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NATURE OF BIOLOGY

VCE UNITS 1 AND 2 FIFTH EDITION

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Judith KINNEAR
Marjory MARTIN

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This book is dedicated to friends and colleagues who generously shared their stories.

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Preface

This fifth edition of *Nature of Biology Book 1* builds on previous editions that were positively received by teachers and students of biology. It has been thoroughly revised and updated and reflects current curriculum decisions with regard to key knowledge and skills expected of biology students.

This book continues to seek to convey a multifaceted sense of biology: as a rigorous scientific discipline with explanatory models that organise the living world for us in a meaningful way; as a dynamic science whose explanations are subject to testing and change, rather than as a fixed and unchanging body of knowledge; as a science that influences everyday life, at the level of the individual where it can inform personal choices and at a societal level where it can inform community and government decisions.

We continue to emphasise recent developments in biotechnology as exemplified by developments in kidney dialysis and the advances in microscopy, such as the use of STED (**st**imulated **e**mission **d**epletion) to create super-resolved fluorescence microscopy, the subject of a Nobel Prize in 2014. We have placed emphasis on case studies relevant to Australia, such as heat stroke deaths in Australian deserts, as well as cases of global interest such as the discovery of complex microbial ecosystems deep under the Antarctic ice sheet.

This fifth edition includes both updated material relating to pre-existing curriculum topics and new material that reflects curriculum changes, such as exploration of key body systems and their malfunctions, the homeostatic mechanisms that regulate body temperature, water balance and blood glucose levels, and an introduction to Mendelian genetics. Relevant sites from the internet are identified for further investigation and research.

Included in each unit are examples to assist students to understand how biological knowledge and skills are applied in a variety of settings. The profiles of 'Biologists at work' are intended to increase student awareness of vocational opportunities. Updated or new profiles introduce a range of persons working in diverse roles such as a TV science reporter, a cardiac specialist, and a palaeontologist and astrobiologist whose discoveries in Western Australia include the oldest fossilised cells found on Earth. We hope that the range of 'Biologist at work' profiles may inspire some readers to explore the domain of biology further through their tertiary studies and become the researchers and the practitioners of the future, or the inspiring teachers of future students of biology.

We have enjoyed writing this book and we hope that our readers will also enjoy reading the text and exploring the visual images, and gain confidence as they grapple with and master the questions associated with each chapter.

This project was greatly enhanced by the generous cooperation of many academic colleagues and friends. In particular, we owe a special debt of gratitude to the following:

Dr John Priscu (Chief Scientist WISSARD project, University of Montana), JT Thomas (WISSARD photographer), Dr Brent C Christner (Louisana State University & WISSARD project), Mark McGrouther (Australian Museum), Dr Bruce Maslin (Department of Environment and Conservation WA), Dr Jonica Newby (ABC Catalyst), Dr Dave Wacey (University of Western Australia), Professor Andrew Taylor (Baker IDI Heart and Diabetes Research Institute), Mary and Jane Rice, Dr Sue Forrest (Australian Genome Research Facility), Dr Jan West (Deakin University), Dr Alison Murray (Nevada's Desert Research Institute), Dr Ian Miller, (Australian Institute of Marine Science), Karyn Jones (Head of Dialysis Unit Epworth Hospital), Carlos Pizzorna, Professor J Colin Murrell (University of East Anglia), Lisette Curnow (Royal Children's Hospital Melbourne), Dave Noble (NSW NPWS), Anthony Walker (ThermoSurvey, UK), Dr Brian Kubicki (Costa Rican Amphibian Research Center), Professor Stefan Hell (Max Planck Institute for Biophysical Chemistry), Dr Julian Sachs (University of Washington), Dr Jane Stout (Indiana University), Dr Torsten Wittmann (University of California, San Francisco), Dr Jan Peters and Dr Heidemarie Hurtl (Research Institute of Molecular Pathology, Vienna), Dr Jorg Reichwein (ATTO-TEC GmbH, Seigen Germany), Dr Alexia Loynton-Ferrand (University of Basel), Dr Kieran Boyle (University of Glasgow), Christopher F Hansen, Dr Carrine Blank (University of Montana), Dr Ewald R Weibel (University of Bern), Libby Sakker, Shane Williams (Arctic Heat), Stan Sheldon, Andrew Lock OAM, Dr Christine Cooper (Curtin University), Dr Fiona Wood (Royal Perth Hospital), Harry Chartomatsidis (Theo's Fish Bar) and Jethro Harcourt.

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How to use this book

Nature of Biology 1 VCE Units 1 and 2 has the following features.

CHAPTER

1 Cells: basic units of life on Earth

FIGURE 1.1 Dr John Priscu carries a Niskin bottle containing water from Lake Whillans, a subglacial lake in Antarctica. This water could provide evidence that microbial life exists in the extreme conditions of the lake. Key evidence for the existence of life would be the presence of living cells. In this chapter, we will explore the Lake Whillans project and examine some aspects of living cells. (Image courtesy of Dr J Priscu and JT Thomas)

KEY KNOWLEDGE

This chapter is designed to enable students to:

- appreciate the scope of life on planet Earth
- understand that cells are the basic units of structure and function of living organisms
- understand and apply the concept of surface-area-to-volume ratio
- list the defining characteristics of prokaryotic and eukaryotic cells
- recognise the plasma membrane as the boundary separating the cell from its external environment
- describe the various modes of transport across the plasma membrane.

An overview of the Key knowledge and outcomes addressed in this chapter

Odd facts provide real-life, engaging, biological examples.

ODD FACT

A single cell lining the small intestine may have up to 10 000 microvilli on its apical surface facing into the gut lumen. How would this affect the surface area available for absorption of digested nutrients, compared with a cell with no microvilli?

KEY IDEAS

- Cells are the basic structural and functional units of life.
- Cells are typically too small to be seen by an unaided eye.
- The unit of measurement used for cell size is the micrometre (μm), one millionth of a metre.
- Microbial cells are much smaller than plant and animal cells.
- The metabolic needs of a cell are determined by its metabolically active cytoplasmic volume.
- The ability of a cell to meet its metabolic needs is determined by the surface area of the cell.
- As a cell increases in size, its internal volume expands at a greater rate than the area of its plasma membrane.
- The surface-area-to-volume ratio (SA:V ratio) of a smaller object is higher than that of a larger object with the same shape.
- The continued decrease in SA:V ratio as metabolically active cells increase in size places an upper limit on cell size.

Key ideas panels provide a summary of the main points covered in this section. These are followed by Quick check revision questions.

QUICK CHECK

7 Identify whether each of the following statements is true or false.
- **a** Cells are typically too small to be seen with an unaided eye.
- **b** Bacterial cells are typically larger than animal cells.
- **c** Viral particles are smaller than microbial cells.
- **d** As a given shape increases in size, its surface-area-to-volume ratio increases.
- **e** Beyond a given cell size, the two-way exchange of materials across the cell surface cannot occur at a rate sufficient to meet the needs of a cell.

8 Two spheres (A and B) have different diameters, with A being larger than B. Which has the higher SA:V ratio?

References to studyON summary screens encapsulate key knowledge and provide questions with answers and worked solutions, to reinforce learning.

studyON

Unit 1 › AOS 1 › Topic 1 › Concept 2 **Prokaryotes** Concept summary and practice questions

Prokaryotes: no nuclear envelope!

The remarkable living community discovered deep under the Antarctic ice sheet in subglacial Lake Whillans consists of microbes belonging to two different classification groups (bacteria and archaea). The cells of all these microbes can be readily distinguished from the cells of the other major groups of living organisms: fungi, plants and animals. **The key distinguishing feature of archaea and bacteria is that their cells lack a membrane-bound nucleus** (see figure 1.18a). Cells with this characteristic are described as **prokaryotic** cells and organisms displaying this feature are called **prokaryotes**. Prokaryotes are generally assumed to be the oldest existing form of life on planet Earth. The absence of a distinct nucleus does *not* mean that prokaryotes, such as archaea and bacteria, lack genetic material. Like all other kinds of organism, archaea and bacteria have DNA in their cells, but the DNA in prokaryotic cells is dispersed, not enclosed within a separate membrane-bound compartment.

In contrast, the cells of all other organisms — protists, fungi, plants and animals — have a definite nucleus (see figure 1.18b). The nucleus is enclosed by a double membrane, called the **nuclear envelope**. Organisms with this feature are termed **eukaryotes** and their cells are described as being eukaryotic. The nucleus of a **eukaryotic** cell contains DNA, the genetic material of cells. In addition, eukaryotic cells contain many membrane-bound cell organelles that are not present in prokaryotic cells (see table 1.1).

CHAPTER 1 Cells: basic units of life on Earth 17

Biochallenge sections focus on applying knowledge in response to visual stimuli and data.

BIOCHALLENGE

Exploring the plasma membrane

1 The plasma membrane has been described as being like a 'train track'. This was because the first images of the plasma membrane showed it as two dark lines separated by a lighter region. Figure 1.40 shows part of the plasma membranes of two adjoining cells. The plasma membranes have been sectioned so that their surfaces are oriented horizontally at right angles into the plane of this page.

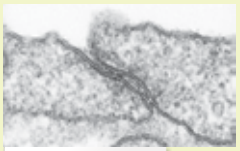

FIGURE 1.40 Plasma membrane

a How thick is the plasma membrane in nanometres? In micrometres?
b What kind of microscope was needed to produce the image in figure 1.40?
c What are the 'rails' of the train track composed of?
d What is present in the space between the rails?

2 Key information about the nature of the plasma membrane came from an experiment carried out in 1925 by two Dutch scientists. They took a known number of red blood cells and, based on the average size of these cells, they estimated their combined surface area. Then they extracted only the lipid from the plasma membrane of these cells and allowed it to spread out on a water surface where it formed a monolayer or single layer of molecules. (Remember, lipids will not mix with water!) To their surprise, the scientists found that the area of the lipid monolayer on the water surface was twice the combined surface area of the red blood cells that were the source of the lipid.

Consider this finding and suggest what key information this result provided about the structure of the plasma membrane.

3 In 1970, Frye and Edidin carried out an experiment in which they took a human cell and a mouse cell and fused them to form a human–mouse hybrid cell. They showed the distribution of the surface proteins on the plasma membrane of each cell by using anti-human and anti-mouse antibodies labelled with a different fluorescent dye. A red dye showed the positions of the surface proteins on the membrane of the human cell. A green dye showed the positions of the surface proteins on the membrane of the mouse cell.

Figure 1.41a shows the initial observation immediately after the fusion of the two cells. After 40 minutes, the researchers carried out a second observation and their findings are shown in figure 1.41b.

From the results of this experiment, which of the following is it reasonable to conclude?

a Surface proteins are fixed in position on the plasma membrane.
b Surface proteins from each cell type have fused.
c Surface proteins can move laterally across the plasma membrane.

4 True or false?

The results of this experiment provide support for the fluid mosaic model of membrane structure. Briefly explain.

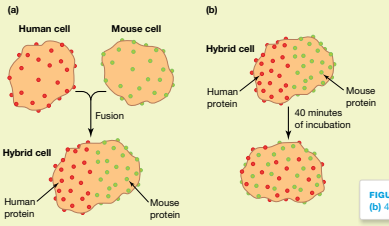

FIGURE 1.41 **(a)** Start of experiment **(b)** 40 minutes later

The studyON topic review has additional multiple choice, short answer and extended response questions; these are different to the end-of-chapter review questions.

A list of the key words used in the chapter to enhance the vocabulary of the student is provided.

Chapter review questions check and challenge students' understanding.

Chapter review

studyON
Unit 1
AOS 1
Topic 1
Cell size, structure and function
Sit topic test

Key words

active transport
aquaporins
archaea
bacteria
biogenesis
carrier proteins
cell membrane
cell surface markers
Cell Theory
channel proteins
endocytosis
eukaryotes
eukaryotic
exocytosis
extremophiles
facilitated diffusion
fluid mosaic model
glycoprotein
hydrophilic
hydrophobic
hypertonic
hypotonic
integral proteins
isotonic
lysosome
nuclear envelope
osmosis
peripheral proteins
phospholipids
pinocytosis
plasma membrane
prokaryotes
prokaryotic
proteins
pumps
receptors
selectively permeable
semipermeable
simple diffusion
sodium–potassium pump
surface-area-to-volume ratio
trans-membrane
vesicle

Questions

1 **Making connections** → The key words listed above can also be called concepts. Concepts can be related to one another by using linking words or phrases to form propositions. For example, the concept 'compound light microscope' can be linked to the concept 'lenses' by the linking phrase 'contains at least two' to form a proposition. An arrow shows the sense of the relationship: when several concepts are related in a meaningful way, a concept map is formed. Because concepts can be related in many different ways, there is no single, correct concept map. Figure 1.42 shows one concept map containing some of the key words and other terms from this chapter.

Use at least six of the key words above to make a concept map relating to the movement of substances across a cell membrane. You may use other words in drawing your map.

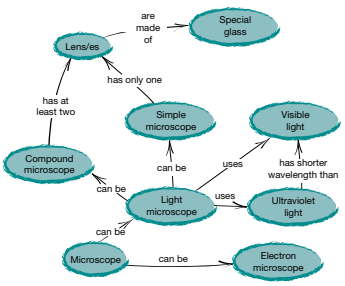

FIGURE 1.42 Example of a concept map

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CHAPTER

1 Cells: basic units of life on Earth

FIGURE 1.1 Dr John Priscu carries a Niskin bottle containing water from Lake Whillans, a subglacial lake in Antarctica. This water could provide evidence that microbial life exists in the extreme conditions of the lake. Key evidence for the existence of life would be the presence of living cells. In this chapter, we will explore the Lake Whillans project and examine some aspects of living cells. (Image courtesy of Dr J Priscu and JT Thomas)

KEY KNOWLEDGE

This chapter is designed to enable students to:

- appreciate the scope of life on planet Earth
- understand that cells are the basic units of structure and function of living organisms
- understand and apply the concept of surface-area-to-volume ratio
- list the defining characteristics of prokaryotic and eukaryotic cells
- recognise the plasma membrane as the boundary separating the cell from its external environment
- describe the various modes of transport across the plasma membrane.

Searching for life

Life abounds on planet Earth. In every habitat on this planet where life exists, living organisms are built of one or more cells.

Living organisms can exist only where:

- an **energy source** is available that can be trapped and utilised by an organism for metabolic processes that maintain its living state
- **liquid water** is available to allow biochemical reactions to occur, and to dissolve chemicals and transport them both within cells and to and from cells
- **the chemical building blocks required for life** are available for use by an organism in cellular repair, growth and reproduction. These chemical building blocks include carbon, oxygen, nitrogen and hydrogen, and each is able to form chemical bonds with other elements (see Odd fact). Carbon, in particular, is the most versatile chemical building block, as it can bond with many other elements, forming a variety of complex biomolecules, including long chains.
- **stable environmental conditions exist** within the range of tolerance of an organism, such as pressure, temperature, light intensity, pH and salinity.

Where these conditions are met, living organisms can use energy to perform the complex set of chemical transformations (metabolic activities) within their cells that sustains their living state. These activities include not only capturing energy but also taking up nutrients and water and removing wastes, so that their internal environment is kept within narrow limits.

Provided the above conditions can be met, life is possible even in extreme and hostile environments, such as:

- around superheated hydrothermal vents at crushing pressures deep in the mid-ocean (the world record holder is an archaeon that survives at high pressure and temperatures of 122 °C)
- in volcanic hot springs waters
- kilometres below the Earth's surface in mines
- in very acidic or very alkaline or extremely salty, or even radioactive bodies of water (see figure 1.2).

ODD FACT

Carbon (C) atoms can each form 4 bonds, oxygen (O) can form 2 bonds and hydrogen (H) can form 1 bond.

FIGURE 1.2 The Paralana radioactive hot springs near Arkaroola in the Flinders Ranges, South Australia. These radioactive hot springs are one of only three radioactive hot springs in the world. The waters are hot from the heat produced by the decay of underlying uranium-rich rocks that emit gamma radiation, and the water contains radon, a highly radioactive gas. Several microbial species including cyanobacteria thrive in these radioactive waters.

Organisms that live in these extreme environments are termed **extremophiles**. Most commonly, they are unicellular microbes — **bacteria** and **archaea**. Until the late 1970s all microbes were classified as bacteria. However, the microbiologist Carl Woese (1928–2012) was the first to recognise that, based on many biochemical differences, the group once known as 'bacteria' included two different groups of microbes. Members of this new group of microbes were given the label 'archaea' to differentiate them from classical bacteria.

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Extreme Slime: a *Catalyst* story

Given the existence of extremophiles in many harsh environments, one group of scientists set out to answer the question:

> Could living organisms thrive under nearly a kilometre of ice sheet in Antarctica in a frigid environment, in complete darkness and having been isolated from direct contact with the atmosphere, probably for thousands of years?

The answer to this question was to be found at Lake Whillans.

Reaching Lake Whillans

It is 28 January 2013. A scientist walks across the icy surface of Antarctica carrying a specialised container, known as a Niskin bottle, with its precious contents (refer to figure 1.1). (A Niskin bottle is a specialised water sampler that consists of an open tube with valves at each end that can be closed by remote control.) The scientist is Dr John Priscu, chief scientist for the WISSARD (**W**hillans **I**ce **S**tream **S**ubglacial **A**ccess **R**esearch **D**rilling) project. The Niskin bottle that he carries contains a sample of water collected from Lake Whillans.

Collecting water from a lake sounds like an easy task — just toss an empty container on a rope into a lake and pull the container out, full of water. However, this was not the case at Lake Whillans.

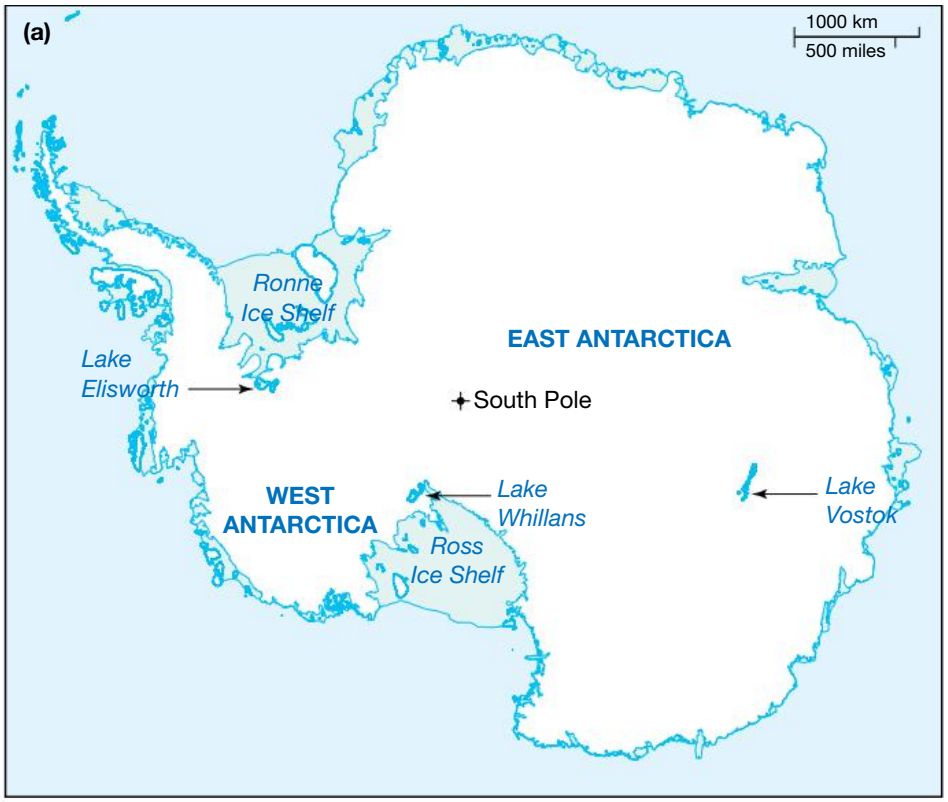
Obtaining a water sample from this lake was an enormous challenge because Lake Whillans is a subglacial lake in Antarctica and is buried under the pressure of an 800-metre-thick layer of ice. The lake is cold, is in complete darkness and, for at least tens of thousands of years, has been isolated from direct contact with the atmosphere (see figure 1.3a & b). The team that faced the challenge of reaching the lake comprised 50 scientists, drillers, technicians and other support staff. Not only did the team have to reach the lake, they then had to avoid introducing any contamination from the surface or the overlying ice into the lake.

How can subglacial water lakes exist in Antarctica? The water in these lakes remains liquid because of the flow of heat from the Earth's interior and the overlying pressure of the ice sheet. The heat causes very slow melting at the base of the ice sheet and the resulting water drips into the lake. Air bubbles trapped in the melting ice supply oxygen to the lake.

One of the questions that the scientists set out to answer was: does life exist in the extreme conditions of Lake Whillans? **To answer 'Yes' to this question requires demonstrating the key evidence for the existence of life, that is, the presence of living cells.** Evidence of living cells comes from demonstrating the existence of cells that show metabolic activity and are capable of self-replication.

In the process of drilling into the lake the scientists took extreme care to ensure that:

- the drilling equipment, Niskin bottles and other equipment that would enter the borehole and penetrate the lake were ultra-clean. This was achieved by sterilising this equipment using intense UV radiation and hydrogen peroxide spray (see figure 1.4). Following decontamination, the equipment was enclosed in sterile plastic wrapping for transport to the drilling site.
- the hot water used to drill through the ice sheet was sterilised using ultra-filtration and microbe-killing UV radiation.



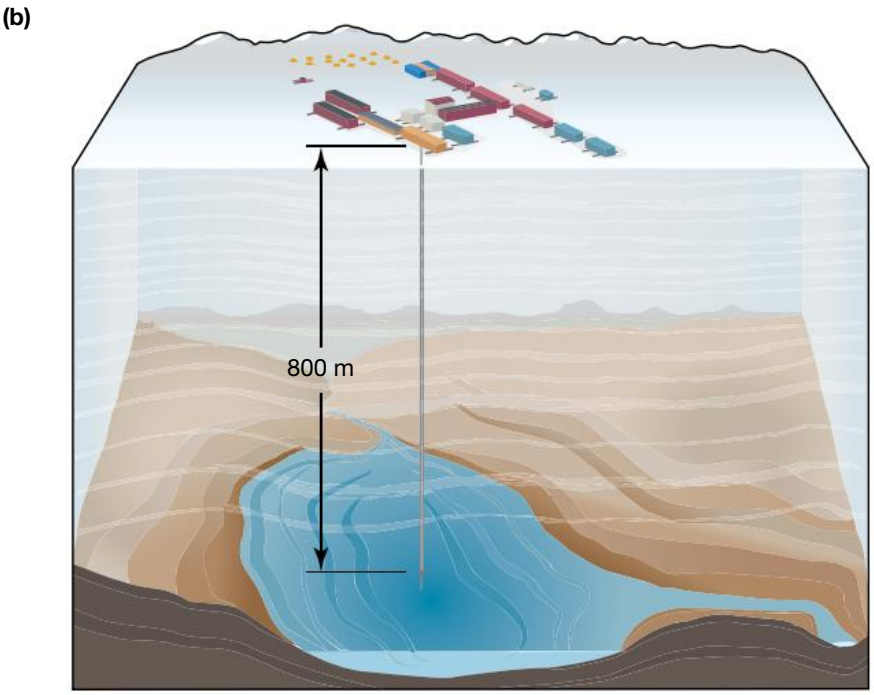


FIGURE 1.3 **(a)** Lake Whillans is located near the edge of the Ross Ice Shelf, 640 km from the South Pole. The lake is one of hundreds of subglacial lakes that have been identified in Antarctica using techniques such as air-borne radar and satellite-based radar altimetry. **(b)** Lake Whillans lies under an ice sheet that is 800 m thick.

Why were these precautionary steps taken? These rigorous sterile precautions were designed to prevent any cells from the surface or the overlying ice reaching the lake. This ensured that any living cells found in the samples from the lake originated from the lake itself and were not introduced contaminant cells from the surface.

Pressurised hot water was used to drill through the 800 m of ice overlying Lake Whillans. After seven days of drilling, the last layers of ice were broken

FIGURE 1.4 A piece of equipment is sterilised by spraying with hydrogen peroxide. This chemical is a powerful oxidising agent that acts as a biocide, or cell killer. Why was this precaution taken?

through and the lake was reached through a 60-centimetre-wide borehole. A Niskin bottle was inserted down the borehole into the water to obtain a water sample. The valves on the Niskin bottle were remotely closed and the bottle was raised to the surface (see figure 1.5a). Had the valves on the Niskin bottle closed? Was there a sample of lake water in the bottle? A quick check showed that the valves had closed, trapping the first water sample from Lake Whillans.

In total, the scientific team collected about 30 litres of lake water and eight samples of sediment from the lake bottom. These samples would allow the scientists to discover if living organisms were present in Lake Whillans.

The first sample of lake water from the Niskin bottle was carefully carried to a temporary field laboratory. Scientists extracted samples of lake water and began their examination (see figure 1.5b).

FIGURE 1.5 **(a)** Scientists Brent Christner (left) and John Priscu (right) retrieve the first water-sampling Niskin bottle from the borehole in subglacial Lake Whillans. (Image courtesy of JT Thomas) **(b)** Scientists processing water samples from Lake Whillans in the field laboratory

Signs of life under the ice?

The first test was to add a DNA-sensitive dye to a sample of the lake water. DNA is the genetic material of all cells. If cells were present in the lake water, this DNA-sensitive dye would reveal them as glowing green dots when viewed under a microscope. Imagine the scientists' delight when this test gave a positive result (see figure 1.6a). The presence of cells was a strong indication that microbial life existed in Lake Whillans . . . but were they living cells?

Scanning electron microscopy of the lake water samples showed that the microbial cells varied in shape and included rod-shaped, curved and spherical microbial cells. Figure 1.6b, for example, shows a spherical microbial cell against a background of sediment particles.

However, it was necessary to confirm that the cells were living. Living cells carry out a diverse range of metabolic activities, including uptake of nutrients, and synthesising DNA and proteins. When cells from samples of lake water were exposed to thymidine, one of the building blocks of DNA, the cells took up this compound and incorporated it into their DNA. This observation confirmed that the cells were living and undergoing cell division. Similar confirmation that the cells were metabolically active came from showing that they were synthesising proteins.

Active cell division of the lake microbes was revealed when samples of lake water were plated onto a nutrient medium and incubated. Individual microbial cells, too small to be seen with an unaided eye, underwent multiple cycles of cell division and produced visible colonies comprising millions of cells (see figure 1.6c).

