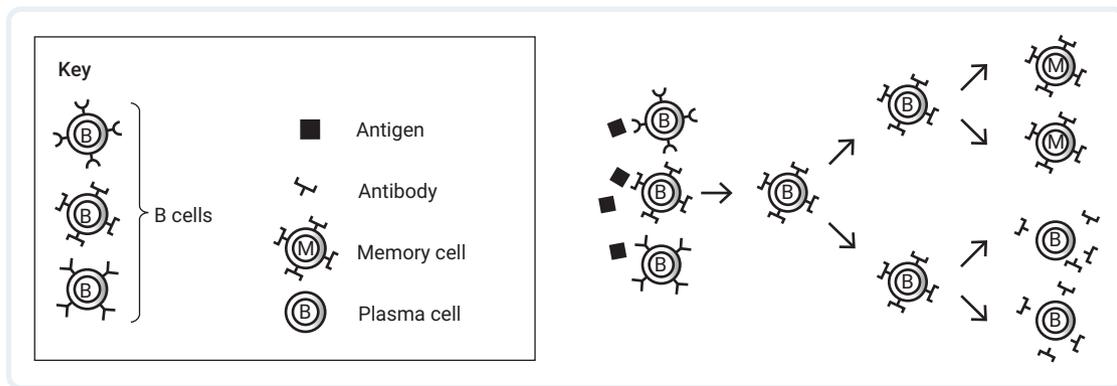
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9. What are the structures X and Y in the diagram?

	X	Y
A	Antibody	Allergen
B	Receptor	Antibody
C	Glycolipid	G protein
D	Antigen	Allergen

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10. Consider the diagram below of clonal selection in B cells.



Victorian Curriculum and Assessment Authority

In adaptive immunity, which part of this process allows long-term (sometimes lifetime) protection against pathogens?

- A Recognition of one antigen by one B cell clone
- B Production of specific antibodies
- C Generation of memory cells
- D Production of plasma cells

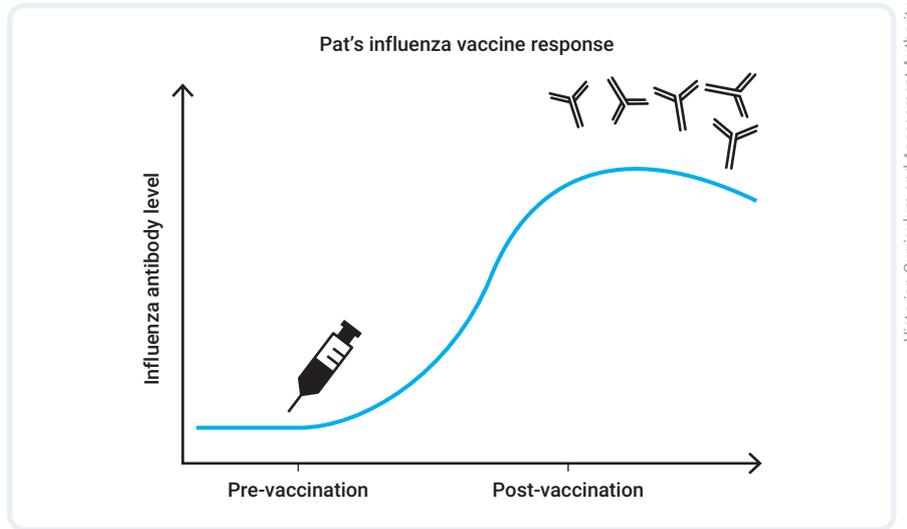
SHORT RESPONSE

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11. Over the weekend, a group of friends went to the movies. They all sat together and shared a drink. The next day, Morgan had symptoms of the flu virus and the doctor told Morgan that they had been infectious when at the movies.
- a **Describe** two components of the immune system's first line of defence that the virus overcame to infect Morgan.
- Alex wakes up a few days later with a sore, inflamed throat.

- b** Using your knowledge of the immune response, **hypothesise** what is happening to cause Alex's sore, inflamed throat.
- c** Pat does not develop symptoms of the flu after Pat's contact with Morgan, who was infectious. Pat had the influenza vaccination this season.

The graph below shows Pat's influenza virus antibody levels before and after vaccination.



Explain Pat's immune response after contact with Morgan, which prevented Pat from developing the flu.

- 12. Describe** one physical defence strategy and one chemical defence strategy used by plants.

CROSS-CHAPTER QUESTION

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- 13.** Australian marsupials, such as wallabies, kangaroos, wombats and koalas, give birth to very undeveloped young called joeys. When a joey enters the mother's pouch, it is at a stage equivalent to a 7-week-old human foetus. It spends many weeks in the pouch feeding on milk produced by mammary glands. Although the pouch provides protection from predators, it is neither sealed nor sterile.

The joey's primary immune tissue (in the bone marrow and thymus) does not mature until 30 days after birth and its humoral immunity does not function effectively until 90 days after birth. Biologists have analysed milk samples from several marsupial species and found that they contain various antibodies. Some of the antibodies in the mother's milk remain in the joey's gut, while others cross the gut wall and enter the joey's bloodstream.

- a Describe** at a molecular level how antibodies perform their function.
- b Recall** the type of immunity that the joey obtains from the antibodies in the milk and **explain** how this form of immunity is beneficial to the joey.

Scientists have found that the milk of the tammar wallaby (*Macropus eugenii*) contains high levels of peptides with antibiotic properties, as well as lysozyme, complement proteins, cytokines and venom inhibitors.

Scientists tested the tammar wallaby milk peptides and found them to be 10 times more effective than antibiotics such as tetracycline and ampicillin, which are commonly used to fight human diseases. The scientists are keen to find a pharmaceutical company that will support further testing and development of these peptides with antibiotic properties.

- c **Hypothesise** what the scientists would hope to achieve as a result of further testing of these peptides with antibiotic properties.

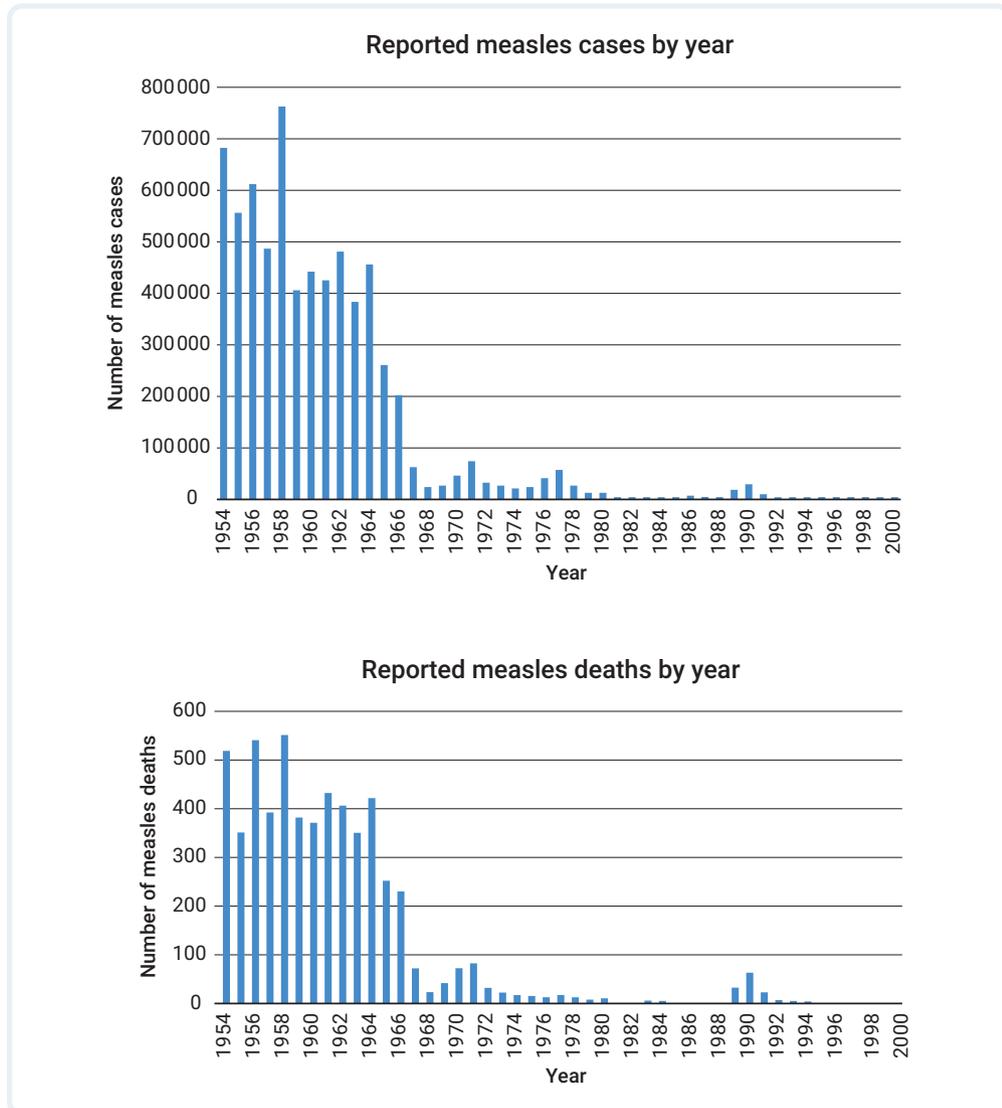
DATA ANALYSIS QUESTIONS

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14. Analyse data

Measles is a highly infectious and dangerous disease. Young children and individuals with impaired immunity are especially susceptible to measles.

The following graphs show the number of people in the USA who were infected with measles during the period 1954–2000 and the number of people who died as a result of having measles during the same period.



Apply understanding

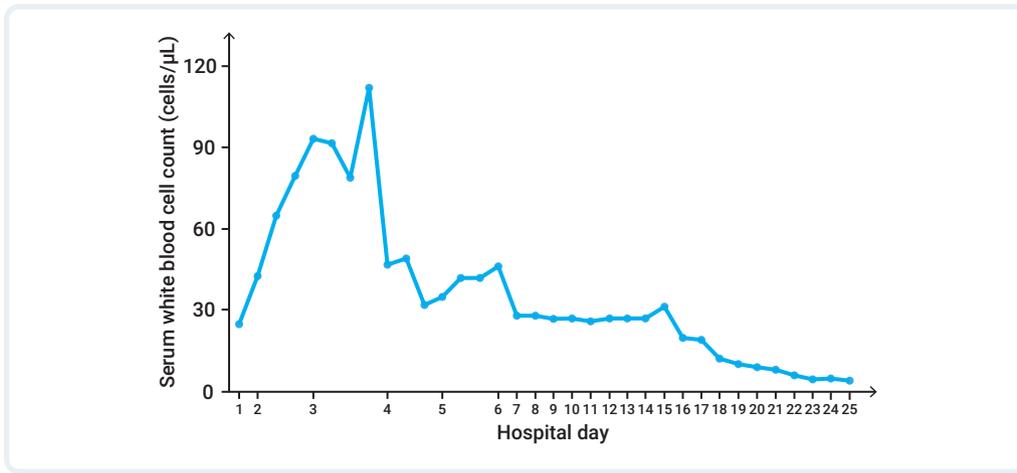
- a i Identify** the year that had the greatest number of reported measles cases.

Analyse evidence

- ii Compare** the two graphs
iii Identify any trends.

15. Interpret evidence

The following graph shows the white blood cell count of a patient suffering from a bacterial infection known as Clostridial toxic shock syndrome from admission to discharge from hospital.



Deduce the reason for the changing levels of white blood cells from day 1 to day 25.

CHAPTER 12

Transmission and spread of disease



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SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- Describe modes of disease transmission, including direct contact, contact with body fluids, contaminated food, contaminated water and disease-specific vectors.
- Explain how the following factors affect the spread of disease
 - persistence of pathogens within host
 - transmission mechanism
 - proportion of the population that are immune or have been immunised
 - mobility of individuals in the affected population.
- Explain how personal hygiene measures, contact tracing and quarantine are used to control the spread of disease.
- Interpret data from an experiment investigating the effect of an antimicrobial agent on the growth of a micro-organism.
- Analyse data to
 - predict outbreaks
 - determine the source of an outbreak



- infer the mode of disease transmission
- determine the effectiveness of different strategies in controlling the spread of disease.
- Interpret long-term immune response data.

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Introduction

The 1918–19 Spanish influenza outbreak spread rapidly throughout the world, killing up to 100 million people. Despite intensive efforts to stop the disease, the Spanish influenza outbreak killed about 12 000 Australians, many of them healthy and young. There were many reasons for the devastation caused by this disease. The population was exhausted by the recent war and transportation of soldiers around the world rapidly spread the disease. War had also disrupted normal healthcare programs, leaving countries unprepared to respond.

Spanish influenza provides a strong example of the way that many factors contribute to the spread of disease. This chapter explores the factors that affect disease transmission, how disease spread is monitored and how outbreaks are managed.

Worksheet

- Modes of transmission

 Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap



ASSUMED KNOWLEDGE

- ✓ Infectious diseases are caused by pathogens, which can be transmitted between individuals.
- ✓ There are six distinct pathogenic groups: prions, viruses, bacteria, fungi, protists and parasites.
- ✓ Prions and viruses are non-living pathogens. Prions are small infectious proteins containing no genetic material, and viruses contain either RNA or DNA but are unable to replicate without host cell machinery. Neither prions nor viruses can be observed under a light microscope.
- ✓ Bacteria are small (1–10 µm) unicellular prokaryotic organisms that have a cell wall. They can be observed under a light microscope.
- ✓ Bacteria reproduce by binary fission.
- ✓ Fungi, protists and parasites are all eukaryotic organisms.
- ✓ Fungi are distinguished by their cell wall made of chitin. They are larger than bacteria and can be unicellular or multicellular.
- ✓ Protists are unicellular organisms typically characterised by their complex life cycles.
- ✓ Parasites are multicellular organisms that live on (ecto-) or in (endo-) a host organism.
- ✓ Different factors affect the pathogenesis of each pathogen, including adherence factors, invasion factors, capsules and toxins.
- ✓ Science inquiry involves identifying and posing questions and working to answer them. It is concerned with evaluating claims, investigating ideas, solving problems, reasoning, drawing valid conclusions and developing evidence-based arguments.
- ✓ Reliability is the extent to which repeated observations and or measurements yield similar results. It is best addressed through repetition, removal of outliers and averaging.
- ✓ Validity is the extent to which an investigation measures what was intended. It is best addressed through ensuring that all variables, except the independent variable, are controlled.
- ✓ Analysis of data involves the identification and discussion of data to identify trends, patterns and relationships, and to recognise error, uncertainty and limitations of evidence.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe examples of direct contact disease transmission that involve physical contact between an infected individual and a susceptible host
- ✓ describe examples of indirect contact disease transmission that occur when an infected individual sneezes or coughs infectious droplets into the air, which are then inhaled by a susceptible host
- ✓ describe examples of food and waterborne disease transmission which typically occur due to incorrect storage or treatment of food and water sources
- ✓ describe examples of disease-specific vectors. This typically involves protists with complex life cycles that require an intermediate and definitive host
- ✓ explain how the ability of a pathogen to persist within a host increases the likelihood of reproduction and transmission of the disease
- ✓ explain how different modes of disease transmission influence a pathogen's ability to spread disease
- ✓ explain how disease transmission is influenced by the proportion of the population that have immunity to the disease
- ✓ explain how disease transmission is influenced by the mobility of individuals in an affected population

- ✓ explain how strategies such as personal hygiene measures, contact tracing and quarantine are used to control the spread of disease by minimising contact between infected and non-infected individuals
- ✓ interpret data examining the effect of an antimicrobial agent on the growth of a micro-organism
- ✓ analyse data to predict and manage disease outbreaks
- ✓ analyse data to determine the source of disease outbreak and determine the mode of transmission.
- ✓ examine long-term immune response data and propose reasons for the observed results.

12.1 Modes of disease transmission

To be able to persist and survive, pathogens must follow a repeating cycle of **transmission** from current host to future host. This cycle can simply be direct transmission from one host to the next or may involve one or more steps through an intermediate host or a vector. The first step requires the pathogen to escape from the body of its current host. It must then gain transport to a suitable new host, enter their body, establish itself in their tissues and finally ensure it is once again passed to a new host. To identify suitable strategies to control pathogens, it is critical that their cycles of infection are understood.

transmission the passing of an infectious disease from an infected host to another individual

Table 12.1.1 lists some common infectious diseases and their methods of transmission.

TABLE 12.1.1 Common infectious diseases and their general methods of transmission

Disease	Pathogen type	Pathogen name	Mode of transmission
Common cold	Virus	Rhinoviruses and coronaviruses	Body fluids: coughs and sneezes
Influenza	Virus	<i>Influenza virus</i>	Body fluids: coughs and sneezes
AIDS	Virus	HIV	Body fluids
Cold sores	Virus	<i>Herpes simplex</i>	Direct contact
Tinea (athlete's foot)	Fungus	<i>Trichophyton rubrum</i>	Direct contact
Ringworm	Fungus	Species from the genus <i>Microsporum</i> , <i>Trichophyton</i> and <i>Epidermophyton</i>	Direct contact
Giardiasis	Protozoan	<i>Giardia lamblia</i>	Contaminated food and water
Plague	Bacteria	<i>Yersinia pestis</i>	Insect vector: flea
Typhoid	Bacteria	<i>Salmonella typhi</i>	Contaminated food and water
Food poisoning	Bacteria	<i>Staphylococcus aureus</i> and <i>Salmonella</i>	Contaminated food
Gonorrhoea	Bacteria	<i>Neisseria gonorrhoeae</i>	Direct contact during sexual intercourse

Direct contact

Direct contact occurs when one person has direct bodily contact with another person who has the infection, including mucous membranes or bodily fluids (such as saliva, semen, vaginal fluids, urine, mucus, tears or blood). Additionally, the World Health Organization defines a type of 'through the air transmission' called 'direct deposition'. Fluid particles that are released when a person coughs, sneezes, talks or breathes heavily can land on surfaces quickly. This is considered direct contact (direct deposition) when a person is close enough to someone who has respiratory symptoms (e.g. coughing or sneezing) and infectious particles land directly on their mouth, nose and/or eyes.

Examples of diseases transmitted by direct contact include chickenpox (*Varicella zoster* virus), whooping cough, the common cold (rhinovirus) and many sexually transmitted infections (STIs).

Indirect contact with body fluids

However, it is possible to encounter body fluid containing pathogens without direct contact with the infected person.

WHO defines indirect 'through the air transmission' as 'airborne transmission/inhalation'. A study of the physics of disease transmission has shown that infectious particles exist on a spectrum of size and tiny particles remain airborne with the capacity to be inhaled. Therefore, a person can breathe in the droplets even if they are not near the source of the infection (**Figure 12.1.1**). The exact size of droplets and the distance they can travel is currently being researched.

Some illnesses, like the flu, measles and COVID-19, can spread through both the air and direct contact.

Some pathogens can survive on surfaces or objects for a short time. If the same surface is touched by an infectious person followed by a healthy person, transmission can occur if the healthy person touches their mouth, nose or eyes before thoroughly washing their hands. Similarly, if people share objects like drink bottles or cutlery, infectious particles can easily be transferred. Pathogens can also be spread through blood products and medical supplies containing the virus or bacteria.



FIGURE 12.1.1 A short-duration flash photograph of a sneeze, showing the number of droplets expelled. Each droplet may contain thousands of bacterial or viral pathogens.

Contaminated food

One of the easiest ways for a pathogen to enter the body is via the gastrointestinal tract. Food can become contaminated in several ways. Pathogens can be transferred to food by sneezing or coughing, or if an infected person touches their nose or mouth and handles food without washing their hands. In some cases, harmful microbes are spread to food from the faeces of an infected person. Improperly canned foods can also produce an environment for bacterial reproduction.

Bacteria such as *Salmonella*, *Campylobacter*, *Escherichia coli* and viruses such as norovirus, hepatitis A and rotavirus cause these foodborne illnesses, commonly referred to as food poisoning. Although they have been recognised as diseases of humans for thousands of years, they are still common, affecting an estimated 5.4 million Australians each year. Sometimes it is the toxins and sometimes it is the pathogen itself that gives rise to the disease.

Symptoms for these infections typically include diarrhoea, nausea and vomiting.



Weblink
Ways infectious diseases spread

Rotavirus requires an infective dose of only 100–10 000 virus particles, and enough pathogen to cause infection can be transmitted via food unless food handlers follow very strict handwashing procedures. Bacteria, in contrast to viruses, have the advantage of being able to reproduce to an infective dose outside the host. This makes it important to keep food out of the **temperature danger zone** of 5–60°C, where most bacteria can grow and reproduce. Thorough cooking of meat and eggs at temperatures above 60°C kills pathogens, but undercooked food may contain live bacteria that can transmit disease to humans. To prevent food becoming contaminated after cooking, it should be stored below 5°C.

temperature danger zone the range of temperatures at which harmful bacteria can grow and reproduce in food

Contaminated water

Travellers to other countries can become ill when drinking from local water supplies. This is because in many developing countries water is transported in ageing pipes and/or is contaminated by pesticides, sewage overflows, agricultural waste or wildlife. Several important diseases are transmitted in contaminated water. These include bacterial diseases such as typhoid (*Salmonella typhi*), cholera (*Vibrio cholerae*) and *Shigella* infection, and viral diseases such as hepatitis A. Amoebic dysentery, caused by a protist, and endoparasites, such as intestinal worms, can also be transmitted in contaminated water. The South-East Asian blood fluke is carried by more than 200 million people worldwide and is one of several species of fluke that causes the chronic parasitic disease schistosomiasis. Its complex life cycle, shown in **Figure 12.1.2**, includes a human definitive host and an aquatic snail as an intermediate host. Control of schistosomiasis must be based on drug treatment, improved sanitation, health education and snail control that includes draining swamps, because the flukes depend on water to complete their life cycles.

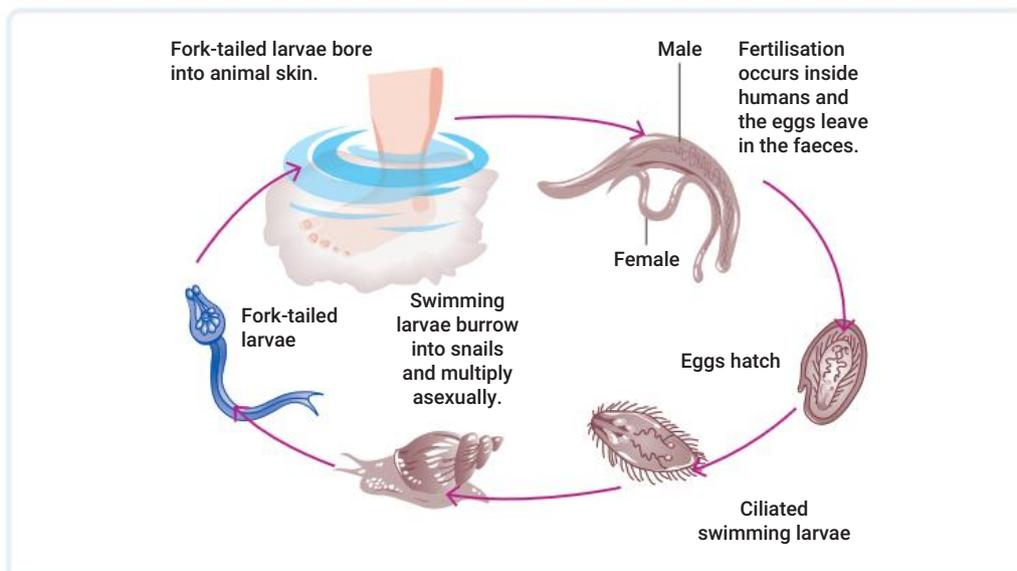


FIGURE 12.1.2 The life cycle of the blood fluke, *Schistosoma japonicum*, which causes schistosomiasis



Worksheet
Modes of transmission

Disease specific vectors

A **vector** is a living organism that transmits pathogens from one host to another. Pathogens may need vectors if they do not easily come into contact with a new host. Or a vector may enable a pathogen to penetrate the outer defences of the host in a way that would not be possible unassisted. Mosquitoes, ticks, fleas, lice and flies are examples of vectors. Often, the pathogen depends on

vector a living organism that transmits pathogens from one host to another; a vehicle used to transfer DNA sequences from one organism to another

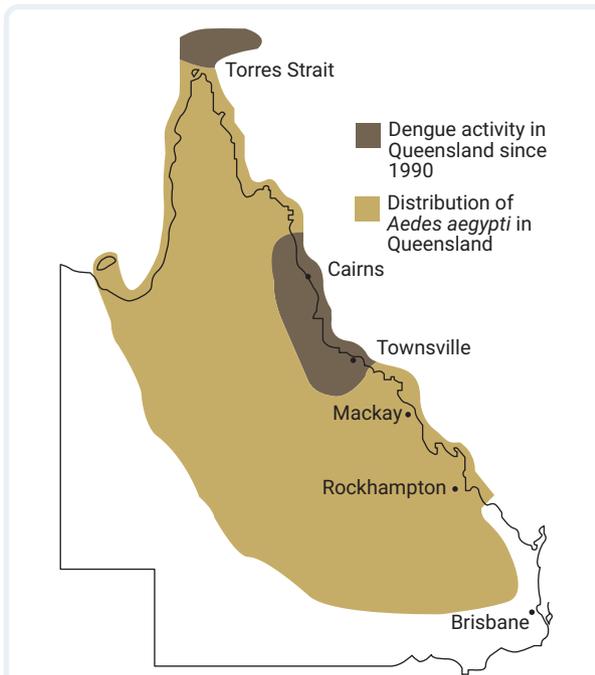


FIGURE 12.1.3 The distribution of the *Aedes aegypti* mosquito and the prevalence of dengue fever in Queensland.

the vector to complete its life cycle. Biting insects are vectors for many diseases. The plague (also known as the Black Death or *Yersinia pestis*) is often thought to be a disease of the past, but each year 1000–2500 cases occur globally. It is a bacterial disease of rodents that can be spread to humans and other animals by infected rat fleas. Deer ticks may carry the bacterium that causes Lyme disease and females of some mosquito species may carry malaria parasites and dengue fever.

The *Aedes aegypti* mosquito is the main type of mosquito that transmits dengue fever and is found in many tropical countries around the world including north and central Queensland and parts of southern Queensland (Figure 12.1.3).

LEARNING CHECK 12.1

DESCRIBING

- 1 **Describe** the five forms of disease transmission by copying and completing the following table.

Mode of transmission	Pathogen adaptations	Example of pathogen
Direct contact		

- 2 State a definition for 'contagious'.
- 3 By referring to the temperature danger zone, **describe** how bacteria can be prevented from growing on food.

APPLYING

- 4 **Explain** the ways in which a lack of running water, sanitation and garbage collection could increase the spread of disease.
- 5 **Explain** why foodborne illnesses are more likely to be caused by bacterial pathogens than viral ones.
- 6 **Explain** why airborne transmission is more common in crowded, indoor environments.
- 7 Female filarial roundworms produce young that move actively through the bloodstream near the skin at night. If a mosquito sucks blood from this infected human, these juveniles may enter the insect's tissues. In time, they move near the insect's proboscis, ready to enter a new host when the mosquito bites another human.
- Identify** the likely mode of transmission of this pathogen and **explain** its benefit for the roundworm.
 - Explain** the advantage of the juveniles moving near the skin of the host at night.
 - Explain** the advantage to the juveniles of migrating to the mosquito's proboscis.

12.2 Factors affecting the spread of disease

The rate of disease transmission is not constant and varies with different diseases, populations and time. However, there are several recognisable patterns of disease transmission, as shown in **Figure 12.2.1**. An **endemic** disease is one that occurs at a relatively constant rate within a population. In contrast, diseases that are uncommon and occur irregularly are said to occur **sporadically** within a population. **Epidemics** occur when there is an increase in the number of **cases** of a disease within a population to above what is considered normal. Sometimes an epidemic may spread across multiple continents or throughout the world, in which case it is referred to as a **pandemic**.

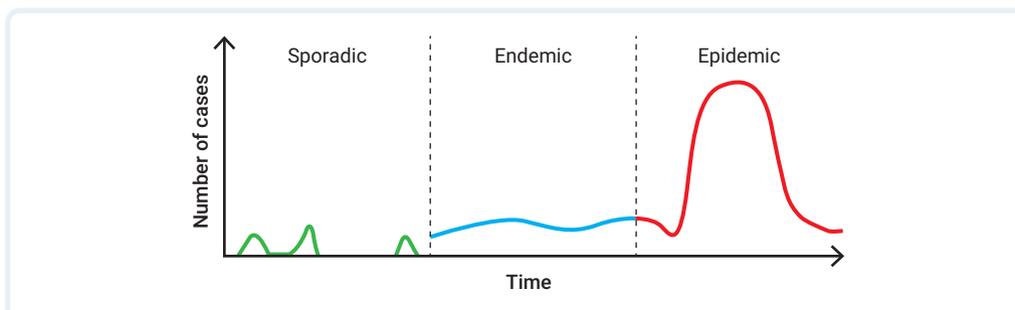


FIGURE 12.2.1 Within a population, a disease may occur sporadically, at an endemic level or, occasionally, as an epidemic.

Persistence of pathogens within hosts

The persistence of a pathogen within its **definitive host** or **intermediate hosts** can contribute to the spread of the disease. Most pathogens require specific adaptations to survive and reproduce within what is the hostile environment of the host. The longer they survive, the more likely they will reproduce and transmit to a new host.

For example, *Plasmodium falciparum*, one of the causative protozoan pathogens of malaria, has a complex life cycle consisting of distinct stages in the intermediate host mosquito vector and in the definitive human host (**Figure 12.2.2**). *P. falciparum* cannot survive outside of their host organism(s).

At each stage of the *P. falciparum* life cycle (merozoites, sporozoite and trophozoite) different antigen molecules are produced. This prevents the host from initiating an effective immune response against the pathogen. Furthermore, while hiding in the red blood cells, *P. falciparum* produces adhesion proteins, which are presented on the surface of the cell. The proteins change the shape of the red blood cells, slowing their movement through blood vessels. This aids the merozoites exiting the cell. This persistence within the host significantly increases the likelihood of reproduction and transmission to new a new host.

Similarly, the influenza virus has a range of adaptations that allow it to persist within a host and transmit to non-infected individuals.