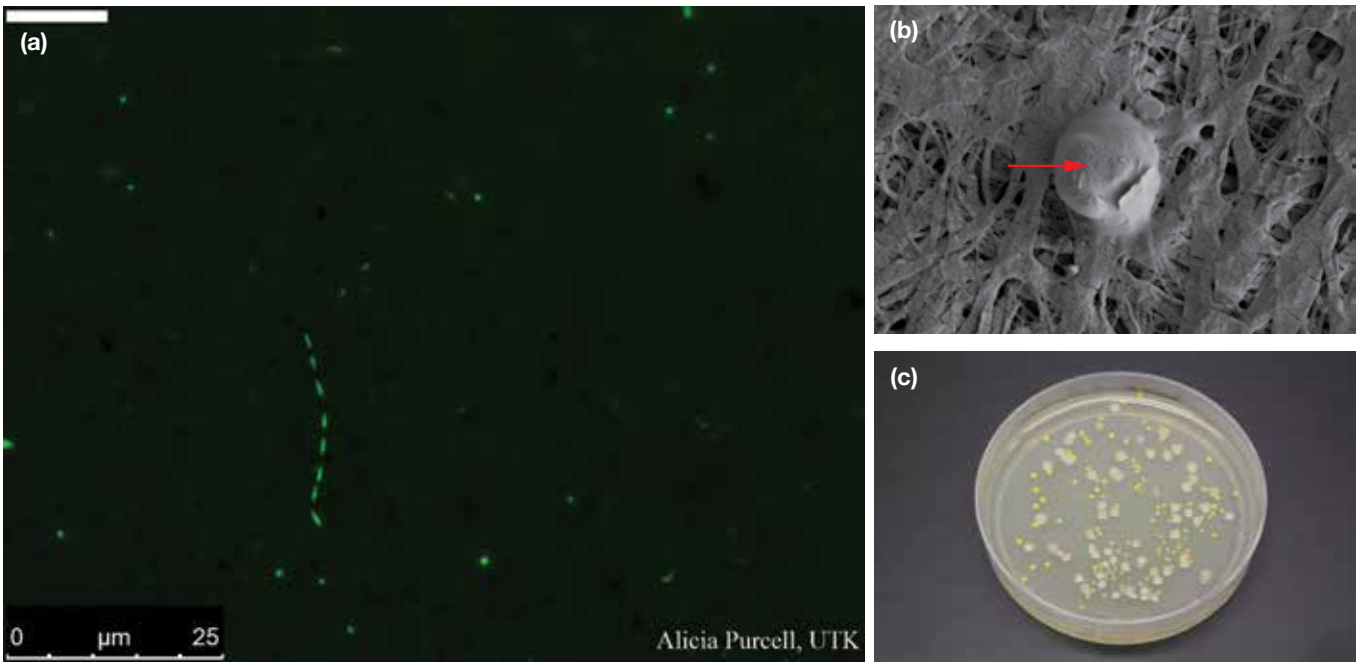


FIGURE 1.6 (a) Epifluorescence microscopy image of DNA-containing microbial cells (green) from the subglacial Lake Whillans water sample (Image courtesy of Dr A Purcell) **(b)** Scanning electron microscope image showing a coccoid-shaped microbial cell with an attached sediment particle from the subglacial Lake Whillans water column (Image courtesy of Trista Vick-Majors, Priscu Research Group, Montana State University) **(c)** Microbial colonies produced by multiple divisions of microbial cells from subglacial Lake Whillans. Different colours and shapes of the colonies indicate different microbial species. (Image courtesy of Dr B Christner)

After showing that living microbial cells existed in Lake Whillans, the scientists then set out to identify the different species. Back in the United States they used DNA sequencing techniques and identified more than 3900 different microbial species — bacteria and archaea — as part of the living community. The discovery of a living microbial community that obtains energy and the chemical building blocks required for life in the cold, dark environment of subglacial Lake Whillans is significant because:

- it provides the first unequivocal evidence of a complex ecosystem in a subglacial lake under the Antarctic ice sheet
- it highlights the possibility that life might exist beyond planet Earth, such as on distant ice-covered bodies in our solar system that conceal oceans below their frozen surfaces.

Life beyond Earth?

The discovery of a diverse microbial ecosystem hidden deep under the Antarctic ice sheet and away from sunlight raises the possibility that life may exist beyond planet Earth. Possible locations for extraterrestrial life include ice-covered moons that circle planets in our solar system. One such location is Europa, one of the large moons of the giant planet Jupiter.

Europa, with a diameter of 3144 kilometres, is a little smaller than Earth's moon (see figure 1.7a). Europa is a frozen world with an ice-covered surface, many kilometres thick and criss-crossed by long fractures (see figure 1.7b). In the period from 1996–99 the *Galileo* spacecraft made 11 flybys past Europa, capturing high-resolution images of the moon's surface and using its remote-sensing instruments to gain information about Europa. *Galileo* gathered strong evidence of a possible sub-surface ocean of salty water on Europa that is sandwiched between the moon's icy surface and its underlying rocky core. The surface of Europa constantly stretches and relaxes in tidal movements as it moves in an elliptical orbit around Jupiter every 3.5 days. The constant flexing of the surface generates heat that would keep a sub-surface ocean in the liquid state.

ODD FACT

The *Galileo* spacecraft was deliberately plunged into Jupiter's crushing atmosphere on 21 September 2003.

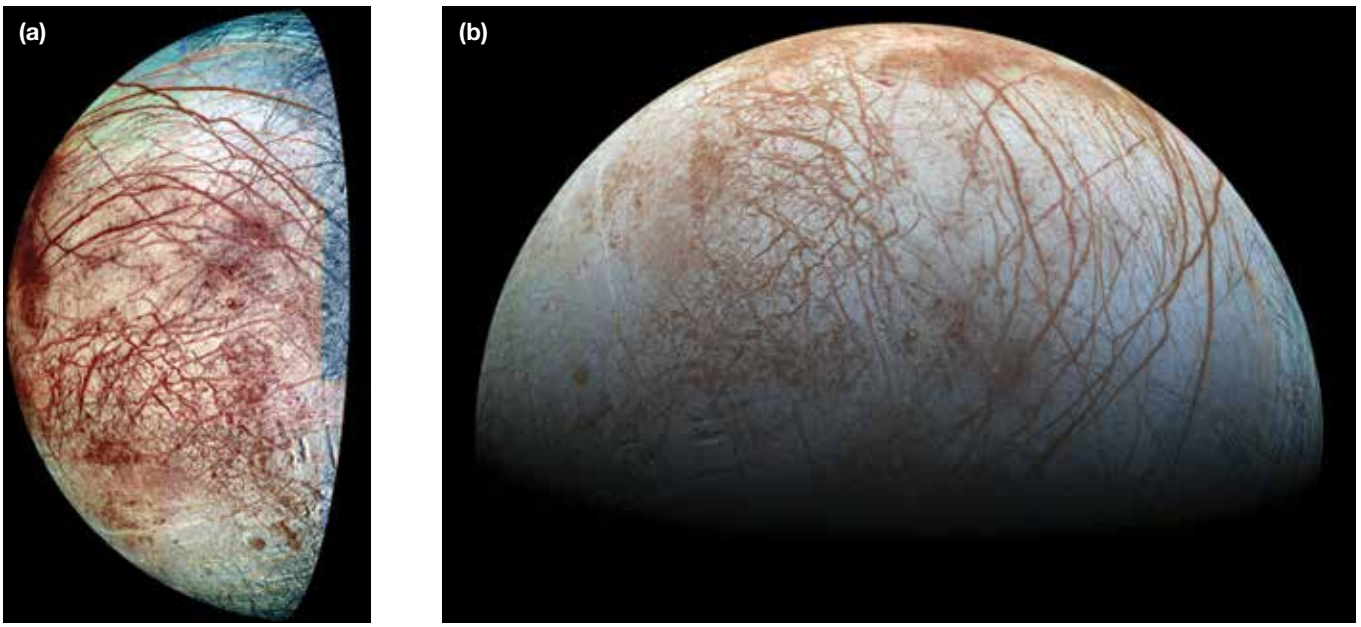


FIGURE 1.7 (a) Europa, a moon of Jupiter. This composite image, taken by the *Galileo* spacecraft, shows the long fractures on the moon's ice-covered surface. This ice may conceal what is regarded as 'perhaps the most promising place in our solar system beyond Earth to look for present-day environments that are suitable for life' (NASA Media Release, www.jpl.nasa.gov/news/news.php?feature=4386). **(b)** Close-up of the surface of Europa showing its fractured ice surface. The blue–white areas are pure water ice, while the ice in the reddish bands is mixed with salts such as magnesium sulfate or with sulfuric acid.

NASA: National Aeronautic and Space Administration

Dr Robert Pappalardo, a scientist from NASA, has described Europa as 'the most likely place to find life beyond Earth'. He continued:

> We think Europa is the most likely place for being habitable because of its relatively thin ice shell, its liquid ocean and that fact that it is in contact with the rock below which is geologically active . . . Europa has the right ingredients for life: it has water and the right chemical elements, as well as an environment that is probably stable over time.
>
> *Source:* As cited in *The Independent*, 15 February 2013.

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Weblink
NASA video — Europa

What might the future bring? If the presence of a sub-surface ocean on Europa is proved and if the conditions appear suitable for life, an unmanned probe might be sent to land on this moon, drill down to its ocean, sample its waters and look for signs of life. What would the most powerful signs of life be? Yes, cells.

KEY IDEAS

- On planet Earth, life exists in hostile and extreme environments and the organisms that survive there are termed extremophiles.
- For life to exist, a set of conditions must be met, including the availability of a source of energy and the presence of liquid water.
- Living cells have been found in a subglacial lake in Antarctica under hundreds of metres of ice sheet.
- The discovery of a diverse microbial ecosystem in a subglacial lake in Antarctica raises the possibility that life might exist under the surface of ice-covered moons in our solar system.
- Critical direct evidence of life (as we know it) is the presence of metabolically active cells.

QUICK CHECK

1. List the conditions that must be met for life to exist.
2. In drilling into Lake Whillans, great care was taken to ensure that the equipment that entered the borehole was sterilised. Why was this precaution taken?
3. What was the first evidence that indicated that it was possible life existed in Lake Whillans?
4. Identify the follow-up experiment that confirmed this finding.
5. What kinds of organism live in the Lake Whillans ecosystem?
6. Why is Europa, one of the moons of planet Jupiter, of interest as a possible location for life beyond planet Earth?

studyon

Unit 1 | AOS 1 | Topic 1 | Concept 1

Cells: structural units of life
Concept summary and practice questions

Cells: the basic units of life

Cells are the basic structural and functional units of life, and all living organisms are built of one or more cells. Cells, with only a very few exceptions, are too small to be seen with an unaided eye. Their existence was not recognised until after the development of the first simple microscopes. This enabled the first observations of cells to be made in the 1660s. However, the recognition of cells as the basic unit of life did not occur until almost 200 years later.

Cells: how big?

Cells are typically microscopic (not visible with an unaided eye). Only a few single cells are large enough to be seen with an unaided human eye, for example, human egg cells with diameters about 0.1 mm and the common amoeba (*Amoeba proteus*), a unicellular organism with an average size ranging from 0.25 to 0.75 mm. (You would see an amoeba as about the size of a full stop on this page.) Contrast this with one of the smallest bacteria, *Plelagibacter ubique*, consisting of a cell just 0.2 µm diameter. How many of these bacteria could fit across an amoeba that is 0.5 mm wide?

- Most animal cells fall within the size range of 10 to 40 µm. Among the smallest human cells are red blood cells with diameters for normal cells in the range of 6 to 8 µm.

1 millimetre (mm) = 1000 micrometres (µm)

1 micrometre (µm) = 1000 nanometres (nm)

studyon

Unit 1 | AOS 1 | Topic 1 | Concept 4

Cell size
Concept summary and practice questions

- Plant cells typically fall in the range of 10 to 100 µm.
- Microbial cells, both bacterial and archaeal, are much smaller than plant and animal cells. Most bacterial cells have diameters in the range of 0.4 to 2.0 µm and 0.5 to 5 µm in length. **On average, microbial cells are about 10 times smaller than plant and animal cells, with sizes typically in the few micrometres range.**

A *non-living* microworld exists beyond that of microbes. This is occupied by viruses that are non-cellular particles that are generally regarded as belonging to the grey area between living and non-living. Why? Because viruses do not have a cellular structure, they cannot carry out metabolic activities in isolation and they cannot self-replicate. (Viruses can replicate only inside and with the assistance of living cells.) Viruses range in diameter from 20 to 300 nanometres (nm); for example, the cold-causing rhinovirus is about 30 nm in diameter and the measles-causing virus is about 220 nm in diameter. Figure 1.8 shows a sample of the range of sizes seen in selected cells. (Other non-cellular structures are included for size comparison.)

Microbial cells are relatively much smaller than the cells of animals and plants, so some animal bacterial infections can involve the invasion of bacterial cells into the cells of the host, where they multiply. Examine figure 1.9 of a human lung fibroblast and note the presence of numerous bacterial cells in a single cell. This image highlights the size difference between microbial cells and the cells of animals (and plants).

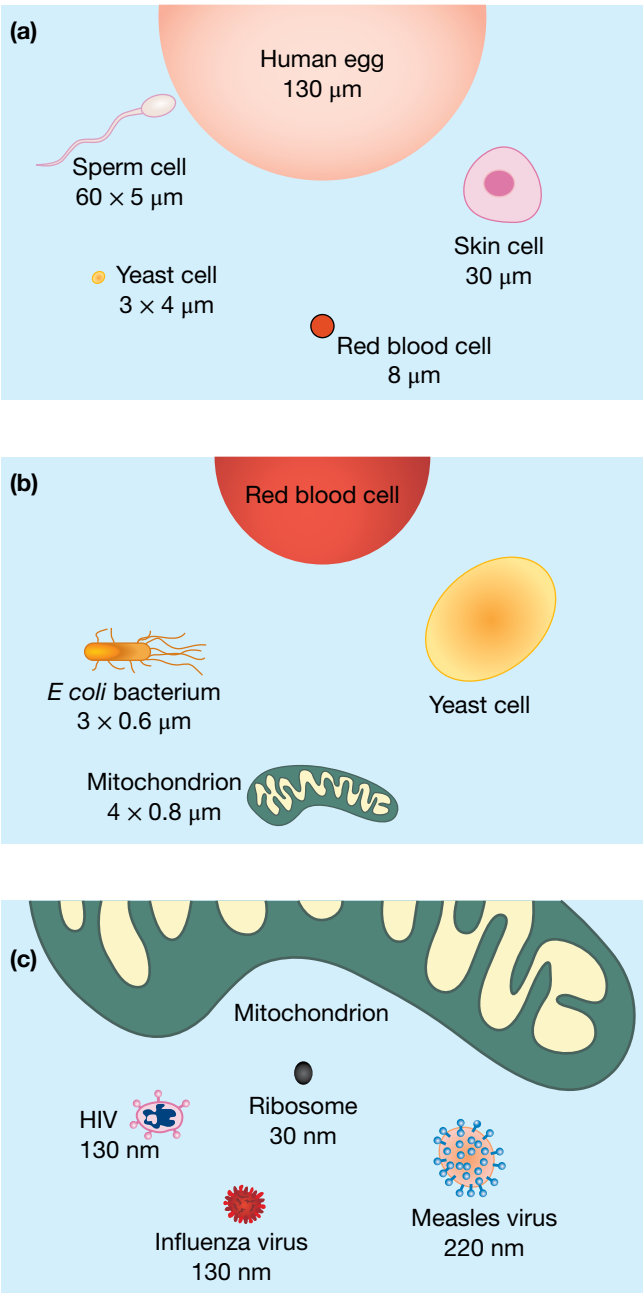
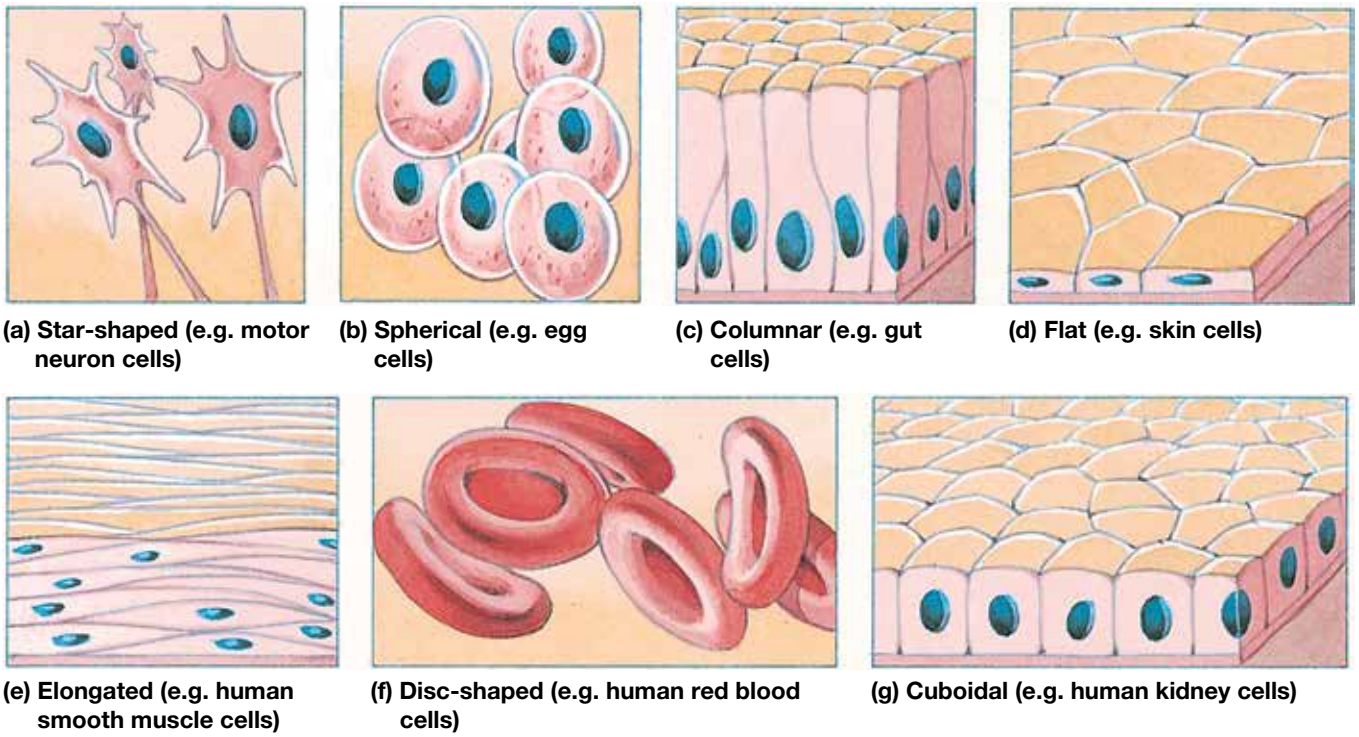


FIGURE 1.8 Diagrams, at increasing levels of magnification, showing cells, cell organelles and viruses. Note the extreme differences in size.
(a) Some human cells showing variation in cell size
(b) A bacterial cell with a mitochondrion, a cell organelle and other small cells shown for comparison
(c) A mitochondrion compared with some viruses

FIGURE 1.9 Transmission electron microscope (TEM) image of a lung fibroblast infected with many bacterial cells (shown as small dark circular and ovoid shapes). The bacteria are *Legionella pneumophila*, the cause of several infections in people, including Legionnaires' disease.

Cells: all sorts of shapes

There is no fixed shape for cells. Cells vary in shape and their shapes often reflect their functions. Figure 1.10 shows some examples of cell shapes. Scan this figure and note that some cells are thin and flattened, others are column-shaped, yet others are spherical.



(a) Star-shaped (e.g. motor neuron cells)
(b) Spherical (e.g. egg cells)
(c) Columnar (e.g. gut cells)
(d) Flat (e.g. skin cells)
(e) Elongated (e.g. human smooth muscle cells)
(f) Disc-shaped (e.g. human red blood cells)
(g) Cuboidal (e.g. human kidney cells)

FIGURE 1.10 Examples of variations in cell shape: **(a)** star-shaped **(b)** spherical **(c)** columnar **(d)** flat **(e)** elongated **(f)** disc-shaped **(g)** cuboidal

Look at figure 1.10a. Note the long axon that is a distinctive feature of motor neuron cells. These cells transmit nerve impulses from a person's spinal cord to voluntary muscles throughout the body. In this case, the shape of the nerve cell is fitted to its conductive function. Can you estimate the approximate length of a motor neuron that has its cell body in the lower spinal cord with its axon reaching to your big toe?

Look at figure 1.10e. Note the spindle-shaped smooth muscle cells. Smooth muscle cells contain special proteins that criss-cross the cell, and when these proteins contract the smooth muscle fibres shorten. The spindle shape of these cells is suited to their contractile function. Bundles of smooth muscle cells are found in the gut wall, in the walls of blood vessels, in ducts of secretory glands and in the wall of the uterus. These bundles of smooth muscle cells can generate sustained involuntary contractions in these organs.

Microbial cells also vary in shape (see figure 1.11). Note that some bacteria are rod-shaped, such as the gut-dwelling bacterium *Escherichia coli*; some are corkscrew-shaped, such as *Borrelia burgdorferi,* the causative agent of Lyme disease; while others are more or less spherical, such as *Streptococcus pneumonia*, the cause of many infections, including pneumonia.

ODD FACT

Motor neurons in animals, such as the giant squid (*Architeuthis* sp.), may be as long as 12 metres.

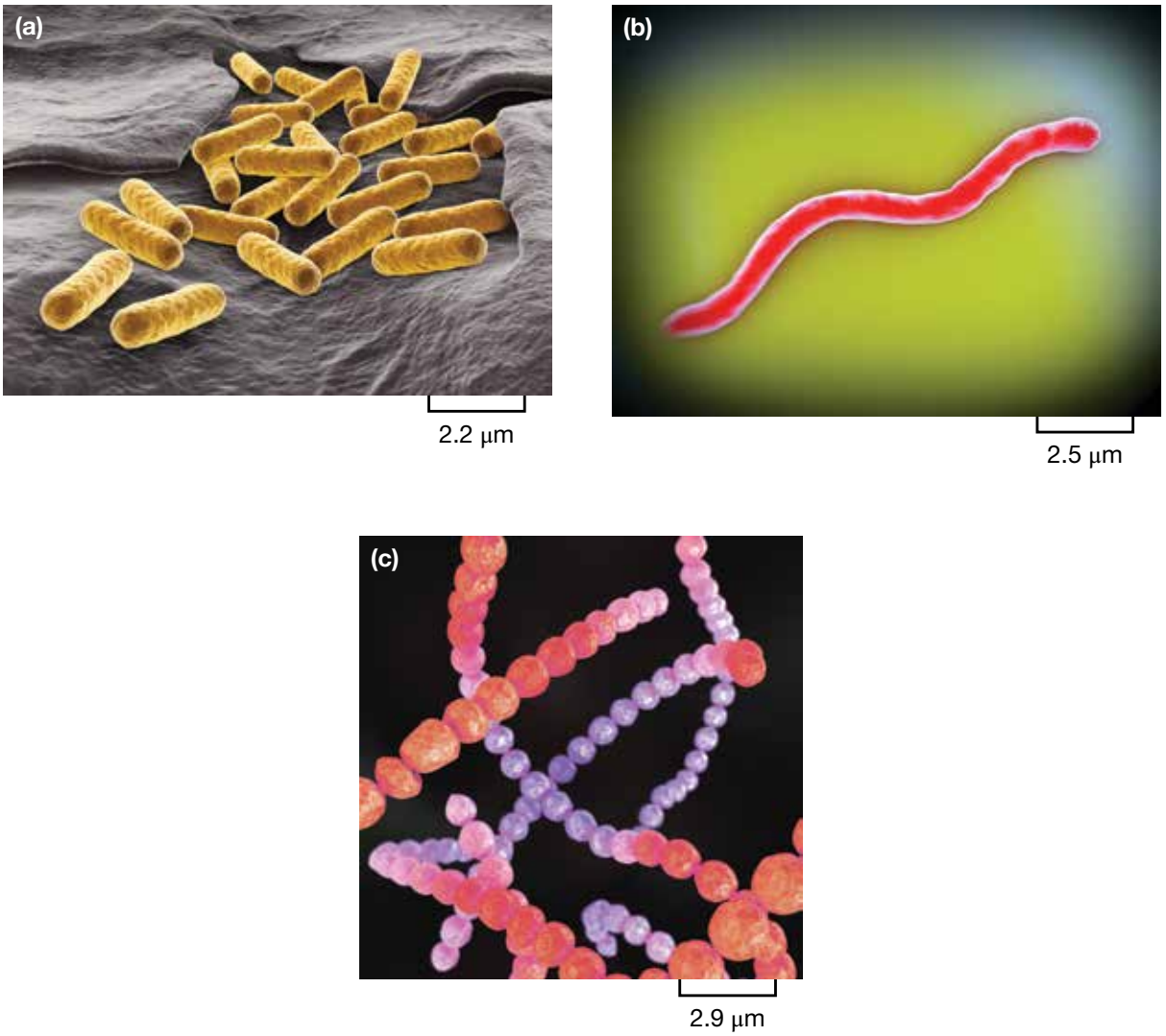
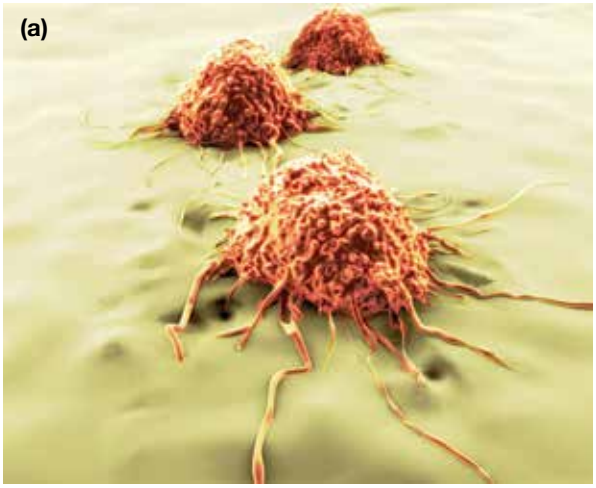


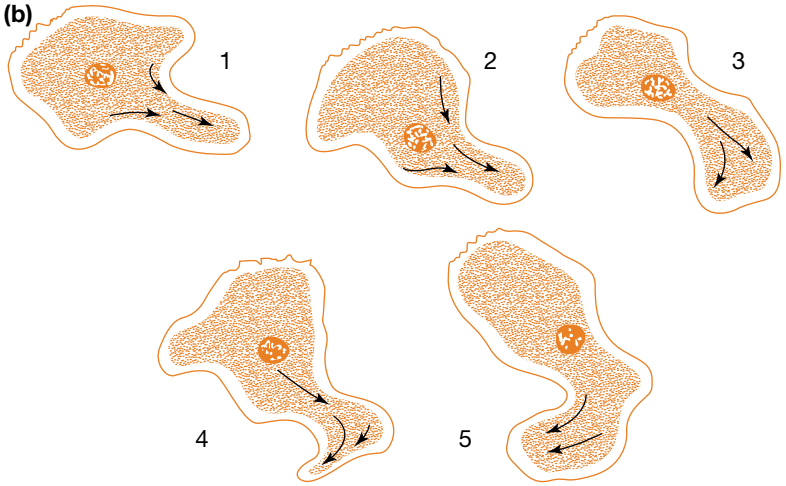
FIGURE 1.11 Bacterial cells come in many shapes. Some are **(a)** rod-shaped bacilli (singular: bacillus) **(b)** spiral-shaped and **(c)** spherical cocci (singular: coccus).

Not all cells have a fixed shape. For example, some cells are able to move actively, and these self-propelled cells do not have fixed shapes because their outer boundary is their flexible plasma membrane. So, as these cells move, their shapes change. Examples of cells capable of active self-propelled movement include:

- cancer cells that migrate into capillaries and move around the body when a malignant tumour undergoes metastasis (see figure 1.12a). The thread-like protrusions (known as filopodia) that fold out from the plasma membrane of cancer cells make a cancer cell self-mobile and able to migrate from a primary tumour and invade other tissues.
- white blood cells that can squeeze from capillaries into the surrounding tissues where they travel to attack infectious microbes (refer to figure 1.21, p. 22)
- amoebas as they move across surfaces (see figure 1.12b).

Some other cells that have a fixed shape because of the presence of a rigid cell wall outside their plasma membranes can self-propel. However, this ability depends on the presence of cilia or flagella to power their movement. For example, the green alga, *Chlamydomonas* sp., moves due to the beating of its two flagella (see figure 1.12c).





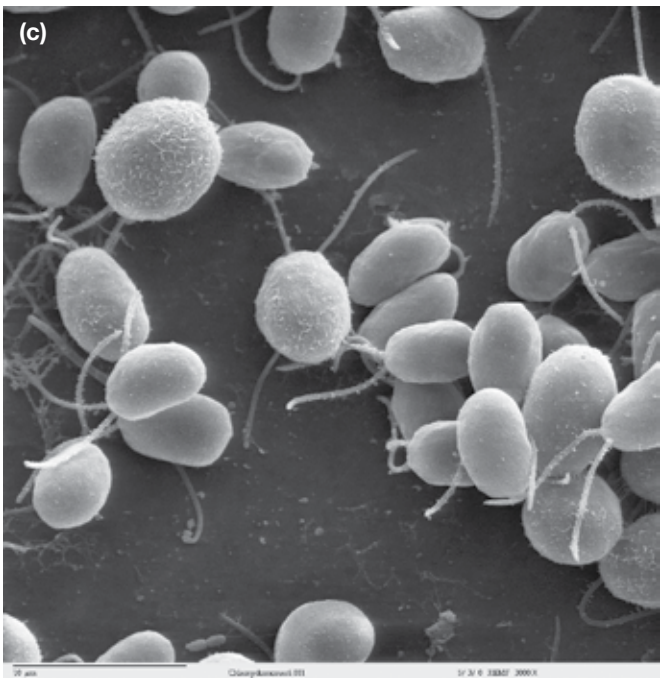


FIGURE 1.12 (a) Cancer cells. Note the many thread-like projections (filopodia) that enable these cancer cells to be mobile or self-propelling. The ability to move is an important factor in the spread of a malignant cancer. **(b)** Outlines showing the changing shape of an amoeba as it moves **(c)** Scanning EM image of *Chlamydomonas reinhardtii*, a single-celled green alga. Note the presence of two flagella that make this organism able to self-propel. What is the reason for the fixed shape of this organism? Like all algae, this organism has a rigid cell wall that defines its shape.

Cells: why so small?

Why are cells microscopically small? Would it be more efficient to have a larger macroscopic unit to carry out cellular processes rather than many smaller units occupying the same space? To answer these questions we need to look at the concept of surface-area-to-volume ratio.

Surface-area-to-volume ratio

Every living cell must maintain its internal environment within a narrow range of conditions, such as pH and the concentrations of ions and chemical compounds. At the same time, a cell must carry out a variety of functions that are essential for life. These functions include trapping a source of energy, obtaining the chemical building blocks needed for cellular repair, growth and reproduction, taking up water and nutrients, and removing wastes.

- These essential functions require a constant exchange of material between the cell and its external environment.
- The site of exchange where materials are moved into or out of a cell is the plasma membrane, also termed the cell membrane. The plasma membrane

must enable enough exchange between the external and internal environments to support these life functions.

- The exchange of materials must occur at rates sufficient to ensure that substances are delivered fast enough into cells to meet their nutrient needs and that wastes are removed fast enough from the cells to avoid their accumulation.

A critical issue in keeping a cell alive is the surface area of plasma membrane available to supply material to or remove wastes from the metabolically active cytoplasm of the cell. This can be quantified by a measure termed the **surface-area-to-volume ratio**, abbreviated SA:V ratio. This ratio provides a key clue to the answer to the question: why are cells so small?

Let us look at the SA:V ratio for some identical shapes of different sizes.

Consider some cubes.

The surface area of a cube is given by the equation:

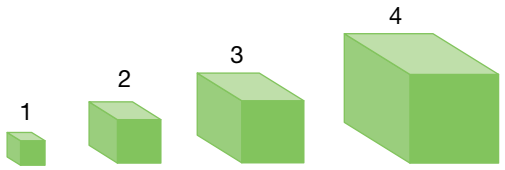
$$\mathbf{SA} = \mathbf{6L}^2$$

where L = the length of one side of the cube

The volume of a cube is given by the equation:

$$\mathbf{V} = \mathbf{L}^3$$

Examine figure 1.13. Note that as the cubes increase in size, their volumes enlarge faster than their surface areas expand. As the side length doubles, the surface area increases by 4 but the volume increases by 8. This is reflected in a decrease in the SA:V ratio as the cube grows bigger.



Length of side	1	2	3	4
Surface area	6	24	54	96
Volume	1	8	27	64
SA:V	6:1	3:1	2:1	3:2

FIGURE 1.13 The surface area (SA) and volume (V) of cubes with increasing side lengths (L). With each increase in the length of a side, an increase occurs in both the surface area and the volume of the cube. Do these two measures increase at the same rate? If not, which parameter — surface area or volume — increases more rapidly?

This generalisation applies to other shapes; that is, the SA:V ratio of a smaller object is higher than that of a larger object with the same shape. The higher the SA:V ratio, the greater efficiency of two-way exchange of materials across the plasma membrane; that is, efficient uptake and output of dissolved material is favoured by a high SA:V ratio.

The same principle applies to cells. **As cells increase in size through an increase in cytoplasm, both their surface areas and volumes increase, but *not* at the same rate. The internal volumes of cells expand at a greater rate than the areas of their plasma membrane.** This means that the growth of an individual cell is accompanied by a relative decrease in the area of its plasma membrane.

The metabolic needs of a cell increase in proportion to the volume of metabolically active cytoplasm. But, the inputs/outputs of materials to meet these needs increase only in proportion to the cell surface area. So, as a cell increases in cytoplasmic volume, its metabolic needs increase faster than the cell's ability to transport the materials into and out of the cell to meet those needs. The continued decrease in SA:V ratio as metabolically active cells increase in size places an upper limit on cell size. This is the one clue to why metabolically active cells are so small.

In general, the rate at which nutrients enter and wastes leave a cell is inversely proportional to the cell size, as measured in metabolically active cytoplasm; in other words, the larger the cell, the slower the rate of movement of nutrients into and wastes out of a cell. **Beyond a given cell size, the two-way exchange of materials across the plasma membrane cannot occur fast enough to sustain the volume of the cell contents.** If that cell is to carry out the functions necessary for living, it must divide into smaller cells or die.

Some cells show features that compensate for the decrease in SA:V ratio with increasing size. This occurs, for example, in the cells that function in the absorption of digested nutrients from your small intestine. These cells greatly increase their surface area with only a minimal increase in cell volume. How is this achieved? This is achieved by means of extensive folding of the plasma membrane on the cell surface that faces into the gut lumen (see figure 1.14). These folds are termed microvilli (singular: microvillus). Surfaces of other cells with either a major absorptive or secretory function also show microvilli. Another compensatory strategy seen in some cells involves their overall shape; SA:V ratio is higher in a long thin cell than in a spherical cell.

ODD FACT

Surface-area-to-volume ratio considerations apply not only to individual cells but also to entire organisms; for example, the sea anemone has many thin tentacles, each armed with stinging cells — these provide a greatly increased surface area for gaining nutrients for the whole animal (as compared with a single flat sheet of cells).

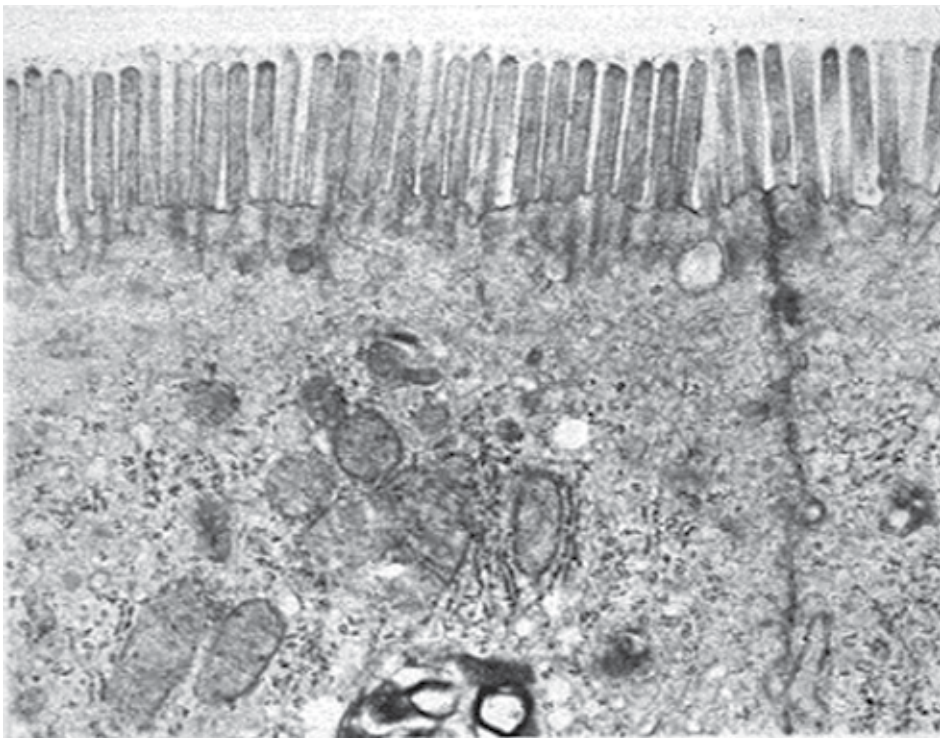


FIGURE 1.14 TEM image showing a section through part of two cells from the lining of the small intestine. Note the multiple folds of the plasma membranes on the apical surfaces of these cells (the apical surface faces into the intestinal space, or lumen). These folds, known as microvilli, produce a great increase in the surface area for absorption of digested nutrients. Does the folding also produce a great increase in cell volume?

SEEING, THEN INTERPRETING CELLS

When he examined thin slices of cork using a simple microscope, the Englishman Robert Hooke (1635–1703) became the first person to see and record evidence of cells. What Hooke saw, using his simple microsope, were not living cells, but the cell walls of dead and empty plant cells (see figure 1.15b). In his book *Micrographia*, published in 1665, Hooke used the word 'cell' to describe these structural units. 'Cell' is short for the Latin word *cellula* that means 'little compartment'. Hooke's observations were significant because he was the first person to recognise that the plant material had an organised structure that was built of small units, visible only through a microscope.

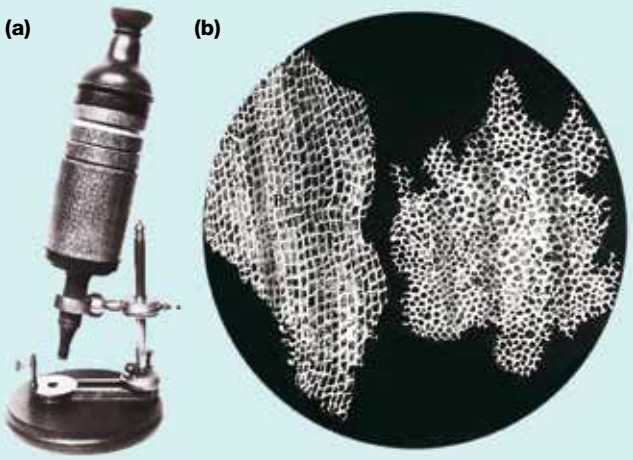


FIGURE 1.15 (a) The microscope built by Robert Hooke that he used to make his first observations of 'little compartments', or cells **(b)** First drawing made by Hooke in 1665 of 'cells' from a thin piece of cork. Were these living cells?

In the 1670s, a Dutch cloth merchant, Anton van Leeuwenhoek (1632–1723), built a simple microscope and was then the first person to see and record living cells that he called 'little animacules' (see figure 1.16). These cells were crescent-shaped bacteria present in a scraping of plaque from between his teeth.

However, until the nineteenth century the findings of Hooke and Leeuwenhoek were regarded as isolated and unrelated observations.

Early in 1838, a German botanist, Matthias Schleiden (1804–81), carried out microscopic examinations of a variety of plant tissues and came to the conclusion that cells were the basic structural unit of all plants. Early in the following year, a German physiologist, Theodor Schwann, (1810–82) having examined various animal tissues recognised that animals were built of cells. At that time, however, plant and animal cells were not seen as having much in common, so no link was made between these separate observations of plant and animal cells; they were regarded as separate worlds. Theodor Schwann also discovered the digestive enzyme pepsin and that yeast was a living organism, and introduced the term 'metabolism'.

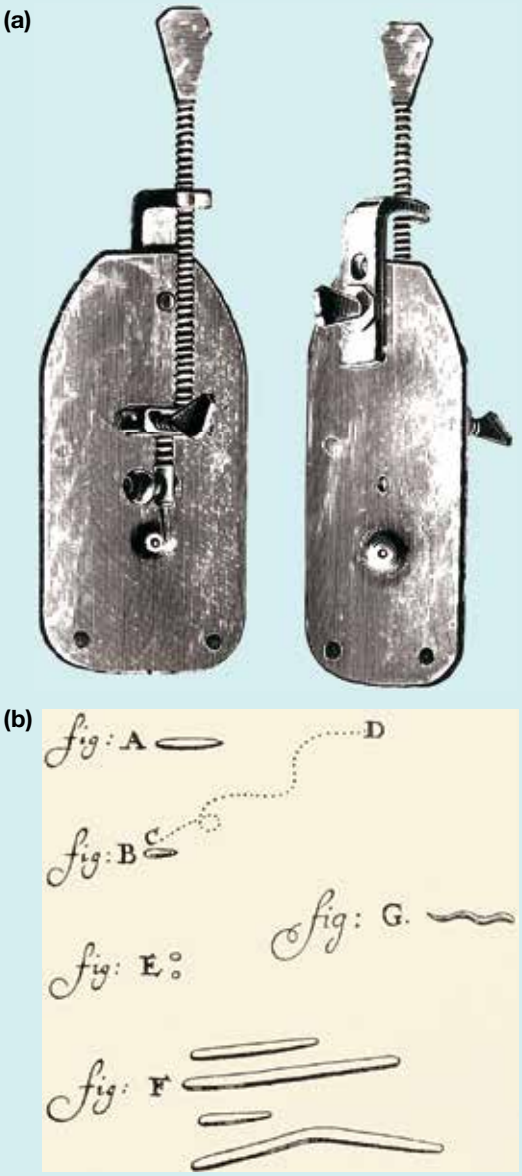


FIGURE 1.16 (a) The simple microscope built by Leeuwenhoek that revealed 'little animacules'. The specimen was placed on top of the pin, the microscope was held up to the eye and viewed through a quartz lens just 2 mm wide. **(b)** Some of the 'little animacules' seen by Leeuwenhoek — these were various bacteria.

(continued)

In October 1839, Schleiden and Schwann were chatting over dinner. Schleiden mentioned that another botanist, Robert Brown, had examined a variety of plant cells and found that all the cells contained a large organelle that Brown called the nucleus. (Robert Brown (1773–1858) was the botanist on the *Investigator* voyage from 1801–03 captained by Matthew Flinders, who charted the coastline of Australia.) Schwann realised that he had seen a similar structure in animal cells. Schleiden and Schwann then understood that cells were the common basic structural unit of all plants and all animals. This insight, now known as the **Cell Theory**, is one of the major unifying themes of biology.

The cell is the fundamental structural and functional unit of all living organisms.

The Cell Theory also applies to the complex microbial world that was first seen by Leeuwenhoek in the 1670s. All microbes, both bacteria and archaea, are composed of cells, the basic units of all living organisms.

Later, the Cell Theory was extended by the work of the German biologist Rudolf Virchow (1821–1902) and the French biologist Louis Pasteur (1822–95). In 1858, Virchow formulated the concept of **biogenesis** (bio = life; genesis = origin) that stated that cells arise only from pre-existing cells. Conclusive evidence for this concept was provided by experiments carried out by Pasteur, who in 1862 showed that:

All new cells are produced by pre-existing cells.

Figure 1.17 shows examples of plant and animal tissues. Examine each tissue in turn and see that it is composed of smaller units called cells that can differ in size and shape.

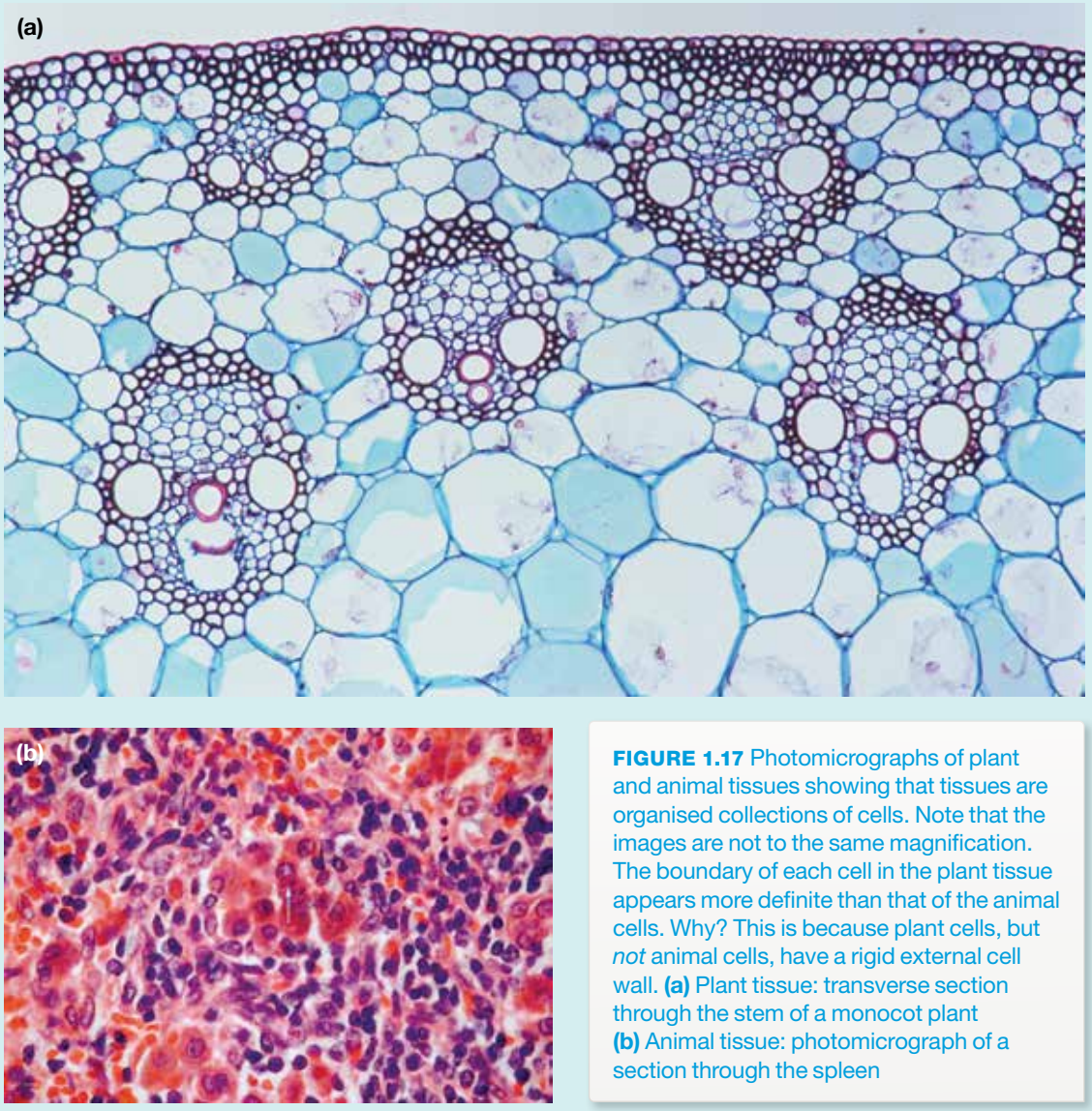


FIGURE 1.17 Photomicrographs of plant and animal tissues showing that tissues are organised collections of cells. Note that the images are not to the same magnification. The boundary of each cell in the plant tissue appears more definite than that of the animal cells. Why? This is because plant cells, but *not* animal cells, have a rigid external cell wall. **(a)** Plant tissue: transverse section through the stem of a monocot plant **(b)** Animal tissue: photomicrograph of a section through the spleen

ODD FACT

A single cell lining the small intestine may have up to 10 000 microvilli on its apical surface facing into the gut lumen. How would this affect the surface area available for absorption of digested nutrients, compared with a cell with no microvilli?

KEY IDEAS

- Cells are the basic structural and functional units of life.
- Cells are typically too small to be seen by an unaided eye.
- The unit of measurement used for cell size is the micrometre (μm), one millionth of a metre.
- Microbial cells are much smaller than plant and animal cells.
- The metabolic needs of a cell are determined by its metabolically active cytoplasmic volume.
- The ability of a cell to meet its metabolic needs is determined by the surface area of the cell.
- As a cell increases in size, its internal volume expands at a greater rate than the area of its plasma membrane.
- The surface-area-to-volume ratio (SA:V ratio) of a smaller object is higher than that of a larger object with the same shape.
- The continued decrease in SA:V ratio as metabolically active cells increase in size places an upper limit on cell size.

QUICK CHECK

7 Identify whether each of the following statements is true or false.
- **a** Cells are typically too small to be seen with an unaided eye.
- **b** Bacterial cells are typically larger than animal cells.
- **c** Viral particles are smaller than microbial cells.
- **d** As a given shape increases in size, its surface-area-to-volume ratio increases.
- **e** Beyond a given cell size, the two-way exchange of materials across the cell surface cannot occur at a rate sufficient to meet the needs of a cell.

8 Two spheres (A and B) have different diameters, with A being larger than B. Which has the higher SA:V ratio?

studyon

Unit 1 › AOS 1 › Topic 1 › Concept 2

Prokaryotes
Concept summary and practice questions

Prokaryotes: no nuclear envelope!

The remarkable living community discovered deep under the Antarctic ice sheet in subglacial Lake Whillans consists of microbes belonging to two different classification groups (bacteria and archaea). The cells of all these microbes can be readily distinguished from the cells of the other major groups of living organisms: fungi, plants and animals. **The key distinguishing feature of archaea and bacteria is that their cells lack a membrane-bound nucleus** (see figure 1.18a). Cells with this characteristic are described as **prokaryotic** cells and organisms displaying this feature are called **prokaryotes**. Prokaryotes are generally assumed to be the oldest existing form of life on planet Earth. The absence of a distinct nucleus does *not* mean that prokaryotes, such as archaea and bacteria, lack genetic material. Like all other kinds of organism, archaea and bacteria have DNA in their cells, but the DNA in prokaryotic cells is dispersed, not enclosed within a separate membrane-bound compartment.

In contrast, the cells of all other organisms — protists, fungi, plants and animals — have a definite nucleus (see figure 1.18b). The nucleus is enclosed by a double membrane, called the **nuclear envelope**. Organisms with this feature are termed **eukaryotes** and their cells are described as being eukaryotic. The nucleus of a **eukaryotic** cell contains DNA, the genetic material of cells. In addition, eukaryotic cells contain many membrane-bound cell organelles that are not present in prokaryotic cells (see table 1.1).

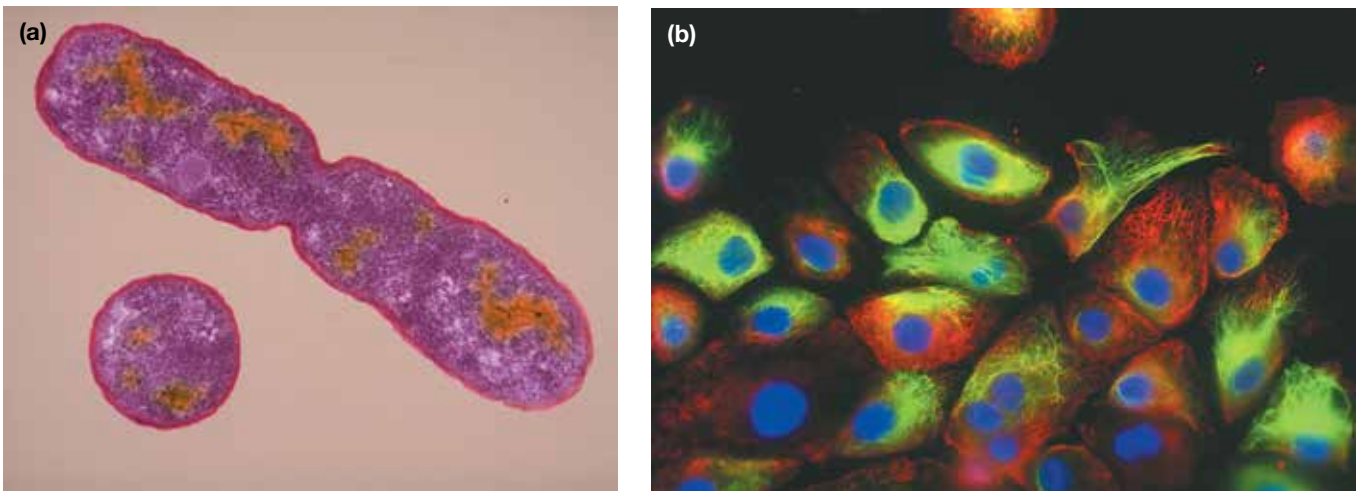


FIGURE 1.18 Images of cells (not to same magnification) **(a)** Image of prokaryotic cells. One is in the process of dividing. Note that the cells do not have a discrete nucleus enclosed within a membrane. Instead, the genetic material (stained orange) is dispersed. **(b)** A confocal fluorescence microscope view of human breast cells, examples of eukaryotic cells. The position of the nucleus that encloses the genetic material is shown by the discrete blue area within each cell. The cells have been treated with special stains to highlight two different cytoskeleton proteins: vimentin (green), found in cells within cancerous tissue, and keratin (red).

Comparing prokaryotes with eukaryotes

pro = before + *karyon* = kernel, nucleus

eu = well, good + *karyon* = kernel, nucleus

Figure 1.19 shows the structure of a typical prokaryotic cell in comparison with a eukaryotic cell. Note that a prokaryotic cell has a simple architecture in contrast to a eukaryotic cell that has a more elaborate structure owing to the presence of many membrane-enclosed compartments within the cell.