- The virus surrounds itself in a capsule of lipids and **glycans** from the host cell as it exits. By hijacking these host cell molecules, the virus can avoid detection by the immune system while outside host cells.
- The influenza A virus has a high mutation rate, referred to as antigenic drift. Changes in the haemagglutinin (H) and neuraminidase (N) surface proteins (antigens) mean the host's immune system will not recognise the virus even if it has been encountered previously,

endemic broadly, common to a particular area; specifically, a pathogen that is prevalent at a constant rate within a population

sporadically refers to a disease that occurs infrequently and irregularly within a population

epidemic an increase in the occurrence of a particular disease above the baseline level for that population; tends to refer to larger, more serious events than an outbreak

case an individual who is infected with an infectious disease

pandemic an epidemic that has spread across many continents or worldwide

definitive host a host in which the adult phase of a parasite produces gametes

intermediate host an organism in which a pathogen or parasite undergoes development and spends a small part of its life cycle

glycan a carbohydrate usually found attached to proteins and lipids in living organisms; released by some pathogens to help them evade the host's immune system

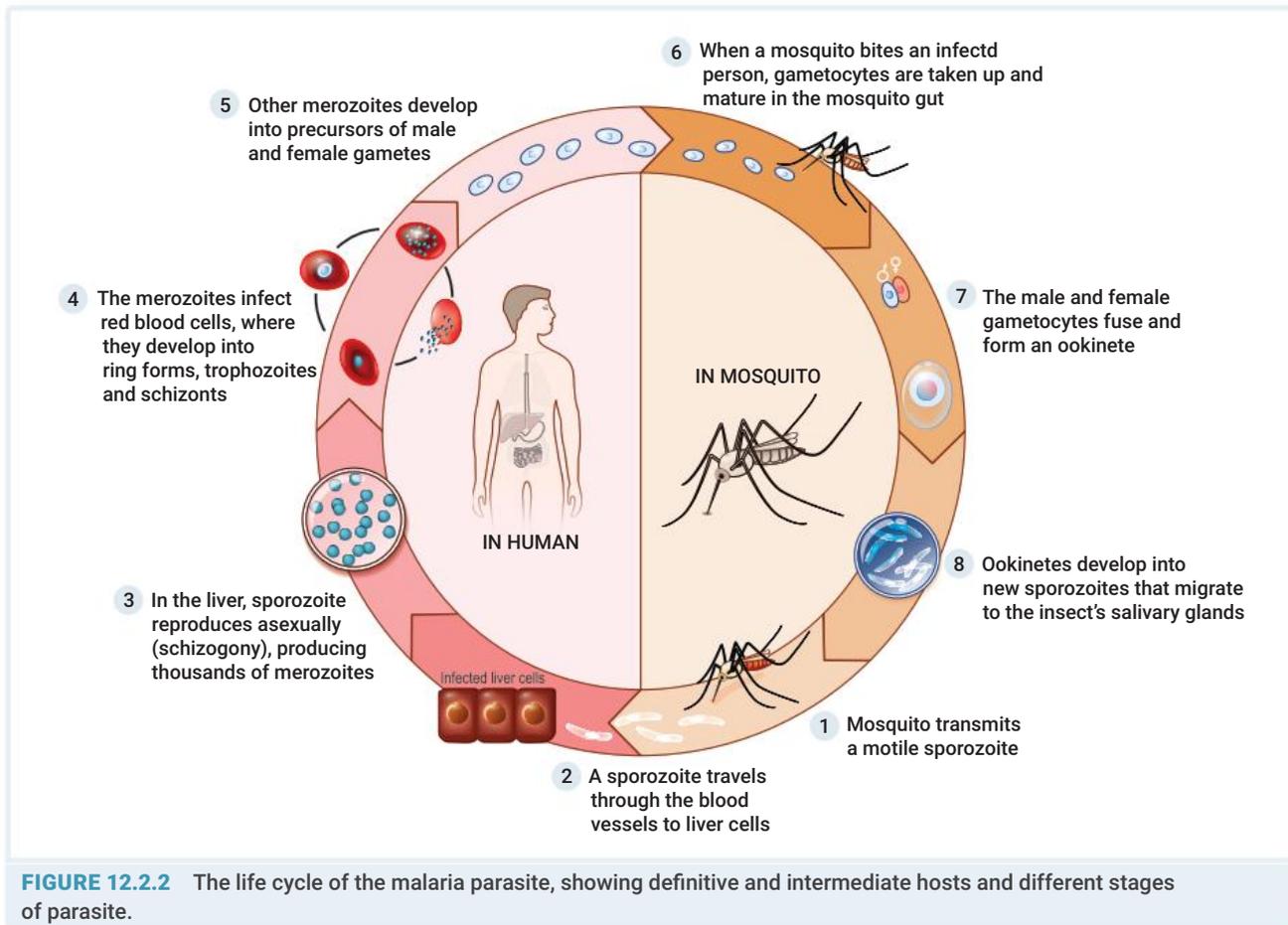


FIGURE 12.2.2 The life cycle of the malaria parasite, showing definitive and intermediate hosts and different stages of parasite.

carrier an individual who harbours a pathogen but who does not show symptoms of disease and can transmit the infection

because there is no 'memory' of the variant. This results in ongoing transmission of the virus. Antigenic drift makes it necessary to develop annual vaccines against the two primary variants (H1N1 and H3N2) responsible for seasonal flu outbreaks.

- Antigenic shift occurs when there is a new version of the H or N surface proteins introduced into the human population. Importantly, this can involve zoonotic strains exchanging genetic

information with human influenza A strains, resulting in antigens not previously encountered by the human immune system. The lack of recognition by the immune system results in rapid transmission of the virus and is responsible for major influenza pandemics, including the 1918 pandemic and the more recent 2009 swine flu pandemic, both H1N1 variants.

Some pathogens may persist in asymptomatic **carriers** who are still capable of transmitting infection to others.

At the beginning of the 20th century, several outbreaks of the diarrhoeal disease typhoid were traced back to food prepared by a single cook, Mary Mallon, in New York City. An asymptomatic carrier of the bacterium *Salmonella typhi*, Mallon was unaffected by typhoid but was still able to pass on the disease. Mallon, infamously known as 'Typhoid Mary', refused to give

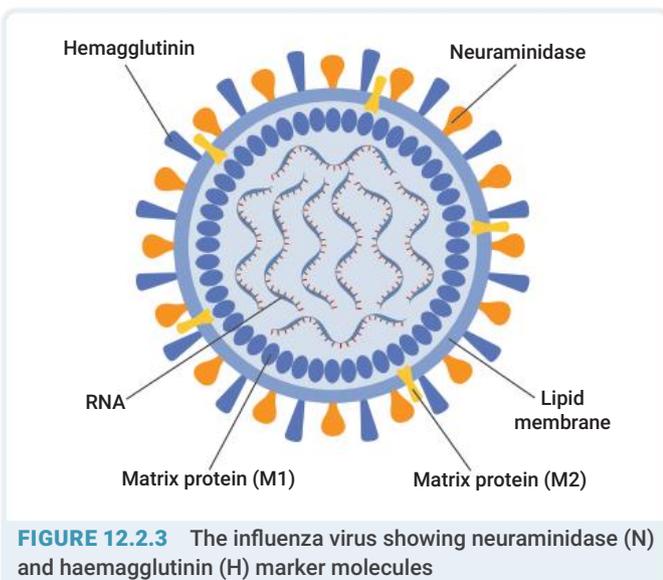


FIGURE 12.2.3 The influenza virus showing neuraminidase (N) and haemagglutinin (H) marker molecules

up work as a cook and was held in isolation for much of her life on North Brother Island to prevent spread of the disease.

Mechanism of transmission

The mechanism of transmission of a disease strongly affects the ability of a pathogen to spread within a particular population. Some modes of transmission restrict the spread of disease to particular climates or geographic areas. For example, malaria is transmitted between human hosts by the female *Anopheles* mosquito, which acts as a vector. Malaria only occurs in parts of South America, Africa and Asia that are near the equator because these are the only areas where that species of mosquito can live. In contrast, influenza can spread throughout the world because its 'through air transmission' transmission does not depend on a vector or specific environmental conditions.

The transmission of disease is also influenced by a pathogen's **infectivity**: the ability of a pathogen to spread from one host to another host. Diseases with a high infectivity, such as influenza, are readily spread through a population. It is important to understand that the infectivity of a pathogen is distinct from its **virulence** – the capacity of a pathogen to cause severe disease within its host. For example, rabies kills all people who are infected with the virus once symptoms begin, making it an extremely virulent disease. Some pathogens with a high level of virulence may have low infectivity, and vice versa.

infectivity the ability of a pathogen to spread from one host and infect another host

virulence a measure of a pathogen's ability to cause disease within its host

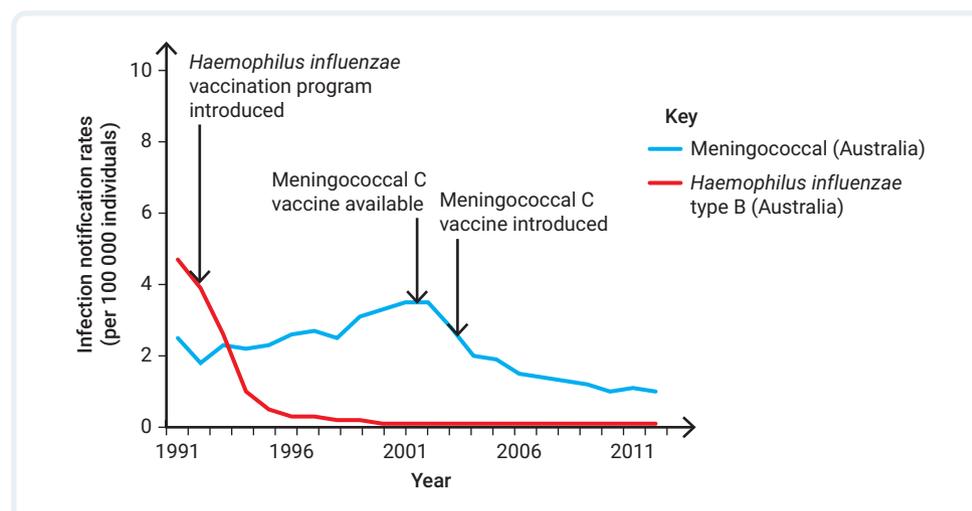
Proportion of population that is immune

The spread of a disease is also affected by the proportion of the population that is immune to that disease. Reducing the number of susceptible individuals to a given disease is the basis for immunisation.

Immunisation is a highly effective public health intervention that has substantially reduced worldwide **morbidity** and **mortality** from infectious diseases. In Australia, children are routinely vaccinated against many infectious diseases, including hepatitis B, pertussis (whooping cough), measles, tetanus and poliomyelitis. Groups that are at high risk of infection, such as the elderly or chronically ill, may also need additional vaccinations. **Figure 12.2.4** shows the effectiveness of immunisation. The rates of infection of *Haemophilus influenzae* and meningococcal C dropped significantly after vaccination against these pathogens was introduced.

morbidity the impact of a disease within a population, measured by the number of people affected by that disease

mortality the impact of a disease within a population, measured by the number of deaths caused by that disease



Sources of data: National Notifiable Diseases Surveillance System (NNDSS) and Department of Health, Victoria

FIGURE 12.2.4 Rates of *Haemophilus influenzae* type B and meningococcal infection since the introduction of vaccines against these organisms



FIGURE 12.2.5 A child infected with smallpox. As a result of vaccination programs, the disease was declared to have been eliminated in 1980.



Weblink

Infectious disease in an era of global change

Immunisation programs also have the potential to eradicate diseases by making spread impossible. Smallpox (**Figure 12.2.5**), the first disease for which a vaccine was created, was also the first disease to be eradicated through vaccination. A coordinated global strategy to eliminate the disease involved mass vaccination and intense targeted vaccination. In 1980, WHO declared smallpox to be eradicated worldwide.

Mobility of individuals in an affected population

The movement of individuals and populations can facilitate the spread of disease. This is because individuals carrying disease can infect other individuals in the areas they are travelling to, allowing diseases to spread faster and over larger geographical areas than they otherwise could. Contact can be devastating because the previously unexposed individuals usually have no immunity.

Europeans introduced smallpox, measles, influenza and typhoid into the previously uninfected populations of First Nations Australians with disastrous effects. In April 1789, a major smallpox epidemic broke out. Without previous exposure to the smallpox virus, upwards of 70 percent of First Nations Australians died. The spread of smallpox was followed by influenza, measles, tuberculosis and sexually transmitted diseases. With no resistance to these diseases, First Nations people suffered significant population loss.

People are now able to travel large distances by plane quickly and frequently. Increasing mobility means that emerging infectious diseases now have the potential to spread worldwide very rapidly. The severe acute respiratory syndrome (SARS) outbreak in 2003 and the COVID-19 pandemic are striking examples of how air travel can facilitate the rapid transmission of infectious diseases.

COVID-19 was first reported in Wuhan, China, in December 2019. By January 2020, cases had been identified in Australia, the USA and Europe, and from there quickly spread to almost all parts of the globe. The rapid spread occurred because of air travel and the inability of health agencies across the world to act quickly enough to counter the spread. Current estimates have the COVID-19 death toll at nearly 7 million.

LEARNING CHECK 12.2

DESCRIBING

- 1 State the term that best **describes** the frequency of occurrence of disease for each of the following.
 - a In India, tuberculosis occurs at a high but relatively constant rate within the population.
 - b In 2009, a new strain of influenza (H1N1) spread rapidly across the globe.
 - c An unusually high number of cases of listeriosis was noted by public health authorities.
- 2 **Describe** the four types of factors that may affect the spread of a disease, providing an example for each.

APPLYING

- 3 **Explain** how persisting for a long time within a host serves as a selective advantage to a pathogen.
- 4 Using an example, **explain** how the mechanism of pathogen transmission affects the spread of a disease in a community.
- 5 Summarise reasons why air travel has implications for the control of infectious diseases.

12.3 Strategies to control the spread of disease



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Infection prevention and control systems

To predict and control disease outbreaks, public health authorities need to know when and where particular infections are occurring. In Australia, the number of cases of a particular disease is monitored by health authorities in each state. WHO is the organisation that monitors and coordinates global responses to outbreaks. In addition, authorities need to evaluate which combination of strategies is the most effective in controlling the spread of disease.

Personal hygiene measures

Regular and vigorous handwashing with soap and water for at least 20 seconds and the use of sterile equipment are key elements in effective health care. Regular handwashing can prevent individuals from contracting infections, particularly those that are spread by faecal–oral or direct contact routes. On a global scale, handwashing can significantly reduce the mortality from certain infections, such as diarrhoeal illnesses.

Other personal hygiene measures include staying home when ill, covering the mouth when coughing and sneezing and keeping a metre away from people who are sick as well as wearing of masks. As well, people are advised to limit actions such as shaking hands, hugging and kissing, and to avoid touching surfaces and objects that are used and shared by others.

Contact tracing

If an outbreak of disease occurs, investigators need to find affected people. An important component of this is **contact tracing**, whereby recent contacts of an infected individual are contacted and screened for the infection. The type of contacts sought will vary with the mechanism of transmission. For example, if the disease is sexually transmitted, only sexual contacts of the infected individual are contacted by investigators. On the other hand, for an airborne disease such as tuberculosis, investigators will contact all people who have been in close proximity with the infected individual. In Australia during the early months of the COVID-19 pandemic, state health departments were responsible for contact tracing after a person tested positive for the virus. Once identified, close contacts were required to follow strict guidelines for two weeks.

Another way to locate people with an infectious disease is by notifying public authorities upon diagnosis. In Australia, the list of **notifiable diseases** contains a diverse mix of more than 70 conditions, including chickenpox, syphilis, rabies and influenza. A doctor who diagnoses one of these conditions must report the case to the relevant state health authority. Outbreaks or cases of unusual diseases can then be investigated. However, there are limitations to data collected this way. Infections can be under-reported because not all infected patients seek health care and those who do will not necessarily receive a diagnosis. Delays between the onset of symptoms, diagnosis and reporting can also limit the ability of public health authorities to respond quickly to epidemics and pandemics.

Quarantine

Quarantine is a highly effective way to stop individuals exposed to infectious diseases from carrying disease into healthy populations. Exposed individuals are prevented from entering a healthy population until the incubation period of that disease has passed, proving that they are not infected. In Queensland, a person testing positive to COVID-19 was required to report their positive test to Queensland Health and isolate for 7 days (**Figure 12.3.1**).

contact tracing a process for identifying potential cases; recent contacts of an infected individual are contacted and screened for the infection

notifiable disease a disease that, if diagnosed, is required to be reported to public health authorities

quarantine the enforced isolation of individuals at risk of carrying disease to prevent the spread of that disease into healthy populations



FIGURE 12.3.1 Infected individuals and close contacts during the COVID-19 pandemic were required to isolate.

Quarantine is currently used in this way to prevent the spread of animal pathogens. When people import pet cats or dogs into Australia from overseas, the animal is held at a quarantine facility for at least 30 days. Quarantine measures to protect human health can still occur. Captains of planes and ships are required to report passengers displaying symptoms of certain infections. In exceptional circumstances, intensified quarantine measures may be implemented at airports to try to prevent the spread of disease by air travel.

Goods brought into Australia on passenger planes and commercial shipments are also inspected for high-risk items such as meat or plant products. These products can then be stopped from entering the country. Australia has particularly strict quarantine laws because of the potentially devastating impact of imported pathogens on

our unique flora and fauna. As an island, protecting our borders from imported pathogens and pests is easier than in many other parts of the world.

LEARNING CHECK 12.3

DESCRIBING

- 1 **Identify** three personal hygiene measures that could prevent the spread of disease.
- 2 **Define** 'contact tracing' and outline why it is an essential component in controlling disease outbreaks.
- 3 **Describe** what is meant by a notifiable disease, giving an example.
- 4 **Describe** the role of personal hygiene measures in global health care and why they are of particular importance in healthcare and hospital settings.

APPLYING

- 5 **Explain** the role of quarantine in controlling disease outbreaks.
- 6 Imagine you are the organiser of a music festival, and the government wants you to cancel the event because of an influenza outbreak. **Explain** whether you would cancel the event, giving reasons for your decision.
- 7 **Explain** how the lessons learnt in the aftermath of the 2003 SARS outbreak contributed to the response during the COVID-19 pandemic.

12.4 Analysing disease data

National and international organisations, such as a country's government or the World Health Organization (WHO), collect data to help monitor the health of populations, with the aim of identifying health concerns and ultimately improving health care.

Data can be collected in many ways, including surveys, laboratory or case studies, disease registries (e.g. notifiable diseases), public health/medical records, mortality rates, environmental monitoring or a census. Once collected, professionals analyse the data and use it to:

- determine the source of outbreaks
- identify the mode of disease transmission
- determine the effectiveness of strategies used to control the disease
- predict outbreaks.

Determining the source of outbreaks

WHO defines an outbreak as the presence of a disease at levels above what would normally be expected for the time of year, population and location. Consideration is given to the number of people, their location upon falling ill, the type of illness they have, water supply, sanitation, climate and food.

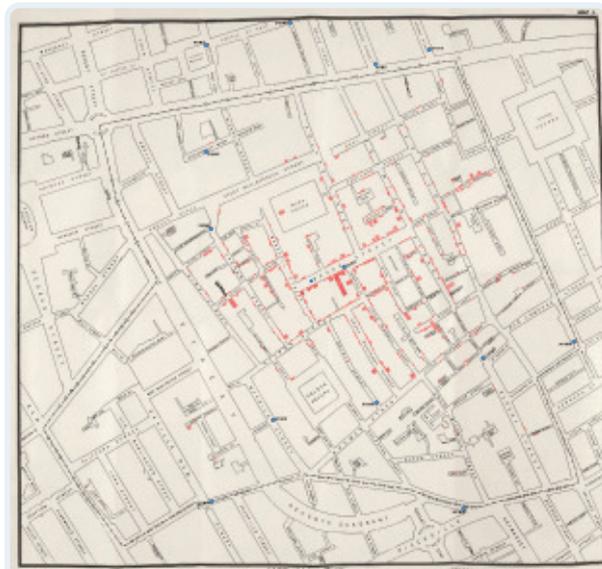
An early example of these processes was completed by John Snow in 1854, when he made the link between cholera and contaminated drinking water, as shown in the map of London in **Figure 12.4.1**. There were a significant number of cholera cases clustered around specific water pumps, suggesting contaminated water was the source of the outbreak.



Weblinks

John Snow: Pioneer of epidemiology

Forecasting infectious diseases



Science Photo Library/British Library

FIGURE 12.4.1 A reproduction of John Snow's map showing cases of cholera in red and pumps marked as blue circles. The cluster of cholera cases around the Broad Street pump strongly suggests a link between the water and the disease.

Identifying modes of disease transmission

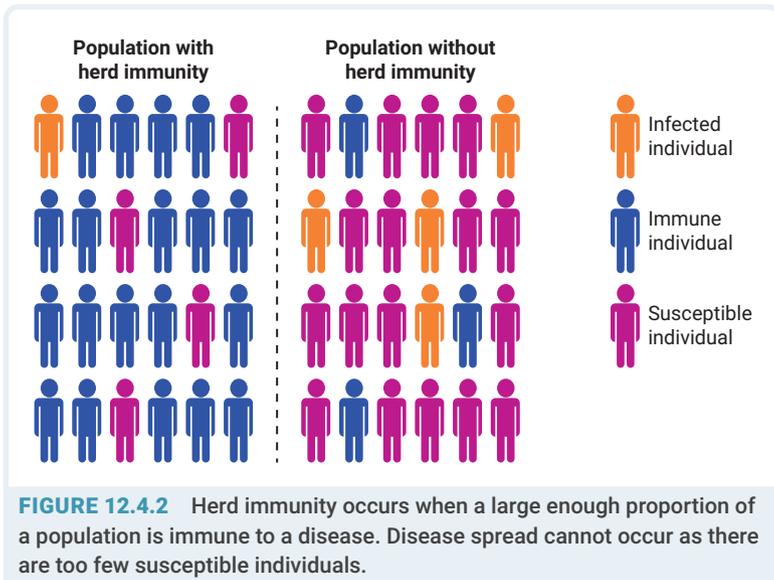
Infectious diseases occur because pathogens interact with their host and the environment. If the mode of transmission can be identified, transmission may be reduced or prevented. (Modes of transmission are explained in section 12.1.) Interventions specific to each mode can be used to disrupt the transmission of pathogens, which may involve a combination of practices, including:

- masking and respiratory protection
- increasing distance and isolation
- illness monitoring
- testing
- managing exposure.

For example, if the disease being experienced requires direct contact for transmission, wearing a mask will not reduce the transmission of the disease. HIV is most commonly transmitted through sexual contact, whereas colds and flu can be transmitted by direct or indirect contact. Sharing a drink bottle or using the same spoon allows for the transmission of colds or flu, but not HIV.

With COVID-19, Queenslanders initially had stay-at-home orders, with social distancing and hygiene measures in place. By April 2020, some restrictions were eased, with people being able to:

- travel to within 50 km of home
- go on an outing with members of the same household or an individual and one friend.



However, fewer than 0.7 per cent of adults in Queensland were COVID-19 positive in 2020–21 and the number of deaths was low (0.1 per cent of the population). This suggests that the measures introduced disrupted COVID-19 transmission. In contrast, during 2020, Spain had a mortality rate of 15 per cent, and 1.04 per cent of Spain’s population had been admitted to hospital by the end of 2021.

One important preventative method to reduce disease transmission is vaccination (Chapter 11), with the aim of inducing herd immunity (Figure 12.4.2). The more people with immunological resistance to the pathogen, the less likely the pathogen is to come into contact with a susceptible individual.

Determining effectiveness of strategies used to control disease spread

Disease control in a particular area aims to reduce the number of people who acquire the pathogen, reduce the effects of the pathogen on those people who are already sick and reduce deaths. Methods used to control diseases include the strategies listed above, as well as vaccines and medications. For example, the graph in Figure 12.4.3 shows active COVID-19 cases in Australia from February 2020 to February 2024. The Australian Government closed Australia’s borders in March 2020. The borders reopened in February 2022. The low numbers of COVID-19 infections prior to February 2022 suggest this was an effective strategy to control this disease.

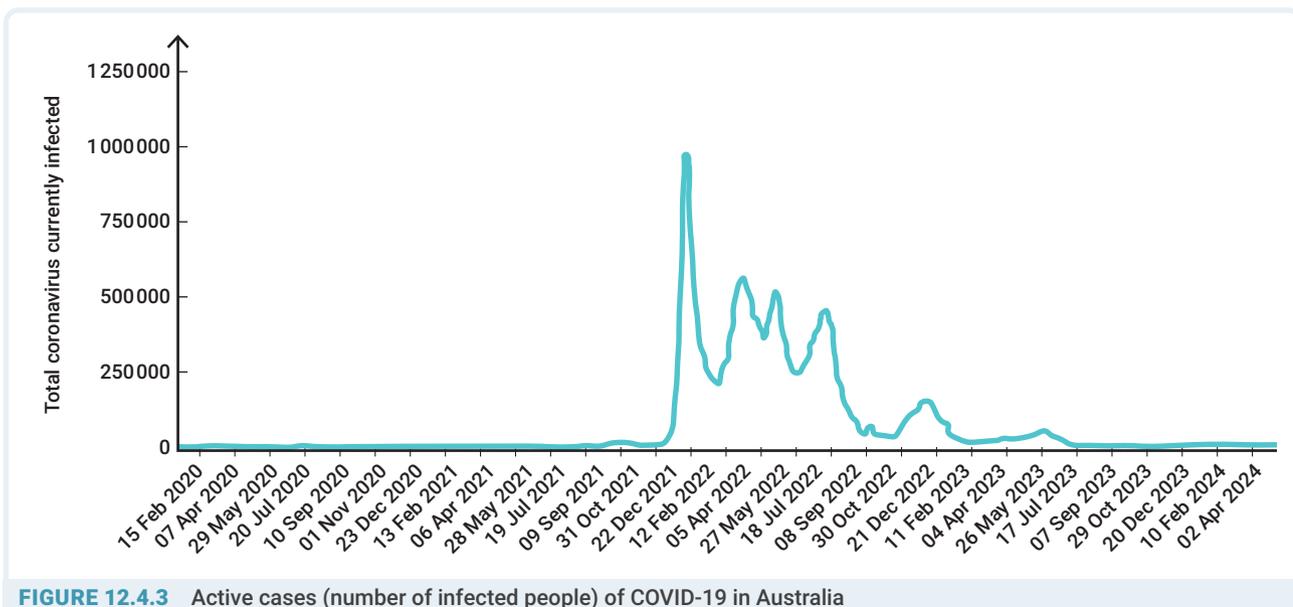
Beyond disease control, public health can also focus on elimination (stopping the transmission of a disease in a specific area) and/or eradication (permanent removal of a disease worldwide).

Smallpox is the only disease officially declared eradicated by WHO in 1980.



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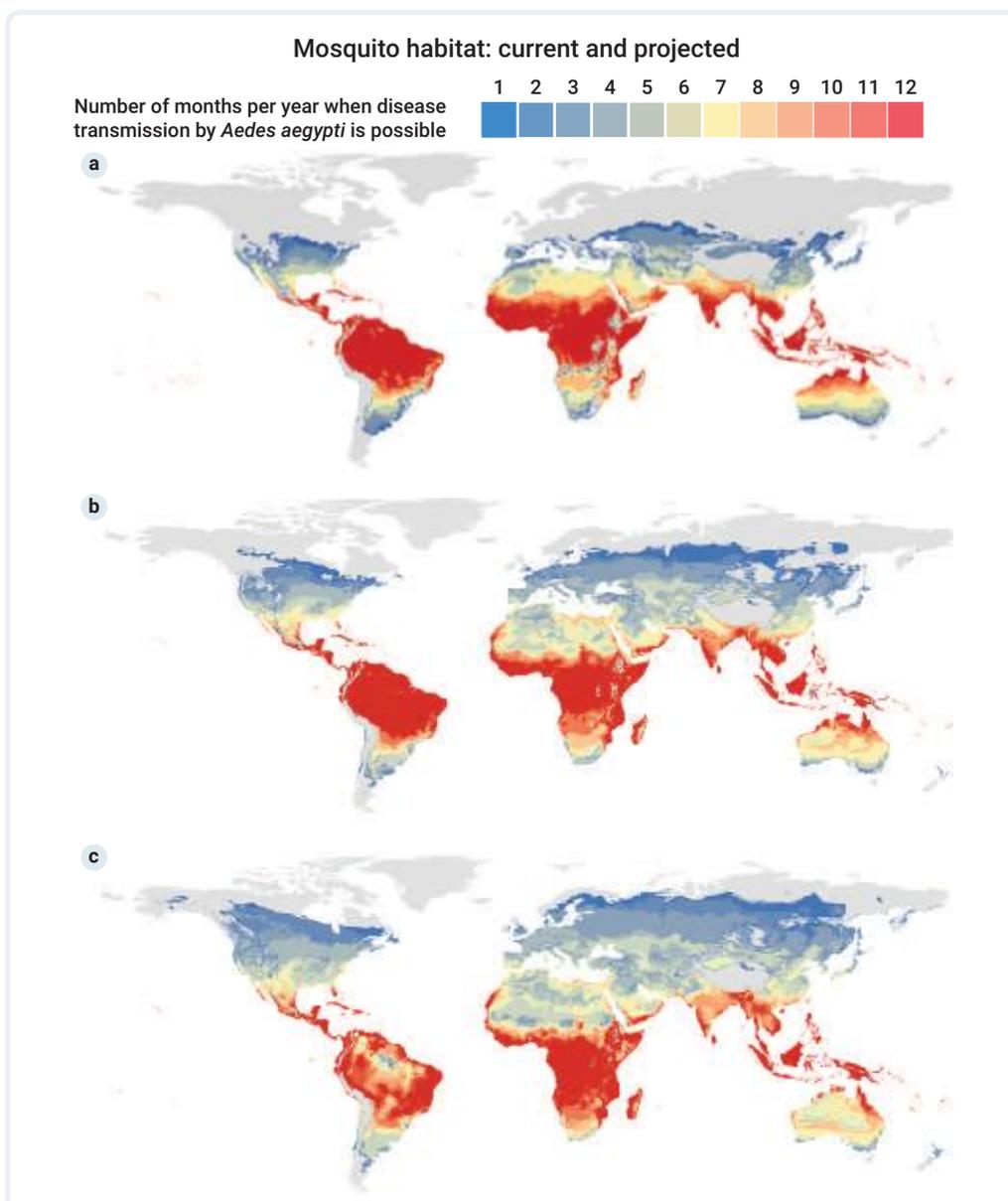
Number of COVID-19 cases reported to WHO



Predicting outbreaks

Knowing the mode of disease transmission and factors influencing transmission can be useful when developing models for predicting the spread of disease and controlling outbreaks. These models can also be used to explore the likely effects of newly emerging pathogens and to predict the possible spread of disease under changed environmental conditions.

Using current and historical data, scientists can make reasoned predictions about the likelihood of particular diseases occurring in the future. **Figure 12.4.4a** shows the current environmental conditions suited to the survival of the dengue fever vector, the mosquito *Aedes aegypti*, reflecting its distribution. **Figure 12.4.4b,c** shows the result of changing environmental factors that make environments more suited to the survival of *Aedes aegypti*. Should the conditions change as suggested, it is possible that there may be outbreaks of dengue fever in areas where people have not built up any immunity to this virus.



Ryan, S.J., Carlson, C.J., Mordecai, E.A., Johnson, L.R. (2019). Global expansion and redistribution of *Aedes-borne virus* transmission risk with climate change. *PLoS Negl. Trop. Dis.*, 13(3), e0007213. <https://doi.org/10.1371/journal.pntd.0007213>

FIGURE 12.4.4 Maps of number of months per year when disease transmission by *Aedes aegypti* is possible, for predicted mean monthly temperatures under current climate and future scenarios. (a) Current. (b) Projected–2050. (c) Projected–2080.

Modelling also suggests that increases in temperature and changes in rainfall are likely to cause the spread of *Anopheles* spp. (the vector that transmits the plasmodium causing malaria), into areas that were previously uninhabitable for the mosquitoes.

To make predictions like these, models include several assumptions about the way that different variables behave. The spread of disease is a very complex process and is affected by many factors, so the accuracy of these models depends on these assumptions being met. A good model is one that takes this complexity into consideration.

Case study: COVID-19 (SARS-CoV-2)

Figure 12.4.5a shows the effectiveness of a lockdown to prevent transmission by direct and indirect contact. Cases in Victoria dropped to zero after both Lockdown 1 and Lockdown 2.

Figure 12.4.5b shows that mortality rates were significantly higher in unvaccinated patients than in vaccinated patients. Although people can still contract COVID after vaccination, the risk of severe illness or mortality is much lower.

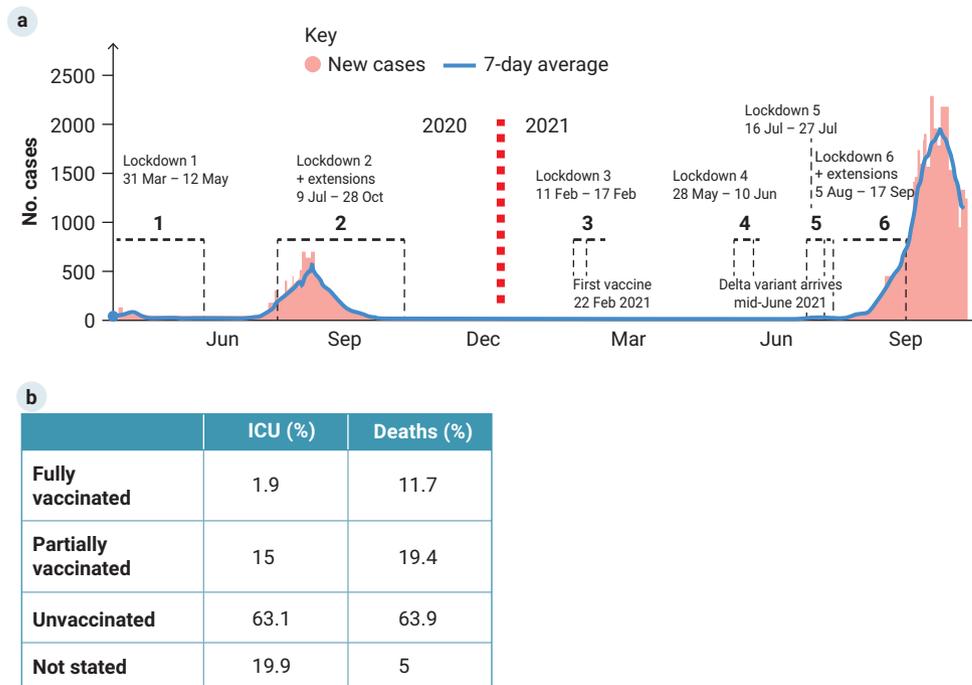


FIGURE 12.4.5 (a) The number of Victorian COVID-19 cases and lockdown periods. (b) The proportion of vaccinated versus unvaccinated patients in intensive care units and deaths.