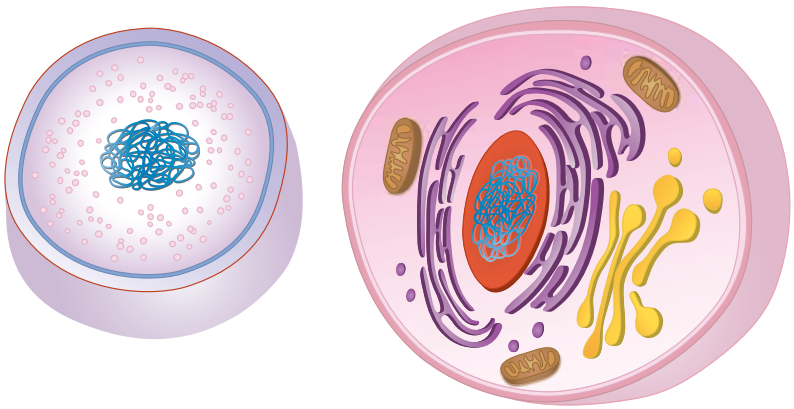


FIGURE 1.19 Diagram showing a basic comparison of a prokaryotic cell (left) and a eukaryotic cell (right). The key distinction between these cells is the presence in the eukaryotic cell of only membrane-bound organelles, in particular the nucleus that contains the genetic material, DNA. (Cells are not drawn to scale.)

Table 1.1 outlines a comparison between the structures of prokaryotic and eukaryotic cells. The critical difference is the absence of membrane-enclosed organelles in prokaryotes, in contrast to eukaryotic cells. We will explore details of eukaryotic cells in chapter 2.

In general, prokaryotic cells are about 10 times smaller than eukaryotic cells. However, size is *not* an absolute distinction; there are some rare exceptions:

- Large prokaryotic cells exist, such as the giant bacterium, *Thiomargarita namibiensis,* (0.1 × 0.3 mm in diameter) that lives in the muddy sea floor off the coast of Namibia.
- Relatively small eukaryotic cells exist, such as the single-celled green alga, *Ostreococcus tauri* that is just 0.8 µm in diameter.

TABLE 1.1 Comparison of prokaryotic and eukaryotic cells.

Feature	Prokaryote	Eukaryote
size	small: typically ~1–2 µm diameter	larger: typically in range 10–100 µm
chromosomes	present as single circular DNA molecule	present as multiple linear DNA molecules
ribosomes	present: small size (70s)	present: large size (80s)
plasma membrane	present	present
cell wall	present and chemically complex	present in plants, fungi, and some protists, but chemically simple; absent in animal cells
membrane-bound nucleus	absent	present
membrane-bound cell organelles	absent	present; e.g. lysosomes, mitochondria
cytoskeleton	absent	present

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In general, prokaryotic cells are unicellular and the great majority of eukaryotes are multicellular. However, it cannot be assumed for certain that a unicellular organism is a prokaryote (either a bacterium or an archaean), because a number of eukaryotes are unicellular. Unicellular eukaryotes are protists, such as *Amoeba*, *Paramecium* and *Euglena*, some algae such as *Chlorella* and the diatoms, and fungi such as yeasts.

While there are some differences in aspects of the structure of eukaryotic and prokaryotic cells, there are many similarities in their structures and functioning. These common features reflect the inter-connectedness of life forms.

For example, both prokaryotic and eukaryotic cells:

- have DNA as their genetic material; however, in comparison with eukaryotes, prokaryotes have only about 0.001 times the amount of DNA
- have plasma membranes that selectively control the entry and exit of dissolved materials into and out of the cell
- use the same chemical building blocks including carbon, nitrogen, oxygen, hydrogen and phosphorus, to build the organic molecules that form their structure and enable their function
- produce proteins through the same mechanism (transcription of DNA and translation of mRNA on ribosomes)
- use ATP as their source of energy to drive the energy-requiring activities of their cells.

One or more compartments?

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What is strikingly different is that every prokaryotic cell is a single compartment, with no further subdivisions of the cell. This is in contrast to eukaryotic cells that are organised internally into various compartments, each enclosed by a membrane. Because of the multi-compartmental structure of eukaryotic cells, their ultrastructure is more complex than that of prokaryotic cells.

Table 1.2 shows the relative volumes of the different compartments in a eukaryotic cell, a liver cell.

TABLE 1.2 Relative volumes of the major compartments within a liver cell

Intracellular compartment	Percentage of total cell volume*
cytosol	54
mitochondria	22
rough endoplasmic reticulum	9
smooth endoplasmic reticulum	6
nucleus	6
lysosomes, peroxisomes, endosomes	3

*More than half of the cell volume is occupied by the cytosol.

The multicompartment structure of a eukaryotic cell enables it to maintain different conditions within each membrane-enclosed compartment that are suitable for the particular function of that compartment. Think about a house that is subdivided into rooms with different functions: you shower in the bathroom, not in the kitchen; the stove is in the kitchen, not in the bedroom. A eukaryotic cell can be likened to a house — its many compartments are like different rooms where different tasks are carried out. (In chapter 2, we will explore these various compartments in eukaryotic cells.)

KEY IDEAS

- Prokaryotic cells lack a membrane-bound nucleus, and organisms lacking a nuclear envelope are termed prokaryotes — bacteria and archaea.
- Prokaryotes differ from eukaryotes in the absence of membrane-bound cell organelles of any kind.
- Eukaryotic cells are typically about ten times larger than prokaryotic cells.
- Eukaryotic cells have a membrane-bound nucleus in addition to other membrane-bound organelles.
- Organisms built of cells that have a nucleus enclosed within a nuclear envelope are termed eukaryotes — protists, fungi, plants and animals.

QUICK CHECK

9 Identify whether each of the following statements is true or false.
- **a** Prokaryotes are unicellular organisms, comprising bacteria and archaea.
- **b** The presence of a membrane-bound nucleus in its cells provides evidence that an organism is a eukaryote.
- **c** All eukaryotes are multicellular organisms.
- **d** The various compartments within eukaryotic cells would be expected to have identical conditions.

10 List two similarities between prokaryotic and eukaryotic cells.

11 A unicellular organism was found in a sample of pond water. Is it reasonable to conclude that this organism must be either a bacterium or an archaeon? Briefly explain.

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Unit 1 AOS 1 Topic 2 Concept 1

Structure of the plasma membrane
Concept summary and practice questions

Plasma membrane: the gatekeeper

The cells of all living organisms have a boundary that separates their internal environment from the external environment of their surroundings. From single-celled organisms, such as amoebae or bacteria, to multicellular organisms, such as mushrooms, palm trees and human beings, each of their cells has an active boundary called the **plasma membrane**, also known as the **cell membrane**.

The plasma membrane forms the outer boundary of the living compartment of every cell. Within this compartment, conditions can be established that differ from those in the external environment and that support the living state. The plasma membrane can exclude some substances from entering the cell, while permitting entry of other substances and elimination of yet other substances. Without such a boundary, life could not exist, and indeed could not have evolved.

The plasma membrane boundary can be thought of as a busy gatekeeper selectively controlling the entry and exit of materials into and out of cells. As such, the plasma membrane is said to be **semipermeable** or **selectively permeable**,

meaning that it allows only some substances to cross it — in or out — by diffusion.

This gatekeeper function ensures that materials required by the cell are supplied and that excesses and wastes are removed, both entry and exit occurring at rates sufficient to maintain the internal environment of the cell within narrow limits. This is quite a cellular balancing act! In addition to its role in transportation of materials into and out of the cell, the plasma membrane plays other important cellular roles (see p. 25).

The cells of fungi, plants and many bacteria and archaea have rigid cell walls outside their plasma membranes. The animal cells do not have a cell wall. Cell walls do *not* control which materials enter or leave cells; instead, cell walls provide strength and give a fixed shape to those cells that possess them (see chapter 2, p. 60). A cell wall is fully permeable so that gases and dissolved solutes can pass freely across it. It is only when these substances reach the plasma membrane that their passage may be blocked.

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Structure of the plasma membrane

ODD FACT

In addition to phospholipids, the plasma membrane of animal cells also contains cholesterol as part of its structure.

Small, but vitally important, the plasma membrane is just 8 nanometres (nm) wide and so is only visible using transmission electron microscope (TEM). A TEM image of the plasma membrane has a 'train track' appearance with two dark lines separated by a more lightly stained region. These images were important clues in elucidating the structure of the plasma membrane (see Biochallenge, p. 42).

The plasma membrane has two major components:

1. **phospholipids**. These are the main structural component of the plasma membrane (see below).
2. **proteins**. Most proteins are embedded in the plasma membrane, while others are attached at the membrane surface (see next page).

Let's consider each of these components in turn.

Phospholipids

Hydrophilic (water-loving) molecules dissolve readily in water.

Lipophilic substances dissolve readily in organic solvents such as benzene.

Hydrophobic (water-fearing) molecules are usually lipophilic (lipid-loving).

The plasma membrane consists of a double layer (bilayer) of phospholipids. Each phospholipid molecule consists of two fatty acid chains joined to a phosphate-containing group. The phosphate-containing group of a phospholipid molecule constitutes its water-loving (**hydrophilic**) head. The fatty acid chains constitute the water-fearing (**hydrophobic**) tail of each phospholipid molecule.

Examine figure 1.20. Notice that the two layers of phospholipids are arranged so that the hydrophilic heads are exposed at both the external environment of the cell and at the cytosol (the internal environment of the cell). In contrast, the two layers of hydrophobic tails face each other in the central region of the plasma membrane. Water and lipids do not mix.

At human body temperature, the fatty acid chains in the inner portion of the plasma membrane are not solid. Instead, they are viscous fluids — think about thick oil or very soft butter — this makes the plasma membrane flexible, soft and able to move freely. This property of the plasma membrane is very important as it enables cells to change shape (provided they do not have a cell wall outside the plasma membrane). For example, red blood cells are about 8 micrometres (μm) in diameter. When circulating red blood cells reach a capillary bed, they must deform themselves by bending and stretching in order to squeeze through capillaries, some of which have diameters as narrow as 5 micrometres. Likewise, when white blood cells reach sites of infection, they must squeeze out of small gaps between the single layer of cells that forms the capillary walls (see figure 1.21). Shape changes by animal cells are only possible because of the flexible nature of the lipids in the plasma membrane. Flexibility and shape changes are not possible for cells with cell walls.

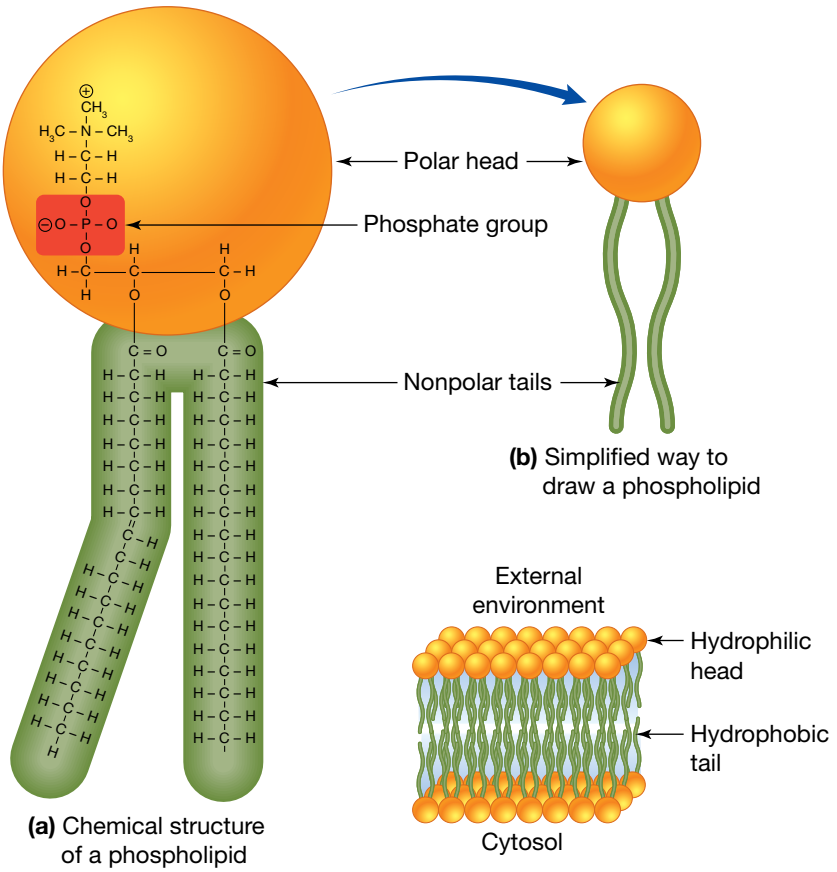

FIGURE 1.20 (a) Chemical structure of a phospholipid (left) and a stylised representation (right) showing the hydrophilic head and the two fatty acid chains that make up its hydrophobic tail **(b)** Diagram showing part of the bilayer of phospholipid molecules in the plasma membrane. Notice that the tails face each other and are enclosed in the central region of the membrane, while the heads face outwards to the cell's external environment and inwards to its cytoplasm.

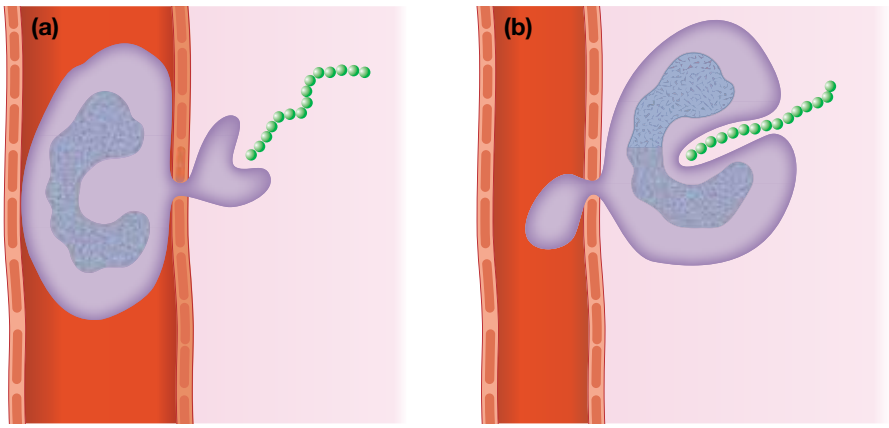

FIGURE 1.21 Diagram showing a white blood cell squeezing between the cells of the one-cell-thick wall (endothelium) of a capillary to engulf bacteria. What feature of the plasma membrane enables the white blood cell to do this?

Proteins

Proteins form the second essential part of the structure of the plasma membrane. Many different kinds of protein comprise part of the plasma membrane. They can be broadly grouped into:

- integral proteins
- peripheral proteins.

Integral proteins, as their name implies, are fundamental components of the plasma membrane. These proteins are embedded in the phospholipid bilayer. Typically, they span the width of the plasma membrane with part of the protein being exposed on both sides of the membrane (see figure 1.22). Proteins like this are described as being **trans-membrane**. In some cases carbohydrate groups, such as sugars, are attached to the exposed part of these

proteins on the outer side of the membrane, creating a combination called a **glycoprotein**. Integral proteins can be separated from the plasma membrane only by harsh treatments that disrupt the phospholipid bilayer, such as treatment with strong detergents.

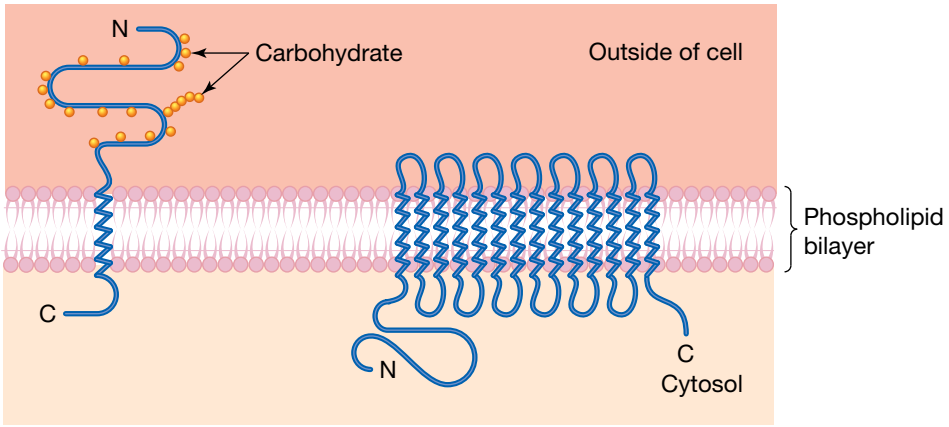

FIGURE 1.22 Diagram showing two integral proteins embedded in and spanning the plasma membrane. Part of each protein is exposed on each side of the membrane. Note that carbohydrate groups are attached to the exposed part of one protein on the outer side of the membrane. What name could be given to this kind of protein?

The prefix 'glyco' means sugar.
sugars attached to a protein = glycoprotein
sugars attached to a lipid = glycolipid

Peripheral proteins are either anchored to the exterior of the plasma membrane through bonding with lipids or are indirectly associated with the plasma membrane through interactions with integral proteins in the membrane. Peripheral proteins can be more easily separated from the plasma membrane than integral proteins.

The various roles of the proteins in the plasma membrane are outlined on pages 25–6 of this chapter.

Fluid mosaic model of plasma membrane

Both phospholipids and proteins are key components of the structure of the plasma membrane. But how are they organised?

An early view was that the proteins present in the plasma membrane were concealed within the phospholipid bilayer. However, in 1972, Singer and Nicolson proposed the **fluid mosaic model** of membrane structure. This is now generally accepted as the structure for the plasma membrane. The fluid mosaic model also applies to the membranes that form the outer boundary of cell organelles, such as the membranes that surround the cell nucleus and other cell organelles.

The fluid mosaic model proposes that the plasma membrane and other intracellular membranes should be considered as two-dimensional fluids in which proteins are embedded.

The term 'fluid' comes from the fact that the fatty chains of the phospholipids are like a thick oily fluid, and the term 'mosaic' comes from the fact that the external surface (when viewed from above) has the appearance of a mosaic because of the various embedded proteins set in a uniform background. Figure 1.23 shows a diagrammatic representation of the fluid mosaic model.

A good working definition of the plasma membrane is that it is the active boundary around all living cells that consists of a phospholipid bilayer and associated proteins and which separates the cell contents from their external environment.

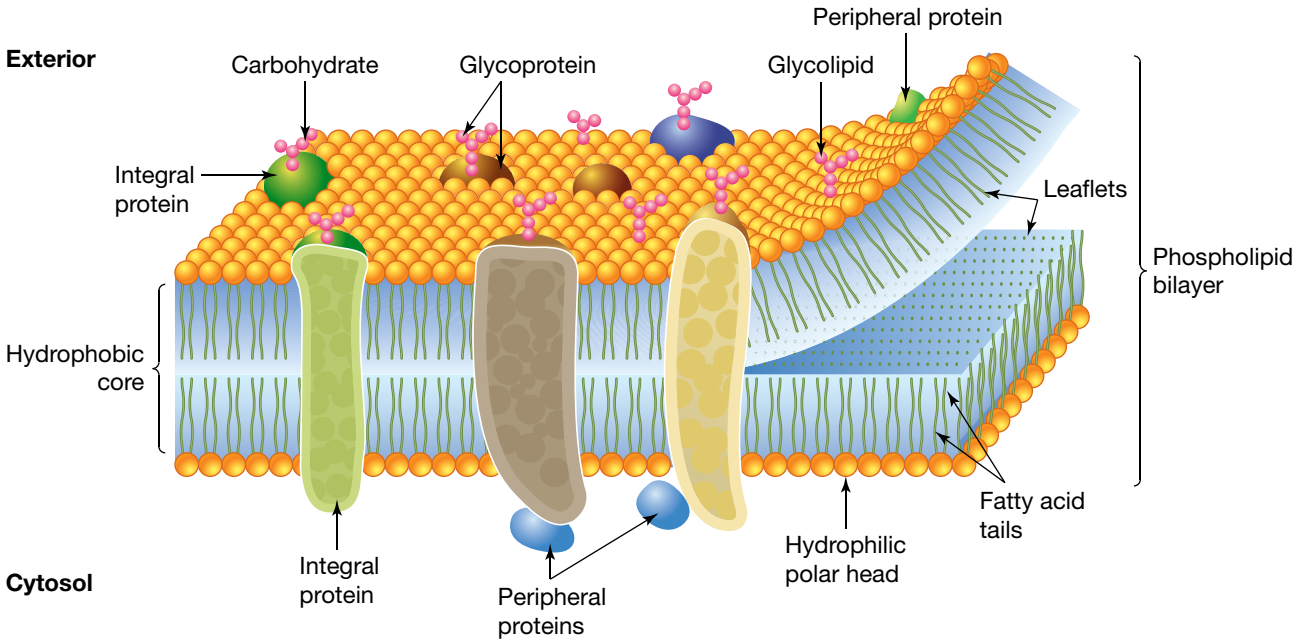

FIGURE 1.23 Diagram showing the fluid mosaic model of membrane structure. Note the bilayer of phospholipids. What are the two components of the phospholipids? Note the integral proteins, some of which extend through the bilayer and are exposed at both the outer and the inner surface of the membrane. Do any of these proteins have carbohydrate chains attached to their exposed regions? Note the peripheral proteins that are more loosely associated with the membrane.

KEY IDEAS

- A major role of the plasma membrane of a cell is to act as a gatekeeper that controls the entry and exit of materials into and out of the cell.
- The major structural component of plasma membrane is a bilayer of phospholipid molecules, each with a hydrophilic head and hydrophobic tail.
- The fatty acid chains within the plasma membrane confer flexibility on the plasma membrane.
- Proteins comprise the other essential component of the plasma membrane; these are both integral proteins and peripheral proteins.
- The fluid mosaic model of membrane structure is currently accepted as the best description of the structure of the plasma membrane (and other cellular membranes).

QUICK CHECK

12 What are the two major components of a plasma membrane?
13 Identify whether each of the following statements is true or false.
- **a** The plasma membrane is present as a boundary in all living cells.
- **b** The plasma membrane consists of layers of proteins in which phospholipids are embedded.
- **c** A key role of the plasma membrane is the control of transport of materials into or out of cells.
- **d** Trans-membrane proteins span the width of the plasma membrane.

14 What is a glycoprotein?
15 What part of a plasma membrane is responsible for its flexibility?
16 Briefly outline the fluid mosaic model of the plasma membrane.

Functions of the plasma membrane

The plasma membrane carries out several important functions for a cell. The plasma membrane:

1. is an active and selective boundary
2. denotes cell identity
3. receives external signals
4. transports materials.

The active boundary

The plasma membrane forms the active boundary of a cell, separating the cell from its external environment and from other cells; it allows the passage of some substances only. The plasma membrane forms the boundary of a compartment in which the internal environment of a living cell can be held within a narrow range of conditions that are different from those of the external environment.

Within the cell, similar membranes form the active boundaries of cell organelles, including the nucleus, the endoplasmic reticulum, the Golgi apparatus and lysosomes. In other cell organelles, such as mitochondria and chloroplasts, membranes form both the external boundary and part of the internal structure. Because of the presence of their membrane boundaries, membrane-bound cell organelles can maintain internal environments that differ from those in the surrounding cytosol and can perform different functions. (Refer to chapter 2 for more detail.)

Cell identity

ODD FACT

The human blood group A and B antigens are present on red blood cells as glycolipids and as glycoproteins — they differ by one sugar group.

Glycoproteins on the outer plasma membrane function as **cell surface markers**, also known as antigens or cell identity tags. Each cell type has a different combination of surface markers. In mammals, these markers enable the immune system to identify these cells as 'self' and distinguish them from foreign cells. Glycolipids on the plasma membrane play a role in tissue recognition.

Receiving external signals

Cells receive signals from their external environment. In the case of a multicellular organism, the signal may originate from another cell within that organism. In the case of unicellular organisms the signal may come from other organisms in its neighbourhood or from its external environment. These external signals are often chemical compounds, for example, hormones.

Trans-membrane proteins on the outer surface of the plasma membrane are the **receptors** for these signals, and each cell has many different kinds of receptor protein. The signal binds to the receptor protein and this binding alters the shape of the receptor protein and starts a specific response in the cell. For example, *Saccharomyces cereviseae* is a single-celled yeast used in winemaking, brewing and bread making. During one stage of the yeast life cycle, haploid yeast cells exist in one of two different mating types, designated 'a' and 'α' (alpha). When one type is ready to mate, it releases a small chemical, called a mating factor, into its environment. The mating factor is a signal to nearby yeast cells of the other mating type that it is ready to mate (see figure 1.24). The signal from an a-type yeast cell can be received by receptors on the surface of the plasma membrane of yeast cells of the other mating type. The signal binds to a specific receptor and causes a change in the behaviour in the receiver yeast cell — it changes its shape and moves

towards the source of the signal. The originator of the signal also changes shape in response. The end result is the fusion of the two haploid yeast cells to form one diploid yeast cell.

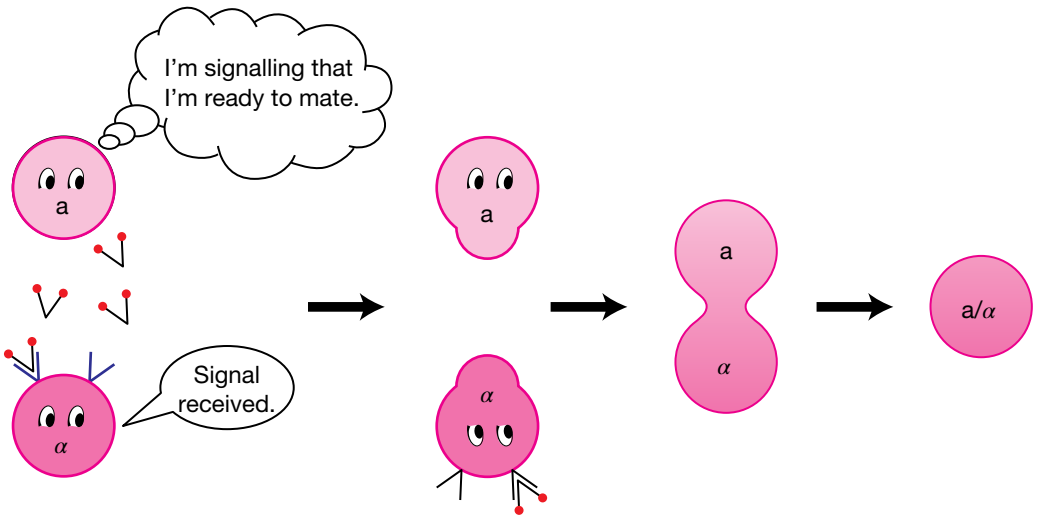

FIGURE 1.24 Two mating types (a and α) of haploid cells occur during the life cycle of yeast. Chemical signals released by a yeast cell of one mating type can travel to surface protein receptors on neighbouring cells of yeasts of the other mating type. This signal is an invitation to mate. Reception of the signal causes a change in the behaviour of the receiver cell.

Transport

All cells must take in or expel a range of substances and the plasma membrane forms a selectively permeable barrier between a cell and its external environment. An impermeable barrier allows no substances to cross it; a fully permeable barrier allows all substances to cross it, while a selectively permeable barrier allows some substances to cross it but precludes the passage of others.

Some substances can cross the hydrophobic phospholipid bilayer of the plasma membrane. Other substances can cross the plasma membrane, but only with the assistance of special trans-membrane proteins, collectively called transporters, that are embedded in the plasma membrane. In the next section, the various modes by which molecules can be transported into and out of cells will be explored, including those that involve transporter proteins.

KEY IDEAS

- The plasma membrane performs a range of cellular functions.
- Functions involving the plasma membrane include creating a compartment that separates the cell from its external environment, receiving external signals as part of communication between cells, providing cell surface markers that identify the cell and transporting materials across the plasma membrane.
- Transport proteins in the plasma membrane enable movement of substances that cannot cross the lipid bilayer of the membrane.

QUICK CHECK

17 Is the plasma membrane impermeable, selectively permeable or fully permeable?
18 Identify two functions of the plasma membrane.
19 What kind of proteins act as cell identity tags?
20 What advantage might result from creating several membrane-enclosed compartments within a cell?
21 What is the role of receptor proteins in the plasma membrane?
22 Give an example of a problem that arises from the malfunction of a protein transporter in the plasma membrane.

Crossing the plasma membrane

Generally, substances entering or exiting a cell are in aqueous solution. Several factors determine whether or not dissolved substances can diffuse down their concentration gradients across the phospholipid bilayer of the plasma membrane (see table 1.3).

TABLE 1.3 Factors affecting the ease with which substances can diffuse across the plasma membrane

molecular size	Smaller molecules cross more easily than larger molecules; however, very large molecules (macromolecules), such as proteins and nucleic acids, cannot cross the plasma membrane.
presence of net charge (+ or –)	Gases, such as CO_2 and O_2, and small uncharged molecules, such as urea and ethanol, can cross the plasma membrane. In contrast, mineral ions, such as Na^+, K^+, Cl^- cannot cross because they are repelled by the hydrophobic lipid component of the plasma membrane.
solubility in lipid solvents	Lipophilic molecules can cross easily, but hydrophilic molecules, such as glucose, cannot cross because they are repelled by the hydrophobic lipid component of the plasma membrane.
direction of concentration gradient	Movement down a gradient (from a region of higher to a region of lower concentration of a substance) does not require an input of energy and can occur by diffusion. Movement against a gradient cannot occur by diffusion.

From this table, it may be seen that the smaller the molecule and the more lipophilic (lipid-loving) it is, the more easily it can diffuse across the plasma membrane down its concentration gradient. This is summarised in figure 1.25.

It is apparent that many substances are prevented from crossing the plasma membrane because they are repelled by the hydrophobic lipid component of the plasma membrane and/or because their concentration gradients are in the wrong direction. However, at any time, many substances are entering or leaving cells. These include substances that *cannot* cross the hydrophobic lipid bilayer of the plasma membrane, such as glucose, sodium ions and calcium ions. Yet movement of these substances across the plasma membrane is essential for life. **So, it may be concluded that simple diffusion down a concentration gradient across the phospholipid bilayer *cannot* be the only means by**

which substances cross the plasma membrane. Instead, additional means of entry to and exit from cells must exist. These additional means of transport for dissolved substances involve the proteins of the plasma membrane, such as facilitated diffusion and active transport (see the following section).

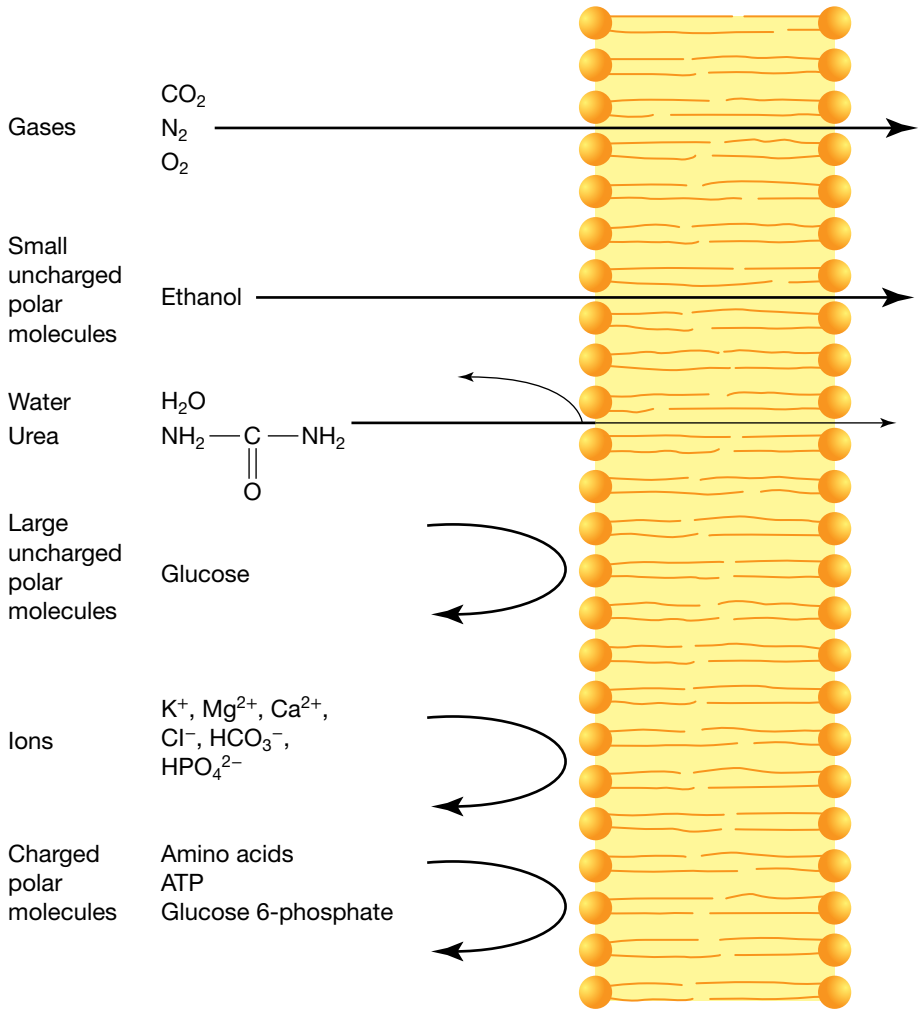

FIGURE 1.25 Diagram showing the semipermeable nature of a phospholipid bilayer membrane. The membrane is fully permeable to some substances, partially permeable to others and impermeable to yet other substances. Note that the term 'polar' refers to molecules with an unequal distribution of electrons such that one side of a molecule has more electrons (and so is more negative) than the other side that has fewer electrons (and so is more positive). This is different from ions that have lost or gained an electron and so have a net electric charge.

Various ways of crossing the boundary

Movement of substances across the plasma membrane into or out of cells can occur by several mechanisms:

1. **Simple diffusion** is the means of transport of small lipophilic substances. Water can also move across the plasma membrane by diffusion; this is a special case of diffusion known as **osmosis**.
2. **Facilitated diffusion** involves protein transporters and is the means of transport of dissolved hydrophilic substances down their concentration gradients.
3. **Active transport** involves protein transporters known as pumps and is the means of transport of dissolved hydrophilic substances against their concentration gradients.
4. **Endocytosis/exocytosis** are the means of bulk transport of macromolecules and liquids.

Simple diffusion

Simple diffusion is the movement of substances across the phospholipid bilayer from a region of higher concentration to one of lower concentration of that substance; that is, *down* its concentration gradient (see figure 1.26a).

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Movement across the membrane: Passive transport
Concept summary and practice questions

Movement down a concentration gradient by simple diffusion does *not* require any input of energy. It is the gradient that drives the diffusion (like letting a ball roll down a slope). The end point of simple diffusion is reached when equal concentrations of the substance are reached on both sides of the plasma membrane.

Substances that move easily across the plasma membrane by simple diffusion are small lipophilic molecules that can dissolve in the lipid bilayer. Among these substances are steroid hormones, alcohol and lipophilic drugs.

Figure 1.26b shows the stages in simple diffusion of a dissolved substance (X) across a plasma membrane. Its molecules are in constant random motion, some colliding with the membrane. If the concentration of substance X outside the cell is greater than that inside the cell, more movement of X into the cell will occur compared with movement in the opposite direction. This will produce a net movement of substance X into the cell. Net movement stops when collisions on both sides of the membrane equalise. This occurs when the concentrations of X on both sides of the membrane are equal.

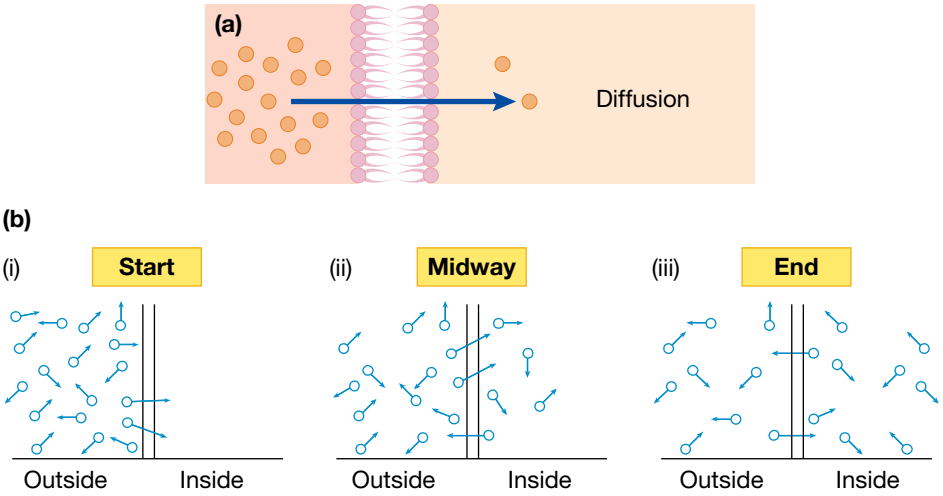

FIGURE 1.26 **(a)** Simple diffusion involves the movement of substances through the phospholipid bilayer of the plasma membrane. The direction of movement is down the concentration gradient of the diffusing substance (from high to low concentration). Does this process require an input of energy? **(b)** Stages of simple diffusion: (i) At the start, substance X starts to move into the cell because of random movement that results in some collisions with the membrane. (ii) Midway, molecules of substance X are moving both into and out of the cell, but the net movement is from outside to inside. (iii) When the concentration of X is equal on each side of the membrane, the number of collisions on either side of the membrane is equal and the net movement of molecules of substance X stops. Does this mean that collisions of molecules of substance X with the membrane stop?

Osmosis: a special case of diffusion

Osmosis is a special case of diffusion that relates to the movement of solvents and, in biological systems, that solvent is water.

Osmosis can be defined as the net movement of water across a semipermeable membrane from a solution of lesser solute concentration to one of greater solute concentration. A condition for osmosis is that the membrane must be permeable to water but not to the solute molecules. Solutions that have a high concentration of dissolved solute have a lower concentration of water, and vice versa. **The net movement of water molecules in osmosis from a solution of high water concentration to one of lower concentration is known as osmotic flow.**

solute = substance that is dissolved
solvent = liquid in which a solute dissolves
solution = liquid mixture of the solute in the solvent

When an external solution is compared with the dissolved contents of a cell, the external solution may be found to be either:

- **hypotonic** — having a lower solute concentration than the cell contents
- **isotonic** — having an equal solute concentration to that of the cells
- **hypertonic** — having a higher solute concentration than the cell contents.

Osmosis can be seen in action when cells are immersed in watery solutions containing different concentrations of a solute that cannot cross the plasma membrane. Remember that as the concentration of solute molecules increases, the concentration of the water molecules decreases.

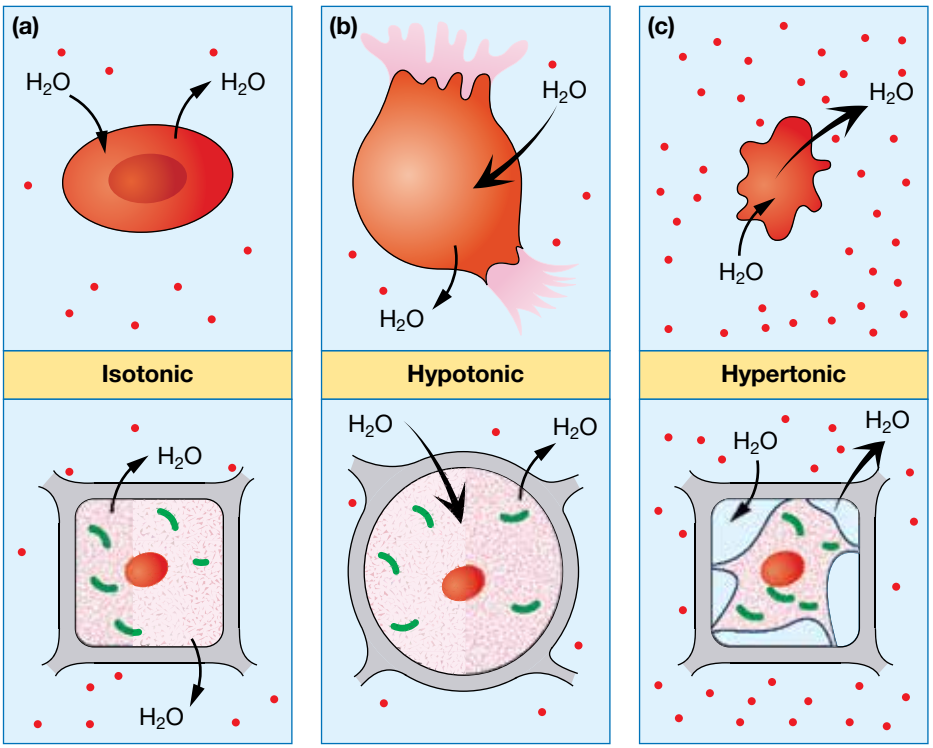

FIGURE 1.27 Osmosis in action: behaviour of animal and plant cells in solutions of different concentrations of a dissolved substance (solute molecules). Solute molecules are denoted by red dots. Note the presence of a cell wall outside the plasma membrane in the plant cells. The solute molecules are too large to cross the plasma membrane, but water molecules will move down their concentration gradient, in a process called osmotic flow. Does the movement of water by osmosis require an input of energy?

Look at figure 1.27a. The water molecules of the external isotonic solution are at the same concentrations as those in the cell contents. Since there is no concentration gradient, no net uptake of water molecules occurs in either cell; in a given period, the same number of water molecules will diffuse into the cell as will diffuse out.

Now look at figure 1.27b. The water molecules of the external hypotonic solution are more concentrated than those of the cell contents. Water molecules will diffuse down their concentration gradient from the hypotonic solution into the cell, resulting in a net uptake of water by the cell. As the red blood cell takes up the water molecules, it continues to swell until its plasma membrane bursts, dispersing the cell contents. The plant cell also takes up water, swells until it becomes rigidly swollen (turgid), but the cell does not burst because of the thick cell wall that lies outside the plasma membrane. The cell wall acts as a pressure vessel

preventing the plasma membrane from swelling to a point of bursting. Net entry of water molecules into the plant cell finally stops as a result of the increasing outward pressure of the cell contents that opposes the net inward flow of water.

Finally look at figure 1.27c. The water molecules of the external hypertonic solution are at a lower concentration than those in the cell contents. Water molecules will diffuse down their concentration gradient from the cells into the external solution, resulting in a net loss of water from the cells. The red blood cell shrinks, becoming crenated. The plant cell within its plasma membrane shrinks away from its cell wall.

Looking at water movement

Water is a major constituent of all living organisms and cells are about 50 to 70 per cent water. The adult human body is about 60 per cent water overall, with the water content of different tissues varying: brain is about 73 per cent water, lungs more than 80 per cent and bones about 30 per cent water.

Examples of the movement of water by osmosis follow.

The freshwater protozoans

Protozoans are single-celled organisms with an outer plasma membrane boundary. One example is *Paramecium caudata*. *Paramecium caudata* lives in fresh water, a habitat that is hypotonic relative to the cell contents (cytosol) of this organism. Consequently, water constantly flows by osmosis from the high concentration outside the cell to the low concentration inside the cell. Look at figure 1.28 and note the ducts surrounding a contractile vacuole. These ducts collect water from the cytosol and move it into the contractile vacuole. From there, it is forced to the outside when the vacuole contracts in an energy-requiring process. Would you expect this to be a continuous process? Why?

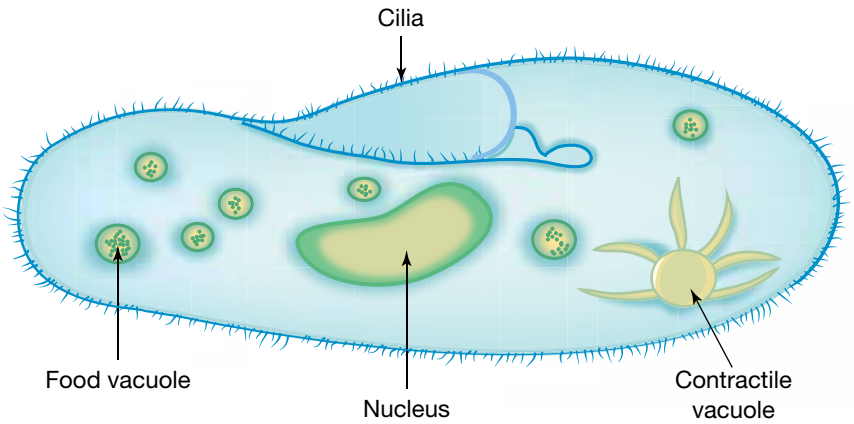

FIGURE 1.28 Drawing of *Paramecium caudata*, a single-celled organism that lives in fresh water. A constant flow of water by osmosis occurs from the external fresh water into the cell. Ducts surrounding the contractile vacuole carry the water to the vacuole which then forces the water out of the cell. Can you predict what would happen if the contractile vacuole stopped operating?

The salted meat

Preserving means either slowing down the multiplication of microbes that cause food spoilage (e.g. by chilling or freezing), or inhibiting or killing the microbes that are responsible for food spoilage (e.g. by salting).

Salt (sodium chloride) is a highly effective food preservative, commonly used to preserve meat, particularly before freezing was possible. In the past for long sea voyages, meat was preserved by building up layers of meat and salt in wooden barrels (see figure 1.29). Another technique was to immerse meat in a solution of up to 20 per cent salt. For the long voyage of Christopher Columbus

ODD FACT

Seawater is hypertonic to the cells of the human body. Instead of quenching thirst, drinking seawater results in a person becoming dehydrated.

FIGURE 1.29 Barrels of salted pork. Meat preserved with salt was carried on board sailing ships to provide rations during long voyages at sea. How does salt preserve meat?

in 1492 from Spain to the Americas, the food carried on board his ships was olive oil, wine, sea biscuits and salted meat.

Why does salt work as a preservative? Salt draws water out of microbial cells on the surface of the meat by osmosis. Dissolved salt on the meat surface is hypertonic to the microbial cell contents so that the water flows down its concentration gradient out of these cells. This osmotic flow of water dehydrates the cells of the microbes that cause food spoilage, thus preserving the meat. Until refrigeration became available in the 1880s, salting continued to be used for the preservation of meat on long sea voyages.

The crying albatross

Seawater is hypertonic to the extracellular fluid of marine birds, such as the wandering albatross (*Diomedea exulans*). These birds drink only seawater to supply their water requirements, but in so doing, they take in large amounts of salt, a situation that could lead to fatal dehydration in a person. In these birds, salt from the intake of seawater moves from the gut into the bloodstream and the extracellular fluid (ECF) that bathes the body cells. The higher concentration of salt in the ECF relative to that in the body cells leads to the movement of water molecules from the body cells into the ECF by osmosis. The loss of water from the cells stimulates salt-secreting glands in the bird's head to remove the excess salt (see figure 1.30) and keep the internal environment of the cells within narrow limits. The cells in these glands take up salt from the bird's body fluids and produce a secretion with a very high concentration of salt — more salty than the bird's body fluid and even saltier than seawater. This fluid passes down ducts that lead to the bird's nostrils from where it is discharged.

ODD FACT

The first successful refrigerated shipment of meat left Dunedin in New Zealand in February 1882 en route to England.

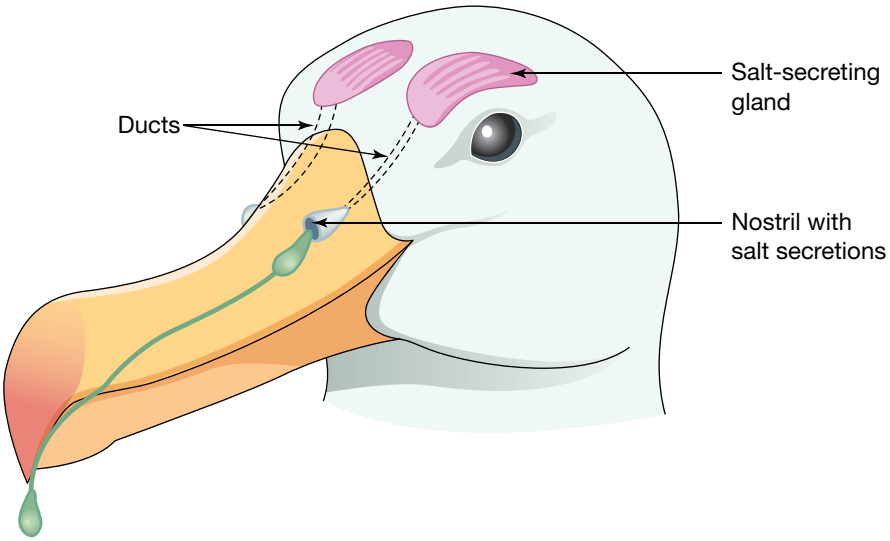

FIGURE 1.30 Diagram showing the position of the two salt-secreting glands in the head of an albatross. The highly salty excretion from the glands is removed by dripping from the bird's nostrils.

ODD FACT

Each day about 2 litres of fluid are taken into the gut in food and drinks. This is increased by a further volume of about 7 litres from secretions, including those of the salivary glands, stomach, liver and pancreas.

The dehydrated person

A person suffering from a prolonged bout of diarrhoea is severely dehydrated and may need to be admitted to hospital. Normally, the cells lining the small and large intestine absorb the large volume of fluid and dissolved salts that enter the gut daily (see Odd fact). Several bacterial infections, including *Staphylococcus sp.*, can inhibit this absorption. As a result, most of the fluid and the dissolved salts pass into the large intestine and are expelled from the body in large volumes of watery diarrhoea, resulting in dehydration and salt loss. Worsening dehydration is serious because it produces a decrease in blood volume that, if untreated, may lead to cardiovascular failure.

Initial treatment of severe dehydration is replacement of the lost fluid and salts. The rehydration therapy involves an isotonic solution of saline (salt) solution plus glucose. This solution can be administered either orally (by mouth) or by direct infusion into the bloodstream (by intravenous infusion, or IV).

Why does this treatment act as a rehydration therapy? Glucose stimulates the absorption of sodium by the gut cells. The uptake of sodium and glucose from the gut into the extracellular fluid creates a hypertonic internal environment that causes water to move by osmosis from the gut across the cells lining the gut, and so returns water to the extracellular fluid and from there to the body cells.

Facilitated diffusion

Facilitated diffusion is an example of protein-mediated transport. Facilitated diffusion is so named because the *diffusion* across the membrane is enabled or *facilitated* by special protein transporters in the plasma membrane.

Like simple diffusion, facilitated diffusion does *not* require an input of energy. Like simple diffusion, facilitated diffusion moves substances down their concentration gradients. **However, facilitated diffusion of dissolved substances requires the action of protein transporters that are embedded in the cell membrane.**

In the case of ions, which carry either + or – charge(s), it is more correct to say that, rather than moving down their concentration gradients, they move down their electrochemical gradients.

Facilitated diffusion enables molecules that cannot diffuse across the phospholipid bilayer to move across the plasma membrane through the agency of transporter proteins. These transporters are either **channel proteins** or **carrier proteins**. Are transporters required in simple diffusion? (Refer to figure 1.31.)

Channel proteins

One group of transport proteins involved in facilitated diffusion are the channel proteins. Each channel protein is trans-membrane and has a central water-filled pore through which dissolved substances can pass down their concentration gradient. Different channel proteins are specific for the diffusion of charged particles and polar molecules.

Each channel protein consists of a narrow water-filled pore in the plasma membrane through which substances can move down their concentration gradients (see figure 1.31b). By providing water-filled pores, channel proteins create a hydrophilic passage across the plasma membrane that bypasses the phospholipid bilayer and facilitates the diffusion of charged particles, such as sodium and potassium ions, and small polar molecules.

ODD FACT

Channel proteins known as **aquaporins** are trans-membrane proteins that are specific for the facilitated diffusion of water molecules.

Carrier proteins

Another group of membrane proteins involved in facilitated diffusion are carrier proteins. Carrier proteins are specific, with each kind of carrier enabling the diffusion of one kind of molecule across the plasma membrane. **After binding to its specific cargo molecule, the carrier protein undergoes a change in shape as it delivers its cargo to the other side of the plasma membrane** (see figure 1.31c).

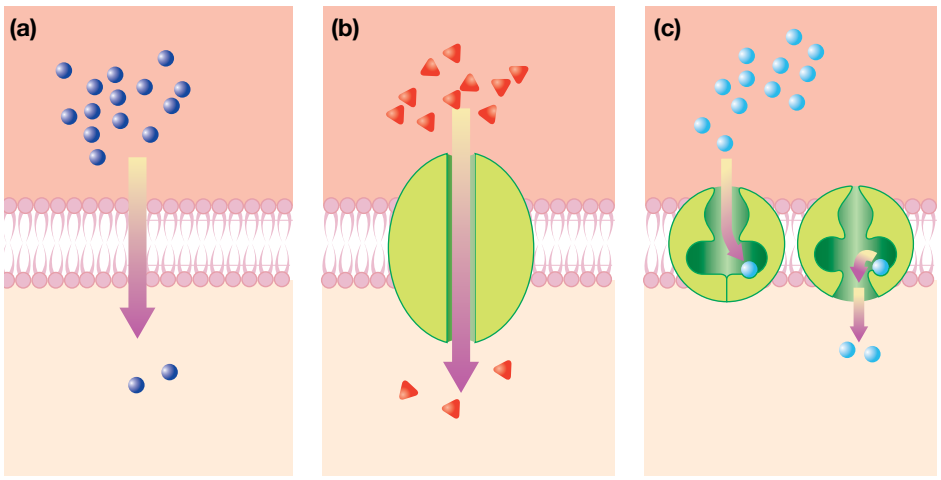

FIGURE 1.31 (a) Simple diffusion. In contrast, facilitated diffusion requires either **(b)** channel proteins or **(c)** carrier proteins to enable certain dissolved substances to diffuse down their concentration gradients. Note the change in shape of the carrier protein as it operates.