LEARNING CHECK 12.4

DESCRIBING

- Describe** two modes of disease transmission.
- Describe** the method used by John Snow to determine the source of the 19th-century cholera epidemic in London.

APPLYING

- Explain** how herd immunity can protect an entire population from a serious disease.



4 Explain how a reasonable combination of methods offers the best opportunity to control the spread of disease during a pandemic.

ANALYSING

5 Legionnaire's disease is a bacterial lung infection caused by *Legionella* bacteria. The bacteria breed in aquatic environments and are transmitted to humans when they inhale contaminated water vapour. Outbreaks of legionnaire's disease are usually linked to a particular source, such as a spa, a hot water system or an air conditioner.

Suppose that the local health department has received reports of four cases of legionnaire's disease occurring in the same suburb over 3 days. The epidemiologist leading the investigation used detailed interviews to produce the data in **Table 12.4.1**.

TABLE 12.4.1 Epidemiological evidence gathered from legionnaire's outbreak investigation

	Case			
	1	2	3	4
Residence	Apartment block A	Apartment block B	Apartment block A	Private home
Occupation	Store manager at local shopping centre	Builder working on carpark extension at shopping centre	School teacher	Retired
Other places visited in previous week	Bank Swimming pool Movie cinema	Apartment block A Shopping centre	Shopping centre Zoo Hospital	Hospital Swimming pool Shopping centre

Identify a relationship to show where the individuals contracted the infection.

12.5 Interpreting long-term immune response data

The following scenarios provide examples of how data can be interpreted and explained.

Figure 12.5.1 shows antibody production after an initial and subsequent exposure to an antigen. Imagine that the antigen in this situation is from the varicella zoster virus, which causes chickenpox. When first exposed to the virus, the body produces antibodies, but it takes some time before enough are produced to fight off the virus. This is why people develop symptoms of chickenpox when first exposed to the virus.

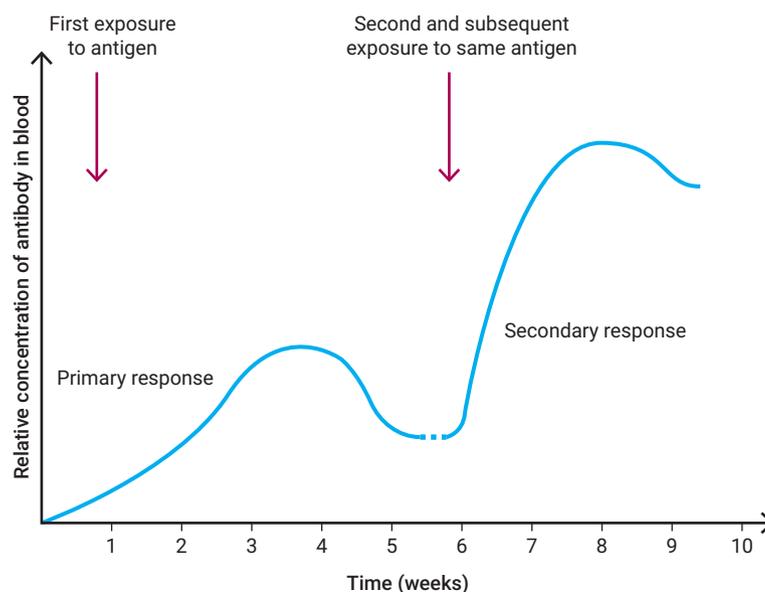


FIGURE 12.5.1 Antibody levels after an initial exposure to an antigen and after a second exposure to the same antigen

An analysis of the data in the graph in Figure 12.5.1 shows three differences between the responses to the initial exposure and subsequent exposure to the chickenpox virus. Compared with the **primary response**, in the **secondary response**:

- more antibodies are produced
- antibodies are produced faster
- antibody levels remain higher for much longer.

Interpretation: These three differences can be explained as follows. When a person is first exposed to the virus, activated B cells develop into both plasma and memory cells. The plasma cells secrete antibodies. The second exposure to the antigen activates the memory cells, allowing them to produce antibodies much more rapidly and in much greater amounts. This means that the person is now effectively immune to chickenpox, which is why most people only experience chickenpox once in their lives. After an initial infection and bout of the disease, they become immune to future infections.

Case study: Immunosuppression

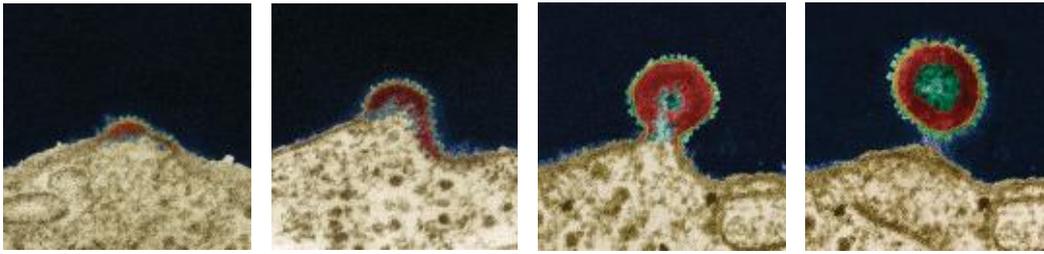
Human immunodeficiency virus (HIV) is one of the most significant infectious diseases of modern times. This viral infection results in a severe form of **immunodeficiency** known as acquired immunodeficiency syndrome (AIDS). When a defective immune system renders someone vulnerable to infection, this is known as immunodeficiency.

HIV generally targets T_h cells by binding to specific receptors on these cells and injecting its RNA. The helper T cell is then stimulated to produce more viral particles, which bud from the host cell's own plasma membrane, ready to infect other helper T cells (**Figure 12.5.2**).

primary response the response generated when an antigen is encountered for the first time

secondary response the response generated when the body encounters a pathogen to which it has previously generated an immune response

immunodeficiency a state in which the immune system does not function properly, leaving a person susceptible to infections the immune system could normally fight off



Eye of Science/Science Photo Library

FIGURE 12.5.2 Transmission electron micrographs of HIV budding out of a helper T lymphocyte

After several years, an infected individual becomes prone to multiple infections from pathogens that would normally be relatively harmless. Many sufferers die from simple yeast or bacterial infections, pneumonia or unusual tumours and cancers.

The graph in **Figure 12.5.3** shows numbers of helper T cells and viral particles over a 10-year period after infection.

An analysis of the data in the graph shows:

1. Trend: From year 0 to year 1, there is an increase in the numbers of helper T lymphocytes.
2. Trend: From year 1 to year 8, there is a steady decrease in numbers of T_h lymphocytes.
3. Trend: Over the first 6 months after infection, the numbers of HIV viral particles rapidly increase, then rapidly decrease.
4. Trend: From year 1 to year 10, the HIV particle numbers gradually and steadily increase to a maximum 10 years post infection.
5. Relationship: When the T_h lymphocytes decrease, the HIV particles increase.
6. Interpretation: Early during HIV infection, the immune system is capable of producing a response to the virus. This explains the rise in helper T cells and the decrease in viral particles in the first year. However, as more and more helper T cells are infected with the virus and killed, the effectiveness of immune responses decreases and the number of viral particles present increases as shown over years 1 to 10.



Weblink
HIV

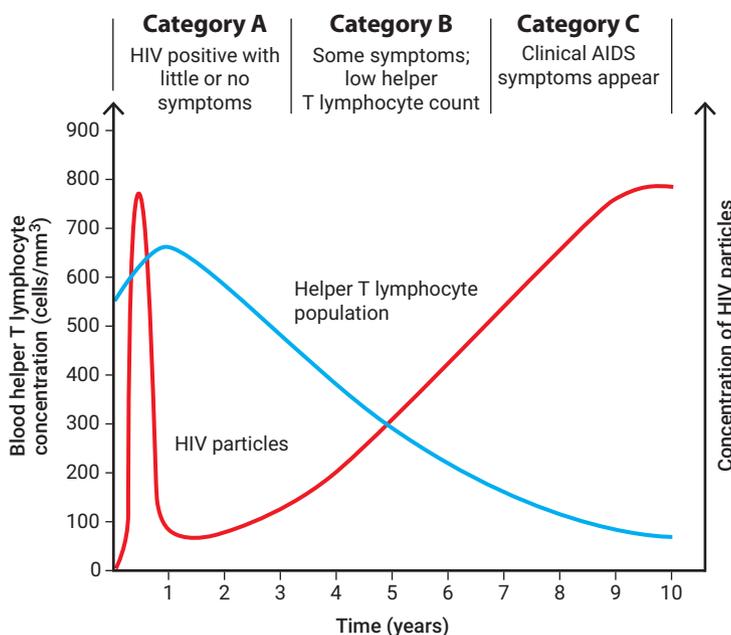


FIGURE 12.5.3 The stages of infection by HIV

Case study: HPV vaccination



Human papillomavirus (HPV) is a sexually transmitted infection responsible for more than 99 per cent of cervical cancer cases. It is important to note that although HPV is contagious, cervical cancer itself is classified as a non-infectious disease. The virus infects cervical cells, disrupting normal cellular processes, including cell division and communication, resulting in pre-cancerous lesions that progress to invasive cervical cancer over the next 10–30 years if left untreated (**Figure 12.5.4**).

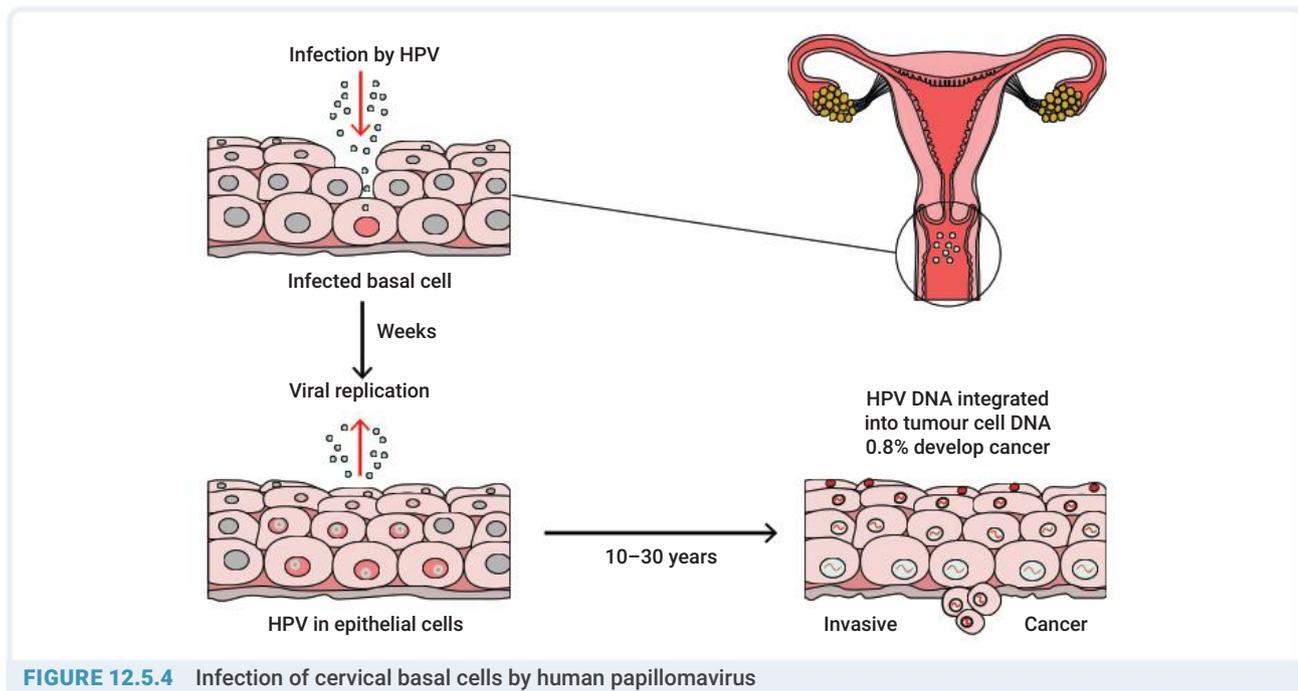


FIGURE 12.5.4 Infection of cervical basal cells by human papillomavirus

The link between HPV and cervical cancer was first established in the 1970s and efforts quickly turned to the development of a vaccine. In 1995, Australian scientist Professor Ian Frazer and his team from the University of Queensland developed the first HPV vaccine. Human trials began in 1998 and in 2007 a national HPV vaccine program was introduced. Administered in the early years of high school, initially only female students were eligible to receive the vaccine, then, in 2013, males were added to the eligibility list. This change was prompted by the recognition that HPV can cause various cancers in males, and they can serve as carriers of the virus. As of 2020, more than 85 per cent of Australian girls were fully vaccinated by age 15 (**Figure 12.5.5**).

There is a positive correlation between the national HPV vaccination program and a decrease in the age-standardised incidence of cervical cancer falling from 7.5 per 100 000 women in 2007 to <5 per 100 000 women in 2020.

The Australian Government Department of Health and Aged Care has a target of 90 per cent of 15-year-old females and males being fully immunised against HPV by 2030. Combined with increased screening targets of older age brackets and a 95 per cent treatment target of pre-cancerous lesions, cervical cancer caused by HPV will have effectively been eliminated from the Australian population.

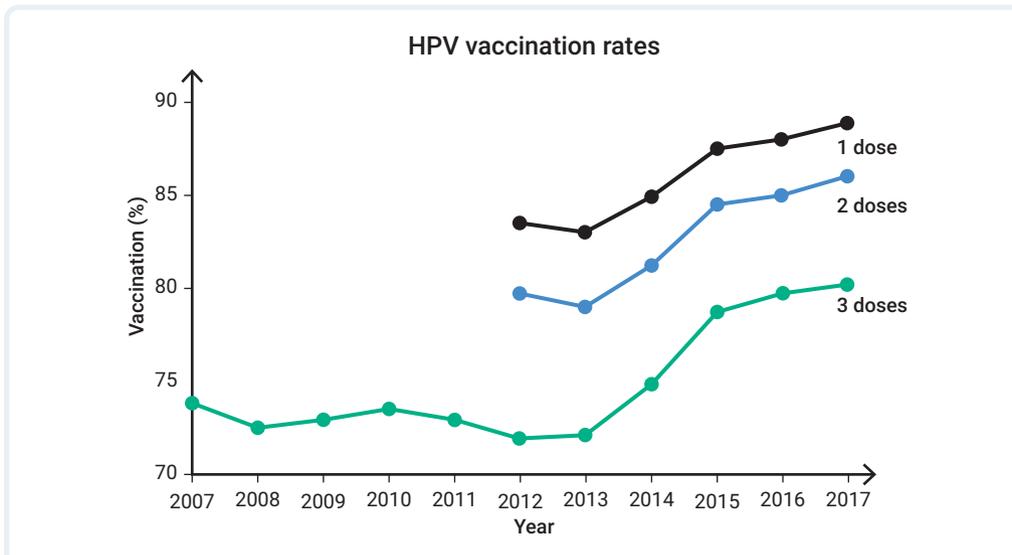


FIGURE 12.5.5 The proportion of the population aged 15 years who have received the first, second and third doses of the HPV vaccine, 2007 to 2020

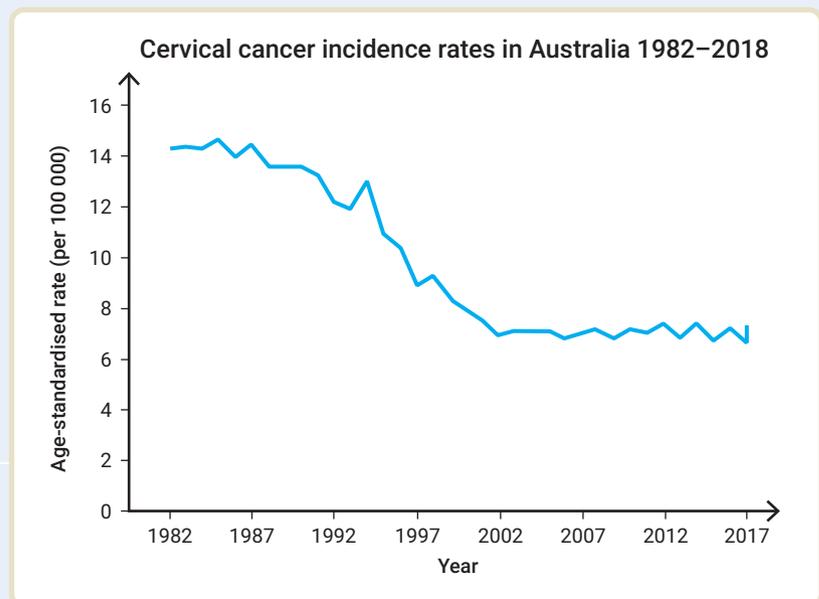
LEARNING CHECK 12.5

ANALYSING

- Compare** the primary and secondary responses to a pathogen such as the chickenpox virus.
- The graph shows the age-standardised incidence rates for cervical cancer in Australia between 1982 and 2018.
 - Identify** the independent and dependent variables.
 - Identify** a trend, a pattern and a relationship in the data.

INTERPRETING

- Draw a conclusion as to whether the HPV vaccine is having a positive effect.



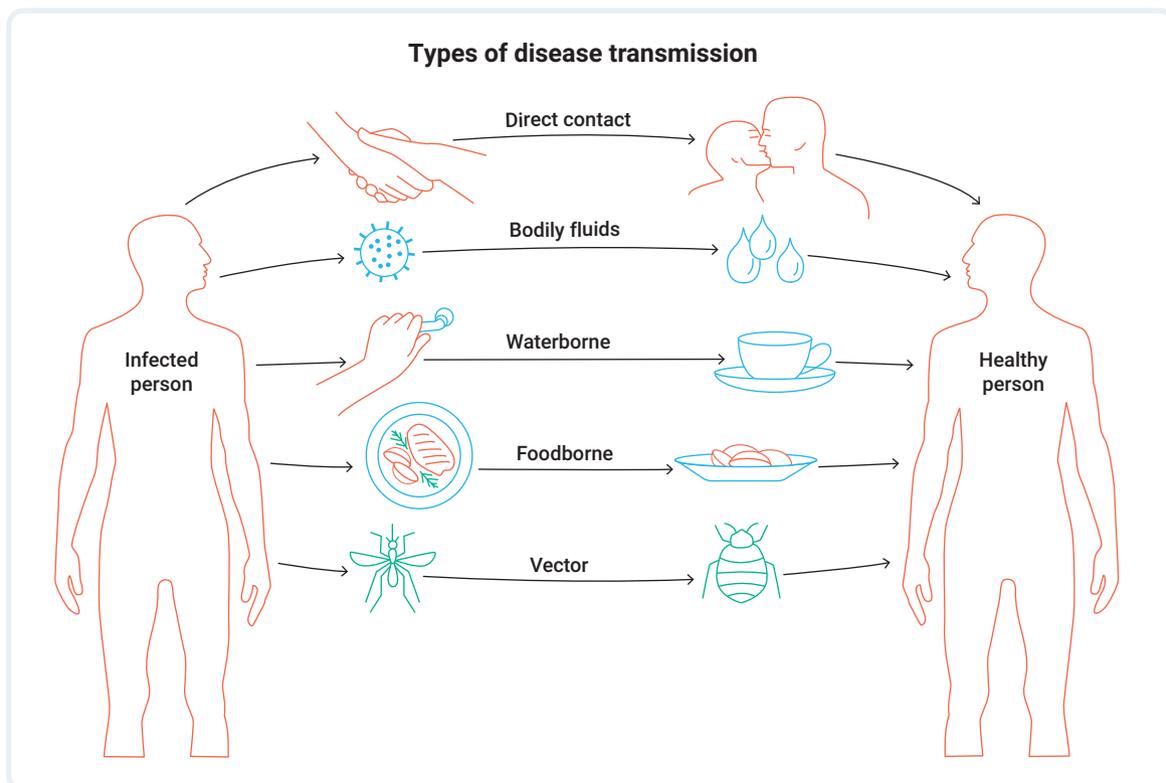
CHAPTER SUMMARY

Factors affecting transmission and spread of disease

- The transmission and spread of infectious diseases are influenced by a range of factors, including the:
 - mode by which the pathogen is transferred from an infected person to a non-infected person
 - density and mobility of individuals in a population
 - percentage of individuals in a population who already have immunity from a disease
 - control measures in place at the local, regional and global level to minimise contact between infected and non-infected individuals
 - effectiveness of data collection and analysis to predict and monitor diseases.

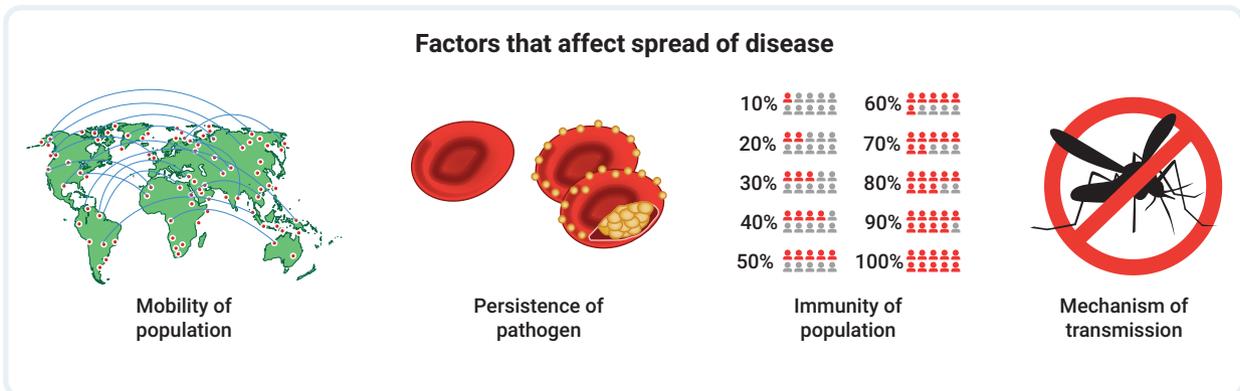
Modes of disease transmission

Direct transmission	Indirect contact – body fluids	Foodborne transmission	Waterborne transmission	Vector transmission
Physical contact leads to exchange of pathogen	Droplets and aerosols sneezed or coughed into air	Pathogen enters gastrointestinal tract via contaminated food	Pathogen enters gastrointestinal tract via contaminated water	Pathogen typically transferred from intermediate host to definitive host via vector

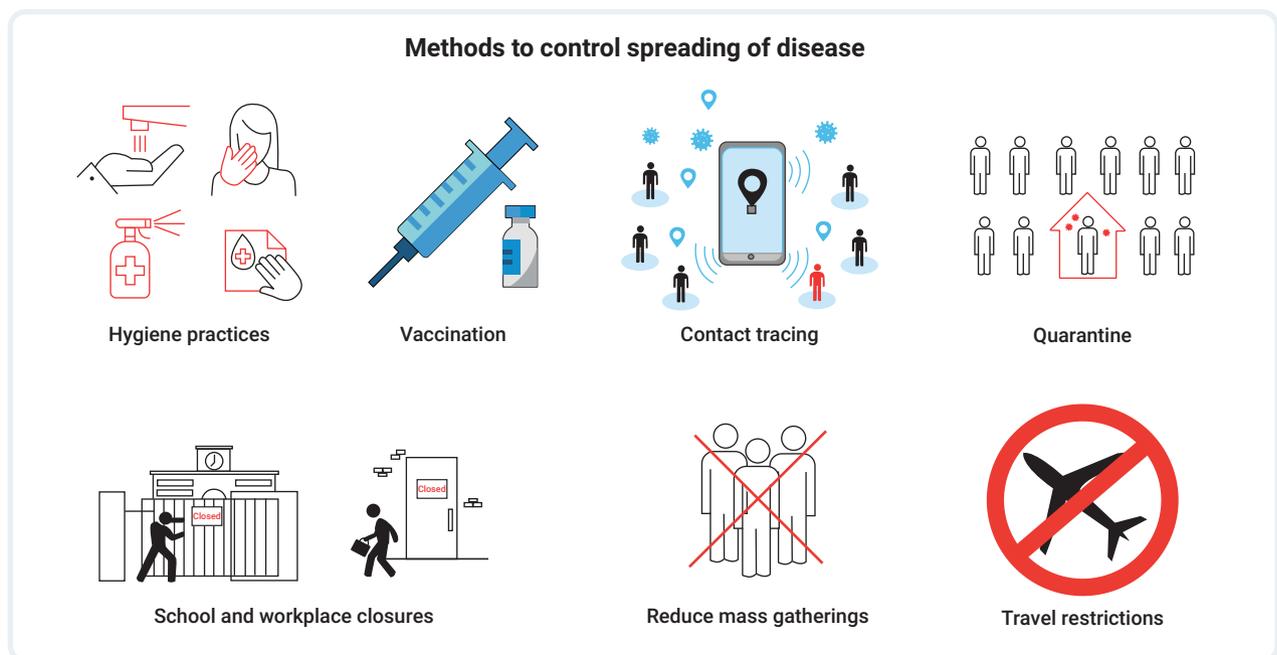


Shutterstock/Double Brain

Factors affecting disease spread



Factors that control the spread of disease



Data for disease management

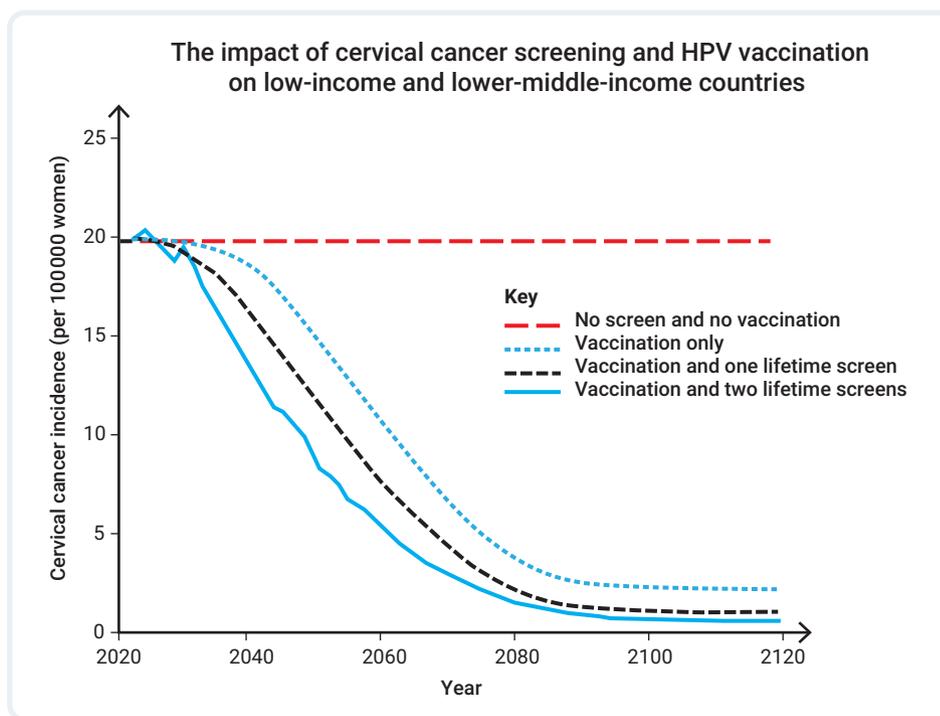
- Data analysis to assist in disease management:
 - Scientists can create sophisticated digital surveillance models that generate data to accurately predict outbreaks.
 - Data allows health authorities to be more proactive in implementing control measures that minimise spread.
 - Data is used in many ways to prevent, predict and control disease outbreaks.

MULTIPLE CHOICE

1. A living organism that transmits pathogens from one host to another is a:
 - A carrier.
 - definitive host.
 - fomite.
 - vector.

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2. The World Health Organization (WHO) runs a campaign to eliminate cervical cancer globally. In response to this campaign, a study was conducted to model the impact of cervical cancer screening along with a human papillomavirus (HPV) vaccination program in low-income and lower-middle-income countries. HPV is the cause of most cervical cancers. The results of the modelling are shown below.



- Which one of the following conclusions is supported by the data in the graph?
- The incidence of cervical cancer would be unaffected by a cervical cancer screening program.
 - The largest factor in reducing the incidence of cervical cancer in the long term is vaccination.
 - With vaccination only, it is possible to achieve fewer than 10 cervical cancer cases per 100 000 women by 2050.
 - Vaccination and one lifetime screen would be more effective than vaccination and two lifetime screens by 2070.

3. What is the primary route of transmission for foodborne illnesses?
- A Airborne transmission
 - B Bloodborne transmission
 - C Faecal–oral transmission
 - D Vector-borne transmission

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4. The population of a Victorian town has herd immunity to measles, a contagious disease. The effect of herd immunity on this population will be that:
- A people will have increasing levels of antibodies to measles over time.
 - B the transmission of measles from person to person is unlikely.
 - C each individual is equally protected against measles.
 - D only unvaccinated children will get measles.
5. What impact does the asymptomatic phase play in the transmission of some infectious diseases?
- A The recovery period is prolonged.
 - B It increases the severity of symptoms.
 - C Carriers can unknowingly spread the disease.
 - D There is no impact because an individual is not infectious during the asymptomatic phase.

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6. Viruses can be detected in sewage. Human faecal matter is the main source of pathogenic viruses in sewage. Infected individuals shed viral particles in their faeces.
- Which one of the following is an advantage of testing sewage for viral particles in order to control possible virus outbreaks?
- A Infected individuals can be prevented from shedding the virus.
 - B Infection in a community can be rapidly identified.
 - C Infected individuals can be located quickly.
 - D Sewage can be treated for the virus.
7. Which of the following would be the best choice to slow the spread of an airborne infectious disease?
- A Quarantine of sick individuals
 - B Vaccination of sick individuals
 - C A combination of quarantine and lockdown
 - D A combination of quarantine and vaccination of sick individuals

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8. Bovine spongiform encephalopathy (BSE) is a prion disease of cattle. It is sometimes called mad cow disease. It is caused by feeding cattle food that contains prions from other infected animals. The time between infection and symptoms appearing can be up to five years. There are concerns that variant Creutzfeldt-Jakob disease (vCJD) in humans could be caused by eating infected cattle meat.

Yellow fever is a viral disease that affects humans. The yellow fever virus can cause symptoms three to six days after infection. The virus is carried by a mosquito vector.

Which combination of approaches would be most effective at controlling the risk of outbreaks of both vCJD and yellow fever?

	vCJD	Yellow fever
A	Prevent all cattle that show symptoms of mad cow disease from reproducing.	Remove breeding grounds for mosquitoes.
B	Test all cattle for the presence of the prions.	Ensure that all healthcare professionals wear gloves when working with infected patients.
C	Destroy all cattle that have been fed infected food containing the prions.	Ensure that people take measures to reduce their chances of being bitten by mosquitoes.
D	Stop selling cattle meat.	Instruct people who are infected with yellow fever to wear masks in public places.

9. Which of the following factors contributes to the spread of vector-borne diseases such as Zika virus and malaria?
- A Increased vaccination rates
 - B Restricted international travel
 - C Overuse and misuse of antibiotics
 - D Climate change and the expansion of mosquito habitats

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10. A four-month investigation was undertaken in the classrooms of a large number of Year 2 and Year 3 students from four primary schools. For the first two months, half of the classes from each school used an antimicrobial gel hand sanitiser, while the other half used soap and water for regular hand hygiene. The students then switched hand-cleaning methods for the final two months. No significant differences in illness were observed between the groups.

The purpose of this investigation was most likely to:

- A reduce water use in schools.
- B encourage students to wash their hands more often.
- C reduce the number of students who are away from school due to illness.
- D decide if purchasing antimicrobial gel hand sanitiser for students was worthwhile.

SHORT RESPONSE

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11. Measles in Samoa

Measles is one of the most contagious viruses affecting humans.

The Pacific island nation of Samoa had a significant measles outbreak in 2019. This started when a person who had measles arrived in Samoa by plane in August 2019. In the following months over 5000 measles cases were recorded and more than 70 people died.