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Diffusion

Carrier proteins are important in the facilitated diffusion of hydrophilic uncharged substances, such as glucose and amino acids. In the absence of carrier proteins, these hydrophilic molecules cannot cross the plasma membrane directly.

Rates of diffusion

In the previous sections, two types of diffusion of dissolved substances across plasma membranes have been explored: simple diffusion and facilitated diffusion. Do these two types of diffusion differ in the rate at which substances can move down their concentration gradients in either direction across a plasma membrane?

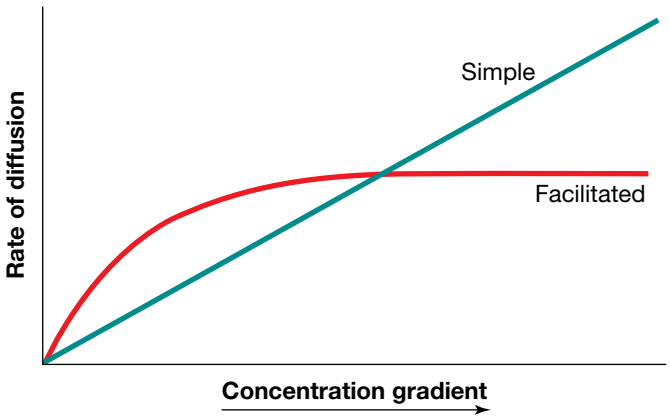

FIGURE 1.32 Graph showing rates of simple and facilitated diffusion with increasing concentration gradient of the diffusing substance. Note that the rate of simple diffusion continues to increase as the concentration gradient increases. In contrast, the rate of facilitated diffusion is initially linear, but begins to taper off and finally reaches a plateau. The maximum rate is reached when all the transporters are fully occupied.

In simple diffusion, the rate at which substances move across the plasma membrane by simple diffusion is determined by their concentration gradient, that is, the difference in the concentration of the substance inside and outside the cell. **The higher its concentration gradient, the faster a substance will move by simple diffusion down this gradient and across a plasma membrane.** (Think of this as like rolling a ball downhill — the steeper the incline, the faster the ball rolls.)

In facilitated diffusion, the rate of movement of a substance is also influenced by the steepness of its concentration gradient on either side of the plasma membrane. The steeper the concentration gradient, the faster the rate of facilitated diffusion, *but only up to a point* (see figure 1.32).

Why the difference between simple diffusion and facilitated diffusion? Facilitated diffusion requires the involvement of transporters, either channel proteins or carrier proteins, for the movement of substances. These

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channel and carrier proteins are present in limited numbers on the plasma membrane. Because their numbers are limited, eventually a concentration of the diffusing substance will be reached when all the transporters are saturated (fully occupied). So, as the concentration gradient increases, the rate of facilitated diffusion of a substance will at first increase, then become slower, and finally will reach a plateau. The plateau is the maximum rate of facilitated diffusion. When this is reached, all the transporter molecules are fully occupied.

Active transport

Active transport is the process of moving substances across the plasma membrane against the direction that they would travel by diffusion; that is, **active transport moves dissolved substances from a region of low concentration to a region of high concentration of those substances. Active transport can occur only with an input of energy**, and the energy source is typically adenosine triphosphate (ATP).

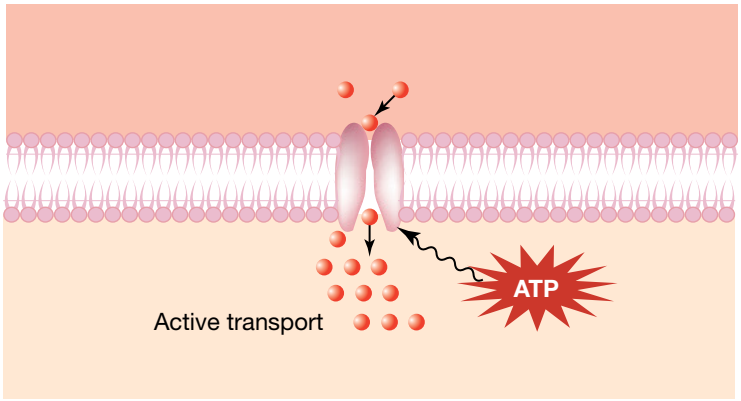


FIGURE 1.33 Diagram showing a simplified representation of active transport. A pump is a trans-membrane protein that is both a carrier and an ATPase enzyme. The enzyme component of the pump catalyses the energy-releasing reaction that powers active transport.

Special transport proteins embedded across the plasma membrane carry out the process of active transport. The proteins involved are called **pumps** and each different pump transports one (or sometimes two) specific substance(s). Important pumps are proteins with both a transport function and an enzyme function. The enzyme part of the pump catalyses an energy-releasing reaction:

$$ATP \rightarrow ADP + Pi + \textit{energy}$$

The transport part of the pump uses this energy to move small polar molecules and ions across the plasma membrane *against* their concentration gradients. During this process, the protein of the pump undergoes a shape change (see figure 1.33).

Cells use pumps to move materials that they need by active transport. Active transport is essential for the key function of cells including pH balance, regulation of cell volume and uptake of needed nutrients. Examples of active transport include:

- uptake of dissolved mineral ions from water in the soil by plant root hair cells against their concentration gradient
- production of acidic secretions (pH of nearly 1) by stomach cells that have a low internal concentration of hydrogen ions (H+) but produce secretions (gastric juice) with an extremely high concentration of hydrogen ions
- uptake of glucose from the small intestine into the cells lining the intestine against its concentration gradient, that uses the glucose–sodium pump
- maintenance of the difference in the concentrations of sodium and potassium ions that exist inside and outside cells (see table 1.4) by action of the sodium–potassium pump that actively transports these ions against their concentration gradients (see below).

Some pumps actively transport a single dissolved substance against its concentration gradient. Other pumps transport two substances simultaneously, for example, the **sodium–potassium pump**. The importance of the sodium–potassium pump is highlighted by the fact that, in the human body overall, about 25 per cent of the body's ATP is expended in keeping the sodium–potassium pump operating. For brain cells, the figure is even higher, about 70 per cent.

Why is this pump needed? Table 1.4 provides a clue to the answer.

ODD FACT

Compared with the concentration of H^+ ions in the contents of stomach cells, the gastric juice in the stomach has about a concentration about three million times higher. This is achieved by active transport of these ions out of the stomach cells against their concentration gradient.

TABLE 1.4 Approximate concentrations of sodium and potassium ions in the cytosol of cells and in the surrounding extracellular fluid

Ion	Inside cell	Outside cell
sodium (Na^+)	10 mM	142 mM
potassium (K^+)	150 mM	5 mM

ODD FACT

The Danish scientist, Jens Skou, was awarded the Nobel Prize in chemistry for his discovery of the ion-transporting enzyme, Na^+, K^+ ATPase, otherwise known as the sodium–potassium pump.

Table 1.4 shows the concentrations of sodium and potassium ions inside and outside cells. Note that these concentrations differ greatly. In what direction would sodium ions tend to flow passively? What about potassium ions? How are these concentration differences maintained? The high concentration of sodium ions inside cells and the high concentration of potassium ions outside cells are maintained by the sodium–potassium pump that is present in all animal cells and constantly expends energy in active transport, pushing sodium ions out of the cell and pulling potassium ions in. For each ATP molecule expended, the pump pushes three sodium ions out and drags two potassium ions in. This process of active transport compensates for the constant passive diffusion of sodium ions into cells and of potassium ions out of cells, both down their concentration gradients.

The sodium–potassium pump plays a key role in excitable cells, such as nerve cells and muscle cells. During the transmission of a nerve impulse, sodium ion channels open and sodium ions rapidly flood into the nerve cell by facilitated diffusion. After the nerve impulse has passed, the sodium channels close and the sodium–potassium pump then restores the concentrations of sodium and potassium ions to their resting levels by actively pushing sodium ions across the membrane out of the cell and dragging potassium ions into the cell (refer back to table 1.4). Restoring these concentrations involves active transport against the concentration gradients of these ions.

When transport goes wrong . . .

The importance of transport proteins in moving substances becomes apparent if they do not operate as expected, as may be seen in cystic fibrosis and in cholera infections.

ODD FACT

Before accurate genetic testing for cystic fibrosis became available, an early test was the so-called 'sweat test' that measured salt levels in a baby's sweat.

Cystic fibrosis

Symptoms seen in persons affected by the inherited disorder cystic fibrosis result from a defect in one transporter protein on the plasma membrane of cells. This protein is a channel that normally allows chloride ions (Cl^-) to move out of cells. Cystic fibrosis affects various organs, including the lungs, the pancreas and the skin. A faulty chloride ion channel protein, such as occurs in cystic fibrosis, blocks the movement of chloride ions. This affects the various organs as follows:

- *Lungs*. Normally, the inner surfaces of a person's lungs are covered with a thin layer of mucus. This mucus is important in a healthy lung because it traps microbes and other particles, and it is constantly removed from the lungs by the beating action of hair-like projections (cilia) that line the airways. Cough or clear your throat and that mucus and those trapped particles are gone. In the lungs, the chloride ion channel normally moves chloride ions out of lung cells.

  In cystic fibrosis, however, the defect in the transporter stops

  i the movement of Cl^- ions out of the cells into the lung cavity
  ii the consequential flow of sodium (Na^+) ions that move in response to the electrochemical gradient created by the movement of the negative chloride ions into the lung cavity
  iii osmotic flow of water into the lungs that normally thins the mucus.

  These effects of the faulty chloride ion channel mean that the mucus in the lungs is abnormally thick, sticky and difficult to move and, rather than being

FIGURE 1.34 Capsules and tablets containing the missing pancreatic enzymes (lipase, protease, amylase) are taken by persons affected by cystic fibrosis. Note the enzyme granules in the capsules.

easily cleared, the mucus remains in the lungs affecting breathing and acting as a potential source of infection.

- *Sweat glands in skin*. In the skin, the chloride ion channel is normally involved in reabsorbing salt (NaCl) from fluid within cells of the sweat glands before it is released as sweat. When the chloride ion (Cl^-) transporter is blocked, re-absorption does not occur and very salty sweat is produced.
- *Pancreas*. Pancreatic enzymes are normally involved in the digestion of some foods. In cystic fibrosis, these enzymes are unable to enter the gut because abnormally thick mucus blocks the narrow duct that connects the pancreas to the small intestine. Without these enzymes, food cannot be fully digested. However, replacement enzymes in the form of tablets, powders or capsules can replace the enzymes normally released by the pancreas (see figure 1.34).

Cholera

The pores of some channel proteins are permanently open, while the pores in other channel proteins open only in response to a specific signal. The chloride ion channel on the plasma membranes of cells lining the intestine is *not* always open. Normally chloride ions are retained within the cells lining the intestine. Only when this channel is opened can chloride ions move from the cells into the cavity of the intestine.

Cholera results from a bacterial infection of *Vibrio cholera*. A toxin produced by these bacteria causes the chloride ion channels in the cells lining the intestine to be locked in the 'open' position. This results in a flood of chloride ions into the intestinal space that is followed by a flow of sodium ions (down the resulting electrochemical gradient that is created). In turn, the increased concentration of salt in the gut creates a hyperosmotic environment that draws water into the gut by osmosis. The continuous secretion of water into the intestine causes the production of large volumes of watery diarrhoea. If left untreated the water loss caused by this diarrhoea can be fatal within hours. Cholera epidemics have caused many deaths (see figure 1.35). Cholera can be spread by water that is contaminated by contact with untreated sewage or by the faeces of an infected person. Cholera can be spread by food that is washed in or mixed with water contaminated by cholera bacteria, or by food that is inappropriately handled by a person infected with cholera.

FIGURE 1.35 Cholera epidemics and pandemics have taken many lives. During the period 1899 to 1923, a cholera pandemic that began in India spread across the globe and reached as far as Russia and Eastern Europe. This French publication from 1912 illustrates the public fear and the widespread deaths that this cholera pandemic caused.

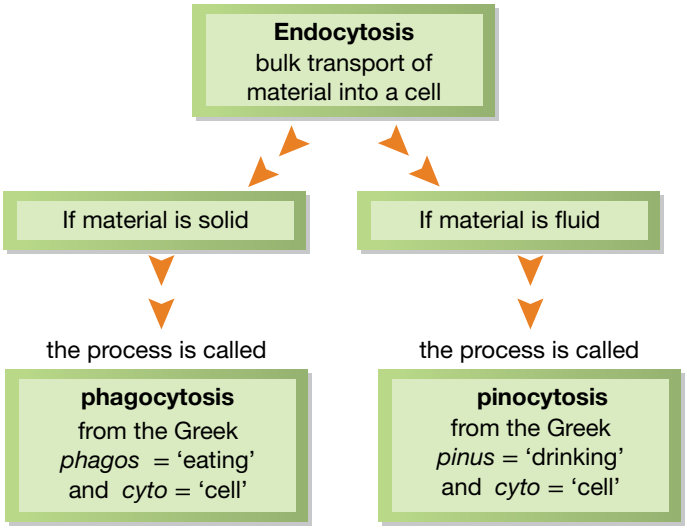


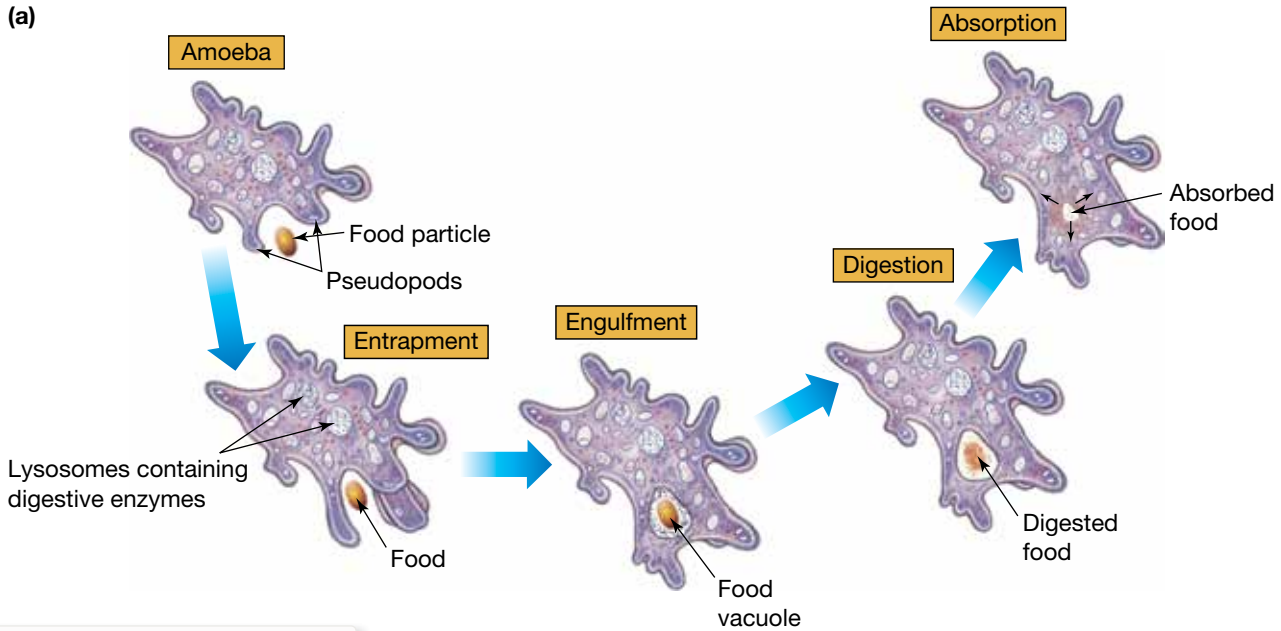
FIGURE 1.36 Endocytosis — a summary

Bulk transport of solids and liquids

To this point, we have been concerned with movement of dissolved substances across the plasma membrane. In addition, small solid particles and liquids in bulk can be moved across the plasma membrane into or out of cells. Figure 1.36 gives a summary of how bulk material can enter cells.

Endocytosis: getting in

Solid particles can be taken into a cell. For example, one kind of white blood cell is able to engulf a disease-causing bacteria cell and enclose it within a **lysosome** sac where it is destroyed. Unicellular protists, such as *Amoeba* and *Paramecium*, obtain their energy for living in the form of relatively large 'food' particles, which they engulf and enclose within a sac where the food is digested (see figure 1.37a).



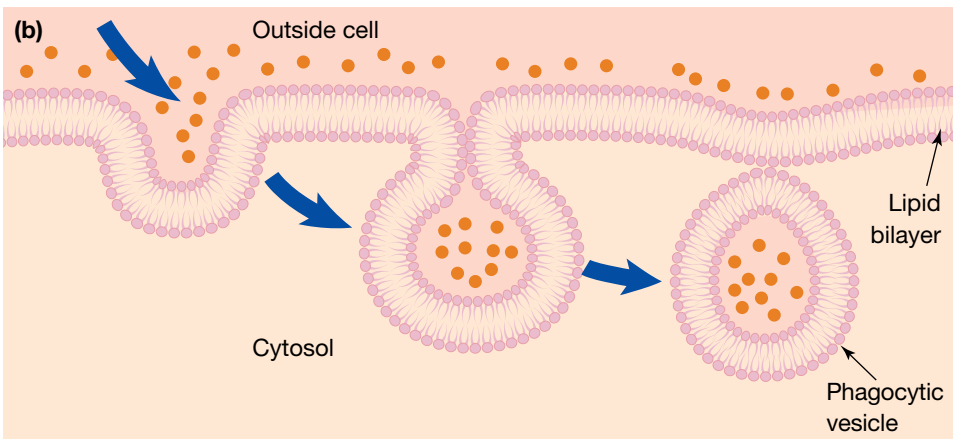


FIGURE 1.37 **(a)** Transport of a solid food particle across the membrane of an Amoeba **(b)** Endocytosis occurs when part of the plasma membrane forms around food particles to form a phagocytic vesicle (or phagosome). This vesicle then moves into the cytosol where it fuses with a lysosome, a bag of digestive enzymes. (Believe it or not, this fused structure is called a phago-lysosome.)The same digestive process can also occur to microbes.

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Note how part of the plasma membrane encloses the material to be transported and then pinches off to form a membranous **vesicle** that moves into the cytosol (figure 1.37b). This **process of bulk transport of material into a cell** is called endocytosis. When the material being transported is a solid food particle, the type of endocytosis is called phagocytosis.

Although some cells are capable of phagocytosis, most cells are not. Most eukaryotic cells rely on **pinocytosis**, **a form of endocytosis that involves material that is in solution** being transported into cells. The process of endocytosis is an energy-requiring process and requires an input of ATP.

Exocytosis: getting out

Bulk transport out of cells (such as the export of material from the Golgi complex, discussed in chapter 2, p. 67) is called exocytosis. **In exocytosis, vesicles formed within a cell fuse with the plasma membrane** before the contents of the vesicles are released from the cell (see figure 1.38). If the released material is a product of the cell (e.g. the contents of a Golgi vesicle), then 'secreted from the cell' is the phrase generally used. If the released material is a waste product after digestion of some matter taken into the cell, 'voided from the cell' is generally more appropriate. The process of exocytosis requires an input of energy in the form of ATP.

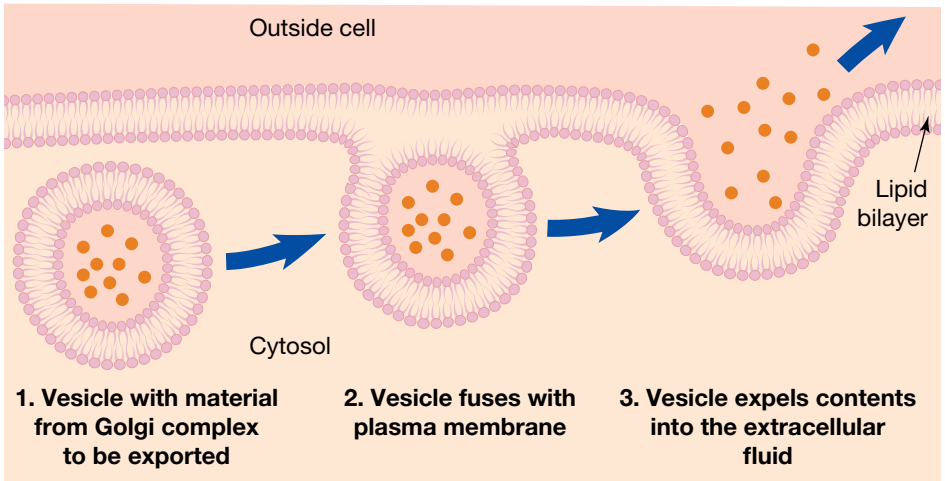


FIGURE 1.38 Exocytosis (bulk transport out of cells) occurs when vesicles within the cytosol fuse with the plasma membrane and vesicle contents are released from the cell.

KEY IDEAS

- Simple diffusion moves dissolved substances across the plasma membrane down their concentration gradient and requires no input of energy.
- Osmosis is a special case of diffusion, being the movement of water across the plasma membrane down its concentration gradient.
- Facilitated diffusion moves dissolved substances across the plasma membrane down their concentration gradients, but this movement occurs through involvement of transport proteins, either channel or carrier proteins, and requires no input of energy.
- Active transport moves dissolved substances across the plasma membrane *against* the concentration gradient, a process that can occur only via the action of protein pumps.
- Active transport requires an input of energy that commonly comes from ATP, catalysed by the ATPase enzyme that is part of some protein pumps.
- Endocytosis is the bulk transport of material into cells; if solids are being moved, the process is termed phagocytosis and, if liquids, the process is termed pinocytosis.
- Exocytosis is the bulk movement of materials via secretory vesicles out of cells.

QUICK CHECK

23 What is the process by which bulk materials are exported out of cells?

24 Consider passive diffusion and facilitated diffusion:

a Identify one difference between these processes.

b Identify one similarity that they share.

25 Identify one difference between diffusion and active transport.

26 Which transport process relies on the involvement of either a carrier or a channel protein?

27 By which process do cells of the stomach lining manage to move hydrogen ions out of the cells to produce a highly acidic gastric secretion?

28 What process is involved in the movement of water down its concentration gradient and across a layer of cells from outside the body to inside?

SCIENTIST AT WORK

Jonica Newby — TV Science Reporter

I'll be honest with you. When I chose to focus on science in high school, I did it because I thought it was so much easier than the pain of creative writing. Now though, as a TV science reporter/producer, I have to write creatively *and* still understand the science! Argh!

But of course, I love it; it's the best of both worlds. I have the privilege of being one of the reporters on ABC television's longstanding TV science program, *Catalyst*. It's an amazing and sometimes crazy job. What are some of the things I've done in the last couple of years? I've lain inside a vertical wind tunnel to see what wind speed it would take to make me fly; I sourced motion activated infra-red cameras to see what animals were visiting my yard at night; I jumped out of a plane with a parachute to see how fear interferes with language centres of the brain; I staged a full scale mock cyclone in an unsuspecting family's house to show how climate change might bring cyclones as far south as the Gold Coast; and I got bitten by a tick while filming — you guessed it — how not to be bitten by a tick!

Although the filming days are probably the most exciting — and stressful — they only take up a small portion of the job. What I'm doing most of the time is ringing scientists to talk about what they do for a living, and then trying to come up with a way to make a film about it, complete with the scripted words and images. My science background is crucial, because I'm basically getting a crash course in anything from Quantum physics to the neurobiology of fear. ('Ok Jonica, you have one week to understand everything there is about the science of Mammalian Meat Allergy. Go!'). And all the rest is creative.

The process goes like this. We have an idea for a story. Then we (me and a TV researcher) research it quickly. Then I have to sit down and write a shoot script — and it's still a painful process being creative, I can tell you. Then we organise the shoot. On shoot days, I'm the film director as well as the onscreen presenter; and that's why it's pretty stressful, trying to keep everyone on schedule, working with cameramen and sound technicians, and encouraging scientists who may not have been on TV before. Then we take the content back to base and look at every single camera tape many times. From these I have to write an edit script. Then I give this edit script to the editor, who assembles the rough cut. We then work together to make decisions about shortening this, rewriting that, and eventually it becomes the story you can see on TV. Phew! It may be only a few minutes of broadcast, but it takes weeks to months of full time work to prepare every piece.

And in case you're wondering what my 'Dr' stands for, I trained originally as a veterinarian. Yes indeed — plenty of looking after cows, and vaccinating dogs and cats for me. I did that for about 3 years after I graduated. And it was great but in the end, despite my fear of the creative side of life, I was drawn to be more creative and so I set about on the long path to the job I have now. It's not for everyone, and there are very few jobs like mine, but it just goes to show, you never know where a good grounding in science will take you. Flying inside a wind tunnel, maybe . . . that was fun!

FIGURE 1.39 Jonica Newby on a shoot

BIOCHALLENGE

Exploring the plasma membrane

1 The plasma membrane has been described as being like a 'train track'. This was because the first images of the plasma membrane showed it as two dark lines separated by a lighter region. Figure 1.40 shows part of the plasma membranes of two adjoining cells. The plasma membranes have been sectioned so that their surfaces are oriented horizontally at right angles into the plane of this page.

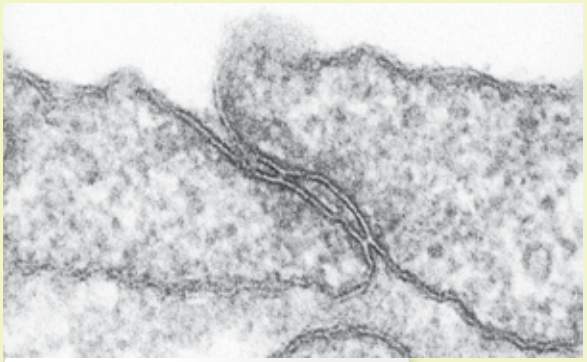


FIGURE 1.40 Plasma membrane

- a How thick is the plasma membrane in nanometres? In micrometres?
- b What kind of microscope was needed to produce the image in figure 1.40?
- c What are the 'rails' of the train track composed of?
- d What is present in the space between the rails?

2 Key information about the nature of the plasma membrane came from an experiment carried out in 1925 by two Dutch scientists. They took a known number of red blood cells and, based on the average size of these cells, they estimated their combined surface area. Then they extracted only the lipid from the plasma membrane of these cells and allowed it to spread out on a water surface where it formed a monolayer or single layer of molecules. (Remember, lipids will not mix with water!) To their surprise, the scientists found that the area of the lipid monolayer on the water surface was twice the combined surface area of the red blood cells that were the source of the lipid.

Consider this finding and suggest what key information this result provided about the structure of the plasma membrane.

3 In 1970, Frye and Edidin carried out an experiment in which they took a human cell and a mouse cell and fused them to form a human–mouse hybrid cell. They showed the distribution of the surface proteins on the plasma membrane of each cell by using anti-human and anti-mouse antibodies labelled with a different fluorescent dye. A red dye showed the positions of the surface proteins on the membrane of the human cell. A green dye showed the positions of the surface proteins on the membrane of the mouse cell.