A measles outbreak was declared by the Samoan Government in October 2019. Ninety per cent of the deaths were among children less than five years old. More than one in five Samoan babies aged six to 11 months contracted measles during this outbreak and more than one in 150 babies in this age group died.

Prior to the measles outbreak in Samoa, the vaccination rate for measles for five-year-old children in the country had fallen to 31 per cent in 2018. One of the responses of the government to the outbreak was a mandatory vaccination program for all people. By early December 2019 over 90 per cent of the population had been vaccinated.

Reference: K Gibney, 'Measles in Samoa: How a small island nation found itself in the grips of an outbreak disaster', *The Conversation*, 12 December 2019, <https://theconversation.com/au>

- a Is the measles outbreak discussed in the article best described as an epidemic or a pandemic? **Justify** your reasoning.
- b Some children (e.g. those undergoing chemotherapy) cannot be vaccinated. **Explain** how high vaccination rates can also protect unvaccinated individuals.
- c **Describe** two strategies, other than vaccination, that could reduce the transmission of measles.

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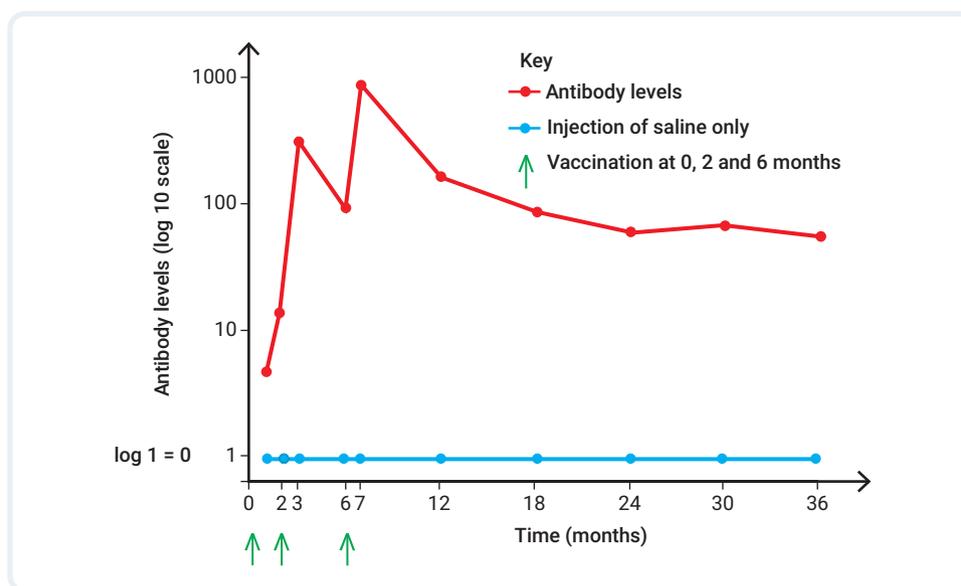
12. Mpox is a disease that is endemic to West and Central Africa. It is caused by a virus that was first discovered in monkeys. Symptoms of mpox include fever and blisters on the skin. The virus is transmitted from one person to another by direct skin contact with an infected person, or through contaminated materials such as bedding. In early 2022, cases of mpox were identified in countries where the virus is not endemic.
- a Mpox is classified as endemic to West and Central Africa. What does this mean about the disease?
 - b The incubation period for mpox is 5–21 days. Considering this, what would be two of the most effective methods to control the spread of mpox from Africa to other continents? **Justify** your answer.

CROSS-CHAPTER QUESTION

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13. Cervical cancer is a rare consequence of persistent infection by the human papilloma virus (HPV) in some women. The virus is transmitted sexually and may cause genital warts in both males and females. The natural immune response to this virus is not very effective.

Recently a vaccine has been produced to prevent this viral infection and therefore reduce the incidence of cervical cancer. The vaccine contains virus-like particles from the protein coat of the virus in a saline solution. The graph below shows the antibody response to a trial vaccination program in 16–23-year-old women, to whom three doses were given. Another group of women received injections of saline only.



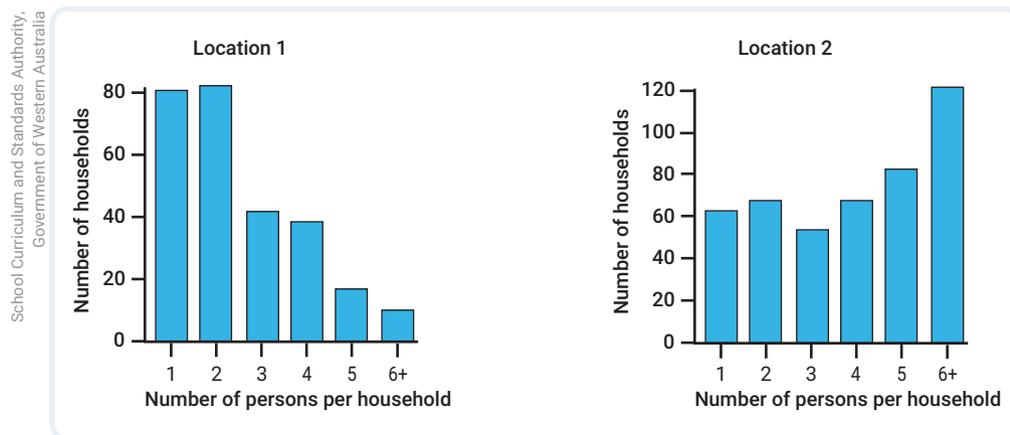
Explain whether the use of the HPV vaccine is effective at preventing cervical cancer.

DATA ANALYSIS

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14. Analyse evidence

A group of biologists developed a model for predicting the spread of influenza in human populations. As a part of this, they collected data on the number of individuals per household in two locations, which are shown in the figure below.



Compare the number of people per household in the two locations. Use data from the figure to support your answer.

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15. Interpret evidence

Fish farming is when fish are grown in ponds, cages, tanks or other types of enclosures, usually for food.

A major problem in fish farming is infectious diseases such as those caused by bacteria. A team of biologists investigated the types of bacteria present in two species of fish in four settings:

- ponds
- cages
- tanks
- a lake where both species occur naturally.

The biologists identified the bacteria present by sampling the water from each setting.

The following table shows the numbers of each type of bacteria found in the water.

Type of bacteria	Number of bacteria in each sample			
	Ponds	Cages	Tanks	Lake sites
<i>Aeromonas hydrophila</i>	13	3	12	3
<i>Aeromonas sobria</i>	8	1	0	1
<i>Edwardsiella tarda</i>	2	1	1	0
<i>Flavobacterium</i> spp.	1	1	0	0
<i>Streptococcus</i> spp.	1	2	0	0
<i>Pseudomonas aeruginosa</i>	2	0	6	0
<i>Pseudomonas fluorescens</i>	3	1	0	1
<i>Vibrio cholerae</i>	5	0	0	0
<i>Ralstonia picketti</i>	1	0	0	0
<i>Comamonas testosteroni</i>	4	0	0	0
<i>Citrobacter freundii</i>	0	2	0	0
<i>Plesiomonas shigelloides</i>	9	2	0	1
<i>Chryseobacterium indoligenes</i>	5	1	0	0
<i>Pseudomonas stutzeri</i>	1	0	0	0
<i>Burkholderia cepacia</i>	1	0	0	0
<i>Klebsiella</i> spp.	1	0	0	1
<i>Serratia marcescens</i>	0	2	0	0
<i>Proteus</i> spp.	8	1	0	1
Number of different types of bacteria	16	10	3	6

A fish farmer reviewed the data and concluded that fish in tanks have fewer infections than those in ponds, cages or the lake. **Determine** whether the fish farmer is correct. Provide reasoning.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- Appreciate that for thousands of years, First Nations peoples' knowledges of natural antiseptics and bush medicines have been used to prevent and treat infections.

Biology 2025 v1.1 General Senior Syllabus © QCAA 2024

First Nations Australians traditional medicine

The history of First Nations Australians' development of medicines started over 65 000 years ago. In that time, First Nations Australians have accumulated a wealth of knowledge surrounding the identification of the medicinally important components of plants and animals to treat various ailments. This has led to a vast pharmacopoeia. These medicines and treatments are based on thousands of years of accumulated knowledge gained through experimentation and acute observation. Each First Nations Australian cultural group has subsequently developed their own suite of medicines sourced from their particular Country, and at times, important medicines are traded between groups. Some examples of traditional medicines developed by First Nations groups in Queensland are included in **Table 1**.

TABLE 1 Some traditional medicines of select First Nations groups in Queensland and their active ingredients

Name	Uses	Pharmaceutically isolated active ingredient
Eucalyptus oil (<i>Eucalyptus</i> sp.) ¹	There are more than 700 <i>Eucalyptus</i> species across Australia. The oils have been long used for their natural antimicrobial and antiseptic properties.	1,8-Cineole Now used commercially in mouthwash, throat lozenges and cough suppressants.
Tea tree oil (<i>Melaleuca alternifolia</i>) ²	Endemic to Australia. It is used as an antibacterial to treat wounds and infections.	Terpinen-4-ol and 1,8-cineole, α -terpineol and γ -terpinene Now used commercially in antibacterial hand wash.
Clay pills (<i>Kaolin</i>) ³	It is used to treat diarrhoea	Phyllosilicates

An example of First Nations groups in Queensland using this medicine:

¹Mbabaram Peoples

²Bundjalung Peoples

³Pitta-Pitta Peoples

Research from pharmaceutical companies has reaffirmed the long-held knowledge of First Nations Australians regarding the medicinal properties of these traditional medicines. Since colonisation, commercial companies have isolated the active ingredients from these medicines and patented the active ingredient in order to:

- provide a commercially reliable and consistent product
- ensure long-term financial benefit from their research and product development.

However, the increasing interest in these traditional medicines and pharmaceutical advancements has intensified concerns about **biopiracy** and the exploitation of First Nations Australians' knowledge without proper acknowledgement or compensation. Ethical, moral and legal considerations arise when determining ownership of intellectual property, particularly as First Nations Australians have utilised these products for thousands of years.

In 2004, Queensland was the first Australian jurisdiction to introduce laws to regulate biodiscovery. Key considerations included:

- the acknowledgement that First Nations Australians' cultures have used traditional medicines for thousands of years for their healing properties. Patents and exclusive research rights have the potential to restrict local First Nations Australians communities from using their traditional medicines.
- pharmaceutical companies invest significant time and millions of dollars researching medicines for active ingredients. They have a reasonable expectation of financial return on their investment.

While the original legislation had some significant limitations, subsequent revisions of the law brought it in line with the 2014 Nagoya Protocol. In 2014, the internationally recognised Convention on Biological Diversity published the Nagoya Protocol, providing a legal framework for the effective implementation of the fair and equitable sharing of benefits arising out of the use of genetic resources. Under the revised Queensland law, anyone engaging in biodiscovery must take all reasonable measures to form agreement with the custodians of First Nations Australians' knowledge being used.

biopiracy patented without the informed consent or appropriate benefit sharing with the Indigenous community



FIGURE 1 Tea tree oil harvested from *Melaleuca alternifolia*

Tea tree oil

Melaleuca alternifolia (Figure 2a) is a native Australian plant found in coastal New South Wales and Queensland (Figure 2b). The Bundjalung Peoples of eastern Australia have long used tea tree oil to treat skin wounds.

It wasn't until the 1920s that scientific research was conducted to identify the antimicrobial properties of tea tree oil. Findings from the research reaffirmed the traditional use of tea tree, showing the antimicrobial activity of the oil was 10 times more potent than Western antimicrobial agents (e.g. phenol).

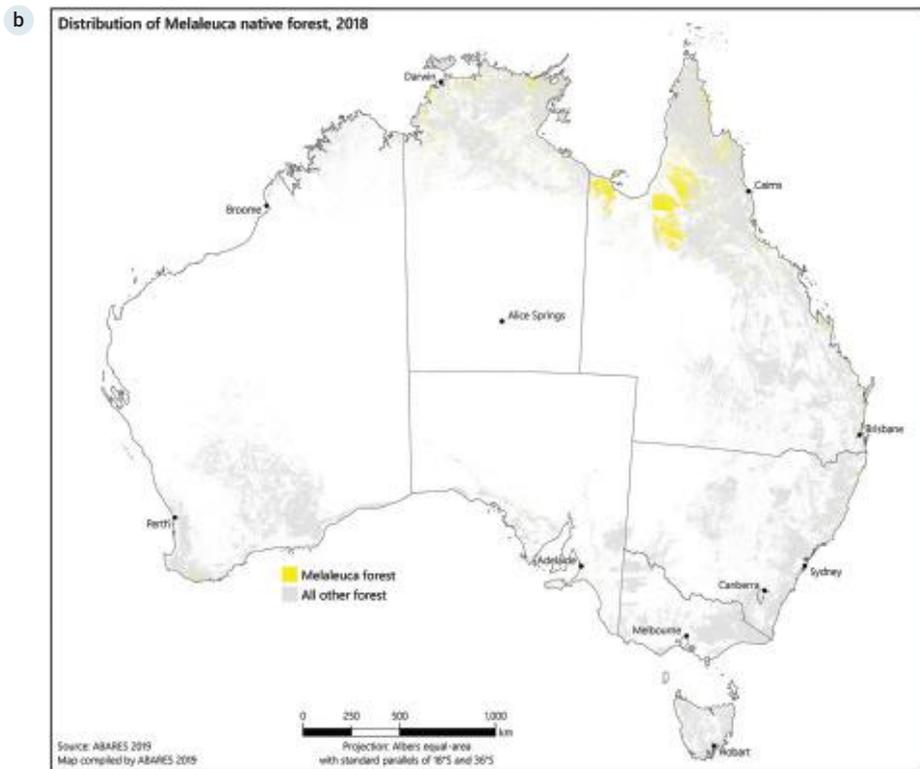


FIGURE 2 (a) *Melaleuca alternifolia*, also known as tea tree. (b) The distribution of *Melaleuca* native forest.

Over the past century, there has been increasing interest in tea tree oil. Studies are now showing the activity of tea tree oil against a range of different bacteria (Table 2). More recently, there has been interest in the activity of tea tree oil against antibiotic resistant bacteria.

TABLE 2 Susceptibility data for bacteria tested against *Melaleuca alternifolia* oil

Bacterial species	% (vol/vol)	
	Minimum inhibitory concentration	Minimum bactericidal concentration
<i>Acinetobacter baumannii</i>	1	1
<i>Actinomyces viscosus</i>	0.6	>0.6
<i>Actinomyces</i> spp.	1	1
<i>Bacillus cereus</i>	0.3	
<i>Bacteroides</i> spp.	0.06–0.5	0.06–12
<i>Corynebacterium</i> sp.	0.2–2	2
<i>Enterococcus faecalis</i>	0.5–>8	>8
<i>Enterococcus faecium</i> (vancomycin resistant)	0.5–1	0.5–1
<i>Escherichia coli</i>	0.08–2	0.25–4
<i>Fusobacterium nucleatum</i>	0.6–>0.6	0.25
<i>Klebsiella pneumoniae</i>	0.25–0.3	0.25
<i>Lactobacillus</i> spp.	1–2	2
<i>Micrococcus luteus</i>	0.06–0.5	0.25–6
<i>Peptostreptococcus anaerobius</i>	0.2–0.25	0.03–>0.6
<i>Porphyromonas endodontalis</i>	0.025–0.1	0.025–0.1
<i>Porphyromonas gingivalis</i>	0.11–0.25	0.13–>0.6
<i>Prevotella</i> spp.	0.03–0.25	0.03
<i>Prevotella intermedia</i>	0.003–0.1	0.003–0.1
<i>Propionibacterium acnes</i>	0.05–0.63	0.5
<i>Proteus vulgaris</i>	0.08–2	4
<i>Pseudomonas aeruginosa</i>	1–8	2–>8
<i>Staphylococcus aureus</i>	0.5–1.25	1–2
<i>Staphylococcus aureus</i> (methicillin resistant)	0.04–0.35	0.5
<i>Staphylococcus epidermidis</i>	0.45–1.25	4
<i>Staphylococcus hominis</i>	0.5	4
<i>Streptococcus pyogenes</i>	0.12–2	0.25–4
<i>Veillonella</i> spp.	0.016–1	0.03–1

References

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Weblinks

Protecting Indigenous bush foods and medicines against biopiracy

The Nagoya Protocol

Biopiracy in Queensland: A broken record that needs repair

Aboriginal medicinal plants of Queensland

ANSWERS

CHAPTER 1 CELLS AND CELL SPECIALISATION

LEARNING CHECK 1.1

DESCRIBING

- 1 Genetic material in prokaryotic cells is in the form of DNA. The DNA is located in a single large circular chromosome as well as in smaller rings called plasmids.
- 2 Ribosomes or cell membrane or cytoplasm or DNA.
- 3 Plasmids are small rings of DNA in the cytoplasm that can be exchanged between bacterial cells.

APPLYING

- 4 The absence of organelles reduces the metabolic efficiency of the cell. Organelles provide compartments for the cell to carry out different metabolic functions, under different conditions, at the same time, which is not possible for prokaryotic cells. Without organelles, all metabolic reactions have to occur in the same environment.

LEARNING CHECK 1.2

DESCRIBING

- 1 a, iv; b, iii; c, i; d, v; e, ii
- 2 Lipids and phospholipids
- 3 Rough ER is predominantly involved in the production, folding and modification of proteins, along with some transport.

APPLYING

- 4 a Chlorophyll is the coloured pigment that traps light energy, whereas a chloroplast is the membrane-bound organelle that is the site of photosynthesis, containing chlorophyll.
b Rough ER is studded with ribosomes and is the site of protein assembly and transport, whereas smooth ER does not have attached ribosomes and is the site of lipid and phospholipid assembly.
c Chloroplasts are organelles containing chlorophyll that trap light energy to transform CO_2 and H_2O into $\text{C}_6\text{H}_{12}\text{O}_6$ and O_2 , whereas mitochondria transform $\text{C}_6\text{H}_{12}\text{O}_6$ and O_2 to release energy in the form of ATP and CO_2 and H_2O .
- 5 Plant cells require mitochondria to convert the glucose produced in photosynthesis into ATP that can be used by the plant's cells for the process of respiration.
- 6 Muscle cells contract and relax often; therefore, they require more energy to function. They need more mitochondria to produce more ATP via respiration.

LEARNING CHECK 1.3

DESCRIBING

- 1 Cytoplasm, cell membrane and ribosomes
- 2 Mitochondria and chloroplasts are thought to have a common evolutionary past because:
 - both make copies of themselves and split in two, just like bacteria
 - they can only arise from pre-existing mitochondria and chloroplasts; they cannot be formed in a cell that lacks them
 - they are similar in size to small bacteria, and have their own genetic material, which, like that in bacteria, is contained on a circular DNA molecule
 - they contain ribosomes and RNA molecules so that they can make their own proteins, and they have two membranes: the outer one was probably derived from the host membrane when it engulfed the bacteria, and the inner one is probably the membrane of the ingested bacteria.
- 3 a Features unique to prokaryotic cells include: single, circular chromosomes; plasmids (extra cellular DNA), pili; capsules; no nucleus
b Features unique to eukaryotic cells include: linear chromosomes encased in the nucleus; membrane-bound organelles

APPLYING

- 4 Cytosol is the fluid part of the cytoplasm where chemical reactions occur. The cytoplasm describes the content of the cell between the nucleus and the cell membrane. It includes cytosol and organelles.

ANALYSING

- 5 Similarity: chromosomes are made of DNA
Difference: Prokaryotic cells have a circular chromosome in the cytoplasm, whereas eukaryotic chromosomes are linear and contained within a membrane-bound nucleus.

INTERPRETING

- 6 The absence of organelles suggests prokaryotic cell. However, the size of 0.3 mm suggests eukaryotic cell, as prokaryotic cells are not typically larger than $5\ \mu\text{m}$. To reach a clear conclusion, electron microscopy techniques could be used to see whether a circular chromosome (prokaryotic) or linear chromosomes in a nucleus (eukaryotic) are present.

LEARNING CHECK 1.4

DESCRIBING

1 Electron microscope

2

Objective lens	Total magnification eyepiece lens \times 10	Total magnification eyepiece lens \times 5
\times 4	40	20
\times 10	100	50
\times 40	400	200

INTERPRETING

- 3 a Figure 1.4.3 shows a eukaryotic cell, because membrane-bound organelles and a nucleus are visible.
- b Figure 1.4.3 was taken with a transmission EM because it shows a high degree of detail and is therefore taken at high resolution.
- c The cell has been cut into thin sections for viewing; therefore, some organelles were not sliced through in that particular thin section.
- d Organelle i is a chloroplast (containing a large starch grain) and organelle ii is the nucleus therefore this cell is most likely a plant cell due to the presence of the chloroplast. Therefore, it is a plant cell.
- 4 Set-up 1 HP:
HP diameter = $2.5 \text{ mm} \times \frac{20}{40}$
= 1.25 mm
- Set-up 2 HP:
HP diameter = $4.0 \times \frac{10}{100}$
= 0.4 mm
- Set-up 2 is best for 0.5 mm, whereas Set-up 1 is best for 1.5 mm and 2.5 mm

LEARNING CHECK 1.5

DESCRIBING

- 1 Two unique characteristics of stem cells include the potential to divide and replicate, and they are unspecialised. They can differentiate into other cell types. They have the potential to divide for long time periods.
- 2 Totipotent stem cells have the potential to develop into any type of cell, whereas unipotent stem cells can only differentiate into one type of cell.

APPLYING

- 3 In adults, stem cells are important because they can help to replace damaged tissue and cells and also assist in the healing process as a result of injury.
- 4 Skin cells would be an example of multipotent stem cells. Multipotent cells can develop into a limited number of other cell types. Skin cells would be able to differentiate into cell types specific to skin and its structure, e.g. sweat glands and hair follicles.

LEARNING CHECK 1.6

DESCRIBING

- 1 The main phases of mitosis are prophase, metaphase, anaphase and telophase.
- Prophase – DNA condenses and forms sister chromatids; centrioles appear and spindles start to form.
- Metaphase – The chromatids line up along the spindle's equator.
- Anaphase – Sister chromatids separate and chromosomes are drawn to each pole of the cell.
- Telophase – Chromosomes reach the poles and the nuclear envelope reforms. The chromosomes decondense.
- 2 Specialised cells have specific structures that make them optimal for their function.

APPLYING

- 3 The prefixes for the stem cells indicate their potency.
- 'Toti' – total. Totipotent cells can form any type of cell necessary for embryonic development.
- 'Pluri' – many. Pluripotent cells can become any type of body cell but not those required for embryonic development.
- 'Multi' – multiple. Multipotent cells can form multiple different types of cells.
- 'Uni' – single. Unipotent cells can only form one cell type.
- 4 Zygotes can differentiate into any type of cell, including those during embryonic development. As a result, zygotes can be considered as a stem cell (totipotent).

INTERPRETING

- 5 a True. During cellular differentiation, cells become more specialised with specific structures and functions. This process is how cells become more specialised.
- b False. All cells contain the same DNA; however, the genes are expressed differently. This means that, depending on the cell type, some genes are expressed while others are not. This allows them to have different functions.
- c True. Stem cells are the precursors for all cells. During development, stem cells differentiate to become different types of cells with specialised functions.

LEARNING CHECK 1.7

DESCRIBING

- 1 Cells have specific structures that optimise them for their particular function. For example, goblet cells produce mucins that are proteins. These are then secreted from the cell to support the digestive and respiratory system. To do so, they have a prominent Golgi apparatus to allow them to transport high volumes of the mucin proteins. Prominent rough ER to produce proteins and high number of secretory vesicles.
- 2 The cilia in epithelial cells in the trachea must move constantly in order to remove mucous from the lungs. This movement requires a lot of energy. As a result, mitochondria occur close to the cilia to produce and provide ATP (energy) to allow for this movement.

APPLYING

- The Golgi apparatus is responsible for transporting proteins. The main function of red blood cells is to transport oxygen around the body and therefore they are not required to produce and transport proteins. As such, red blood cells can operate without the Golgi apparatus.
- All the different specialised cells in multicellular organisms are totally dependent on each other, because each cell type only performs certain functions of the many that are required. Therefore, it is necessary for there to be communication and coordination between cells so that the organism as a whole can function. For example, the respiratory system and circulatory system need to communicate to ensure that sufficient oxygen is being transported around the body, while also removing carbon dioxide.
- The alveoli have a flattened shape so that there is a shorter distance for oxygen and carbon dioxide to move between the cells and into/out of the lungs and blood. These cells also have fewer organelles which allows for a better surface to give a shorter diffusion distance.
 - Red blood cells have a flat and concave structure to allow them to fit through the blood vessels – particularly the narrow capillaries. They do not contain organelles, so space for haemoglobin (which binds to oxygen) is maximised.

CHAPTER EXAM

MULTIPLE CHOICE

- | | | | | |
|-----|-----|-----|-----|------|
| 1 B | 3 A | 5 C | 7 C | 9 C |
| 2 A | 4 D | 6 A | 8 B | 10 C |

SHORT RESPONSE

- Ribosomes are involved with protein assembly. Without ribosomes, cells would not be able to assemble the proteins required for communication, structural support, transport, storage and immune responses.
- Although all cells have identical genetic material, only a small portion is actively 'switched on'. Therefore, the particular structure and function of a specialised cell depends on which parts of the genetic material are actively expressed. This allows for cells of different types to develop from the same stem cell.
- Prokaryotic cells do not have organelles. Therefore, the structure of the cell cannot be altered in the same way as a eukaryotic cell, where the number and type of organelles can be changed.

DATA ANALYSIS

- Plant cell, *Trypanosoma*, RBC, *Chlamydomonas*, *E. coli*, tobacco mosaic virus, T4 bacteriophage, HIV, polio virus.
- $l = 3 \text{ cm}$ (this will depend on the size of the image on the page) = 30 mm = 30 000 mm

$$A = 7 \mu\text{m}$$

$$M = \frac{30\,000}{7}$$

$$= 4286 \text{ or } \times 4286$$

CHAPTER 2 CELL MEMBRANE

LEARNING CHECK 2.1

DESCRIBING

- A selectively permeable membrane allows certain molecules to move through, but not others, based on size, charge or polarity.
- Membrane receptor proteins
 - Cholesterol
 - Protein channels in cell
- Channel proteins form channels within membranes to allow the passage of some substances across the membrane.
- The phospholipid bilayer of the cell membrane is described as fluid and membrane proteins form the mosaic part.

APPLYING

- The phospholipid bilayer is described as fluid because it has the ability to flow and change shape, like a two-dimensional fluid. Membrane proteins are referred to as a mosaic because they are embedded in the lipid in various patterns like a mosaic.

LEARNING CHECK 2.2

DESCRIBING

- Solvent: water; solute: salt
- Any two of: larger surface area, higher concentration gradient, shorter diffusion distance
- Facilitated diffusion is a type of diffusion that occurs through a channel in the membrane of the cell as charged particles or relatively large molecules are helped to cross the membrane, e.g. glucose, amino acids, sodium ions and chloride ions.
- Plant cells do not burst when placed in a hypotonic solution because they have cell walls.

APPLYING

- If red blood cells were kept in pure water, the water would diffuse into the cells (from high to low concentration of water) and they would burst because the environment would be hypotonic. Therefore, they are kept in an isotonic saline solution, so net movement of water is in equilibrium.
- To restore the crispness of limp salad greens, soak lettuce in cool water. This is because water diffuses from outside the lettuce into the cytoplasm of the cells from a high to low concentration of water (hypotonic environment). Water then diffuses into the vacuole, pressing outwards towards the cell wall and making the cells turgid.
- Isotonic sports drinks have a similar concentration of dissolved substances to normal blood levels. This means that the sports drink should not create a hypertonic environment, leading to further dehydration.

INTERPRETING

- Solution Z was hypertonic compared with the animal cell.
 - Cells in solution Y were isotonic with the solution.
 - In solution X, plant cells would be turgid and swollen as the net movement of water is into the cell and therefore

hypotonic. In solution Y, they would not change size, as the water should move in and out at the same rate and therefore isotonic. In solution Z, plant cells would become flaccid and plasmolysed, meaning the cell membrane would pull away from the cell wall as there is a net movement of water out of the vacuole and cell and therefore hypertonic.

LEARNING CHECK 2.3

DESCRIBING

- 1 Membrane channel proteins
- 2 During endocytosis, the cell membrane sends projections out that surround the substance and when projections of the membrane meet, membrane fusion occurs, resulting in formation of a vesicle inside the cytoplasm.
- 3 Phagocytosis is a process involving the transport of particular solid particles into the cell. Since not all substances are transported into the cell by this process, phagocytosis can be considered as selective.
- 4 Size/charge/concentration gradient
- 5 The larger the concentration gradient, the greater the rate of diffusion.
- 6
 - In active transport, substances move against a concentration gradient, across a cell membrane, using energy; but in simple diffusion, substances move down their concentration gradient without energy being used.
 - Diffusion is not necessarily movement across a cell membrane.

APPLYING

- 7 For example: Intestinal cells actively transport glucose into the body from digested food to ensure it is not excreted and seaweeds actively uptake essential minerals such as iodine that are in low concentrations in the sea. This occurs because the substance is moved to where it may already be in higher concentrations.
- 8 Certain white blood cells are known as phagocytes because they engulf invading bacteria (solid particle) by surrounding them with projections from the cell membrane.
- 9 Phagocytosis is a type of endocytosis. Endocytosis includes taking in both solid and liquid material in vesicles, while phagocytosis refers only to the uptake of solid material. Therefore, endocytosis and phagocytosis are not the same.

ANALYSING

- 10 Similarity:
 - Ions and water can move down a concentration gradient from an area of high concentration to an area of low concentration. Ions do so through facilitated diffusion and water does so through osmosis.
 Differences:
 - Passive movement of ions through the membrane requires membrane transport proteins, whereas water does not require these.

- Ions can be transported against the concentration gradient by active transport, which requires energy and carrier proteins.

- 11, 12
 - a Out of the cell: If an *Amoeba* is washed into the sea during a storm, water diffuses out of the cytoplasm of the *Amoeba*, from a high concentration of water inside the cell (hypotonic), out into the sea where the water is in a lower concentration because the presence of salt in the sea makes it hypertonic.
 - b Out of the cell: Respiration will increase the concentration of carbon dioxide inside working muscle cells; therefore, it will diffuse out of cells towards a lower concentration in the bloodstream, where the movement of blood maintains the concentration gradient.
 - c Into the cell: Oxygen moves into red blood cells (low concentration) from a high concentration in lungs.
 - d Cannot cross: Sodium and chloride ions cannot diffuse across membranes because they are hydrophilic; therefore, cannot move through the hydrophobic lipid tails.

INTERPRETING

- 13 During dialysis, for the wastes to continue diffusing out of the dialysis tube, the surrounding solution must be replaced with fresh solution that does not contain wastes. If this is not done, the wastes in the blood would be at the same concentration (isotonic) as the solution and they would stop diffusing out of the blood.

LEARNING CHECK 2.4

DESCRIBING

- 1 Surface area-to-volume ratio reduces as cells enlarge.
- 2 Cells can increase the rate of diffusion of substances across their cell membrane by removing it from inside the cell, by either using the substance or by converting it to another substance.

APPLYING

- 3 Surface area of a cube = $6 \times (\text{length of side})^2$
 $= 6 \times (2)^2$
 $= 24 \text{ cm}^2$
 Volume = $2 \text{ cm} \times 2 \text{ cm} \times 2 \text{ cm}$
 $= 8 \text{ cm}^3$
 So, SA:V = 24:8 = 3:1

- 4 Being long, thin or flat increases a cell's surface area-to-volume ratio. While the volume of the cell remains the same, changing the shape in this way increases the surface available for each unit of volume.
- 5 As a cell increases in size, both surface area and volume increase, but volume grows faster than surface area, causing a reduction in surface area-to-volume ratio. The actual rate of diffusion does not change, but the cell reaches a point where exchange of essential substances and wastes across the membrane are not fast enough to service the increased volume of the cell.

ANALYSING

- 6 Table 2.4.1 shows that with a diameter of 1 cm, the object would have a SA:V ratio of 6:1. This drops significantly (halves) to 3:1 with an increase of diameter to 2 cm, and with another increase in diameter to 3 cm, the SA:V ratio drops to 2:1. This data shows there is not a linear relationship between size and surface area-to-volume ratio.

CHAPTER EXAM

MULTIPLE CHOICE

- 1 A 3 C 5 D 7 D 9 C
2 B 4 C 6 D 8 C 10 C

SHORT RESPONSE

11 a, b

Treatment	Change	Explanation
Distilled water	Gained	Solutions that contain a low concentration of solutes have a high concentration of water (hypotonic). This means that water will diffuse by osmosis from a solution of low solute concentration (outside the cell) to a solution of high solute concentration (inside the cell).
Salt water	Lost	Solutions that contain a high concentration of solutes have a low concentration of water (hypertonic). This means that water will diffuse by osmosis from a solution of low solute concentration (inside the cell) to a solution of high solute concentration (outside the cell).
Boiled and salt water	No change	Boiling would damage the structure of the cell membrane; therefore, the membrane would not control what moves in or out.

- 12 Hypotonic environment → cell membrane → cytoplasm → across contractile vacuole membrane → return to hypotonic environment

CROSS-CHAPTER QUESTION

- 13 a The phospholipid bilayer controls what enters and exits the cell. If this membrane is destroyed, the cell has no ability to keep the required contents inside the cell and keep unwanted substances outside the cell. Therefore, the cell can no longer function.
- b If the mitochondrial membrane is damaged, they will no longer be able to carry out phases 2 (Krebs cycle) and 3 (oxidative phosphorylation and electron transport chain) of aerobic respiration. This reduces the production of ATP significantly and the cell would only be able to carry out anaerobic respiration.

DATA ANALYSIS

- 14 The ion concentration in the isotonic drink is a total of 35.5 mmol L⁻¹ which is 210.8 mmol L⁻¹ lower than the concentration of 246.3 mmol L⁻¹ in Person A.

Similarity:

- Concentration of potassium ion is lowest for both.
- They contain the same ions and sugar.

Difference:

- Person A has a much lower sugar concentration (4.7 mmol L⁻¹) than the drink (333 mmol L⁻¹)
- Person A has a higher concentration of potassium and chloride ion than the drink.

- 15 Total concentration of solute for drink:

$$21 + 3.5 + 11 + 333 = 349.5 \text{ mmol L}^{-1}$$

Total concentration of solute for Person A:

$$140 + 4.3 + 102 + 4.7 = 293.3 \text{ mmol L}^{-1}$$

Person A blood serum is hypotonic to the drink; therefore, water moves to the drink. This causes the volume on the side of the sports drink to rise.

CHAPTER 3 SYSTEM SPECIALISATION

LEARNING CHECK 3.1

DESCRIBING

- 1 Cells → tissues → organs → systems
- 2 Tissues are a group of cells that have a specific function, whereas organs consist of different tissues working together.
- 3 Large surface area, thin, moist, have a concentration gradient

APPLYING

- 4 Increasing the surface area of the capillaries would allow for greater exchange; however, it may make the capillary too narrow for red blood cells to pass through, causing clots or other serious issues.

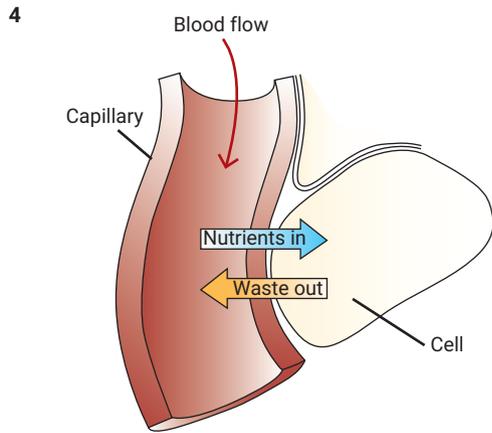
LEARNING CHECK 3.2

DESCRIBING

- 1 In a closed circulatory system, the blood is confined to vessels.
- 2 The capillaries are the smallest blood vessels in the body. They are one cell thick tubes to allow for the efficient exchange of nutrients.

APPLYING

- 3 Capillaries meet the four characteristics because they are thin (i.e. one cell thick), have a large surface area (because of the small diameter), are kept moist by the blood and have a concentration gradient that allows for diffusion of nutrients into tissues and removal of waste out of cells as the blood flows to take nutrients away.



Nutrients carried in the blood through the capillaries move down a concentration gradient into the cells. At the same time, wastes such as carbon dioxide move down a concentration gradient out of the cell and into the blood in the capillaries.

5 Having a closed system:

- allows for efficient transport of nutrients and waste
- allows for blood flow to be regulated
- means that the blood doesn't mix with the other fluids in the body.

ANALYSING

6 Similarities: Capillaries, arteries and veins all function within the circulatory system and are all lined with endothelial cells

Differences:

- Wall thickness – capillaries are only one cell thick, whereas arteries have thick, muscular walls. The walls of veins are thinner than arteries; however, they are thicker than capillaries
- Diameter – both veins and arteries have a larger diameter than capillaries.

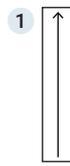
LEARNING CHECK 3.3

DESCRIBING

- 1 The alveolus has thin walls, a large surface area, and a concentration gradient and is kept moist by the surrounding fluid.
- 2 a Oxygen
b Carbon dioxide
- 3 To move from the blood into the external air environment, gases need to diffuse from red blood cells through the endothelium of the capillaries, then through the epithelium of the alveoli to be expelled from the body.
- 4 Gases diffuse from an area of high concentration to low concentration.

APPLYING

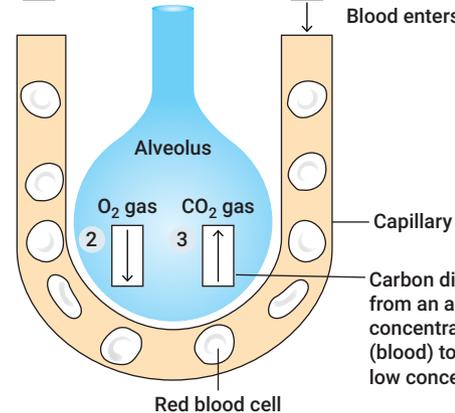
5 Pulmonary vein



Pulmonary artery



Oxygenated blood enters the capillary. Oxygen moves from an area of high concentration (air) to an area of low concentration (blood). Blood enters the capillary.



Carbon dioxide moves from an area of high concentration (blood) to an area of low concentration (air).

INTERPRETING

6 Having too much mucus would increase the barrier for gas exchange by making the exchange surface thicker, thereby increasing the diffusion distance; therefore, potentially decrease the ability of the body to obtain oxygen and remove carbon dioxide. Too little mucus would make the exchange surface too dry to be effective, not allowing substances to dissolve.

LEARNING CHECK 3.4

DESCRIBING

- 1 Mucosa/epithelium
- 2 Capillaries and lacteals
- 3 Villi in the intestines have a large surface area, thin walls, are moist (mucus produced by the mucus-producing cells) and are within close proximity to capillaries and lacteals that allow for a concentration gradient.

APPLYING

4 The presence of villi increases the surface area for nutrient absorption in the digestive system. A lack of this would significantly decrease the amount / efficiency of nutrient absorption into the body as this decreases surface area.

LEARNING CHECK 3.5

DESCRIBING

- 1 Glomerulus → proximal tubule → loop of Henle → distal tubule → bladder
- 2 a i Filtration is a process where the blood is filtered in the glomerulus, allowing the movement of plasma and small molecules or ions to move through the capillary walls.

- ii Reabsorption is a process where important substances such as water, glucose and ions are returned from the filtrate back into the body.
 - iii Secretion is the process of balancing the pH of the interstitial fluid by moving substances such as ammonia and H^+ into the nephron structures.
- b i** Filtration – glomerulus
- ii Reabsorption – tubules of the nephron, including proximal tubule, loop of Henle, distal tubule, collecting ducts
 - iii Secretion – mainly the nephron tubules, including distal tubule and collecting ducts

APPLYING

- 3** a Blood c Filtrate e Blood
 b Filtrate d Blood f Filtrate
- 4** Glomerular filtration is a non-specific process where most of the water and small substances in the blood are filtered out, whereas selective reabsorption and secretion are both highly specific processes where only specific substances are moved. Also, glomerular filtration and secretion both move substances into the nephron, whereas selective reabsorption moves substances back into the blood.

INTERPRETING

- 5** The colour of urine can be affected by the amount of water removed from the body. During dehydration, the body will reabsorb most of the water from the filtrate, resulting in the production of highly concentrated darker urine. When the body is not dehydrated, more water will be found in the urine, resulting in the production of a less concentrated lighter urine.
- 6** People with nephron syndrome have a high protein urine level. This suggests proteins are being emptied into the filtrate when they are a large molecule that should not pass through the glomerulus. Damage to the glomerulus would result in large amounts of protein entering the filtrate and passing through to the urine.

CHAPTER EXAM

MULTIPLE CHOICE

- 1 A 3 C 5 A 7 D 9 C
 2 D 4 D 6 B 8 B 10 B

SHORT RESPONSE

- 11** Similarities:
- All have structures that are thin, moist, have a concentration gradient and increased surface area to allow for more efficient exchange of substances.
- Differences:
- The main exchange surface for the respiratory system is the alveoli, villi for the digestive system and nephrons in the kidneys.

- The blood keeps the excretory system surface moist, whereas mucus can achieve that function for the digestive and respiratory systems.

12 Similarities:

- Filtration and selective reabsorption occur in the nephrons.
- Both involve the movement of substances between the blood and filtrate.

Differences:

- Selective reabsorption helps specific substances be reabsorbed into the body through active transport, e.g. glucose and amino acids. Glomerular filtration is not as specific as selective reabsorption and allows smaller molecules and ions to be exchanged through a pressure difference.
- Selective reabsorption moves substances from filtrate to the blood, whereas glomerular filtration moves substances from blood to filtrate.

CROSS-CHAPTER QUESTION

- 13** Currently, the exchange at the alveoli involves the passive diffusion of gases, which are considered small particles, into the blood. If the size of the gas particles increases so that they could no longer passively diffuse across the membrane, the body would need to actively transport gas molecules between the alveoli, capillary and body cells. This would drastically increase the energy required to obtain oxygen and dispose of carbon dioxide. Breathing may no longer be an effective means of gas exchange.

DATA ANALYSIS

- 14** a, b, c
- 15** The villi are important structures that increase the surface area of the digestive system, enabling the efficient absorption of nutrients into the body. By causing the villi to shrink, coeliac disease would result in the body not being able to properly absorb nutrients due to a decrease in surface area, especially at the rate necessary for the body. As a result, the individual may develop deficiencies of particular nutrients over time.

CHAPTER 4 BIOMOLECULES AND ENZYMES

LEARNING CHECK 4.1

DESCRIBING

1

Biomolecule	Carbohydrates	Proteins	Lipids
Macromolecules	Starches Glycogen Cellulose	Structural proteins Functional proteins Enzymes	Triglycerides Phospholipids Steroids
Component parts	Glucose	Amino acids	Glycerol Fatty acids

- 2** Proteins
3 Glucose and fructose

- 4 Both carbohydrates and lipids are a source of energy.
- 5 Both carbohydrates and proteins can be used for structures (eg. cellulose and keratin) or can be found in the cell membrane (e.g. as glycoproteins).
- 6 Proteins can function as enzymes and compounds that support the transport of substances around the body (e.g. haemoglobin)

APPLYING

- 7 A low protein diet may result in reduced enzyme activity as well as a reduction in the production of important structures such as transport proteins and structural proteins as well as impair the growth of cells (e.g. muscle).

ANALYSING

- 8 Both are lipids, made of C, H and O, but while saturated fatty acids have no carbon double bonds, unsaturated lipids have at least one carbon double bond. This means that saturated fatty acids are generally solids at room temperature, whereas unsaturated fatty acids are usually liquids (oils).
- 9 According to the graph, as the calories from saturated fat increases, so does the percentage change in mortality.

LEARNING CHECK 4.2

DESCRIBING

- 1
 - a Carbohydrases assist in the digestion of carbohydrates.
 - b Proteases assist in the digestion of proteins.
 - c Lipases assist in the digestion of lipids.
- 2 Digestive enzymes help speed up the reactions involved in the digestion of different macromolecules. In doing so, they allow for the effective breakdown of the macromolecules into their component parts so that they can be absorbed through the digestive system and into the body to support growth, repair and maintenance.

APPLYING

- 3 Individuals who are lactose intolerant do not contain the enzyme lactase, which prevents lactose digestion. As a result, the lactose cannot be digested and remains in the intestines, where it causes bloating and abdominal pain.

LEARNING CHECK 4.3

DESCRIBING

- 1 Most enzymes are a tertiary structured protein whose shape supports an active site, where the substrate binds, and a catalytic site, where the reaction is catalysed.
- 2 After an enzyme has catalysed a reaction, the products are released and the enzyme resumes its original shape to become available to catalyse another reaction.
- 3 The enzyme–substrate complex is a substance formed when an enzyme and its substrate molecule bind at the active site.

APPLYING

- 4 Enzymes lower the activation energy for a reaction by providing an alternative pathway for the reaction to occur that requires less energy.
- 5 Since enzymes are highly specialised in the substrates they interact with (and therefore the reactions they catalyse), complex chemical reactions that require multiple steps would require multiple enzymes.
- 6 Similarities:

- Both models describe the interaction of an enzyme, its active site and the substrate.

Differences:

- The lock-and-key model suggests that the substrate and active site match perfectly, whereas the induced-fit model suggests that the active site can change on binding to the substrate so that it 'fits' better.

ANALYSING

- 7 Similarities:

- Intracellular and extracellular enzymes are protein-based molecules.
- Both enzyme types are produced within the cell.

Differences:

- Intracellular enzymes act within the cell and speed up reactions that occur within the cell, whereas extracellular enzymes catalyse reactions occurring outside the cell.

Significance:

- In both models, the active site and substrate must interact and form the enzyme–substrate complex in order for the enzyme to be able to catalyse the reaction.

LEARNING CHECK 4.4

DESCRIBING

- 1
 - a Denaturation refers to an enzyme losing its functional shape.
 - b The saturation point is the point at which there are no free enzymes and therefore an increase in substrate concentration does not increase the rate of the reaction beyond this point.
 - c Inhibition is the interference with an enzyme's ability to interact with its substrate.
- 2 Factors affecting enzyme activity include:
 - Temperature – an increase in temperature results in an increase in the rate of reaction; however, high temperatures cause denaturation.
 - pH – a change in pH outside the optimum range (for the enzyme) can cause denaturation.
 - Substrate concentration – an increase in substrate concentration results in an increase in the rate of reaction; however, at the saturation point, all enzymes are 'occupied' and the rate of production cannot increase any further.
 - Inhibitors – inhibitors can interfere with the ability of the active site and substrate to form a complex.

- 3 Enzyme activity is limited at low substrate concentration. This is because there are fewer substrate molecules available to bond to the active site, so they do not come into contact with the active site as frequently.

APPLYING

- 4 At a temperature of higher than 42°C, proteins can start to denature. This would affect a lot of reactions in the body that require enzymes.
- 5 At a low pH, the H⁺ ions disrupt the interaction between the positive side chains of the amino acid and their negative side chain partners. This destroys the bonds that help the protein hold its functional shape. As a result, the enzyme is denatured. At a low temperature, the rate of reaction will decrease due to a decrease in movement of the substrate molecules; however, the enzyme maintains its shape as bonds are not affected.

ANALYSING

- 6 Non-competitive inhibitors bind to an area on the protein that is not the active site, whereas competitive inhibitors compete with the substrate for the active site.
- 7 Similarities:
- When enzymes are denatured, whether by temperature or pH, their functional structure is destroyed.

Differences:

- When denaturation occurs due to high pH, the interactions between the positive and negative side chains in the amino acids become disrupted, which also causes the enzyme to lose its functional shape.
- Denaturation by high temperature is caused by the increased movement in the atoms of the backbone and side chains, jostling apart the bonds that held the enzyme in its functional shape, whereas denaturation by high pH is caused by the interference of OH⁻ ions pulling positive side chains away from their negative partners.

Significance:

- The loss of functional shape from either high pH or high temperature disrupts the bonds that hold together the structure of the functional enzyme. This disruption renders the enzyme as inactive.

CHAPTER EXAM

MULTIPLE CHOICE

- 1 A 3 A 5 B 7 A 9 C
2 C 4 B 6 B 8 D 10 A

SHORT RESPONSE

- 11 Similarities:
- Structure: Lipids, proteins and carbohydrates contain the same key elements C, H and O.
 - Function: Proteins, lipids and carbohydrates can all be found in the cell membrane where they assist with the movement of materials into and out of the cell.

Differences:

- Structure: Carbohydrates are composed of monosaccharides (sugars), whereas proteins are composed of amino acids and lipids made from fatty acids and glycerol.
 - Function: Carbohydrates are predominantly used as an energy source, whereas proteins can catalyse reactions (enzymes) and provide structural integrity to cells, and lipids generally function as a long-term energy storage and are also important for the structure of cell membranes.
- 12 The active site has a particular shape that will only interact with specific substrates.

CROSS-CHAPTER QUESTION

- 13 • Compartmentalising the location of substrate and enzyme improves the likelihood that enzymes and substrates interact to catalyse reactions, increasing substrate concentration.
- It can also help to maintain an optimal pH within that part of the cell to ensure that the enzymes can perform optimally.
 - It can also help to separate enzymes from molecules that are structurally similar to its substrate so that it is not inhibited unless required.

DATA ANALYSIS

- 14 According to the data in the table, an increase in pH from 1 to 7 progressively decreases the time it takes for the substrate to break down. However, an increase of pH above 7 results in a progressive increase in the time taken to break down the substrate.
- 15 According to the results, the enzyme functions optimally at pH 7. Based on the information, it is seen that different areas of the body have a pH of around 7 (e.g. blood, small intestines, saliva and pancreas). As a result, it is likely that this enzyme would function in the human body.

CHAPTER 5 CELLULAR ENERGY

LEARNING CHECK 5.1

DESCRIBING

- 1 a Metabolism is the sum of all the chemical reactions that occur in an organism to keep it alive.
- b Anabolic reactions occur when simple molecules are combined to make more complex molecules.
- c Catabolic reactions occur when complex molecules are broken down to smaller molecules.
- 2 a Exergonic reactions are those that release energy (catabolic).
- b Endergonic reactions are those that absorb energy (anabolic).

- 3 ATP captures energy from catabolic to anabolic reactions. ATP is a nucleotide that contains adenosine attached to a ribose, which is then bound to a chain of three phosphate groups.
- 4 a Anabolic reactions require energy and therefore are considered endergonic.
- b Catabolic reactions release energy and therefore are considered exergonic.

APPLYING

- 5 a Anabolic c Anabolic e Catabolic
b Catabolic d Anabolic
- 6 When energy is released during catabolism, ATP synthase uses the energy to add a third phosphate to ADP. This allows ATP to carry the energy from catabolism.
- 7 The ATP–ADP cycle is similar to a battery in that the ATP molecule stores energy, which is released when required when a phosphate is broken off the ATP molecule. ADP is similar to an uncharged battery that can be recharged by ATP synthase returning the third phosphate to produce ATP again.

ANALYSING

- 8 Similarities:
- Both reactions are catalysed by enzymes.
 - Both reactions are crucial for metabolism.
- Differences
- Anabolic reactions create complex molecules from simpler molecules, such as the production enzymes from amino acids, whereas catabolic reactions break down complex molecules to simpler molecules, such as the breakdown of carbohydrates into glucose.
- Significance
- Although both have different functions, the two types of reactions complement each other to ensure that the body is able to build complex molecules from small molecules and vice versa.

An example of an anabolic reaction is the production of enzymes from amino acids. An example of a catabolic reaction is the breakdown of carbohydrates into glucose.

LEARNING CHECK 5.2

DESCRIBING

- 1 Balanced chemical equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36-38ATP$
- 2 Input: glucose
Output: pyruvate and ATP
- 3 Glycolysis occurs in the cytoplasm, Krebs cycle occurs in the mitochondrial matrix and electron transport chain occurs in the inner membrane of the mitochondria.
- 4 Glycolysis:
- Input: glucose, hydrogen carriers, ATP
 - Output: pyruvate, ATP, loaded hydrogen carriers
- Krebs cycle:
- Input: pyruvate
 - Output: CO_2 , ATP, loaded hydrogen carriers

Electron transport chain:

- Input: loaded hydrogen carriers, O_2
- Output: ATP, H_2O

APPLYING

- 5 Carbon dioxide is produced during the Krebs cycle from pyruvate and water is produced during the electron transport chain from oxygen and hydrogens carried by the loaded hydrogen carriers.
- 6 Multicellular organisms tend to use aerobic respiration because their energy requirements are higher than single-celled organisms and it produces more ATP per glucose than anaerobic respiration.
- 7 When a cell is in a low-oxygen environment, it would not survive at all without producing ATP somehow. Fermentation does produce toxic ethanol, but it also provides a small window of survival that a cell can use to move to a higher oxygen environment or potentially survive until more oxygen is available.

ANALYSING

- 8 Similarities:
- Both produce ATP.
- Differences:
- Anaerobic respiration produces less ATP than aerobic respiration.
 - Anaerobic respiration produces lactic acid in animals and ethanol in plants, whereas aerobic respiration produces carbon dioxide and water in both.

CHAPTER EXAM

MULTIPLE CHOICE

- | | | | | |
|-----|-----|-----|-----|------|
| 1 A | 3 A | 5 C | 7 D | 9 D |
| 2 D | 4 D | 6 D | 8 C | 10 A |

SHORT RESPONSE

- 11 Aerobic respiration involves a series of reactions that produces energy (ATP) from glucose and oxygen. Glucose is first broken down into pyruvate during glycolysis. The pyruvate is then converted to acetyl CoA which is used in the Krebs cycle to produce carbon dioxide and some hydrogen carriers. In the final stage (electron transport chain), water and 36–38 ATPs are produced.
- 12 Similarities:
- Both reactions produce ATP.
 - Both require glucose as the input.
- Differences:
- Anaerobic respiration occurs in the absence of oxygen, whereas aerobic respiration occurs in the presence of oxygen.
 - More ATP is produced in aerobic respiration.
 - Anaerobic respiration produces lactic acid or ethanol, while aerobic respiration produces carbon dioxide and water.

CROSS-CHAPTER QUESTION

- 13 Muscle cells are most likely to have large quantities of mitochondria as they are in constant physical motion and therefore need access to large quantities of ATP.

DATA ANALYSIS

- 14 a 15 arbitrary units
b 30–32 arbitrary units
c 35 arbitrary units
d 20 arbitrary units
- 15 At time Y because ATP production was very high between Time X and Y, which suggests aerobic respiration was highly active. After Time Y, ATP production sharply dropped off, suggesting that aerobic respiration was no longer highly active. This indicates that the tissue depleted its store of oxygen at Time Y and had to rely only on the oxygen that could be delivered to the tissue.

CHAPTER 6 PLANT PHYSIOLOGY

LEARNING CHECK 6.1

DESCRIBING

- 1 ATP and loaded hydrogen carriers
2 Glucose
3 $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$

APPLYING

- 4 Not all plant cells can carry out photosynthesis because not all plant cells contain chlorophyll (or are exposed to light).
- 5 Location: light-dependent reactions occur in the thylakoid membrane in chloroplasts, whereas light-independent reactions occur in the stroma of chloroplasts.
Requirements: light-dependent reactions require light and water, whereas light-independent reactions require carbon dioxide. Products: light-dependent reactions produce loaded hydrogen carriers and ATP, whereas light-independent reactions produce the building blocks for glucose.
- 6 Both photosynthesis and respiration produce ATP and do so through three analogous processes. Glycolysis in respiration is analogous to the two building blocks for glucose combining to form glucose. The Krebs cycle in respiration is analogous to the Calvin cycle. The light-dependent reactions, which are water splitting, light-driven electron flow and ATP synthesis, are analogous to the electron transfer chain, which has water synthesis, electron flow and ATP synthesis.

LEARNING CHECK 6.2

DESCRIBING

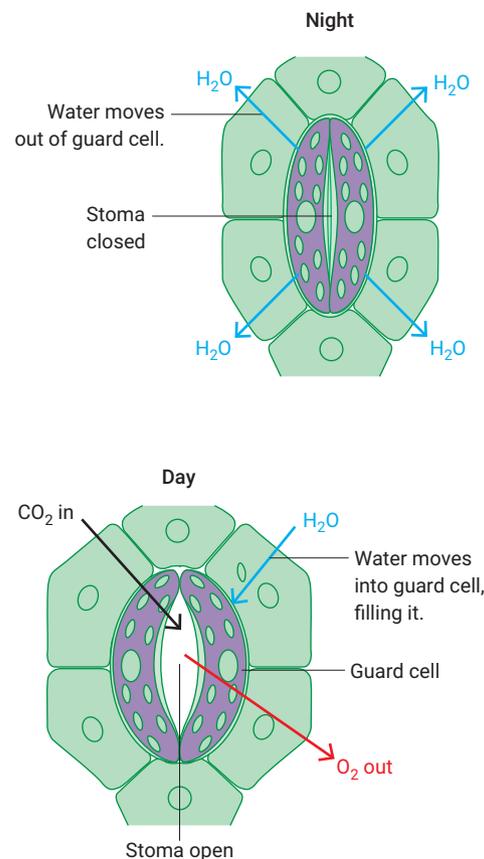
- 1 The stoma (singular) is a pore on the surface of a leaf that controls the movement of gases into and out of the

plant. Stomata is the term for more than one stoma. Guard cells surround stomata and change shape depending on the environment to help open and close each stoma.

- 2 Carbon dioxide, water (vapour) and oxygen
- 3 Stomata open and close depending on the level of abscisic acid, which is affected by light, amount of carbon dioxide and amount of water.
- 4 a The cuticle helps reduce water loss.
b Stomata assist in controlling the movement of gases into and out of the plant.
c Abscisic acid causes the opening and closing of guard cells.
d Guard cells physically open and close stomata.

APPLYING

- 5 At high temperatures, guard cells close the stomata to reduce the loss of water vapour from the plant.
- 6 During the day, guard cells typically swell and cause stomata to open. This allows carbon dioxide to enter the plant. At night, guard cells become more flaccid, causing stomata to close.



- 7 Plants that grow in moist areas because of the minimal dangers of water loss, so they can generally have lots of stomata to allow for efficient exchange of gases. Plants that

grow in dry areas generally have fewer stomata to minimise the loss of water vapour.

Plants that grow in dry, sunny areas generally have stomata on the bottom of leaves to minimise water loss due to transpiration as they are not exposed directly to the sun.

Plants that grow where there is plenty of water/moisture generally have many stomata on the upper surface as water loss is not as dangerous.

LEARNING CHECK 6.3

DESCRIBING

- 1 Plants use xylem and phloem to transport water and nutrients separately, whereas animals use the circulatory system (with a pump) to do both. Plants also transport water and nutrients directly through cells (through vessel elements in xylem or sieve tube cells in phloem), whereas animals have blood vessels lined with epithelial cells but the blood does not pass from cell to cell.
- 2 Tracheids are long thin cells, whereas vessel elements are shorter and wider. Tracheids are present in all vascular plants; however, vessel elements are highly specialised cells that only serve that particular function.
- 3 Sieve tube cells are long cells connected end to end to form tubes. These tubules carry the sugars and nutrients necessary for plant growth suspended in the sieve tube cell cytoplasm. Companion cells are smaller and are connected to sieve tube cells with plasmodesmata. They provide support in the form of energy and enzymes for the sieve tube cells to remain alive.
- 4 Companion cells provide ATP and enzymes to their sieve tube cells and help to remove waste from cytoplasm that passes through their the sieve tube cells.

APPLYING

- 5 Dead cells, such as xylem cells, provide a hollow space for water to move through. Although the cell is dead, the cell wall remains as a structural component.
- 6 The removal of phloem from ringbarking affects the ability of the tree to transport sugars for photosynthesis. This means that the sugars produced in the leaves are not able to reach the roots of the tree and these root cells can no longer produce ATP. The xylem in the tree's wood is still intact, so water still sustains the top, but the roots slowly die without glucose. Once the roots are dead, the tree can no longer take up water either and the top dies.

ANALYSING

- 7 Similarities:
 - Both help to transport substances throughout the plant.
 - Both are found in vascular tissue of plants.
 - Both are made of plant cells stacked into tubules.Differences:
 - Xylem is mainly responsible for transporting water and minerals from the roots, whereas phloem is mainly responsible for transporting sugars from leaves to other areas of plants.

- Xylem tissue is made from tracheids and vessel elements, which are dead, whereas phloem tissue is made up of sieve tube cells and companion cells, which are living.

Significance:

- Phloem and xylem are made of different cells; however, they work in tandem to transport different substances (water, minerals, sugars) around the plant to support survival and growth.

LEARNING CHECK 6.4

DESCRIBING

- 1 Transpiration
- 2 Light, temperature, humidity, wind
- 3 Cool, wet, humid environments reduce the rate of transpiration.
- 4 The cuticle is a waxy hydrophobic layer that covers the leaves and stems. It helps to reduce water loss through evaporation.

APPLYING

- 5 Surrounding the epidermis with hairs traps moist air close to the surface, which reduces water loss from the leaf by reducing wind and increasing humidity and, therefore, the concentration gradient.
- 6 Plants in cold dry conditions need to minimise water loss from the dry environment, while also ensuring their leaves don't freeze. This may produce leaves that are smaller and thicker, with fewer stomata.
- 7 Energy from transpiration comes from the Sun because sunlight drives both evaporation from the leaf surface and photosynthesis, both of which drive transpiration.

INTERPRETING

- 8 Not enough information. Movement of water through the celery would have occurred due to capillary action through the xylem. Xylem is dead tissue and would still operate in a dead piece of celery.

CHAPTER EXAM

MULTIPLE CHOICE

- | | | | | |
|-----|-----|-----|-----|------|
| 1 D | 3 B | 5 B | 7 B | 9 B |
| 2 C | 4 A | 6 D | 8 B | 10 B |

SHORT RESPONSE

- 11 Stomata and guard cells facilitate gas exchange by opening to allow carbon dioxide into the plant for photosynthesis during the day. However, open stomata also lose water quickly, especially during the day when it is sunny and hot. Guard cells must balance the plant's requirement for carbon dioxide with its requirement to retain water by opening and closing stomata regularly in response to the levels of water and abscisic acid in the leaves.
- 12 Photosynthesis is a process in which plants turn light energy into glucose. This occurs over multiple phases.

Light-dependent reactions occur in the thylakoid membranes in chloroplasts where light and water are used to produce oxygen, loaded hydrogen carriers and ATP. Light-independent reactions then take carbon dioxide, loaded hydrogen carriers and ATP to produce glucose.

CROSS-CHAPTER QUESTION

- 13 Photosynthesis uses water and carbon dioxide to produce glucose, which is used in respiration to produce energy (ATP). Since photosynthesis requires water, more photosynthesis would require more carbon dioxide to enter the plant through the stomata, which at the same time causes loss of water vapour. To compensate, plants would need to uptake more water through the roots, increasing the transpiration stream.

DATA ANALYSIS

- 14 Mass lost = $0.1 \text{ g cm}^{-2} \times 15 \text{ cm}^2$
= 1.5 g water
- 15 Heat has the most impact, followed by wind, and then light, which has less impact than the control.

CHAPTER 7 NERVOUS SYSTEM

LEARNING CHECK 7.1

DESCRIBING

- 1 Student examples may be different.
Chemoreceptor, e.g. nose, taste buds in mouth, pancreas
Mechanoreceptor, e.g. ear
Photoreceptor, e.g. eye
Thermoreceptor, e.g. temperature receptors in skin
Nociceptor, e.g. pressure receptors in skin
- 2 The internal environment of an organism consists of the interstitial fluid that bathes the cells and the blood plasma.
- 3 Exteroceptors receive signals from the external environment, whereas interoceptors receive signals from the internal environment of the organism.

APPLYING

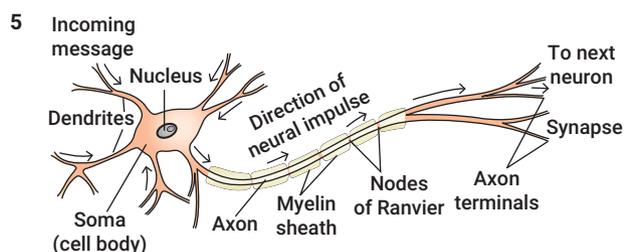
- 4 Student examples may be different.
- a Sound, e.g. its owner calling its name; smell, e.g. the smell of its food at dinner time; pressure, e.g. when someone pats it.
- b Blood glucose concentration, internal body temperature, blood water concentration
- 5 Nociceptors detect intense pain. They have evolved in multicellular organisms to alert organisms that they may be in unsafe environments and to remove themselves from it. This is an adaptation that assists in the survival of the organism.