Figure 1.41a shows the initial observation immediately after the fusion of the two cells. After 40 minutes, the researchers carried out a second observation and their findings are shown in figure 1.41b.

From the results of this experiment, which of the following is it reasonable to conclude?

- a Surface proteins are fixed in position on the plasma membrane.
- b Surface proteins from each cell type have fused.
- c Surface proteins can move laterally across the plasma membrane.

4 True or false?

The results of this experiment provide support for the fluid mosaic model of membrane structure. Briefly explain.

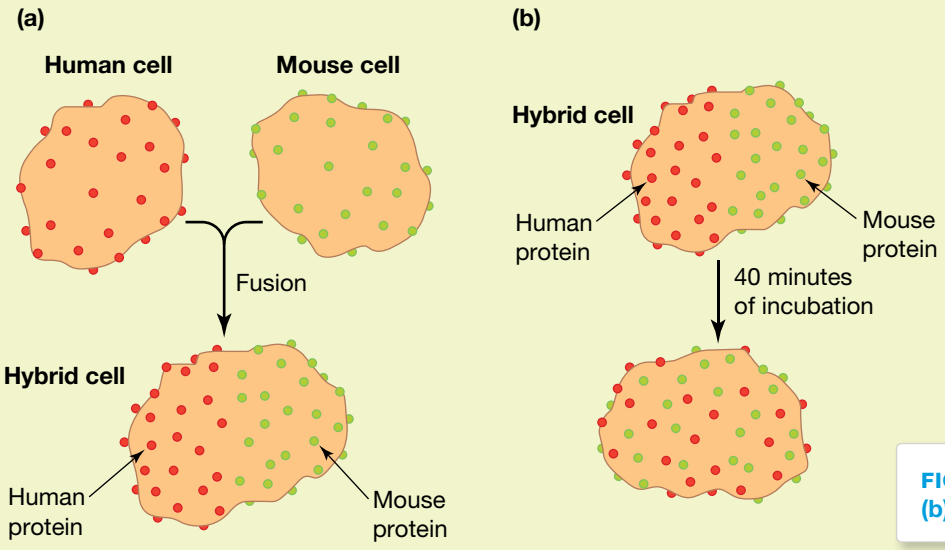


FIGURE 1.41 (a) Start of experiment **(b)** 40 minutes later

Chapter review

Key words

active transport
aquaporins
archaea
bacteria
biogenesis
carrier proteins
cell membrane
cell surface markers
Cell Theory
channel proteins
endocytosis
eukaryotes
eukaryotic
exocytosis
extremophiles
facilitated diffusion
fluid mosaic model
glycoprotein
hydrophilic
hydrophobic
hypertonic
hypotonic
integral proteins
isotonic
lysosome
nuclear envelope
osmosis
peripheral proteins
phospholipids
pinocytosis
plasma membrane
prokaryotes
prokaryotic
proteins
pumps
receptors
selectively permeable
semipermeable
simple diffusion
sodium–potassium pump
surface-area-to-volume ratio
trans-membrane
vesicle

Questions

1 **Making connections** ➜ The key words listed above can also be called concepts. Concepts can be related to one another by using linking words or phrases to form propositions. For example, the concept 'compound light microscope' can be linked to the concept 'lenses' by the linking phrase 'contains at least two' to form a proposition. An arrow shows the sense of the relationship: when several concepts are related in a meaningful way, a concept map is formed. Because concepts can be related in many different ways, there is no single, correct concept map. Figure 1.42 shows one concept map containing some of the key words and other terms from this chapter.

Use at least six of the key words above to make a concept map relating to the movement of substances across a cell membrane. You may use other words in drawing your map.

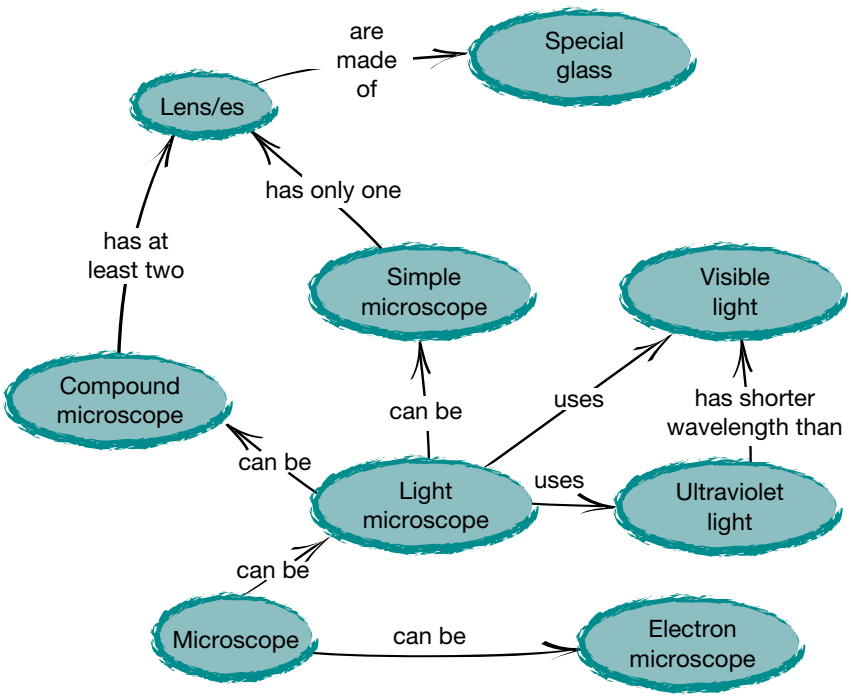


FIGURE 1.42 Example of a concept map

2 **Applying your knowledge and understanding** ➜ Sterile saline (NaCl) solutions, with or without glucose, may be used to treat a person in certain circumstances. The treatment may be delivered either orally or directly into a vein by intravenous infusion. The normal salinity level of body cells and the surrounding extracellular fluid is 0.9 per cent sodium chloride.

Fluids that might be administered include:

- normal-strength saline solution with 0.9 per cent saline, with solutes in balance with normal body fluids making the solution isotonic
- half-strength saline solution with 0.45 per cent salt, with fewer electrolytes making it hypotonic to body fluids; or
- double-strength saline, with greater than 0.9 per cent dissolved solutes, making it hypertonic to body fluids.

FIGURE 1.43 Infusion of an intravenous saline drip is performed by experienced medical professionals who decide which saline strength should be used, whether the solution should also include glucose, and calculate the correct rate of flow for the particular patient.

A patient (MM) is in urgent need of treatment following blood loss. To increase the circulating blood volume and raise the blood pressure, an emergency treatment while waiting on blood typing results, might be the intravenous infusion of a saline solution.

a Would you expect the saline solution selected for this purpose to be:
  i isotonic
  ii hypotonic
  iii hypertonic?

Explain your decision.

b The treatment was given intravenously. Would it be equally effective if given by mouth (orally)? Briefly explain.

3 Another patient (NN) is suffering from severe dehydration and salt loss. A possible treatment in this case involves administration of a sterile saline solution.

a Would you predict the saline solution used in this case to be:
  i isotonic
  ii hypotonic
  iii double strength?

Explain your decision.

b Is glucose likely to be included with the saline? Explain.

4 Another patient (PP) is immobilised in bed recovering from an operation. PP is given an infusion of an intravenous saline drip in order to prevent edema; that is, an accumulation of excess extracellular fluid in his body tissues.

Would you predict the saline solution to be:
  i normal strength
  ii half strength
  iii double strength?

Explain your decision.

5 **Applying your understanding** ➜ Consider the information in table 1.5.

TABLE 1.5 Data for three different shapes, each having the same volume. (Where necessary, figures have been rounded.)

Cell	Shape	Dimensions	Surface area	Volume	SA:V ratio
A	flat sheet	$10 \times 10 \times 0.1$	204	10	20.4
B	cube	$2.15 \times 2.15 \times 2.15$	28	10	2.8
C	sphere	diameter: 1.67	22	10	2.2

a If these shapes represented cells, which cell (A, B or C) would be most efficient in moving required materials into and removing wastes from the cell? Explain.

b Which cell would be least efficient? Explain.

c Can you suggest a biological consequence of your conclusion?

d Identify one way in which a cell might retain its overall shape, but greatly increase its surface area with a minimal increase in volume. (Clue: This strategy is used by cells involved in absorption of material, such as those lining the small intestine.)

6 Analysing information and drawing conclusions ➜ Consider the data in table 1.6.

TABLE 1.6 Data for two sets of cells of identical shape but of decreasing sizes.

Cell	Shape	Dimensions	Surface area	Volume	SA:V ratio
P	flat sheet	$10 \times 10 \times 0.1$	204	10	20.4
Q	flat sheet	$5 \times 5 \times 0.05$	51	1.25	40.8
R	flat sheet	$1 \times 1 \times 0.01$	2.04	0.01	204
H	sphere	diameter: 10	314.2	523.6	0.6
K	sphere	diameter: 5	78.5	65.5	1.2
L	sphere	diameter: 1.0	3.14	0.52	6

Note: relative to the first shape in each set, the dimensions of other members of the set are scaled down by a factor of 2 and by a factor of 10.

- **a** A student stated the same shape scaled down should retain the same surface-area-to-volume ratio, the student's reason being 'the shapes stay the same'. Do you agree with this student? Explain your decision.
- **b** With regard to the information in table 1.6, identify how scaling a shape (up or down) affects the SA:V ratio of a given shape by completing the following sentences:
  - i If the size of a given shape is doubled, its SA:V ratio is . . .
  - ii If the size of a given shape is halved, its SA:V ratio is . . .
- **c** A particular shape has an SA:V ratio of 10.
  - i What would happen to this ratio if this shape were scaled up by a factor of 5?
  - ii What would happen to this ratio if this shape were scaled down by a factor of 2?
- **d** Sphere (M) has a diameter of 0.5 units. Refer to table 1.6 and predict its SA:V ratio.
- **e** Consider a different shape, such as a cube or a pyramid, that is changed in scale. Would its SA:V ratio be expected to follow a similar or a different pattern to that shown by the flat sheets and the spheres?

7 Communicating understanding ➜ Two cells (P and Q) have the same volume, but the surface area of cell P is 10 times greater than that of cell Q.

- **a** Placed in the same environment, which cell would be expected to take up dissolved material at a greater rate? Why?
- **b** What might reasonably be inferred about the shapes of these two cells?
- **c** Which measure — surface area or volume — determines the rate at which essential materials can be supplied to a cell?
- **d** Which measure — surface area or volume — determines the needs of a cell for essential materials?
- **e** Briefly explain why the surface-area-to-volume ratio provides a clue as to why cells are microscopically small?

8 Analysing information and drawing conclusions ➜ Identify the following statements as true or false. For (d) and (h) only, briefly justify your choice.

- **a** Osmotic flow of water occurs from a region of high to low solute concentration.
- **b** Simple diffusion does not require the involvement of transporter proteins.
- **c** Facilitated diffusion requires the involvement of a protein pump.
- **d** The movement by diffusion of charged ions, such as Na^+ and Cl^-, across the plasma membrane is blocked by the lipid bilayer in the middle of the plasma membrane.
- **e** Water is moved into and out of cells by active transport.
- **f** Solid particles cannot cross the plasma membrane.
- **g** Plant cells immersed in a hypertonic solution would be expected to burst.

9 Applying your understanding ➜ Sucrose cannot cross the plasma membranes of red blood cells, but glucose can. Red blood cells are immersed in the following solutions:

- a hypertonic sucrose solution
- a hypertonic glucose solution
- a hypotonic sucrose solution
- a hypotonic glucose solution.

- **a** Which solution would be expected to cause the greatest water loss and shrinkage of the red blood cells? Explain.
- **b** Which solution, if any, might cause the red blood cells to burst? Explain.

10 Making valid comparisons ➜

- **a** Name the two types of diffusion that are involved in the movement of dissolved substances across the plasma membrane.
- **b** Identify two similarities in these two types of diffusion.
- **c** Identify how these two types of diffusion differ.
- **d** A student stated 'Surely two types of diffusion are unnecessary'. Indicate whether you agree or disagree with this statement and give a reason for your decision.
- **e** Identify one key difference between diffusion and active transport of a substance.

11 Analysing information and drawing conclusions ➜ Suggest a possible explanation for the following observations:

- **a** Proteins can move laterally across the plasma membrane.

b A person with cystic fibrosis is at high risk of lung infections.
c Lipophilic substances cross the plasma membrane by simple diffusion, but not charged particles.
d A baby with cystic fibrosis produces abnormally salty sweat.
e Persons with a cholera infection suffer severe diarrhoea.

12 Making valid predictions based on your knowledge ➜ An artificial membrane, composed of a phospholipid bilayer only, was manufactured. Its behaviour was compared with that of a natural plasma membrane.

Predict if these two membranes might behave in a similar or a different manner when tested for their ability to allow the following dissolved substances to cross them:

- small lipophilic substances
- charged particles, such as sodium ions
- glucose
- proteins.

Briefly justify each of your decisions.

13 Performing calculations ➜ The width of an average head hair from a Caucasian is about 0.6 mm. Refer back to figure 1.11 and estimate about how many red blood cells could fit across the width of such a hair.

14 Making an estimation ➜ Use your knowledge of the structure of the plasma membrane to suggest which of the following dimensions is most likely to designate the width and length of one phospholipid molecule:

- 0.9×3.4 nm
- 0.9×3.4 µm OR 0.9×3.4 mm.

Briefly explain your choice.

15 Refer to figure 1.30 on page 32.
a By what process do the cells in the salt gland produce a secretion with a much higher concentration than that in the cytosol of the gland cells?
b Does this process require an input of energy?
c Would you predict that a salt-secreting mechanism might also be present in:
- marine turtles
- sea snakes
- freshwater crocodiles?

Briefly explain your decisions.

16 Applying your knowledge and understanding ➜ Nerve impulses involve several movements of sodium ions in different directions across the plasma membrane of a nerve cell as follows:
a Before a nerve impulse occurs, sodium ions are more concentrated in the extracellular fluid outside the cell than inside the cell. By what means does the cell maintain this difference?
b During transmission of the nerve impulse, sodium ions flood into the nerve cell from the extracellular fluid. By what means do these ions enter the cell?
c After the impulse has passed, the original concentration of sodium ions is restored to its high concentration outside the cell by a process that moves sodium ions out of the cell. By what means does this restoration occur?

17 Discussion question ➜ In Haiti, a disastrous earthquake in January 2010 killed and injured hundreds of thousands of people, left even more homeless, destroyed buildings and damaged infrastructure including roads, telecommunications, water supplies and water treatment plants. Homeless people sought shelter in camps that soon became overcrowded. Cholera infections broke out and developed into an epidemic. By February 2014, nearly 700 000 cases of cholera had been reported, resulting in more than 8000 deaths.
a What is the causative agent of cholera?
b What causes the particular effects of a cholera infection?
c By what means is cholera spread?
d What possible health consequences would be expected from the destruction of the water supplies and the re-housing of large numbers of people in temporary camps?
e In an attempt to halt the spread of cholera the United Nations and its partners worked with the Haitian Government to introduce measures including:
- repair of water treatment plants
- distribution of water purification tablets and hygiene kits to families
- distribution of oral rehydration salts packs to treatment centres
- introduction of community health education programs
- introduction of oral vaccines for cholera
- introduction of rapid diagnosis tests to distinguish cholera from diarrhoea.

Consider each of these measures in turn and discuss how each might contribute to slowing and stopping the spread of cholera.

CHAPTER

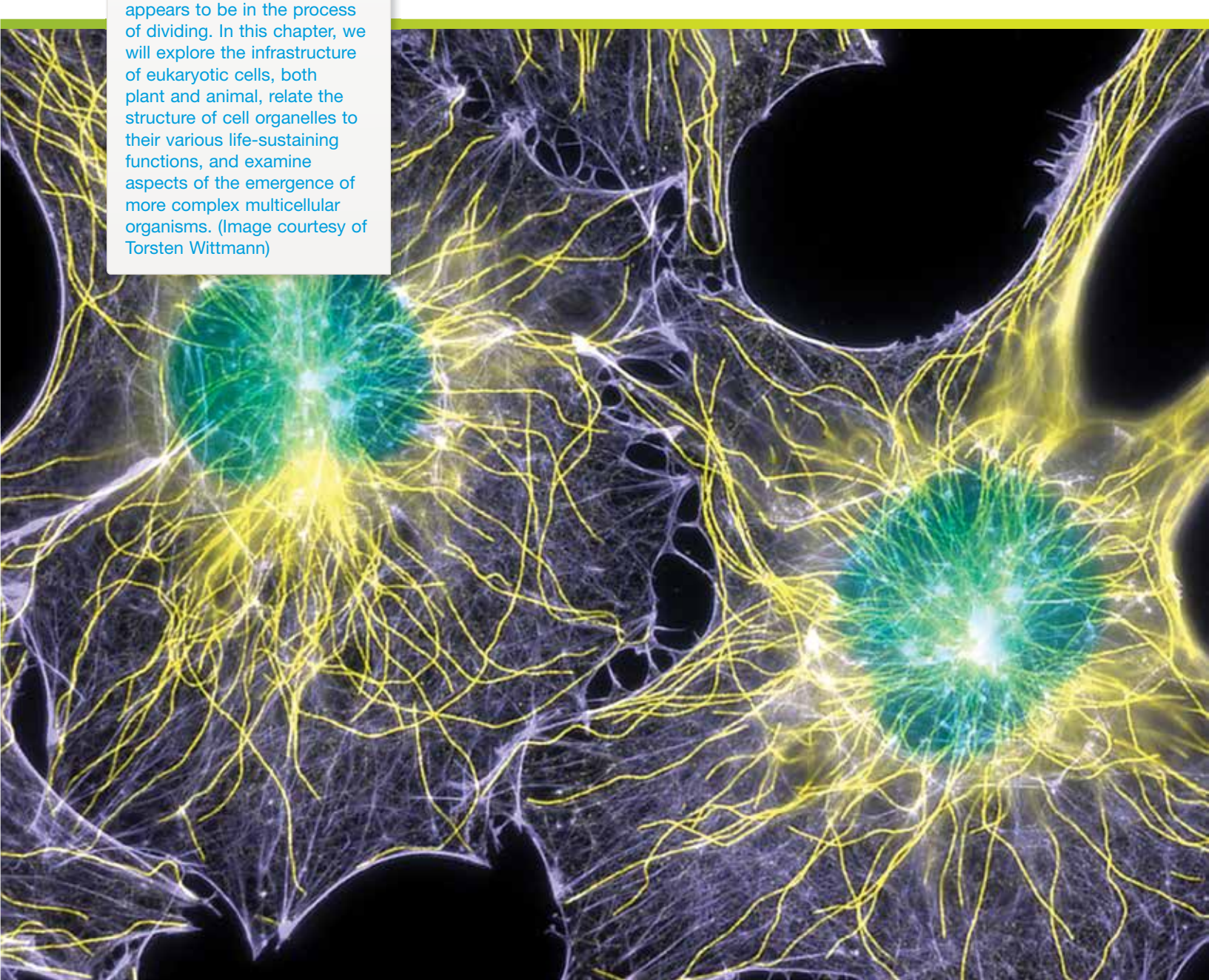
2 Ultrastructure of cells

FIGURE 2.1 This prize-winning image shows eukaryotic cells stained with fluorescent probes. The actin filaments (purple) and the microtubules (yellow) are part of the cytoskeleton of these cells. The nucleus is stained green. Note that the cell on the left appears to be in the process of dividing. In this chapter, we will explore the infrastructure of eukaryotic cells, both plant and animal, relate the structure of cell organelles to their various life-sustaining functions, and examine aspects of the emergence of more complex multicellular organisms. (Image courtesy of Torsten Wittmann)

KEY KNOWLEDGE

This chapter is designed to enable students to:

- gain knowledge of the evidence of the earliest forms of life on Earth
- investigate the various tools for viewing cells
- identify cell organelles in eukaryotic cells and recognise their various functions
- gain understanding of diseases resulting from defects in several cell organelles
- identify the evidence for the endosymbiotic origin of some cell organelles.



First life on Earth

What were the earliest cells like?

No one is sure exactly what these first cells, or **proto-cells**, were like. However, it is reasonable to conclude that the first life forms on planet Earth were simple single-celled (unicellular) microbe-like organisms. Like all living organisms today, these unicellular organisms would have been enclosed by a boundary that separated their internal contents from the external environment. Organic molecules can exist without a plasma membrane, but they cannot become organised into a structure that will show the characteristics of life unless they are separated from their external environment. As outlined in chapter 1, it is the semipermeable plasma membrane that creates this essential separation of the cell's internal environment from its external environment.

As well as a plasma membrane to create a separate compartment, the other necessary conditions for life to have existed include:

- an energy source that can be used by the proto-cells
- chemical building blocks that proto-cells could build into organic macromolecules
- liquid water to dissolve chemicals and provide a medium for chemical reactions
- formation of self-replicating nucleic acids to enable continuity.

Where did life first appear?

Charles Darwin (1809–82) speculated that a 'warm little pond' might be a possible location for the emergence of life. In a letter dated 1 February 1871, sent to a scientific colleague, Darwin wrote:

> But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts,—light, heat, electricity, etc. present, that a protein compound was chemically formed, ready to undergo still more complex changes . . .
>
> (extract from *Life and Letters of Charles Darwin* vol. 3, John Murray, London, 1887, p. 18)

More recent suggestions are that life may have first appeared at hydrothermal vents deep in the ocean or in hot acidic waters of volcanic pools. However, to date, experimental evidence for either of these suggestions has not been found.

When did life emerge?

In 2013, scientists from the University of Western Australia found signs of microbial life preserved in sedimentary rocks — dated to 3.5 billion years ago — from the Pilbara region in Western Australia (see figure 2.2). **Signs of life** are indirect indicators of the activity of cells, past or present, but they are *not* the physical cells themselves. (Cells, living or fossilised, are direct evidence of life.) Signs of life result from past or present interactions of organisms with the environments in which they lived or live. You can see signs of present life around you, such as footprints on a sandy beach, a bird's nest, animal scats. Can you suggest others?

Read about Dr Dave Wacey in the Biologist at work box on page 51, whose discoveries in the Pilbara region of Western Australia include signs of life (biosignatures) from 3.6 billion years ago and fossilised cells from 3.4 billion years ago that are the earliest direct evidence of life.

studyon
Unit 1
AOS 1
Topic 1
Concept 1
Cells: structural unit of life
Concept summary and practice questions

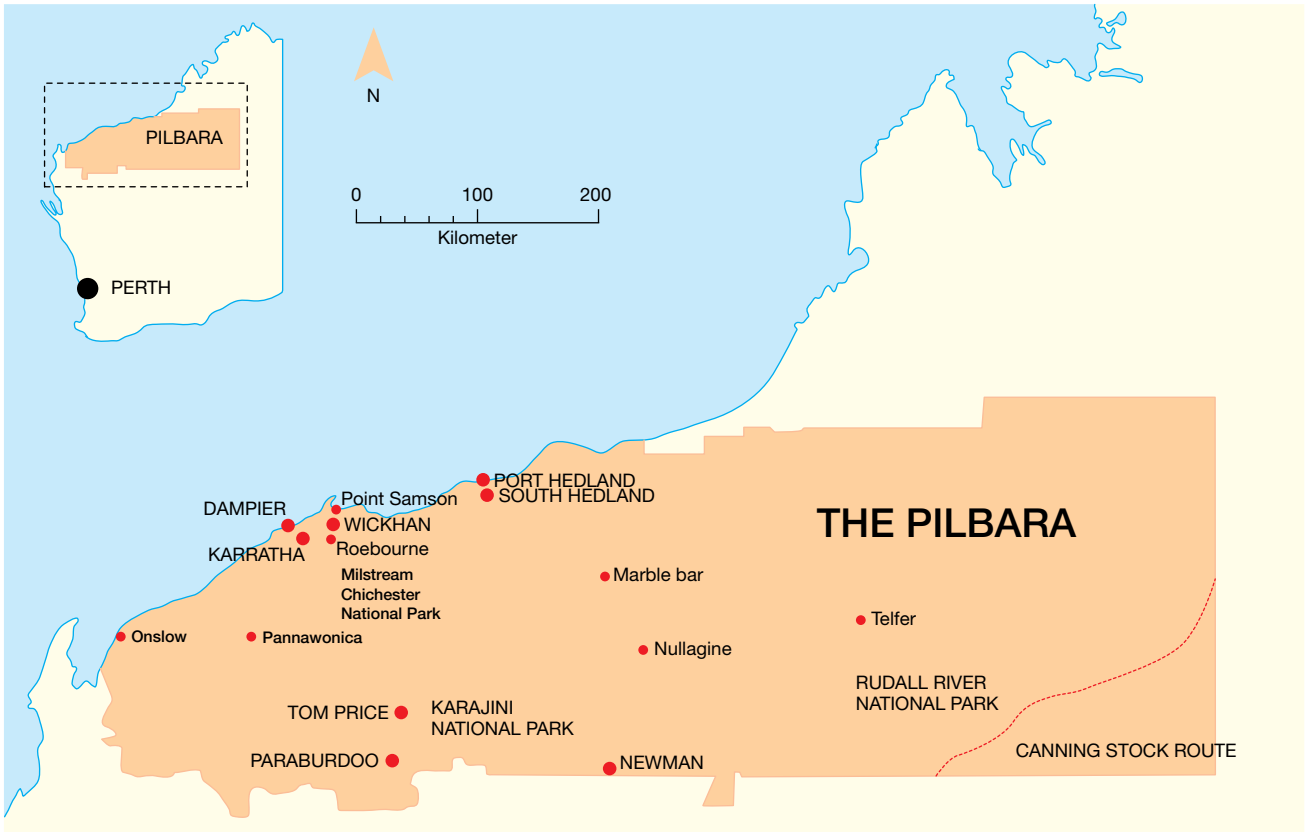


FIGURE 2.2 Map showing the location of the Pilbara region in Western Australia. It is a vast, largely unpopulated region with an ancient bedrock.

The signs of life discovered in the Pilbara are distinctive marks created by **microbial mats** that once flourished on sandy sediments, perhaps a tidal flat. Microbial mats can still be seen today (see figure 2.3). Microbial mats can form on moist or submerged surfaces including lakebeds, on sediments such as mud or sand, on tidal flats, in hypersaline (very salty) pools, in fissures, around hot springs and even around deep ocean vents.