LEARNING CHECK 7.2

DESCRIBING

- 1 a The main cell body of a neuron containing the nucleus
b The tubular extension of a neuron cell body that conducts the nerve impulse

- c The fatty layers of insulation surrounding the axon of a neuron; made of Schwann cells
- d A cell that wraps tightly around the axon of a neuron to form the myelin sheath
- e A small space between the Schwann cells along the axon of a neuron
- 2 A neural impulse starts at the dendrite, and travels down the axon to the axon terminals.
- 3 Many single-celled neuron axons together make a nerve fibre. A bundle of nerve fibres comprises a nerve. Each nerve is wrapped in a tube of connective tissue.
- 4
- Size – some neurons can be very long, such as 1.5 m in your leg
 - Contain dendrites and axon
 - Transfer electrical signal along the cell
 - Electrical signal only travels in one direction
 - Transfer information to or from the CNS
 - Communicate with other neurons using neurotransmitters



APPLYING

- 6 A myelin sheath is formed by a single Schwann cell wrapping many times around the axon of a nerve to form a protective layer of insulation. The gap between one Schwann cell and the next is known as a node of Ranvier. This structure allows an electrical impulse to jump from node to node, meaning that it moves very fast along the length of the nerve. The myelin sheath also keeps the message from accidentally crossing over to adjacent neurons.

INTERPRETING

- 7 Lack of myelin in the nervous system hinders the electrical transmission of the nerve impulse and could cause a disease such as multiple sclerosis or nerve impulses not reaching their intended effector.

LEARNING CHECK 7.3

DESCRIBING

- 1 Sensory neurons, interneurons, motor neurons
- 2 Sensory neurons – to detect changes in internal or external environments
Interneurons – connection between sensory and motor neurons
Motor neurons – transmit information from interneurons to effectors

APPLYING

- 3 If interneurons were damaged, then no impulse could pass from sensory neurons to motor neurons. In severe cases, this could result in paraplegia or quadriplegia.

ANALYSING

- 4 Sample answer:
 Similarities: All contain soma, axons, dendrites; all transmit nerve impulses.
 Differences:

	Sensory neuron	Interneuron	Motor neuron
Soma	Soma located as side bulge	Soma located at dendritic end	Soma located at dendritic end
Dendrites	Dendrites branch off one end of axon Dendritic ends do not terminate in synapses Dendritic ends contain sensory receptors	Dendrites similar to motor neurons	Dendrites terminate in synapses
Axon	Axons terminate in synapses that link to dendrites in interneurons	Axon terminals all way along axon Axons terminate at motor neuron	Axons terminate in end plates Axons terminate in effectors
Direction of impulse	Dendrite to axon Send impulses from receptor to CNS	Dendrite to axon	Dendrite to axon Send impulses from CNS to effector

LEARNING CHECK 7.4

DESCRIBING

- The presynaptic axon terminal is an enlarged end that is filled with organelles, particularly vesicles filled with neurotransmitters.
- The function of the myelin sheath is to insulate neurons from each other so an action potential in one does not cause an action potential in a neighbouring neuron; also to accelerate the transmission speed resulting in a faster reaction time.

APPLYING

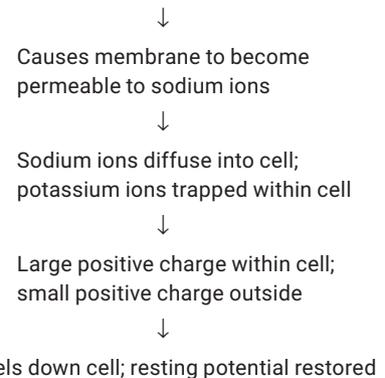
- 3 Resting potential: cell membrane actively pumps three sodium ions out of the cell for every two potassium ions they pump into the cell, causing the outside to be more positive than the inside.
 Action potential: the influx of positive ions causes the membrane to become permeable to sodium ions, causing them to diffuse into the cell. Since the membrane is not permeable to potassium ions, most of them are trapped inside while the sodium continues to flood in. This leads to a large positive charge inside the cell and only a small positive charge outside.
 Restoration of resting potential: cell membrane becomes impermeable to sodium ions; sodium ions pumped out.
- 4 Sodium deficiency could be life-threatening because sodium is required to initiate an action potential in a nerve cell.

If there is insufficient sodium, then the strength of the action potential may be affected, or it may not occur at all.

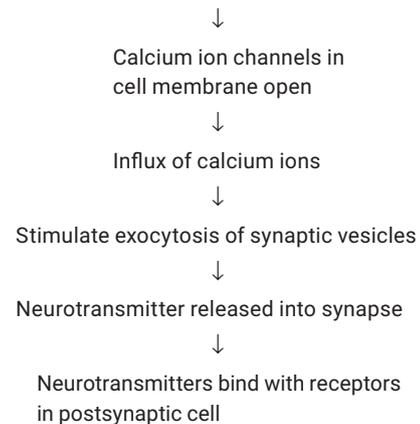
ANALYSING

- 5 Similarities:
- Both mechanisms are involved in the transfer of signal between cells.
- Differences:
- Signal transmission refers to the movement of the electrical impulse along the neuron. Signal transduction refers to the change of the electrical impulse into chemical neurotransmitters to cross the synaptic gap.
 - Signal transmission involves receptors (e.g. for hormones), whereas signal transduction involves neurons moving of impulse.
- 6 Example flow charts shown:

- a Influx of positive ions into dendritic end of neuron



- b Electrical impulse arrives at axon terminal



CHAPTER EXAM

MULTIPLE CHOICE

- 1 C 3 D 5 D 7 C 9 B
 2 B 4 B 6 C 8 A 10 A

SHORT RESPONSE

- 11 Sensory receptors on arm detect change in temperature by opening up ion channels in the cell membrane of the dendrites → Cascade of electrical activity down axon to axon terminal → Production of neurotransmitter to send

message across synaptic gap → Stimulates interneurons in CNS → Production of neurotransmitter to send message across synaptic gap → Stimulates motor neuron, which sends message to arm muscle to move arm away from oven door

12

Number	Description of what is happening
3	Sodium ions flood the membrane – depolarisation
6	Potassium ions begin to flow in past resting potential
7	Resting potential restored
1	Resting potential
5	Potassium ions slowly begin to leave the cell – repolarisation
4	Peak action potential
2	Sodium ion channels open

CROSS-CHAPTER QUESTION

- 13 a Exocytosis is the movement of solids or liquids from inside a cell to outside the cell via vesicle formation.
- b Mitochondria are the organelles that supply energy to the cell. As there are a large number in the axon terminals, this suggests that the cell requires a large amount of energy to convert the electrical impulse into neurotransmitters and then to release these from the cell to cross the synaptic gap.
- c Diffusion is the movement of a substance (gas or liquid) from an area where it is in high concentration to an area where it is in low concentration.
- d Once the neurotransmitter has relayed its message across the synaptic gap, it is either destroyed by enzymes or retaken up by the releasing presynaptic cell for reuse. The neurotransmitter is cleared away quickly, so the effect of the neurotransmitter is not ongoing.

DATA ANALYSIS

- 14 Both myelinated and unmyelinated nerves experience an increase. Although the velocity increases faster initially for the unmyelinated nerves, the myelinated nerves experience a constant increase in velocity with fibre size, whereas the rate of increase in velocity for unmyelinated nerves decreases as the fibre diameter increases.
- 15 a i At 0.22 s: action potential: large positive charge inside the cell and small positive charge outside as sodium ions flood into cell
- ii At 0.37 s: resting potential: where the outside of the cell is more positive because the sodium-potassium pumps actively pump three sodium ions out of the cell for every two potassium ions they pump into the cell
- b The graph does support this statement. The regular spiking of the neurons shows a maximum response each time.

CHAPTER 8 ENDOCRINE SYSTEM

LEARNING CHECK 8.1

DESCRIBING

- An organic compound produced by one part of the body and transported in the circulatory or lymphatic systems to another part of the body to prompt a response from specific cells
 - A ductless gland that produces hormones
 - A protein that binds hormones to form a hormone/receptor complex
- Any two from Table 8.1.1.
- Circulatory and lymphatic systems

APPLYING

- Signalling molecules only have an effect on their target cells because only their target cells have a receptor for that hormone. If the cell does not display a receptor for that hormone, the hormone will pass by with no effect.
- Accept any reasonable hypothesis such as:
 - Water-soluble hormones are broken down faster/easier than fat-soluble hormones.
 - Fat-soluble hormones accumulate in vital organs; water-soluble hormones do not.
 - Water-soluble hormones are removed from the body via the kidneys; fat-soluble hormones are not.

ANALYSING

- Similarities: Travel through blood and can bind to receptors

Differences:

Feature	Water-soluble hormones	Fat-soluble hormones
Derived from	Amino acids	Cholesterol; amines
Polarity	Polar	Non-polar
Receptor	On surface of cell membrane	Intracellular receptors
Travel through the blood	No companion molecule needed	Need to bind to a companion molecule

LEARNING CHECK 8.2

DESCRIBING

- Upregulation involves the increase in the number of receptors produced by the cell, whereas downregulation results in the reduction in the number of receptors on the cell surface.
- Examples are:
 - activation or deactivation of enzymes
 - changed membrane permeability.

APPLYING

- Cell sensitivity is determined by the number of receptors for particular hormones. More receptors mean the cell is more sensitive; fewer receptors mean the cell is less sensitive; no receptors mean the cell is not sensitive to that hormone.

- 4 Fat-soluble hormones don't require signal transduction because they bind to receptors inside the cell or nucleus, which binds directly to their target, usually DNA.
- 5 Hormones can have different effects in different cells because they can bind to different transcription factors in these cells which bring about a different response.

CHAPTER EXAM

MULTIPLE CHOICE

- | | | | | |
|-----|-----|-----|-----|------|
| 1 B | 3 C | 5 D | 7 B | 9 C |
| 2 B | 4 D | 6 D | 8 A | 10 B |

SHORT RESPONSE

- 11 a 1 and 2
b 2 and 3
c Upregulation. When there is a high level of a specific hormone in the blood, the cell will develop more receptors, thereby making it more sensitive to that hormone.
- 12 A cell's sensitivity to any particular hormone is determined by the number of receptors that it expresses for that hormone.
 - More receptors make a cell more sensitive and responsive than fewer receptors.
 - Most cells only permanently express a small number of each type of receptor.
 - When a specific hormone is detected, the target cell quickly produces many more receptors to become more sensitive to this hormone (upregulation).
 - A response that reduces a cellular process is called downregulation. This ensures that target cells can become less reactive to high levels of hormone circulating in the bloodstream.

CROSS-CHAPTER QUESTION

- 13 Golgi apparatus – the hormones produced need to be packaged and transported around the cell to where they are needed.
Mitochondria – more energy is required to 'fuel' the production of more hormones.
Smooth ER – is the main location where lipids are made, which would be highly active when high levels of hormone are being produced.

DATA ANALYSIS

- 14 a The steers showed the greatest liveweight gain over the course of the study. Difference in steer liveweight on day 60: Steers: approx. 30 kg liveweight difference; heifers: approx. 20 kg liveweight difference.
b The results show that the HGP did make an overall difference to the liveweight of the steers and heifers. The total liveweight gain between the control and experimental group was approximately 45 kg.
- 15 a Androsterone and 11-hydroxy-androsterone
b DHEA, 11-keto-androsterone and 11-hydroxy-etiocholanolone
c 9.29 or 9.3

CHAPTER 9 HOMEOSTATIC REGULATION – SYSTEMS WORKING TOGETHER

LEARNING CHECK 9.1

DESCRIBING

- 1 a An internal or external signal that causes a response
b An organ or a structure that detects or receives a stimulus
c An organ, a muscle, a gland, a cell or a protein that acts in response to a stimulus
d The action resulting from a stimulus

APPLYING

- 2 Refer to Figure 9.1.1.
- 3 The maintenance of blood glucose levels in the human body is an example of negative feedback because the original stimulus (e.g. high blood sugar level) produces a response that lowers the blood sugar level. If this were to continue, the organism would die. Therefore, the response to the low blood sugar level has counteracted the original stimulus.
- 4 Individual student response. Response could argue that optimum conditions do exist within our body; otherwise, we would not function at peak effectiveness. It could also argue that, due to negative feedback, close to optimum conditions exist as our body is always adjusting itself around optimum conditions.

ANALYSING

- 5 Similarities:
 - Both processes are involved in homeostasis.
 - Both involve signal transduction.
 Differences:
 - In stimulus–response, the stimulus produces a response that does not affect the original stimulus, whereas in negative feedback the stimulus produces a response that counteracts the original stimulus so a new response is required. This continues to ensure that the stimulus fluctuates around a certain optimal point.

LEARNING CHECK 9.2

DESCRIBING

- 1 Stimuli – blood glucose level too high or too low
Effectors – beta cells of pancreas (release insulin); alpha cells of pancreas (release glucagon)
Processing centre – hypothalamus in brain
Receptor – pancreas
Responses – liver takes up glucose and stores it as glycogen; liver breaks down glycogen and releases glucose
- 2 The arrows guide you around the diagram.

APPLYING

- The pancreas is a large organ made up of many different types of cells. Some of those cells can detect blood glucose concentration and other cells can synthesise and release insulin or glucagon.
- Removal of the pancreas would stop the body's ability to produce insulin. Therefore, the body would not be able to maintain a constant blood glucose concentration. The person would need to monitor their blood glucose concentration and inject insulin when their blood glucose concentration gets too high.

LEARNING CHECK 9.3

APPLYING

- Air is trapped between fur and feathers. Air is gaseous with spread-out particles so is a poor conductor of heat; heat stays close to skin.
- Huddling reduces heat loss when animals huddle in a group with their backs to the outside. This reduces the surface area of the group to the cold. Animals at the centre of the huddle are protected from the cold and maintain a stable body temperature, sometimes overheating. The animals take it in turns to be on the outside, bringing in the colder animals and sharing their body temperature with them.
- Vasodilation widens arterioles, so they come closer to the surface of the skin. As the temperature of the blood is higher than the temperature of the external air, heat energy will radiate from the blood to the air through the skin surface.
- Panting is rapid, shallow breathing that increases the evaporation of water from the respiratory tract. Evaporation of water uses heat energy (as liquid water is changed to water vapour), which assists in the loss of excess heat energy from the body of the dog.
- Stimuli – body temperature rises above normal; body temperature drops below normal
Receptor – hypothalamus
Control centre – brain
Effector – blood vessel muscles, skeletal muscles
Communication pathway – nervous

ANALYSING

- Similarities: Have to manage different temperatures, have to maintain internal core body temperature
Differences:

Problem	Endotherm living at low temperatures	Endotherm living at high temperatures
Maintaining a stable internal core body temperature	Need to increase heat gain and reduce heat loss	Need to reduce heat gain and increase heat loss
If internal core body temperature varies too much it will affect enzyme efficiency	Enzyme function will be reduced	Enzyme function will be reduced and could denature

- Torpor – a state of decreased physiological activity over a short period of time, usually by a reduced body temperature and metabolic rate
Hibernation – a period of dormancy over long periods of cold conditions
Aestivation – dormancy in some animals during periods of drought

INTERPRETING

- Arctic fox lives in very cold environments. It has small ears so less surface area is exposed to cold, with less chance of heat loss and frostbite. Red fox lives in warmer conditions so larger ears to prioritise hearing over heat loss. Fennec fox lives in very hot conditions. It has very large ears to maximise heat loss.

LEARNING CHECK 9.4

DESCRIBING

- The function of osmoregulation is to maintain internal water and solute concentration despite fluctuations in the external environment.
- ADH is produced in the pituitary gland in the brain.

APPLYING

- ADH causes the aquaporins attached to vesicles inside the cell to move to the cell membrane. This allows water to pass from the collecting tubule, through the cell and into the bloodstream.
- Receptor – hypothalamus
Effector – pituitary
Response – kidneys reabsorb more water

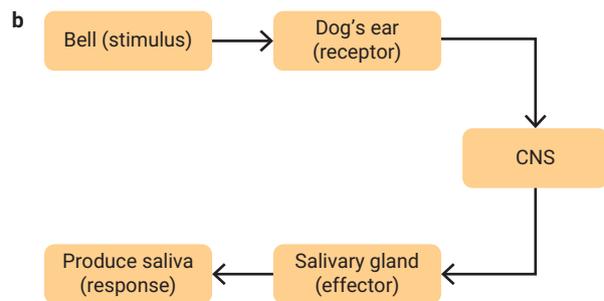
CHAPTER EXAM

MULTIPLE CHOICE

- 1 B 3 B 5 C 7 D 9 D
2 B 4 C 6 A 8 A 10 B

SHORT RESPONSE

- stimulus – bell; receptor – dog's ears; processing centre – brain; effector – salivary glands; response – produce saliva



- c Similarities: Both describe how information is transferred to trigger a response.

Difference: In a stimulus–response model, the response is the end of the process, whereas in a negative feedback model, the response counteracts the original stimulus, causing another response in the opposite direction to be generated.

CROSS-CHAPTER QUESTION

- 12 a Large amounts of dilute urine would be produced.
b Small amount of concentrated urine, high in salt, would be produced.

DATA ANALYSIS

- 13 Both the squirrel and Eskimo dog pup group show a decrease in metabolic rate as the air temperature increases. However, the Eskimo dog pup shows a consistently lower metabolic rate compared to the squirrel.
- 14 a At 0°C, the metabolic rate of the jungle rat would increase to approximately 280, which may still be manageable for the rat in that it can produce enough energy to sustain the rate.
b At –40°C, the metabolic rate would surpass 400, which may not be sustainable for the rat; therefore, the chance of survival would be very low (if at all).

CHAPTER 10 INFECTIOUS DISEASE

LEARNING CHECK 10.1

DESCRIBING

- 1 a A condition that interferes with how an organism functions
b A disease-causing agent
c A disease transmitted from one individual to another
- 2 Pathogens include prions, viruses, bacteria, fungi, protists and parasites.
- 3 The pathogen infects its host, lives on or in it and derives nourishment from it.
- 4 Infectious diseases are caused by an infectious agent, called a pathogen, which can be transmitted to new hosts. Non-infectious diseases are not caused by pathogens, nor can they be transmitted from one host to another; they may be caused by genetic (e.g. cystic fibrosis), environmental (e.g. asbestosis) or lifestyle factors (e.g. type 2 diabetes).

LEARNING CHECK 10.2

DESCRIBING

- 1 Examples include tetanus and cholera.
- 2 Fungi secrete enzymes into their hosts and digest food externally. They then absorb nutrients through their cell walls and membranes.
- 3 Cinnamon fungus growing on jarrah forests and rusts that infect wheat and barley are two fungal diseases of plants.
- 4 The symptoms of *Giardia* include nausea and diarrhoea. Infection occurs when this waterborne pathogen produces resistant cyst stages that are passed in the faeces of a host and transmitted to a new host in drinking water.

- 5 Prions are unique because they have no genetic material, neither DNA nor RNA. They are different from other non-cellular infectious agents because the normal prion protein cellular form exists naturally in our bodies.
- 6 Different strains of bacteria can be identified by the colour they become in the Gram stain, their shape and the shape and colour of their colonies when cultured on agar plates.
- 7 *Plasmodium* is the pathogen that causes the disease, whereas malaria is the disease.

APPLYING

- 8 Prion proteins convert normal proteins to harmful prion forms. When these then convert other normal forms to harmful forms, large numbers of prion proteins aggregate into filaments that kill brain cells.

ANALYSING

- 9 Similarities:

- Both are parasites.
- Both cause harm to their hosts.

Differences:

- Ectoparasites live on the surface of the body. Examples are ticks and fleas. Endoparasites live within the host's body. Examples are nematode worms, tapeworms and flukes.

INTERPRETING

- 10 All viruses are pathogens because they must live and reproduce inside a living cell, relying on their host cell for all their needs as well as cause harm to the host.
- 11 Virus specificity occurs because a virus recognises and binds to its host cell by surface receptors specific for that cell.

LEARNING CHECK 10.3

DESCRIBING

- 1 The pathogenicity of an organism is determined by its ability to stick to or invade a particular cell type, produce toxins, and evade a host's immune system.
- 2 a Characteristics that help bacteria to invade the host, cause disease, and evade host defences, e.g. adherence factors, invasion factors, capsules, toxins and lifestyle changes
b Resistance of an organism to a pathogen
c Time between infection and the onset of symptoms
- 3 Adherence factors are characteristics that help bacteria to bind to host cell surfaces.

APPLYING

- 4 Pathogenicity is the capacity to cause disease (cause harm) and virulence is the measure of the pathogenicity or ability of the pathogen to replicate and/or produce toxins.
- 5 Invasion factors are cell surface components that allow bacteria to invade a host cell. The presence of invasion factors makes it more likely that bacteria will be successful in sticking to or entering a host cell, increasing pathogenicity.

ANALYSING

6 Similarities:

- Endotoxins and exotoxins are similar because they are both poisonous substances and virulence factors.

Differences:

- Endotoxins are lipopolysaccharides released on lysis of a cell, whereas exotoxins are proteins secreted by bacteria.

CHAPTER EXAM

MULTIPLE CHOICE

- 1 B 3 B 5 C 7 D 9 C
2 A 4 A 6 C 8 C 10 C

SHORT RESPONSE

- 11 a Endoparasite
b Sheep (where it reaches sexual maturity)
c Consumed along with grass
d It means that once two liver flukes meet, they will be able to reproduce, as each can release eggs or sperm.
e Provides a safer environment for sexual maturation/development.
- 12 Virulence factors help pathogens invade host cells and cause disease. Depending on the type of virulence factor, the effect on hosts can include destruction of cells and tissue, fever and changes in blood pressure host.

CROSS-CHAPTER QUESTION

- 13 Virulence is influenced by the ability of the pathogen to adhere to or invade a cell. Some cells may contain receptors on the cell surface that can facilitate the adhesion of pathogens. Pathogens that invade cells need to be able to disrupt the cell membrane to gain access to the cell.

DATA ANALYSIS

- 14 Infectious: lower respiratory infections, HIV/AIDS, diarrhoeal diseases, tuberculosis, malaria
Chronic: ischaemic heart disease, cerebrovascular disease, chronic obstructive pulmonary disease, trachea/bronchus/lung cancers.
Other: perinatal conditions
- 15 11.3 million

CHAPTER 11 IMMUNITY

LEARNING CHECK 11.1

DESCRIBING

- 1 Antigens include any substance that triggers an immune response.
2 Proteins or polysaccharide molecules

APPLYING

- 3 The ability of a cell to recognise self from non-self is critical because it ensures that the body does not attack its own cells.

- 4 The MHC is found on all nucleated cells and displays fragments of 'self' on the cell surface to help white blood cells distinguish self from non-self cells.

LEARNING CHECK 11.2

DESCRIBING

- 1 Physical, chemical and biological
2 Answers could include sweat, oil, defensins.
3 Lysozyme
4 Skin microflora prevents colonisation by harmful microbes by occupying space and using nutrients. They form a protective barrier, competing with potential pathogens for resources and making it challenging for harmful microorganisms to become established.

APPLYING

- 5 Host cells have receptors (called 'pattern recognition receptors') that can recognise molecules associated with pathogens.
6 Platelets are attracted to an injury site and are crucial in the formation of a blood clot. The clot seals the wound, preventing the entry of pathogens, and facilitates the healing process.
7 Mucous membranes in the respiratory tract secrete mucus and defensins, trapping and preventing invading pathogens from entering tissues. Cilia, which are hair-like structures, beat in a coordinated manner to move the trapped mucus up the respiratory tract. This action helps in expelling pathogens before they can become pathogenic.

LEARNING CHECK 11.3

DESCRIBING

- 1 Swelling, redness, heat and pain
2 Mast cells release granules containing histamine and prostaglandins. Histamine induces vasodilation, while prostaglandins cause vasodilation, fever and pain, leading to increased blood flow and the delivery of immune cells to the infected area.
3 Monocytes and neutrophils
4 Opsonisation involves the coating of pathogens for phagocytosis.
Induction of chemotaxis, which involves the movement of immune cells towards the site of infection.
Formation of membrane attack complexes, which induces pores in the membranes of target cells resulting in cell lysis.

APPLYING

- 5 Chemotaxis is the directed migration of immune cells along a chemical concentration gradient. It is crucial for recruiting immune cells to sites of infection or tissue damage, as cells move towards increasing concentrations of chemokines, molecules that induce chemotaxis.
6 Phagocytes, like macrophages, contain large numbers of ribosomes for protein synthesis and lysosomes for the digestion of engulfed pathogens. This ensures efficient

phagocytosis and the destruction of pathogens by providing the necessary enzymes and molecular machinery.

- 7 Vasodilation is important in inflammation because it causes blood vessels at the site of infection to widen. This leads to the inflammation response with increased blood flow, redness, swelling and heat in the area. This enhanced blood flow also brings immune cells, such as neutrophils and macrophages, to the infected site, aiding in the immune response.
- 8 Natural killer cells are lymphocytes that patrol the body and distinguish between healthy cells and infected cells via the MHC I pathway. They have a combination of activating and inhibitory receptors. If an infected cell is detected, cytotoxic granules containing perforin are released, which cause lysis of the target cell.

ANALYSING

- 9 II, V, IV, I, III

LEARNING CHECK 11.4

DESCRIBING

- 1 Protein
- 2 Naive, effector and memory
- 3 Humoral and cell mediated
- 4 Antibodies are proteins produced by plasma cells (B lymphocytes) in response to exposure to antigens. Antibodies have a Y-shaped structure with two heavy chains and two light chains. The variable regions at the ends of the chains form antigen-binding sites, allowing antibodies to recognise and bind to specific antigens. In contrast, antigens are the molecules that stimulate an immune response.
- 5
 - 1 Activation of complement system: antibodies can trigger the complement system, which leads to a range of responses, including attracting phagocytes to the site of infection.
 - 2 Opsonisation: antibodies can mark pathogens for destruction by phagocytes.
 - 3 Neutralisation: antibodies bind to pathogens, preventing them from entering host cells or interacting with host tissues.
 - 4 Agglutination: pathogens are trapped in a network of antibodies, making them immobile and susceptible to destruction by immune cells.

APPLYING

- 6 Plasma B cells are responsible for producing antibodies as part of the adaptive immune response. The extensive rough endoplasmic reticulum (ER) in these cells is crucial for the synthesis of proteins, which includes antibodies. Therefore, the more rough ER there is in the plasma B cells, the more antibodies they can produce.
- 7 After initial exposure to an antigen, the adaptive immune system will 'remember' the antigen if exposure occurs again. This leads to a faster and more significant response if another exposure occurs. For example,

when naive killer T cells encounter a specific pathogen, they undergo activation and differentiation into effector T cells, which actively target and eliminate infected cells. Once the infection is defeated, a small number of these activated T cells become memory T cells. These memory T cells persist in the body after the initial infection has been cleared. If the same pathogen re-infects the individual, memory T cells can quickly recognise and mount a rapid and effective immune response against the pathogen.

- 8 Infected 'self' cells present antigens via the MHC class I molecules to cytotoxic T cells. This helps the immune system identify and eliminate infected cells. In contrast, antigen presenting cells (APCs), such as macrophages and neutrophils, present antigens to helper T cells via the MHC class II molecules. Helper T cells play a key role in coordinating the immune response by activating other immune cells, such as B cells and cytotoxic T cells.

LEARNING CHECK 11.5

DESCRIBING

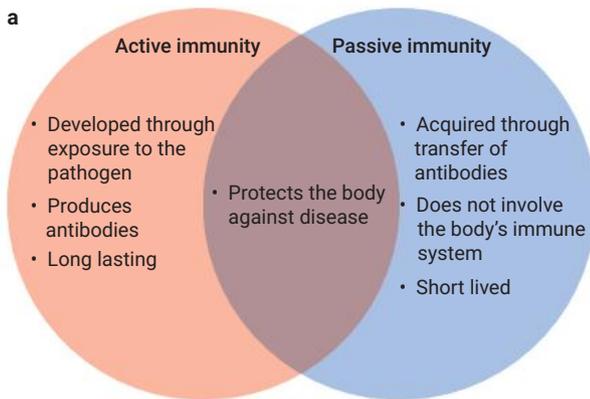
- 1
 - Inactivated or attenuated forms of a pathogen
 - Dead version of the pathogen
- 2 Passive immunity occurs when antibodies are transferred from an external source, e.g. the transfer of antibodies from mother to foetus via the placenta, whereas in active immunity, antibodies are produced.
- 3 Natural active immunity occurs when the immune system is exposed to a pathogen via natural means, leading to the formation of memory B and T cells.
Artificial active immunity results from the intentional exposure to a weakened form of a pathogen via vaccination. This also results in the formation of memory B and T cells.

APPLYING

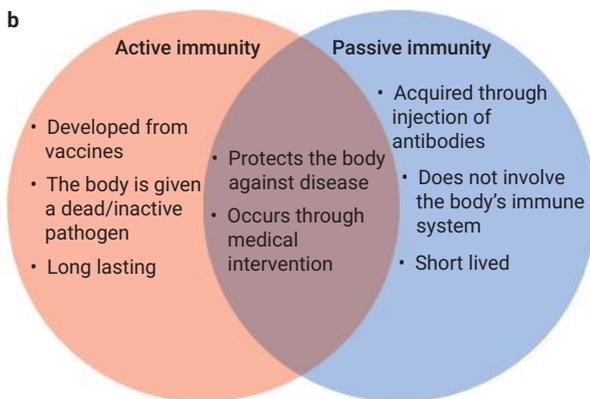
- 4 Passive immunity is temporary because it involves the direct transfer of antibodies, which results in no memory B or T cells being produced. Once antibody levels fall below a certain threshold, the individual loses their immunity.
- 5 The adaptive immune system results in acquired immunity. After initial exposure to a pathogen, the body produces memory B and T cells, which are able to detect the relevant antigens much more rapidly if exposure occurs again. This often occurs without the presentation of symptoms. The individual has acquired immunity to a specific disease.
- 6 Vaccines typically introduce a dead or weakened form of a pathogen. This induces an immune response, leading to the production of memory B and T cells specific to the antigen. The individual will have acquired immunity to the specific disease caused by the pathogen. Because the vaccine contains a dead or weakened form of a pathogen, there will be little to no symptoms in the individual receiving the vaccine.

ANALYSING

7 a



b



LEARNING CHECK 11.6

DESCRIBING

- 1 Their thick waxy cuticle prevents pathogen entry. Thorns can also deter vectors of pathogens.
- 2 Plant defensins are small peptides with antimicrobial properties. They inhibit pathogens by reducing membrane permeability and inhibiting the action of enzymes and ribosomes.

CHAPTER EXAM

MULTIPLE CHOICE

- 1 D 3 A 5 A 7 A 9 A
2 C 4 C 6 A 8 A 10 C

SHORT RESPONSE

- 11 a First-line defences against the virus include any two of the following:
 - Mucous membranes make it difficult for viruses to adhere.
 - Nose hairs are a physical barrier to the virus.
 - Acidic environment of the stomach.
- b Sore and inflamed throat due to:
 - the destruction of cells in the throat, releasing chemicals that increase membrane permeability and swelling

- more immune cells moving to the site due to vasodilation
- mast cells releasing histamines, which produce inflammation.

c The immune response includes:

- viral antigen identified as non-self
- B/T memory cells, previously produced, become active
- plasma cells produced
- antibodies rapidly produced or already present
- virus is neutralised or agglutinated and unable to infect cells.

12 Physical: A thick outer bark on the stem makes it harder for pathogens to invade.

Chemical: Plants can produce defensins that inhibit the development of fungi and other pathogens.

CROSS-CHAPTER QUESTION

- 13 a Antibodies work by recognising specific antigen molecules to form antibody-antigen complex. This causes agglutination to immobilise pathogens, opsonisation that tags the antigen for destruction, neutralisation to block the antigen from binding to other target cells and complement activation.
- b Natural passive immunity provides the joey with protection from pathogens until their immune system is developed at 90 days old.
- c A more effective antibiotic that could be taken as lower doses/less time and fewer side effects

DATA ANALYSIS

14 a 1958

b Similarities:

- The number of cases and deaths both declined over time.
- A greater number of cases and deaths occurred from 1954-1966 but then dropped significantly in the following years.

Differences:

- There are larger number of reported measles cases by year compared to the number of deaths.

15 For the first 4 days, there is an increase in serum white blood cell count, implying that the body is rapidly responding to the bacterial pathogen, predominantly from the innate immune system. On day 4, there was a significant decrease in the serum white blood, which continues to decline to day 5, after which the count increases slightly until day 6. During this period, it is possible that the body is fighting the pathogen; however, the immune response is slowing down while the adaptive immune system starts to produce antibodies. From day 6, with the exception of day 15, the white blood cell count slowly decreases, suggesting that the body has most likely been able to manage the infection (also with the support of medicines from the hospital).

CHAPTER 12 TRANSMISSION AND SPREAD OF DISEASE

LEARNING CHECK 12.1

DESCRIBING

Mode of transmission	Pathogen adaptations	Example of pathogen
Direct contact	Reproduction in skin causing itchy skin lesions, asymptomatic virus shedding	<i>Varicella zoster virus</i> <i>Herpes simplex virus</i>
Airborne	Small, airborne particles facilitating respiratory transmission	Influenza virus
Waterborne	Contaminated water facilitates transmission of waterborne pathogens	<i>Vibrio cholerae</i>
Vector-borne	Dependence on vectors, such as mosquitoes, for transmission	<i>Plasmodium</i> (malaria parasite)
Foodborne	Contamination of food leading to ingestion by hosts	<i>Salmonella</i> , <i>Escherichia coli</i>

- A contagious disease that is spread between individuals usually by direct contact
 - The temperature danger zone is 5–60°C. Food must therefore be kept below 5°C or above 60°C to prevent bacterial growth.

APPLYING

- Stagnant water that is not correctly treated can harbour pathogens, such as cholera. Similarly, poor sanitation and accumulation of garbage are signs of poor communal hygiene. As a result, these factors increase the likelihood of disease transmission as an environment suited to supporting pathogen continues.
- Viruses require a living host for replication. In contrast, bacterial pathogens do not require a host to reproduce. They are able to reproduce in food, producing toxins. As a result, foodborne illnesses are more likely to be caused by a bacterial pathogen.
- Because people are in closer proximity in crowded spaces, an infected individual is more likely to spread pathogens via respiratory droplets. The lack of air circulation in indoor environments further exacerbates the spread.
- The mode of transmission is vector-borne (mosquito). The roundworm benefits as it does not need to facilitate its own transmission to a new host.
 - Because mosquitoes typically feed at night, there is an increased likelihood of the juvenile roundworms being ingested by a mosquito during a blood meal.
 - Movement to the proboscis of the mosquito positions the juvenile roundworms for an increased likelihood of transmission to a new host when the mosquito bites again.

LEARNING CHECK 12.2

DESCRIBING

- Endemic
 - Pandemic
 - Epidemic
- Persistence of pathogen within host – some pathogens can survive longer than others and are able to mutate, e.g. virus.
Mechanism of transmission – pathogens have different modes of transmission, e.g. malaria is transmitted via contact, whereas viruses are transmitted through air.
Proportion of population that are immune – the more people in the population that are immune, the smaller the number of susceptible individuals that can get sick. This can be supported through vaccines, e.g. whooping cough.
Mobility of individuals – infected/carriers of disease who move to different areas can help the disease spread faster, e.g. COVID-19.

APPLYING

- Persisting for an extended period allows the pathogen to evade or adapt to the host's immune responses. In turn, this increases the likelihood of the pathogen being transmitted to a new host.
- The mechanism of transmission determines how a disease spreads within a community. For example, respiratory pathogens such as the influenza or measles viruses spread through airborne droplets, making them highly contagious in crowded places. In contrast, waterborne pathogens, such as cholera, typically lead to more localised outbreaks when contaminated water is consumed.
- Air travel has allowed for the large-scale movement of humans around the globe. As a result, infectious diseases can spread globally in a relatively short period of time. Infected individuals can spread pathogens to different regions within hours, challenging traditional measures used to contain the disease. Recent examples such as SARS and COVID-19 highlight the importance of international cooperation in disease monitoring and control.

LEARNING CHECK 12.3

DESCRIBING

- Regular handwashing, covering the mouth when coughing or sneezing, and staying home when ill
- Contact tracing is the process of identifying and monitoring individuals who have been in recent contact with an infected person. It is an important part of controlling outbreaks because it can be used to locate potential cases and prevent further spread.
- A notifiable disease, such as measles, is one that must be reported to public health authorities when cases arise.
- Personal hygiene measures, such as handwashing, are important in preventing infections. Globally, this reduces transmission, which can slow the spread of infection. In healthcare settings, effective handwashing is vital to prevent nosocomial infections, especially those involving antibiotic-resistant bacteria.

APPLYING

- Quarantine is the mandatory isolation of individuals for a period equal to or greater than the known communicability of a disease of concern. It ensures that individuals who may be carrying the disease do not come in contact with uninfected individuals and thereby spread the disease.
- The event should be cancelled. Influenza is a highly infectious disease. While the severity of outbreaks can vary, the potential for disease spread in mass gatherings poses significant risk. It is likely that health authorities would also require the cancellation of the event due to the risk it poses to the health of the attendees.
- It was learnt during SARS that air travel can facilitate the rapid transmission of infectious diseases. This most likely informed the decision to restrict international air travel for an extended period of time during COVID-19.

LEARNING CHECK 12.4

- Direct contact, through the air
- John Snow plotted cholera cases on a map of Soho (London) and observed that cases were clustered around a particular water pump on Broad Street. When the pump was closed, cases dropped significantly, proving that this particular pump was the source of the outbreak.

APPLYING

- Herd immunity occurs when a significant portion of the population becomes immune to a disease, through either vaccination or previous infection. This reduces the likelihood of infected individuals coming in contact with non-infected individuals as there is less prevalence of the disease circulating at any one time.
- The combination of environmental management (clean water, sanitation, PPE) and quarantine methods offers the best opportunity to control the spread of disease during a pandemic.

Environmental management addresses the sources of infection, while quarantine methods isolate infected individuals, preventing contact with non-infected individuals. This reduces the chance of transmission.

ANALYSING

- The swimming pool or shopping centre are possible sources of the *Legionella* bacteria. For example, both case 1 and case 4 visited the swimming pool. Case 1 lives in apartment block A with case 3 so contact may have occurred. Case 4 visited the shopping centre and may have come in contact with case 2.

LEARNING CHECK 12.5

ANALYSING

- Similarity: Both produce an antibody response.

Difference: With the primary response, it takes a longer period of time to commence antibody production. The levels of antibodies produced are relatively low compared to the secondary exposure. The duration of the response is

prolonged with the primary exposure due to the extended time taken to activate the effector B and T cells. In contrast, the secondary exposure is more rapid, leading to higher levels of circulating antibodies and a much more robust response, often with little or no symptoms.

- Independent variable: year
Dependent variable: standardised incidence rates
 - Trend: From 1982 to 2002 there is an overall decline in the incidence rate
Pattern: The repeated fluctuations
Relationship: 1982–2000 (approx) shows a negative linear relationship. 2002–2017 shows no relationship as there is no change in rate.
- Based on the decrease in incidence, it can be considered that the HPV vaccine is having an overall positive effect.

CHAPTER EXAM

MULTIPLE CHOICE

- | | | | | |
|-----|-----|-----|-----|------|
| 1 D | 3 B | 5 C | 7 C | 9 D |
| 2 B | 4 B | 6 B | 8 C | 10 D |

SHORT RESPONSE

- The outbreak is best described as an epidemic because it is contained within the region of Samoa and did not spread globally over multiple countries or continents.
 - Those who are vaccinated are less likely to produce high numbers of viral particles because they would be destroyed by an immune response. Therefore, they are not able to be passed on.
 - Quarantine or isolation of affected individuals – this reduces the chance of infected individuals passing the disease to other unaffected individuals

Screening – this can help identify those who are carriers of the pathogen that are asymptomatic. Carriers may also have to isolate to reduce spread
- That it is a disease that regularly occurs or is constantly present in Central and West Africa.
 - Hygiene measures that prevent direct contact as this is the mode of transmission.
 - Extended quarantine if arriving from a Mpox area.
 - No sharing of bedding materials as they are likely to be contaminated.

CROSS-CHAPTER QUESTION

- The vaccine shows an increase in the level of antibodies compared to those injected with saline. This could help trigger a rapid immune response if the individual is infected and therefore a decrease in HPV infections.
- Similarity: Both locations had households with number of persons ranging from 1 to more than 4

Differences:
 - (On average) location 2 had more people per household or location 1 had fewer people per household.

- In location 1, most households had two people or one or two people, or there were more households with one or two people than in location 2 whereas in location 2 there were more households with 5 or 6+ people.
 - For location 1, any accurate quote of data which gives both the number of dwellings and the number of persons per household.
- 15**
- Not correct.
 - Tanks had the lowest number of bacterial types; however, higher numbers of individual bacteria per sample
- Total number of bacteria in:
Tanks = 19
Lake = 8 (3 types)
Cages = 18 (11 types)
Ponds = 65 (16 types)
Therefore, the site with the fewest bacteria per sample is the lake.

GLOSSARY

A

abscisic acid a plant hormone produced in response to water stress that closes the stomata

action potential the state of a neural cell membrane in active transmission, when inside the cell is more positive than outside

activation energy the energy required to initiate a reaction

active immunity immunity that develops when the immune system is stimulated by an antigen and effector and memory cells are generated

active site the place on the surface of an enzyme molecule where substrate molecules attach

active transport the process of using energy to move a substance across a membrane from a region of low concentration to a region of higher concentration

adaptive immune response an acquired immune response; after an initial response to a pathogen, the immune system creates a 'memory' that leads to an enhanced response to subsequent encounters with the same pathogen

adenosine triphosphate (ATP) a molecule that stores and transports energy in the cell; composed of adenosine, ribose and three phosphate groups

adenosine diphosphate (ADP) a low-energy compound made up of adenine and ribose and two phosphate groups attached; it is converted to ATP for energy storage when it gains a phosphate group

adhesin a protein that helps bacteria to bind to host cell surfaces

adult stem cell a stem cell harvested from tissues such as bone marrow that are not part of an embryo

aerobic requiring oxygen

aestivation very low metabolic activity in some animals during periods of drought

alveoli tiny air sacs located on the end of bronchioles; site of gas exchange in mammals

amino acid a nitrogen-containing compound that is the building block of proteins

anabolic reaction a reaction in which complex molecules are built up from simple molecules

anaerobic not requiring oxygen

antibody a protein produced by plasma cells that binds to a specific antigen; also called immunoglobulin

antidiuretic hormone (ADH) a hormone responsible for increased permeability of the distal tubules of the kidney, increasing water reabsorption and reducing urine volume

antigen a large molecule, usually a protein or polysaccharide, that generates an immune response

antigen presenting cell a phagocytic cell that expresses a foreign antigen on its surface and presents it to helper T (T_h) cells via the MHC II molecule or to cytotoxic T (T_c) cells via the MHC I molecule

arteriole a small blood vessel that carries oxygenated blood to the tissues

artery a large diameter, elastic-walled blood vessel that takes blood away from the heart

ATP synthase an enzyme that captures energy by creating ATP

autoimmune disease a condition where the immune system attacks the body's own tissues

axon the tubular extension of a neuron soma that conducts the nerve impulse

B

B cell (B lymphocyte) a class of lymphocytes; once activated, they are characterised by the production of antibodies

bacteriophage a virus that invades bacteria

bilayer a double layer

binary fission the division of a cell into two without mitosis; a prokaryotic cell splits to form two daughter cells

biopiracy patented without the informed consent or appropriate benefit sharing with the Indigenous community

Bowman's capsule the nephron structure in which the glomerulus is positioned, and into which the filtrate from the glomerulus is forced

C

callose a polysaccharide formed in plant cell walls in response to injury

capillary a tiny diameter blood vessel with single-cell-thick walls that facilitates nutrient exchange with body cells

capsule a slimy layer sitting outside the cell wall of some species of bacteria

carbohydrates a group of compounds containing carbon, hydrogen and oxygen; important as structural components and as energy sources

carrier an individual who harbours a pathogen but who does not show symptoms of disease and can transmit the infection

carrier protein a protein within membranes that assists other molecules to cross the membrane in facilitated and active transport

case an individual who is infected with an infectious disease

catabolic reaction a reaction in which complex molecules are broken down to simpler products, e.g. cellular respiration

catalyst a substance that speeds up a chemical reaction but is not used up in the reaction

CD4 receptor a cell surface receptor expressed on T_h cells that binds to MHC class II receptors

CD8 receptor a cell surface receptor expressed on T_c cells that binds to MHC class I receptors

cell membrane the insoluble boundary of all living cells that maintains the contents of the cell and regulates movement of substances into and out of the cell

cell-mediated immunity when cytotoxic T cells recognise and destroy virally infected and cancerous cells

cell receptor a protein that binds hormones to form a hormone–receptor complex

cellular respiration a catabolic reaction that breaks down glucose to produce energy for the cell

cellulose a polysaccharide made of β -glucose subunits that is the main component of plant cell walls

channel protein a protein that forms channels within membranes to allow substances to pass through the membrane

chemical digestion the process of breaking a macromolecule into its component parts, e.g. starch to glucose

chemokine a molecule that induces chemotaxis; some cytokines are chemokines

chemoreceptor a receptor that detects a chemical stimulus such as blood glucose concentration and pH

chemotaxis the movement of an organism or cell along a chemical concentration gradient either towards (positive chemotaxis) or away from (negative chemotaxis) the chemical stimulus

chitin a polysaccharide that is the main component of fungal cell walls and the exoskeletons of insects and other arthropods

chlorophyll the green pigment in chloroplasts; it can absorb light energy, making it available for photosynthesis

chloroplast an organelle in plant mesophyll tissue that uses light energy to make glucose through photosynthesis

cholesterol a type of lipid in cell membranes that maintains membrane fluidity

clonal expansion rapid proliferation of clones

closed circulatory system a type of circulatory system in which the fluid is confined to a network of vessels

collecting duct a duct in the kidney that collects and transports fluid from several distal tubules to the renal pelvis

communicable can be communicated (transmitted) from one organism to another

companion cell a specialised plant cell in the phloem, which provides most of the cell functions for the sieve tube cell it is connected to

competitive inhibitor a substance that competes with a substrate for an enzyme's active site

complement system a number of small proteins in the blood that, when activated, promote chemotaxis, cell lysis and phagocytosis

concentration gradient the difference in concentration of a substance between two different regions

conformation the shape of a molecule that is determined by the three-dimensional arrangement of its atoms and bonds; important for molecular functioning

contact tracing a process for identifying potential cases; recent contacts of an infected individual are contacted and screened for the infection

contractile vacuole a vacuole found in some freshwater unicellular organisms that maintains osmotic balance by collecting water and emptying it from the cell

counter-current multiplication a system operating within a hairpin bend, where energy is used to transport particles across the membrane of one arm, enabling the passive diffusion of particles from the other arm, which reinforces further passive diffusion in the original arm

cristae the folds of the inner membrane into the matrix of the mitochondria, thus increasing the total surface area of the inner membrane

cuticle a thin, transparent layer of wax on the outside of a leaf's epidermis to reduce water loss

cytokine a small signalling molecule that coordinates inflammation and immune responses, and that leukocytes use to communicate with one another; includes interleukins and interferons

cytokinesis the process in which the parent cell's cytoplasm divides between the two daughter cells

cytoplasm all the fluid, dissolved materials and organelles between the cell membrane and the nuclear membrane

cytoplasmic streaming the mixing and movement of the cytoplasm

cytotoxic T cell (T_c) a class of lymphocytes that destroys virally infected or cancerous cells by secreting proteins that cause cell death

cytotoxin a toxin that disrupts or kills cells

D

defensin a small peptide that plays an important role in antimicrobial activity of phagocytes, the skin and mucous membranes; secreted by virtually all animals and plants

definitive host a host in which the adult phase of a parasite produces gametes

denaturation the process by which the functional structure of a protein is lost due to factors such as pH and temperature

dendrite a fine, thread-like extension of the neuron that converts external signals to nerve impulses within the neuron

deoxygenated denoting a lower concentration of oxygen

depolarisation a change in a cell's membrane potential so that the inside of the membrane is less negative than the outside

differentiation the process by which unspecialised cells develop special characteristics to suit particular functions

diffusion the passive movement of molecules from a region of high concentration to a region of low concentration

distal tubule the distant tubule; a section of the nephron between the loop of Henle and the collecting duct

downregulation when a cell is prompted to produce less of a particular cellular component, such as receptors

E

ectoparasite a parasite that lives on the surface of another organism

effector an organ, muscle, gland, cell or protein that acts in response to a stimulus

electron transport chain the third and final stage of aerobic respiration involving the flow of electrons through the mitochondrial membrane, their uptake by oxygen, and the production of ATP

embryonic stem cell a stem cell that is cultured from an embryo

encyst when organisms produce a covering around themselves and enter a resting stage

end product a substance that is formed by the action of an enzyme

endemic broadly, common to a particular area; specifically, a pathogen that is prevalent at a constant rate within a population

endergonic reaction a chemical reaction that requires energy, resulting in a net absorption of energy

endocrine gland a ductless gland that produces hormones

endocrine system the collection of ductless glands that produce hormones and secrete them directly into the bloodstream

endocytosis the movement of solids or liquids from the environment into a cell via vesicle formation

endoparasite a parasite that lives inside another organism

endoplasmic reticulum an organelle in eukaryotic cells consisting of an interconnecting system of thin membrane sheets dividing the cytoplasm into compartments and channels

endospore a tough, dormant structure formed by many bacteria to help them resist unfavourable conditions and disperse to new hosts

endosymbiotic theory a theory that suggests that chloroplasts and mitochondria arose from ancient prokaryote cells that were ingested by other prokaryote host cells

endotherm an animal that retains heat generated by metabolic activity

endotoxin a poisonous molecule attached to the outer membrane of certain bacteria that is usually released upon lysis of the bacterial cell

enterotoxin a toxin that disrupts intestinal function

enzyme–substrate complex a substance formed when an enzyme and a substrate molecule join

epidemic an increase in the occurrence of a particular disease above the baseline level for that population; tends to refer to larger, more serious events than an outbreak

epidermis the surface layer of cells in an organism

epithelial cell a cell in a sheet of cells covering any external or internal surface in a multicellular organism

equilibrium the point at which particles are distributed evenly throughout a system; they move at equal rates in all directions

eukaryotic cell a complex type of cell with a nucleus and membrane-bound organelles; a member of domain Eukarya

exergonic reaction a chemical reaction that produces more energy than it requires to start, resulting in a net release of energy

exocytosis the movement of solids or liquids from a cell to the environment via vesicle formation

exotoxin a protein toxin or enzyme actively secreted by pathogenic bacteria into their surroundings

external environment the environment surrounding a cell outside the cell membrane

exteroceptor a receptor that specifically receives signals from outside the body, such as air temperature, painful pressure or odours

extracellular enzyme an enzyme that is produced by cells but functions outside of the cell

extracellular fluid the fluid that bathes the outside of cells in multicellular organisms

F

facilitated diffusion a form of diffusion in which a substance attaches to a specific carrier molecule to move across a membrane

fatty acid a type of organic acid that combines with glycerol to form a triglyceride

feedback mechanism a physiological process that works to return the condition to its optimal state

fermentation a form of anaerobic respiration (no oxygen present); glucose is converted to ethanol, a type of alcohol

fibrin an insoluble, fibrous protein mesh that impedes the flow of blood during clotting

filtrate a liquid that has passed through a filter

flaccid describes the condition of a plant cell that has lost water; floppy

flagellum a whip-like appendage that helps bacteria move

fluid mosaic model the generally accepted model of membranes in which proteins are embedded in a phospholipid bilayer

fungi single-celled to complex multicellular eukaryotic organisms that have cell walls made of chitin and reproduce by spores

G

genetic disease a disease arising from DNA mutations inherited from parents

gland an organ that produces and secretes chemicals or proteins within the body or externally

glomerular filtration the process of removing some water and most solutes from the blood for excretion or reabsorption in the kidneys

glomerulus a network of capillaries contained within the Bowman's capsule, where high pressure forces the blood contents into the capsule

glycan a carbohydrate usually found attached to proteins and lipids in living organisms; released by some pathogens to help them evade the host's immune system

glycerol a molecule that combines with three fatty acids to form a triglyceride

glycogen an important energy-storing polysaccharide in animals, made of α -glucose with extensive branching

glycolipid a lipid that is attached to a glycan

glycolysis an energy-yielding process occurring in the cell cytosol in which glucose is partially broken down to pyruvate in enzyme reactions that do not require oxygen; this first stage of cellular respiration produces two ATP molecules

glycoprotein a protein that is attached to a glycan

Golgi apparatus an organelle in eukaryotic cells that processes, sorts and packages proteins and lipids to be transported towards the cell membrane

guard cells a pair of crescent-shaped cells that enable the opening and closing of a stoma

H

haemoglobin a protein within red blood cells that binds oxygen molecules for transport

helper T (T_h) cells a type of T lymphocyte that, once activated by a specific antigen, stimulates the proliferation and differentiation of B cells and killer (cytotoxic) T (T_c) cells

hibernate a period of very low metabolic activity over long periods of cold conditions

histamine a chemical released by mast cells that increases blood flow and the permeability of capillaries

homeostasis the maintenance of a relatively constant internal environment within small tolerance limits, despite changes in the external environment

hormone an organic compound produced by one part of the body and transported in the circulatory or lymphatic systems to another part of the body to prompt a response from specific cells

host an organism that is infected by a pathogen

humoral an immune response brought about by antibodies that circulate freely in the bloodstream and can lead to the destruction of pathogens

hydrogen carrier a molecule that accepts hydrogen from reactions and releases it to other reactions; transports hydrogen around the cell

hydrophilic tending to interact with and dissolve in water

hydrophilic hormone a hormone that is soluble in water and binds to extracellular receptors to initiate a response in that cell (e.g. peptide and some amine hormones)

hydrophobic avoiding association with water

hydrophobic hormone a hormone that is insoluble in water and binds to intracellular receptors (e.g. steroid and thyroid hormones)

hypertonic a solution with a higher solute concentration than another solution

hypothalamus a region of the forebrain that coordinates the endocrine and nervous systems; it secretes hormones and releasing factors that regulate the anterior pituitary gland, controlling body temperature, thirst, hunger and other homeostatic systems

hypotonic a solution with a lower solute concentration than another solution

I

immune system a complex network of cells, tissues and organs in the body that detects differences between 'self' and foreign organisms, and mounts an immune response

immunodeficiency a state in which the immune system does not function properly, leaving a person susceptible to infections the immune system could normally fight off

impulse the movement of an action potential along a nerve fibre in response to a stimulus; a signal sent along a nerve

incubation period the time between infection and the onset of symptoms

induced-fit model a model of enzyme activity in which an enzyme's active site undergoes specific changes, induced by the substrate, to achieve a high degree of specificity with the substrate

infectious disease a disease caused by a pathogen that can be transmitted from one organism to another

infectivity the ability of a pathogen to spread from one host and infect another host

inflammation an innate response to infection or damage that causes swelling, pain and redness

inhibition the process of blocking enzyme activity

inhibitor a molecule that blocks enzyme activity

innate immune response a non-specific response to pathogens that is not learnt and does not have memory

interneuron a cell that transmits nerve impulses within the central nervous system, between sensory and motor neurons

intermediate host an organism in which a pathogen or parasite undergoes development and spends a small part of its life cycle

internal environment all material contained within the cell membrane

interoceptor a receptor that specifically receives signals from inside the body, such as body temperature, oxygen concentration or pH

interstitial fluid extracellular tissue fluid, fluid in spaces surrounding cells

intracellular enzyme an enzyme that functions inside the cell that produces it, to speed up and control metabolic reactions

intracellular pathogen an organism that lives inside host cells

invasion factor a characteristic that helps pathogens to invade the host

isotonic fluid with an equal solute concentration to another fluid

K

keratin a strong, stable structural protein in skin, hair, horns and nails

keratinised a process by which keratin is deposited in skin cells; the surface becomes tough and waterproof

kleptothermy a form of thermoregulation in which an animal shares in the metabolic heat generated by another animal; its most common form is huddling

Krebs cycle a biochemical pathway that requires oxygen and takes place in the mitochondria as the second stage of aerobic cellular respiration

L

lacteal a vessel that transports non-water-soluble materials to and from the villi of the small intestine; a branch of lymph vessel

ligand a molecule that binds to a receptor

light-dependent reactions the first stage of photosynthesis; it requires light energy that is absorbed by chlorophyll; water molecules split to produce oxygen, hydrogen ions and ATP

light-independent reactions the second stage of photosynthesis; carbon dioxide, hydrogen ions and ATP react to produce glucose

lipopolysaccharide a lipid-sugar compound that forms the outer surface of some types of bacteria

lock-and-key model an old model suggesting that the shape of an enzyme's active site is an exact, static fit for the shape of its substrate molecule

loop of Henle the portion of a nephron that connects the proximal tubule to the distal tubule; the site of selective reabsorption of water

lymphatic system a drainage system in the body that helps maintain a balanced fluid level

lymphocyte a type of leukocyte involved in adaptive immune responses

lymph the extracellular fluid collected by the lymphatic system

lyse to burst

lysis the breakdown of the cell membrane, resulting in the release of cell contents and subsequent death of the cell

lysosome an organelle that contains enzymes that break down biomolecules into smaller units

lysozyme an antibacterial enzyme in tears, saliva and other body fluids

M

macromolecule a large molecule that has an important structural or functional role in cells

macrophage a large white blood cell in tissues that phagocytoses (ingests) pathogens

major histocompatibility complex (MHC) a group of proteins that present antigens to specific white blood cells to distinguish between self and non-self cells; there are two forms: MHC class I and MHC class II

mast cell a cell located in the tissues, which when activated releases granules containing histamine

mast ring a ring of paper with small circular 'offshoots' impregnated with different antibiotics

mechanoreceptor a receptor that detects a physical stimulus such as touch and sound vibration

membrane attack complex a complex of complement proteins that form pores in the membranes of target cells, disrupting the phospholipid bilayer

memory cell an immunological cell that 'remembers' a specific antigen

metabolism the sum of chemical reactions that maintain life within an organism

microflora a community of micro-organisms, including fungi and bacteria, that live in or on another living organism

mitochondrion an organelle within the cytoplasm that is the site of aerobic cellular respiration, which releases energy for the cell

mitosis a type of cell division in which a parent cell produces two daughter cells with exactly the same genetic material as each other and as the parent cell

monocyte a white blood cell that circulates in the blood and matures into a macrophage when it moves from the blood into the tissues

monomer a small molecule that is a building block for polymers

monosaccharide a simple sugar, such as glucose, which cannot be broken down into smaller sugar molecules

morbidity the impact of a disease within a population, measured by the number of people affected by that disease

mortality the impact of a disease within a population, measured by the number of deaths caused by that disease

motor neuron a cell that transmits nerve impulses from the central nervous system to the effector

multipotent stem cell a stem cell that can develop into a limited number of cell types

myelin sheath the fatty layers of insulation surrounding the axon of a neuron; made of Schwann cells

N

naive cell an immature cell that has not been activated

negative feedback a cyclic process where responses counteract disturbances to keep concentrations of substances within narrow limits for optimal cellular function

nephron a specialised structural and functional unit within the kidney which eliminates waste molecules and regulates solute and water levels in the blood

neuron a nerve cell that transmits electrical impulses in the body

neurotoxin a toxin that disrupts the functioning of nerves

neurotransmitter a chemical (protein) that is used by neurons to carry a signal across the synapse

neutrophil a phagocytic leukocyte in blood and tissues

nociceptor a receptor that detects only intense (painful) chemical, mechanical or thermal stimulation

node of Ranvier a small space between the Schwann cells along the axon of a neuron

non-competitive inhibitor a substance that binds to an enzyme at a site other than the active site; this changes the shape of the enzyme so that the substrate can no longer bind to the active site

non-infectious disease a disease that is not transmitted from one organism to another

non-self an agent (e.g. cell, organism, substance) that is not recognised by the immune system as being part of the organism itself; it is foreign

non-specific when the response is the same regardless of the type of pathogen

notifiable disease a disease that, if diagnosed, is required to be reported to public health authorities

nucleus the organelle in a eukaryotic cell containing most of the DNA; its function is to coordinate cell activities

O

opsonisation a process in which a pathogen is coated with antibodies and marked for ingestion and destruction by phagocytes

optimal level the most favourable condition for effective functioning

organ a collection of different types of tissues working together to perform a particular function

organelle a specialised structure or compartment within a cell that has a specific function

osmolarity the concentration of all solutes in a solution measured in the number of particles per litre of solution.

osmoregulation the processes by which internal water and solute concentration are maintained despite fluctuations in the external environment

osmosis the movement of water across a selectively permeable membrane from a region of low solute concentration to a region of high solute concentration

osmotic pressure the concentration of solutes in the blood

oxygenated denoting a higher concentration of oxygen

P

pandemic an epidemic that has spread across many continents or worldwide

parasite an organism that lives on or in its host for all or part of its life, causing harm and gaining nutrition from the host

passive immunity immunity characterised by the transfer of antibodies from one individual to another; this type of immunity does not show memory

passive transport the movement of molecules that does not require the input of energy

pathogen a disease-causing agent

pathogenesis the nature and presentation of disease development

pathogenicity the capacity of a pathogen to cause disease

perforin a glycoprotein that creates pores in the cell membrane of target cells

peritubular capillaries tiny blood vessels that surround the tubules in the nephron and facilitate selective reabsorption and secretion

phagocyte a cell that is capable of phagocytosis; includes macrophages and neutrophils

phagocytosis the bulk transport of solids into a cell inside a vesicle

phagolysosome a membrane-bound vesicle formed from the fusion of a phagosome and lysosome

phagosome a membrane-bound vesicle formed around a particle during phagocytosis

phloem vascular tissue in plants, consisting of living cells, responsible for the bulk transport of sugars

phospholipid a type of lipid that has a hydrophilic head end and a hydrophobic tail end

photoreceptor a receptor that detects light energy

photosystems special proteins embedded in the thylakoid membrane that house chlorophyll molecules for photosynthesis

physical barrier a structural obstruction that protects an organism against microbe entry

phytosterol a type of plant-derived lipid compound that is similar to cholesterol in structure and function

pilus a surface appendage in some bacteria that functions in adherence

pinocytosis the bulk transport of liquids into a cell inside a vesicle

plasma cell an effector B cell that has differentiated to become highly specialised for producing antibodies

plasmid a small ring of DNA that is not a chromosome, most often found in prokaryotes

plasmodesma a tiny channel through a plant cell wall that allows communication and life support between companion cells and sieve tube cells

plasmolysis the point at which the cell membrane pulls away from the cell wall because of water loss

platelet a cell fragment in blood that helps blood to clot

pluripotent stem cell a stem cell that can develop into many, but not all, of the cell types necessary for foetal development

polar a molecule with an uneven distribution of electrons, giving it distinct charged ends

polymer a large molecule built up from linking smaller molecules together in a repeating pattern

polypeptide a polymer of amino acids, also known as a protein

polysaccharide a complex carbohydrate that is made by linking together simple sugars

positive feedback a cyclic process where responses reinforce and strengthen disturbances to normal cellular function

postsynaptic neuron the neuron receiving the signal from the synapse

presynaptic neuron the neuron sending the signal across the synapse

primary response the response generated when an antigen is encountered for the first time

prion a small infectious protein

processing centre the organ or organ system, usually the central nervous system, that receives signals from receptors and sends appropriate responses to effectors

prokaryotic cell a simple type of cell that lacks a nucleus and membrane-bound organelles; a member of domain Archaea or Bacteria

prostaglandins a group of lipid-based molecules produced in response to tissue injury or infection and cause vasodilation, fever and pain

protein channel a passageway formed across the membrane for the movement of specific substances

proximal tubule the nearest tubule; a section of the nephron that leads from the Bowman's capsule to the loop of Henle

pyruvate a 3-carbon compound that is the end product of glycolysis

Q

quarantine the enforced isolation of individuals at risk of carrying disease to prevent the spread of that disease into healthy populations

R

R group a side chain in a molecule that confers distinguishing properties to the molecule; the R group is what differentiates the 20 different kinds of amino acids

renal pelvis the section of the kidney where urine is collected and directed to the ureter

resin a metabolic product secreted by plants in response to damage

resistance the extent to which an organism is or is not affected by an agent such as a pathogen or chemical toxin

response the action resulting from a stimulus

resting potential the state of a neural cell membrane at rest, when outside the cell is more positive than inside

ribosome a small structure in all cells that builds amino acids into complex proteins; is not bound by a membrane

rough endoplasmic reticulum endoplasmic reticulum with ribosomes attached

S

saturated referring to an organic molecule that only has single bonds between its carbons

saturation point the point at which all active sites are filled with substrate, resulting in maximum reaction rate

Schwann cell a cell that wraps tightly around the axon of a neuron to form the myelin sheath

secondary response the response generated when the body encounters a pathogen to which it has previously generated an immune response

selective reabsorption the process of returning selected molecules from the nephron filtrate to the blood

selectively permeable a quality of a membrane that means only certain kinds of molecules can pass through it

self an agent (e.g. cell, organism, substance) that is recognised by the immune system of an organism as being part of that organism

sensory neuron a cell that transmits nerve impulses from the receptor to the central nervous system

sensory receptor an organ or a structure that detects or receives a stimulus

sieve plate the tough cellulose walls between sieve tube cells that contain pores to allow the cytoplasm to flow between cells

sieve tube cell a long, tubular plant cell, without a nucleus, that forms sieve tubes, the main component of the phloem

signal transduction the process of converting a signal into another type of signal in a cell (e.g. electrical to chemical)

signalling molecule a molecule that is released by one type of cell and binds to another type of cell and causes an effect

smooth endoplasmic reticulum endoplasmic reticulum with no ribosomes attached

sodium–potassium pump a membrane protein that uses energy to transport sodium ions out of, and potassium ions into, cells against their concentration gradients

solute a substance that can be dissolved in another substance

solution a mixture of solute and solvent

solvent a substance in which another substance can be dissolved to create a solution

soma the main cell body of a neuron containing the nucleus

specialise to develop specific features suited to specific functions

specific when the response is directed against a particular pathogen

sporadically refers to a disease that occurs infrequently and irregularly within a population

starch an important energy-storing polysaccharide for plants, made of α -glucose with some branching

stem cell an unspecialised, immature cell capable of differentiating into a specialised cell

steroid a hydrophobic signal molecule produced from cholesterol

stimulus an internal or external signal that causes a response

stimulus–response model a model that shows how organisms respond to stimuli

stoma a controlled opening in leaves and young stems that controls the movement of gases into and out of a plant

substrate a substance that enters a reaction; also called reactant or precursor

succulent a plant with thick, fleshy leaves and stems that stores more water in its cell vacuoles than usual

surface area-to-volume ratio the mathematical ratio of the size of the surface area (in two dimensions) to the volume of an object (in three dimensions)

susceptibility the likelihood of an organism being infected by a pathogen

symbiotic a type of relationship between two organisms where at least one organism benefits

symptom a characteristic effect of a pathogen on the body

synapse (synaptic cleft) the tiny space between an axon terminal and its target (neuron, muscle or gland)

system a collection of organs that work together to perform a particular function

T

T cell (T lymphocyte) a class of lymphocytes that mature in the thymus; differentiate into a number of different types of T cells

temperature danger zone the range of temperatures at which harmful bacteria can grow and reproduce in food

thermogenesis the process of heat production in organisms

thermoreceptor a receptor that detects changes in temperature

thermoregulation the process by which animals maintain their body temperature within a normal range

tissue a group of specialised cells working together to perform a specific function

tolerance limit the most extreme point that internal and external conditions can reach for an organism still to function effectively

torpor a state of decreased physiological activity, usually by a reduced body temperature and metabolic rate

totipotent stem cell a stem cell that can develop into any of the types of cells necessary for embryonic development

toxin a naturally occurring poison produced by the metabolic action of a living organism

tracheid a dead elongated cell that forms the xylem of all vascular plants

transmission the passing of an infectious disease from an infected host to another individual

transpiration the loss of water from plants through evaporation

transpiration stream a continuous column of water inside xylem tissue that moves up the stem of a plant

triglyceride a simple lipid formed by linking glycerol with three fatty acids

turgid describes a cell that is tight and rigid from absorbing water

U

unipotent stem cell a stem cell that can develop into only one type of cell

unsaturated referring to an organic molecule that has at least one double bond along its carbon chain; a prefix, such as mono- or poly-, refers to how many double bonds are present

upregulation when a cell is prompted to produce more of a particular cellular component, such as receptors

urea a nitrogenous waste that is excreted in mammalian urine

urine a fluid containing water, urea and other wastes; it is excreted from the kidneys

V

vaccine a solution of antigens or pathogens that is designed to elicit a primary response and promote the formation of memory cells; can be administered through injection, ingestion or intranasally

vacuole an organelle that is predominantly made up of water and stores different materials (including waste products); in plants, they also help with water balance and cell structure

validity how accurately a method measures what it is intended to measure.

vascular relating to plant vessels that conduct fluid

vasoconstriction the constriction of blood vessels by the surrounding smooth muscle cells, which increases blood pressure and redirects blood flow away from the constricted vessel

vasodilation dilation (widening) of blood vessels, particularly arterioles

vector a living organism that transmits pathogens from one host to another; a vehicle used to transfer DNA sequences from one organism to another

vein a non-elastic, thinner walled blood vessel that carries blood to the heart

vesicle a small, membrane-bound sac in the cytoplasm that transports, stores or digests substances

vessel element a dead cell that is perforated at each end and stacked vertically, forming the advanced xylem beside tracheids in flowering plants

villi elongated projections from the lining of the small intestine that hugely increase the surface area and thus the capacity for exchange of materials

virulence a measure of a pathogen's ability to cause disease within its host

virulence factor a characteristic that helps bacteria to invade the host, cause disease and evade host defences

virus a non-cellular agent composed of a protein coat and nucleic acid

W

wilt become limp and floppy

X

xerophyte a plant adapted to dry conditions

xylem vascular tissue in plants, consisting of dead cells, responsible for the bulk transport of water and minerals

Z

zygote a cell formed by the union of two sex cells; usually fertilisation of an egg cell by a sperm cell

INDEX

Note: Page numbers followed by *f* and *t* indicate figures and tables respectively.

- ABA. *See* abscisic acid (ABA)
- abscisic acid (ABA), 133
- acquired immunodeficiency syndrome (AIDS), 282
- action potential, 162, 163*f*
- activation energy, 97, 97*f*
- active immunity, 249
and passive immunity, 250–1
vaccines, 249
- active site, 91, 96, 101
- active transport, 48–9, 49*f*
endocytosis, 50, 50–1*f*
energy for, 49
exocytosis, 51–2, 51–2*f*
large molecules, movement of, 50
- adaptive immune response
in vertebrates, 245–9
- adenosine triphosphate (ATP), 49
- adenovirus, 217*t*
- ADH. *See* antidiuretic hormone (ADH)
- adherence factors, 224–5, 224*f*
- adhesins, 224
- ADP (adenosine diphosphate), 115
- adrenal pituitary endocrine glands, 176*t*
- adult stem cells, 25, 26*t*
- Aedes aegypti*, 279, 279*f*
- Aedes aegypti* mosquito, 270, 270*f*
- aerobic cellular respiration, 117
- aestivation, 197
- agar, 220
- agglutination, 248
- AIDS. *See* acquired immunodeficiency syndrome (AIDS)
- AIDS, 267*t*
- airborne fungal pathogens, 252
- airborne transmission, 268
- alveoli, 73
direction of gas exchange, 73, 73*f*
- amino acids, 90
- amoebic dysentery, 221, 269
- anabolic reactions, 114
absorb energy, 115, 115*f*
- ATP transfers energy from, 115–16, 116*f*
- anaerobic reactions, 117
- anaphase, 28
- antibodies, 246
- antibody–antigen complex, 246
- antidiuretic hormone (ADH)
role of, 203–4, 204*f*
- antigen, 237
- antigen presenting cell (APC), 245
- antigenic drift, 271
- APC. *See* antigen presenting cell (APC)
- aquaporins, 203
- arteries, 71
- arterioles, 242
- arthropod group, 222
- asymptomatic carriers, 272
- athlete's foot. *See* tinea
- ATP. *See* adenosine triphosphate (ATP)
- ATP (adenosine triphosphate), 115, 116*f*
synthase, 115
synthesis, 130
- Australian Federal Government, 278
- Australian Government Department of Health and Aged Care, 284
- autoimmune diseases, 214
- axon, 156
- B lymphocytes (B cells), 245, 246
- Bacillus anthracis*, 218*t*
- bacteriophages, 216
- behavioural responses, 196
kleptothermy, 197, 197*f*
shutting down in extreme conditions, 197–8, 197*f*, 198*f*
- bilayer, 40
- binary fission, 219, 219*f*
- biomolecules, 88
carbohydrates, 89–90, 89*f*, 90*t*
lipids, 92–3, 92*f*
proteins, 90–1, 91*f*, 91*t*, 92*t*
- bitter-tasting tannins, 254
- Black Death. *See* plague
- bloodstream, glucose level in, 193
- body fluids, indirect contact with, 268
- Botrytis cinerea*, 220*t*
- botulinum toxin, 226
- bovine spongiform encephalopathy (BSE), 217
- Bowman's capsule, 77, 78*t*
- Brischoux, François, 197
- brown adipose tissue, 195–6, 196*f*
- BSE. *See* bovine spongiform encephalopathy (BSE)
- Buchner, Eduard, 95
- Burnet, Macfarlane, 246
- caffeine, 254
- callose, 253
- Calvin cycle. *See* light-independent reactions
- Candida albicans*, 220*t*
- capillaries, 71
- capsules, 219, 225
- carbohydrates, 89–90, 89*f*, 90*t*
synthesis of, 12, 12*f*
- carrier proteins, 44, 45*f*
- catabolic reactions, 114
ATP transfers energy from, 115–16, 116*f*
release energy, 114–15, 115*f*, 116*f*
- catalase, 97
- CD4 receptors, 245
- CD8 receptors, 245
- cell cycle and differentiation, 27–9
mitosis and cell cycle, 27–9, 28*f*
- cell-mediated immunity, 245
- cell membrane, 40
active transport, 48–53
passive movement, 43–8
structure of, 40–3, 41*f*
surface area-to-volume ratio, 53–8
- cell sensitivity, 180–1
- cells and cell specialisation
cell cycle and differentiation, 27–9, 28*f*
comparing prokaryotic and eukaryotic cells, 15–17, 16*f*, 17*t*
eukaryotic cells, 7–15, 8*f*, 9*f*
microscope, 17–24

- prokaryotic cells, 6–7, 7f
- properties of stem cells, 24–7
- specialised cells, 30–2
- cellular energy
 - cellular respiration, 117–21, 117–21f
 - metabolism, 114–15, 115f, 116f
- cellular respiration
 - electron transport chain, 119–20, 119f
 - glycolysis, 117–18, 117f
 - Krebs cycle, 118, 118f
 - without oxygen, 120–1, 120f
- cellulose, 90
- central nervous system (CNS), 156
- centrioles, 14
- channel proteins, 42, 44, 45f
- chemical defence strategies, 253–4, 254f
- chemical digestion, 94, 94t
- chemical messengers, hormones as, 176–9, 176t, 177f
- chemokines, 242, 243f
- chemoreceptors, 154, 155t
- chemotaxis, 242, 243f
- chickenpox virus, 282
- chitin, 220
- chlorophyll, 128
- chloroplasts, 10–11, 10f, 129
- cholera bacteria, 226
- cholesterol, 12, 41
- cilia, 240, 240f
- circulatory system, 70–1, 70–1f
 - Claviceps purpurea*, 220t
- clonal expansion, 246
- closed circulatory system, 70
- Clostridium botulinum*, 226
- Clostridium tetani*, 218t
- CNS. *See* central nervous system (CNS)
- cocci-shaped bacteria, 219, 219f
- cold sores, 267t
- cold virus, 223
- collecting duct, 77
- common cold, 267t
- companion cells, 137
- competitive inhibitors, 101
- complement activation, 248
- complement system, 242, 243f
- concentration gradient, 43, 69
- conformation, 181
- connective tissue, 68
- contact tracing, 275
- contaminated food, 268
- contaminated water, 269
- continual maintenance, 193, 193f
- contractile vacuoles, 47, 47f
- cortisol, 181
- Corynebacterium diphtheriae*, 218t
- counter-current multiplication, 80
- COVID-19, 274, 277–8
- Creutzfeldt–Jakob disease (vCJD), 217
- cristae, 11
- cuticle, 132
- cytokines, 242
- cytokinesis, 28
- cytoplasm, 41
- cytoplasmic streaming, 56
- cytoskeleton, 14
- cytotoxic T cells (Tc cells), 245
- cytotoxins, 225, 226, 246
- defensins, 239, 239f
- definitive host, 222, 271
- denaturation, 98
- dendrites, 156
- deoxygenated blood cells, 73, 73f
- depolarisation, 162
- dicotyledon leaf, cross-section of, 253f
- diffusion, 43–4, 43f, 45f
 - facilitated, 44, 45f
 - gas exchange, 72
 - across membranes, 44, 44f
- digestive system, 75, 75f
 - villi, 75f, 76
- Diplocarpon roseae*, 220t
- direct contact, 268
- direct deposition, 268
- distal tubule, 77
- downregulation, 180
- ectoparasites, 222, 222f
- effector, 190
- electron flow, 119
- electron transport chain, 119–20, 119f
 - ATP synthesis, 119
 - electron flow, 119
 - oxygen uptake, 119
- embryonic stem cells, 25, 26t
- encyst, 222
- end plate, 160
- end product, 95
- endemic disease, 271
- endergonic reaction, 115
- endocrine glands, 176t, 177
- endocrine system, 177
 - hormones as chemical messengers, 176–9, 176t, 177f
 - receptor binding, 179–83
- endocytosis, 50, 50–1f
- endoparasites, 222, 222f
- endoplasmic reticulum (ER), 11
- endospores, 219
- endosymbiotic theory, 15
- endothermic animals, 195
- endotherms
 - brown adipose tissue, 195–6, 196f
 - insulation, 195, 195f
 - shape and size, 196, 196f
 - structural features of, 195
- enterotoxins, 225
- enzymes, 95
 - control metabolic processes, 95
 - digestive, 94t
 - discovery of, 95
 - function, factors affecting, 98–104
 - inhibitors, 100–1, 101f
 - pH, 99–100, 99f
 - structure and function, 95–7, 95f
 - substrate concentration, 100, 100f
 - temperature, 98–9, 99f
- enzyme–substrate complex, 95
- epidemics, 271
- epidermis, 132
- epithelial cells, 30–1, 30–1f, 76, 238
- epithelial tissue, 69
- equilibrium, 44
- ER. *See* endoplasmic reticulum (ER)
- eukaryotic cells, 7, 8f, 9f
 - versus and eukaryotic cells, 15–17, 16f, 17t
 - chloroplasts, 10–11, 10f
 - Golgi apparatus, 12, 13f
 - lysosomes, 13, 13f
 - mitochondria, 11, 11f
 - nucleus, 10, 10f
 - other cell components, 14, 14t
 - ribosomes, 12, 12f
 - rough endoplasmic reticulum, 11, 11f
 - smooth endoplasmic reticulum, 12, 12f
 - vacuoles, 13, 141f

- evaporative heat loss, 199
- exchange surfaces, 69
- excretory system
nephrons, 76–8, 77f, 78t
producing urine, 79–80, 79f
- exergonic reaction, 115
- exocytosis, 51–2, 51–2f, 164
- external environment, 40
- external signals, detection of, 154
- exteroceptors, 154
- extracellular enzymes, 95
- extracellular fluid, 202
- facilitated diffusion, 44, 45f
- fat-soluble hormones, 177
- fatty acids, 92
- feedback, 191–2, 191–2f
continual maintenance, 193
mechanism, water balance, 203
negative feedback, 192–3
- feedback–control diagrams, 194–5, 194f
- fermentation, 120
- fibrin protein, 239
- field of view (FOV), 18
- filtrate, 77, 78t
- fimbriae, 224
- flaccid, 48
- flagellin, 237
- flagellum, 219
- flaviviruses, 217t
- fluid mosaic model, 40
- flukes, 222
- food poisoning, 267t, 268
- FOV. *See* field of view (FOV)
- Frazer, Ian, 284
- G protein, 203
- gas exchange, direction of, 72–5, 72–4f
in alveoli, 73, 73f
in body tissue, 73, 74f
in leaf, 132–6, 132f, 133f
- genetic disease, 214
- Giardia lamblia*, 221, 221f
- giardiasis, 267t
- glomerular filtration, 77
- glomerulus, 77, 78t
- glucose, 89
- glycans, 271
- glycerol, 92
- glycogen, 90
- glycolipids, 42
- glycolysis, 117–18, 117f
- glycoproteins, 42, 42f
- goblet cells, 30
- Golgi apparatus, 12, 13f
- Golgi body, 12, 13f
- gonorrhoea, 267t
- guard cells, 132–4, 133f
- haemagglutinin, 271
- haemoglobin, 72
- Haemophilus influenzae*, 273
- helper T cells, 246
- Henle, loop of, 77
- hepatitis A virus, 217t
- herpes simplex type I, 217t
- herpes simplex type II, 217t
- hibernating mammals, 196
- histamine, 242, 243f
- histones, 10
- HIV. *See* human immunodeficiency virus (HIV)
- homeostasis, 154, 191
- homeostatic regulation
feedback–control diagrams, 194–5
osmoregulation, 202–4
stimulus–response model, 190–3
thermoregulation, 195–202
- hormones
as chemical messengers, 176–9, 176t, 177f
targeting specific cells, 178, 179f
transporting, 178, 178f
types of, 177, 178f
- host, 214
- host cells, 237
- HPV. *See* human papillomavirus (HPV)
- huddling, 197
- human immunodeficiency virus (HIV), 217t, 282
- human papillomavirus (HPV), 284, 285
- humidity, 140
- humoral immune response, 245
- humoral immunity, 246–8, 247–8f
- hydrogen carriers, 117, 130
- hydrophilic hormones, 177
- hydrophobic hormones, 41, 177
- hypertonic, 46, 46f
- hypothalamus, 199
- hypotonic, 46, 46f
- immune response
data, interpreting long-term, 281–5
stimulating an, 236–8, 237f, 238f
- immune system, 214
- immunity
active versus passive immunity, 249–52
adaptive immune response in vertebrates, 245–9
inflammatory response, 241–5
innate immune response in vertebrates, 238–41
innate immune responses in plants, 252–4
stimulating an immune response, 236–8
- immunodeficiency, 282
- impulse, 190
- incubation period, 223
- induced-fit model, 96, 96f
- infectious disease
definition of, 214–15
pathogenesis, 223–8
pathogens, 215–23
- infectivity, 273
- inflammation, 242
- inflammatory response
complement system, 242, 243f
natural killer cells, 243, 244f
neutrophils and macrophages, 242–3, 243f, 244f
prostaglandins and vasodilation, 241, 242f
- influenza, 267t
- influenza A virus, 271
- inhibition process, 100
- inhibitors, 100–1, 101f
- innate immune response, 237
in plants, 252–4
in vertebrates, 238–41
- insulation, 195, 195f
- interconnecting neurons. *See* interneurons
- intermediate hosts, 222, 271
- internal environments, 40
- internal signals, detection of, 154
- interneurons, 156, 160, 160f
- interoceptors, 154
- interstitial fluid, 154
- intracellular enzymes, 95

- intracellular pathogens, 225
- invasion factors, 225
- isotonic, 46, 46f
- keratin, 238
- keratinised process, 238
- kleptothermy, 197, 197f
- Koshland, Daniel, 96
- kowari (*Dasyuroides byrnei*), 197, 197f
- Krebs cycle, 118, 118f
- lacteals, 76
- lactic acid fermentation, 120, 120f
- large molecules, movement of, 50
- Legionella pneumophila*, 218t
- light-dependent reactions, 129, 130f
 - ATP synthesis, 130
 - light-driven electron flow, 130
 - water splitting, 130
- light-driven electron flow, 130
- light-independent reactions, 130–1, 131f
- lipids, 92–3, 92f
- lipids, synthesis of, 12, 12f
- lock-and-key model, 96, 96f
- loop of Henle, 77, 78t
- lymph, 178
- lymphatic system, 76, 176, 178
- lymphocytes, 245
- lyse, 47, 240
- lysis, 242, 243f
- lysosomes, 13, 13f
- lysozyme, 240, 240f
- MAC. *See* membrane attack complex (MAC)
- Macromolecule, 88
- macrophages, 242, 242–3, 243f, 244f
- ‘mad cow’ disease, 217
- major histocompatibility complex (MHC), 237
- major histocompatibility complex class I (MHC I), 243
- Mallon, 273
- mast cells, 242
- mast rings, 226
- mechanoreceptors, 154, 155t
- membrane attack complex (MAC), 242, 243f
- membrane proteins, 41–2, 42f
- memory B cells, 246, 247f
- memory cells, 245
- role of, 248
- metabolism, 114
 - anabolic reactions absorb energy, 115, 115f
 - ATP transfers energy from catabolic to anabolic reactions, 115–16, 116f
 - catabolic reactions release energy, 114–15, 115f, 116f
- metaphase, 28
- MHC. *See* major histocompatibility complex (MHC)
- MHC I. *See* major histocompatibility complex class I (MHC I)
- microflora, 239
- microscope, use of, 17–24
- mitochondria, 11, 11f
- mitosis and cell cycle, 27–9, 28f
- monomers, 88
- monosaccharides, 89
- morbidity, 273
- mortality, 273
- motor neurons, 156, 160, 160f
 - and sensory neurons, 161, 161f
- mucosa, 75
- multicellular internal parasites. *See* endoparasites
- multipotent stem cell, 25, 26t
- muscle tissue, 69
- muscularis, 75
- Mycobacterium leprae*, 218t
- myelin, role of, 163
- myelin sheath, 156
- naive cells, 245
- natural killer (NK) cells, 243, 244f
- negative feedback, 192–3, 192f
- nephrons, 76–8, 77f, 78t
- nerve impulse
 - cells that transport, 156–8, 156f
 - passage of, 162–6
- nervous system
 - cells that transport nerve impulses, 156–8, 156f
 - nerve impulse, passage of, 162–6
 - neurons, different types of, 159–62
 - sensory receptors, 154, 155f, 155t
- nervous tissue, 69
- neuraminidase, 271
- neurons, 156
 - distinguishing between sensory and motor neurons, 161
- interneurons, 160
- motor, 160
- sensory, 159
- structure, 156–7, 157f, 158f
- transmission between, 163–5, 164f
- transmission within, 162–3, 163f
- neurotoxins, 225
- neurotransmitters, 164, 164f
- neutralisation, 248
- neutrophils, 242–3, 243f, 244f
- NK. *See* natural killer (NK) cells
- nociceptors, 154, 155t
- nodes of Ranvier, 157
- non-competitive inhibitor, 101
- non-infectious (chronic) diseases, 214
- non-self substance, 236
- non-specific defence, 237
- notifiable diseases, 275
- nucleus, 10, 10f
- opsonisation, 242, 243f, 248
- optimal level, 192
- organelles, 6
- osmolarity, 79
- osmoregulation, 202, 202–4
 - role of ADH, 203–4, 204f
 - water balance feedback mechanism, 203
- osmosis, 45, 45–6f, 139
 - in animals, 47, 47f
 - in plants, 47–8, 47f
- osmotic pressure, 203
- oxygenated blood cells, 73, 73f
- PAMPs. *See* pathogen-associated molecular patterns (PAMPs)
- pancreatic
 - alpha cells, 176t
 - beta cells, 176t
- pandemic, 271
- parasite, 221
 - ectoparasites, 222, 222f
 - endoparasites, 222, 222f
- passive immunity, 250
 - and active immunity, 250–1
- passive movement
 - diffusion, 43–4, 43f, 45f
 - osmosis, 45–8, 46f, 47f
- pathogen-associated molecular patterns (PAMPs), 237
- pathogenesis, 223–8
 - adherence factors, 224–5, 224f

- pathogenesis (*continued*)
capsules, 225
invasion factors, 225
related proteins, 254, 254f
susceptibility, 223–4, 224f
toxins, 225–7
- pathogenicity, 224
- pathogens, 215
bacteria, 218–20, 218t, 218–19f, 220f
fungi, 220, 220f, 221t
within hosts, 271–2
parasite, 221–2, 221–2f
prions, 217–18, 217f, 218f
protists, 221, 221f
virus, 215, 215–16f, 217t
- pattern recognition receptors (PRRs), 237
- PCR. *See* polymerase chain reaction (PCR)
- perforin, 243
- peripheral nervous system (PNS), 156
- peritubular capillaries, 79
- personal hygiene measures, 275
- pH, 99–100, 99f
- phagocytes, 242, 243f
- phagocytosis, 15, 50, 50f, 51f
- phagolysosome, 242–4
- phagosome, 242
- phloem, structure and function, 137–8, 138f
- phosphofructokinase-1 (PFK-1), 100
- phospholipids, 41, 41f
- photoreceptors, 154, 155t
- photosynthesis, 10, 128–9
light-dependent reactions, 129–30, 130f
light-independent reactions, 130–1, 131f
- photosystems, 129
- physical barriers, 252–3
- physical defence strategies, 252, 252f
Phytophthora cinnamomi, 220t
- phytosterol, 41
- pilus, 224
- pinocytosis, 50
- plague, 267t, 270
- plant physiology
gas exchange in leaf, 132–6
photosynthesis, 128–31
transpiration, 139–43
- transport systems, 136–9
- plant transport systems, 136, 136f
phloem structure and function, 137–8, 138f
xylem structure and function, 137, 137f
- plants, innate immune responses in, 252–4
- plasma cells, 246, 247f
- plasma membrane. *See* cell membrane
- plasmids, 6
- plasmodesmata, 137
- Plasmodium falciparum*, 271, 272f
- plasmolysis, 48
- platelets, 239
- pluripotent stem cells, 25, 26t
- PNS. *See* peripheral nervous system (PNS)
- polar molecules, 44
- polymerase chain reaction (PCR), 99
- polymers, 88
- polypeptides, 90
- polysaccharide, 89
- positive feedback, 192
- posterior pituitary endocrine glands, 176t
- postsynaptic neuron, 163
- pox viruses, 217t
- predict outbreaks, 279
- presynaptic neuron, 163
- processing centre, 190
- prokaryotic cells, 6–7, 7f
and eukaryotic cells, 15–17, 16f, 17t
- prometaphase, 28
- prophase, 28
- prostaglandins, 241, 242f
- protein channel, 42
- protein-mediated active transport, 49
- proteins, 90–1, 91f, 91t, 92t
- proteins, synthesis of, 11, 11f
- protists, 221, 221f
- proximal tubule, 77
- PRRs. *See* pattern recognition receptors (PRRs)
- psychrophiles, 98–9
- Puccinia graminis*, 220t
- pyrodictium*, 99
- pyruvate, 117
- quarantine, 275–6, 276f
- R group, 90, 91f
- rate of diffusion, factors affecting, 56
- receptor binding, 179
cell sensitivity, 180–1
- receptors, 154
- red blood cells, 32, 32f
- renal pelvis, 77
- resin, 253
- resistance, 223
- respiratory system, 72
direction of gas exchange, 72–5, 72–4f
- resting potential, 162
restoration of, 163
- rhinoviruses, 217t
- ribosomes, 6, 12, 12f
- ringworm, 220, 267t
- rod-shaped bacterium, 219, 219f
- rotavirus, 269
- rough endoplasmic reticulum, 11, 11f
- roundworms, 222
- Salmonella typhi*, 272
- SARS. *See* severe acute respiratory syndrome (SARS)
- SARS-CoV-2, 217t, 280
- saturated fatty acids, 92, 93f
- saturation point, 100, 100f
- schistosomiasis, 269
- Schwann cells, 157, 158f
- selective reabsorption, 79
- selectively permeable, 40
- self substance, 236
- sensory neurons, 156, 159
and motor neurons, 161, 161f
- sensory receptors, 154, 155f, 155t
- serosa, 75
- severe acute respiratory syndrome (SARS), 274
- sieve plates, 137
- sieve tube cells, 137
- signal transduction, 165, 180
- signalling molecule, 176
- smallpox, 274, 278
- smooth endoplasmic reticulum, 12, 12f
- Snow, John, 277
- sodium–potassium pumps, 49, 162
- solute, 45
- solution, 45
- solvent, 45

- soma, 156
- South-East Asian blood fluke, 269
- specialised cells
 - epithelial cells, 30–1, 30–1*f*
 - goblet cells, 30, 30*f*
 - red blood cells, 32, 32*f*
- specific adaptive immune response, 237
- spiral-shaped bacterium, 219, 219*f*
- sporadically, 271
- starch, 90
- stem cells
 - potency of, 25, 26*f*, 27*f*
 - properties of, 24
- steroids. *See* hydrophobic hormones
- steroids, synthesis of, 12, 12*f*
- stimuli, 154
- stimulus–response model, 190–1, 190*f*
 - feedback, 191–3, 191–2*f*
- stomata, 132–4, 133*f*
- submucosa, 75
- substrate, 95
- substrate concentration, 100, 100*f*
- succulents, 140
- surface area-to-volume ratio (SA:V), 53–4, 54*f*, 54*t*
 - on cell size, 56–8
 - overcoming problems associated with, 55, 55*f*
 - rate of diffusion, factors affecting, 56
- susceptibility, 223–4, 224*f*
- symbiotic micro-organisms, 239, 240*f*
- synapse cleft, 163, 164*f*
- synaptic cleft, 163, 164*f*
- system specialisation
 - circulatory system, 70–1
 - digestive system, 75–6
 - excretory system, 76–80
 - hierarchy, 68–70, 69*f*
 - respiratory system, 72–5
- systemic acquired resistance, 254
- T cells, 245
- tapeworms, 222
- Taq* polymerase, 99
- telophase, 28
- temperature danger zone, 269
- temperature effects
 - enzyme, 98–9, 99*f*
 - mammalian mechanisms of controlling body, 195*f*
- thermogenesis, 199
- thermoreceptors, 154, 155*t*
- thermoregulation, 195, 195–202, 195*t*
 - behavioural responses, 196–8, 197–8*f*
 - endotherms, structural features of, 195–6, 195*f*, 196*f*
 - in humans, 199–202
 - physiological mechanisms, 198–9
- Thermus aquaticus*, 99
- thyroid, 176*t*
- tinea, 220, 267*t*
- Tinea pedis*, 220*t*
- tissue, 68
- tolerance limits, 193
- torpor, 197
- totipotent stem cell, 25, 26*t*
- toxins, 225–7, 237, 253
 - endotoxin, 225
 - exotoxins, 225–6
- tracheids, 137, 137*f*
- transmissible spongiform encephalopathies (TSEs), 217
- transmission
 - within neuron, 162–3, 163*f*
 - between neurons, 163–5, 164*f*
- transmission and spread of disease
 - analysing disease data, 276–81
 - factors affecting, 271–4
 - long-term immune response data, 281–5
 - modes of, 267–70, 267*t*
 - strategies to control, 275–6
- transpiration, 132, 139, 139*f*
 - adaptations to manage rate of, 140, 140*f*
 - factors affecting rate of, 140–3, 140*f*
- transpiration stream, 139
- Trichophyton rubrum*, 220*t*
- triglycerides, 92, 92*f*
- TSEs. *See* transmissible spongiform encephalopathies (TSEs)
- turgid, 47
- typhoid, 267*t*
- Typhoid Mary, 272
- unipotent stem cells, 25, 26*t*
- unsaturated fatty acids, 92, 93*f*
- upregulation, 180
- urea, 76
- urine, producing, 79–80, 79*f*
- vaccines, 249
- vacuoles, 13, 14*f*
- varicella zoster, 217*t*
- varicella zoster virus, 281
- vascular plant, structure of, 132
- vasodilation, 198, 198*f*, 241, 242*f*
- vasomotor control, 198, 198*f*
- vasopressin. *See* antidiuretic hormone (ADH)
- vCJD. *See* Creutzfeldt–Jakob disease (vCJD)
- vector, 269–70
- veins, 71
- vertebrates
 - adaptive immune response in, 245–9
 - innate immune response in, 238–41
- vesicles, 40, 164
- vessel elements, 137, 137*f*
- Vibrio cholera*, 218*t*
- villi, 75*f*, 76
- virulence factors, 224, 273
- water balance, feedback mechanism, 203
- water-soluble hormones, 177
- water splitting, 130
- waxy cuticles, 253
- wilt, 48
- World Health Organization, 276
- xerophytes, 140
- xylem, structure and function, 137, 137*f*
- Yersinia pestis*, 218*t*. *See* plague
- zygote, 24

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