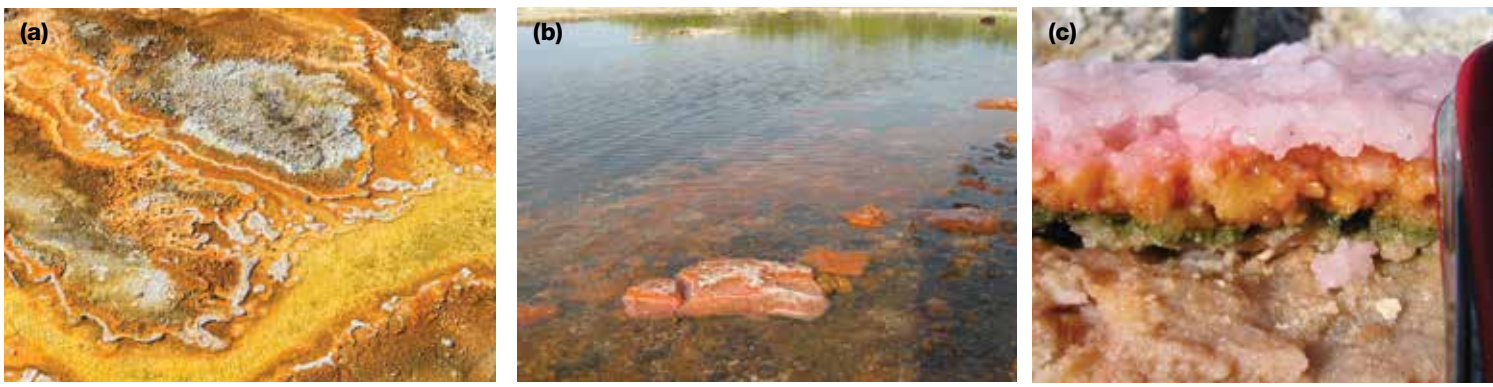


FIGURE 2.3 Microbial mats, composed of multilayers of a community of microbial species, are found in many locations. Different colours indicate the presence of different dominant microbial species. **(a)** A microbial mat in Yellowstone National Park, United States, showing a range of colours **(b)** Microbial mats on the bottom of a hypersaline pond in Kiritimati, an island in the Pacific Ocean. The large pink block at the surface of the pond is solid salt. **(c)** Close-up of a section through a microbial mat located below a pink layer of salt crystals

From their studies of living microbial mats, scientists have identified many characteristic marks and patterns that microbial mats produce on the substrates where they form. These marks can remain on sedimentary rocks that are formed later from these mats. When this happens, the marks are fossilised signs of life. Thus, long after the cells of a microbial mat have disappeared, their distinctive marks and patterns can be preserved on sedimentary rocks, signalling the past existence of the microbes that made them. This is what happened when sandy sediments with their microbial mats were compressed and became part of the rocks of the Pilbara region. The cells of the microbial mats disappeared but the various marks and distinctive patterns that the mats made on sediments have been preserved. These signs of life indicate that unicellular microbial life appeared on this planet 3.6 billion years ago, or even earlier.

In summary, it is reasonable to identify the early forms of life on Earth as unicellular microbe-like organisms, that is, very simple prokaryotes. Based on indirect signs of life, the first cells appeared 3.6 billion years ago or earlier. The earliest *direct* evidence of life on Earth are fossilised cells (microfossils) found in 2011 in Western Australia in rocks known as the Strelley Pool Formation in a remote area of the Pilbara. These rocks have been dated at 3.4 billion years old; this also gives the age of the fossils that they contain.

Since the appearance of the first simple proto-cells on Earth, the microbial world continued to evolve.

The first proto-cells may have gained both the energy and the matter for their structure and functioning from organic molecules in their environment. Because the early Earth had an oxygen-free atmosphere, these first prokaryotes produced energy for living by relatively inefficient fermentation processes, just as occurs today in microbes that live in oxygen-free (anoxic) environments.

From these first prokaryotes, many other kinds of microbes emerged, including microbes that could capture sunlight energy and make their own organic molecules from carbon dioxide; these microbes also produced oxygen as a waste product, which entered the atmosphere. The appearance of oxygen in the atmosphere then set the stage for the emergence of other microbes that could use oxygen in efficient energy-generating processes.

Prokaryotes now occupy an extraordinary range of habitats from ocean depths to the high atmosphere (see Odd fact), and they are very versatile in terms of the energy sources they can exploit. Prokaryotes are the most successful living organisms on this planet. Their absolute numbers and their diversity (number of different species) far exceed those of all eukaryotic species combined. One indication of the diversity of microbial life is the fact that the sediments from subglacial Lake Whillans were found to be home to more than 3900 different microbial species (refer to chapter 1).

Eukaryotic cells with membrane-enclosed nuclei did not appear until much later in Earth's history, perhaps around 2.1 billion years ago, or earlier. (As we will see later in this chapter (see p. 76), all eukaryotic cells carry a reminder of the early evolution of the prokaryotes.) Last of all were the first multicellular organisms that emerged about 600 million years ago.

In the following sections we will explore the ultrastructure of plant and animal cells as examples of eukaryotic cells. First, however, we will look at tools for viewing cells.

studyon
Unit 1
AOS 1
Topic 1
Concept 3
Prokaryotes
Concept summary and practice questions

ODD FACT

Researchers collected large numbers of airborne microbes in samples of air collected about 10 kilometres above the Pacific Ocean. On average, these air samples contained more than 5000 microbial cells per cubic metre of air.

BIOLOGIST AT WORK

Dr Dave Wacey — palaeontologist and astrobiologist

Dave Wacey is a research scientist at the University of Western Australia in Perth. He is a palaeontologist, investigating when and how life first evolved on Earth. He also applies his research findings to the emerging field of astrobiology, helping in the search for life on other planets.

Identifying signs of life on other planets has been a major scientific goal for a number of years and is becoming increasingly significant with each successive Mars mission. The correct decoding of possible biological signals on Earth is critical to our interpretation of extraterrestrial material analysed by or even brought back to Earth from future Mars missions. This is where Dave's work comes in, looking at Earth's oldest rocks, identifying robust signs of life (biosignatures) from within them and formulating biogenicity criteria that can be applied in the future to extraterrestrial rocks.

Dave's research has taken him around the world. He grew up in England where he obtained both his degree in Geology and a PhD from Oxford University. During this time fieldwork took him to Australia, North America and various parts of Europe. After 10 years at Oxford, Dave moved to The University of Western Australia. This move brought him significantly closer to probably the world's best natural laboratory for the study of early life — the approximately 3.5 billion-year-old rocks of the Pilbara region, near Marble Bar.

Since moving to Australia, Dave has made a number of exciting discoveries including finding evidence of communities of bacteria that constructed microbial mats and stromatolites almost 3.5 billion years ago. He also found Earth's oldest **fossil** cells. These are cellular microfossils from 3.43 billion-year-old rocks at Strelley Pool, a remote region of the Pilbara about 60 kilometres west of Marble Bar. They are closely associated with the iron sulfide mineral, pyrite, which suggests that at least some forms of primitive life 'breathed' sulfur compounds instead of oxygen.

Dave investigates early life at a range of scales from kilometres to nanometres. This sees him spend long periods of time in the field (see figure 2.4a), mapping the geological relationships of rocks that look like they may once have been habitable for life, and collecting hand-sized pieces of rock for further study. These pieces are thinly sliced then studied in the laboratory using a number of light, electron and X-ray microscopes to take images of potential microfossils and deduce their chemistry (see figure 2.4b). His field and laboratory experience led Dave to publish a textbook in 2009 called *Early Life on Earth: A Practical Guide*. He is currently working on the 2nd edition of his book.

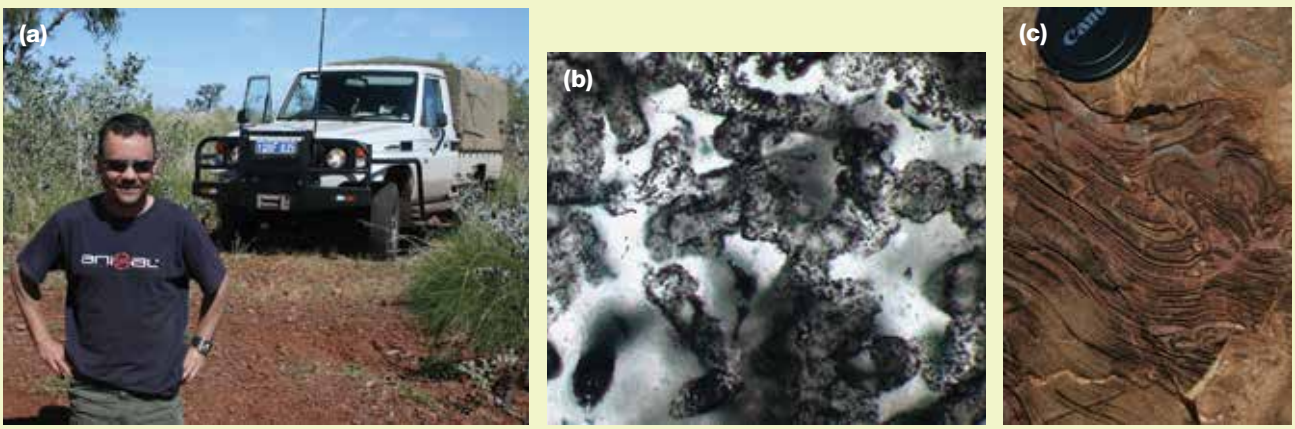


FIGURE 2.4 **(a)** Dave Wacey, palaeontologist, on fieldwork in the Pilbara region of Western Australia
(b) 3.43 billion-year old tubular microfossils discovered in the Pilbara by Dr Wacey. These are the oldest evidence for cellular life on Earth. Each fossil is approximately 1/100th of a millimetre in diameter.
(c) A candidate for Earth's oldest stromatolite, from approximately 3.4 billion-year-old rocks in Australia. Stromatolites are layered and domed structures built by communities of primitive microbes and can be seen today in localities such as Shark Bay, Western Australia.

KEY IDEAS

- The earliest life on planet Earth was that of unicellular microbe-like organisms.
- Signs of life are indirect indicators of the activity of life, past or present.
- Evidence of the earliest form of life on Earth comes from indirect signs of life assumed to have been made by microbial mats.
- Modern microbial mats are found in many environments on Earth.
- From their studies of living microbial mats, scientists have identified characteristic marks and patterns left by modern microbial mats and can identify similar marks and patterns left on ancient rocks.
- Signs of life from fossilised patterns left by microbial mats indicate that the first cells appeared on this planet at least 3.6 billion years ago.
- Life organised as eukaryotic cells appeared on Earth about 2.1 billion years ago or earlier, but much later than the first prokaryotic life forms.
- Multicellular organisms did not emerge on Earth until about 600 million years ago.
- Direct evidence of the earliest forms of life comes from fossilised cells.

QUICK CHECK

1 Identify whether each of the following statements is true or false.
   - **a** Fossilised indirect signs of life could be cells.
   - **b** A modern sign of life could be a footprint.
   - **c** The first cells to appear on planet Earth were eukaryotic cells.
   - **d** The Pilbara region of Western Australia is a source of direct and indirect evidence of early life on Earth.
   - **e** Microbial mats occur in a variety of environments.

2 What is the essential difference between a direct and an indirect sign of life?

Tools for viewing cells

Cells are typically too small to be seen with an unaided eye. Over many years, tools have been developed that have enabled scientists to examine features of cells in more and more detail. The first of these tools were simple microscopes, such as the one used by Robert Hooke who published the first drawings of cells in 1665 (refer to chapter 1, p. 8).

Different kinds of microscope

Today, a range of sophisticated instruments are used to show the ultrastructure of cells in remarkable detail (refer to figure 2.1). These instruments can be broadly classified into two groups: optical (light) microscopes and electron microscopes.

1. In optical microscopy, specimens are illuminated by visible or ultraviolet light, or laser light that is focused on the specimen through the use of lenses. Examples of optical microscopes include the **light microscope**, the **phase contrast microscope**, the **laser scanning confocal microscope** and the **fluorescence microscope**.
2. In electron microscopy, specimens are 'illuminated' by an electron beam that is focused by electromagnets on the specimen. Two types of electron microscope are the **scanning electron microscope (SEM)** and the **transmission electron microscope (TEM)**.

Figure 2.5 shows the different scales over which these two groups of microscopes have traditionally operated. The **resolving power**, or **resolution**, of a microscope refers to the minimum distance apart that two points must be in order for them to be seen as two discrete points. For example, the resolution of optical microscopes is 0.2 micrometres (µm), or 200 nanometres (nm). This means that an optical microscope cannot display two discrete points unless they are separated by more than 200 nm; closer than this and they appear as one larger and blurred point. However, the lower boundary of resolution of 200 nm for optical microscopes has been now pushed to a few nanometres by Nobel-Prize-winning technologies used in research laboratories (see p. 56).

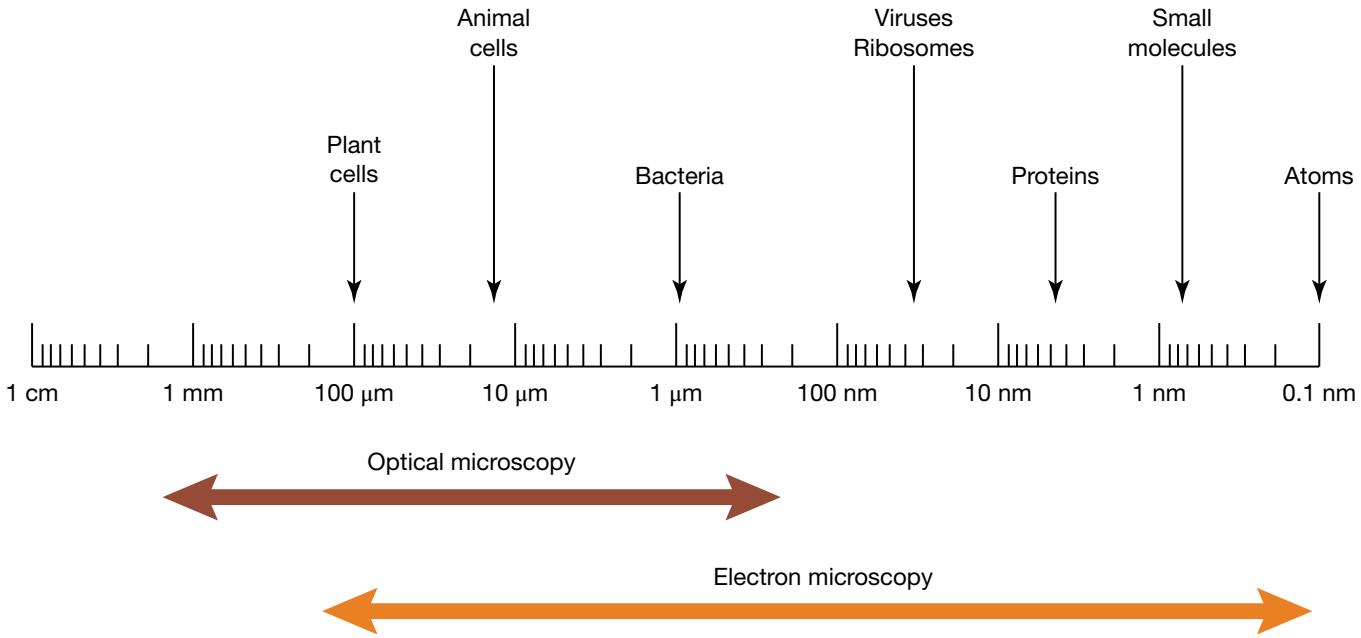


FIGURE 2.5 Scale bar showing approximate sizes of cells, cell organelles, molecules and atoms. The conventional range of operation of light microscopes and electron microscopes is also shown. The lower ends of the ranges, namely about 200 nm for light microscopes, and about 0.1 nm for electron microscopes, identifies the resolving power of the type of microscopy.

ODD FACT

The first electron microscope, with a magnification of 400X was developed in 1931 by Ernst Ruska (1906–88), a German physicist, and Max Knoll (1897–1969), a German electrical engineer. Ruska received the Nobel Prize in Physics in 1986 for the design of the first electron microscope.

Some differences between optical and electron microscopes include:

1. Optical microscopes generally operate at lower levels of resolution and magnification than electron microscopes.
2. Images viewed with optical microscopes are typically coloured, while images viewed with electron microscopes are black and white. The occasional coloured image from an electron microscope is a so-called 'false coloured' image because the colour has been added later.
3. Optical microscopes can be used to view living cells. Living cells cannot be viewed using electron microscopes because electron microscope specimens are dry, coated with an ultra-thin layer of metal, such as gold or osmium and, for imaging, are placed in a vacuum — these are not life-supporting conditions.

The following section provides examples of the many kinds of microscope and of the different types of images of cell(s) that they produce.

Light microscope

Light microscopes typically use visible light to examine cells, including living cells. Cells are usually stained to increase the contrast between various cell components. Resolution of light microscopes is about 0.2 µm (200 nm). Magnification of an image is the product of the magnification of the eyepiece lens by that of the objective lens. For example, if the magnification of the eyepiece lens is 10X and that of the objective lens is 40X, then the image being viewed is magnified 400 times (400X).

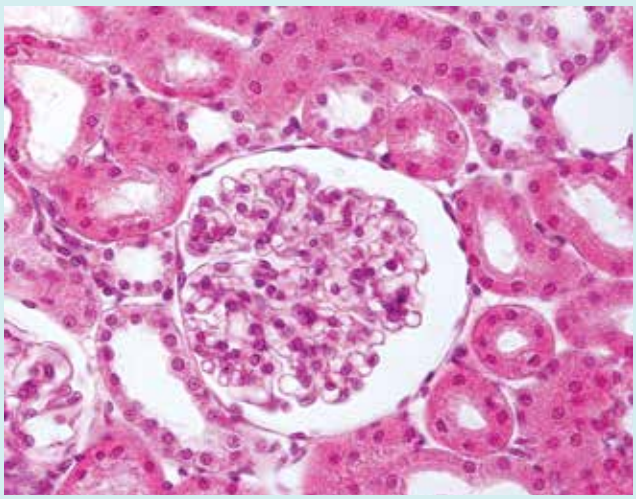


FIGURE 2.6 Light microscope image showing many cells in a section through a human kidney. Note the many purple-stained nuclei.

Laser scanning confocal microscope

Laser scanning confocal microscopy uses high-intensity laser light and special optics to reveal details of a series of successively deeper layers of both living and fixed (dead) cells and tissues. This is done without having to cut the specimen into thin sections. Through the use of computers, the many separate images are combined to create 3D images.

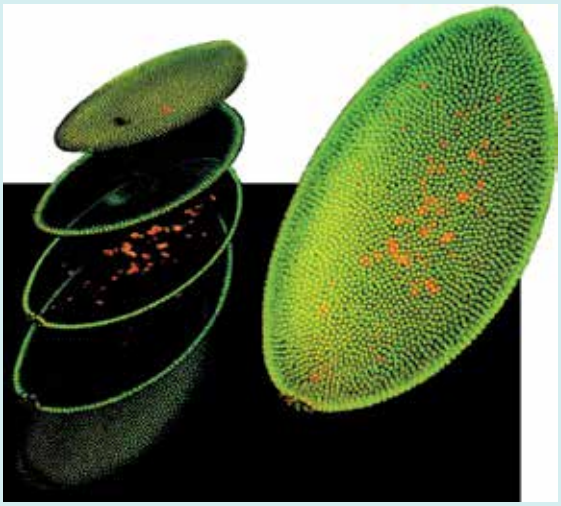


FIGURE 2.7 Technique for laser scanning confocal microscopy. The left-hand side shows some of the 47 laser scans made at different depths through a *Drosophila* embryo. The right-hand side shows the computer-generated final image in which all 47 scans are combined to make a final 3D image of the embryo.

Phase contrast microscope

Phase contrast microscopes are modified light microscopes. They enable transparent or unstained specimens, including living organisms, to be seen in more detail than can be obtained with light microscopes.

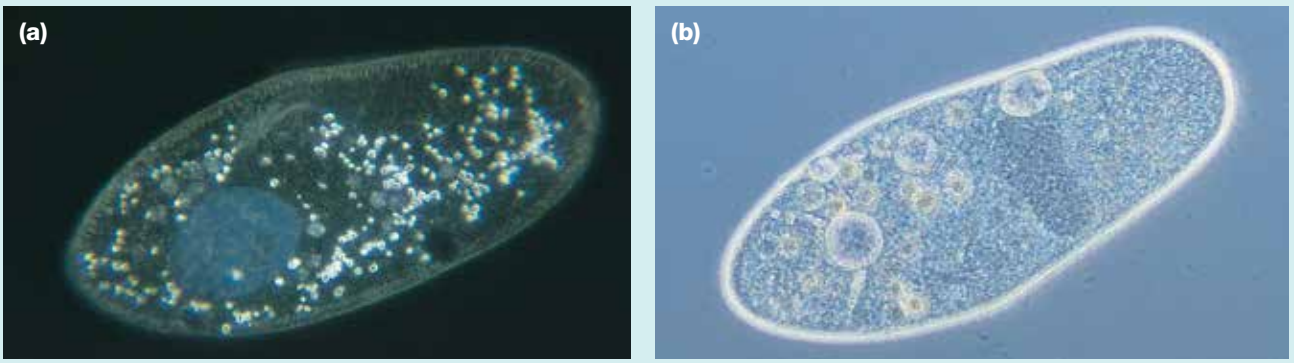


FIGURE 2.8 Image of a living *Paramecium*, a unicellular eukaryotic organism as seen with **(a)** a light microscope and **(b)** a phase contrast microscope. Note the increased detail that is visible with the phase contrast microscope, compared with the standard light microscope.

Fluorescence microscope

In fluorescence microscopy, cells are labelled with fluorescent probes. Different fluorescent probes bind to specific cell organelles, and even to specific proteins. When irradiated with light of a particular wavelength, the probes are excited and fluoresce. Different probes, when excited, produce fluorescence of different colours. Fluorescence microscopy is a very sensitive technique that can be used to identify aspects of the structure and function of living cells.

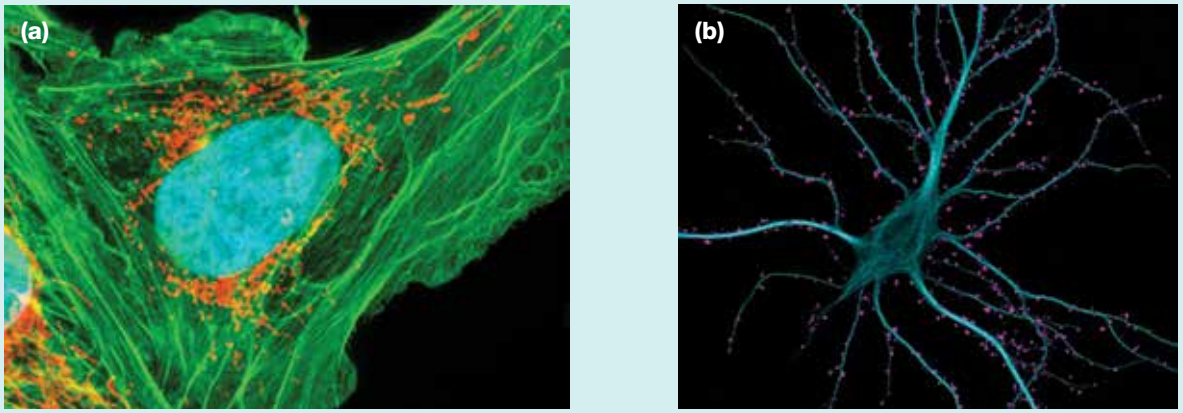


FIGURE 2.9 (a) Fluorescence microscopy image of a human bone cancer (osteosarcoma) cell stained with specific fluorescent probes. Note the mitochondria (orange), the numerous actin filaments of the cytoskeleton (green) and the genetic material, DNA (blue). **(b)** A fluorescence confocal image of a hippocampal neuron (nerve cell) showing excitatory contacts. This was a prize-winning image in an international photomicrography competition. (Image courtesy Dr Kieran Boyle)

Scanning electron microscope (SEM)

In scanning electron microscopy, an electron beam interacts with the surface of a bulk specimen. An SEM can resolve details down to about 2 nm. It reveals texture and surface details, and makes a 3D shape. Depending on the model, an SEM can magnify from 10X to more than 500 000X. SEMs are very good for examining the 3D surface of cells and tissues.

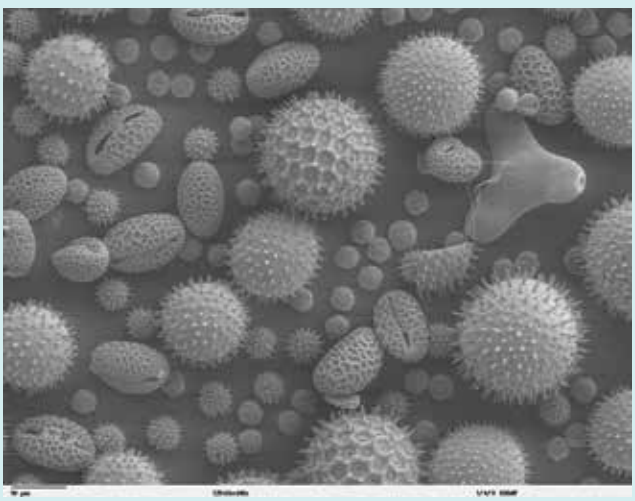


FIGURE 2.10 Image of pollen grains obtained using an SEM. Note the intricate surface details and the 3D shapes.

Transmission electron microscope (TEM)

Transmission electron microscopy uses a focused electron beam that passes through an ultra-thin slice of a cell, revealing very fine detail. Depending on the model, a TEM can magnify to more than 1 000 000X, has a higher resolution than an SEM and can resolve detail down to a separation of less than 0.1 nm, making atoms visible. TEMs are the premier tool for studying cell infrastructure.

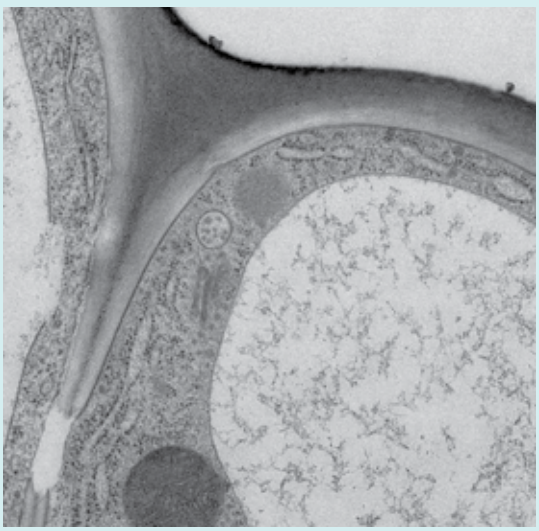


FIGURE 2.11 Section of a plant cell showing detail of infrastructure as revealed by a TEM

From *microscopy* to *nanoscopy*

In 2014, Professor Stefan Hell, from the Max Planck Institute for Biophysical Chemistry in Germany, shared the Nobel Prize in Chemistry for 'super-resolved fluorescence microscopy'. Professor Hell developed a technique known as STED (**st**imulated **e**mission **d**epletion). Using STED, the resolution of fluorescence microscopy has been increased to just a few nanometres. (Compare this with the 200 nm level of resolution of traditional optical microscopy.) This means that objects separated by a distance of just a few nanometres can be resolved as distinct objects, not as a blurred image.

Figure 2.12 shows an image of the nuclear pores in an intact nucleus obtained using STED technology. Note the clarity of the **STED nanoscopy** image that shows the detail of the pores in the nuclear envelope. This is possible because of the increased resolving power of STED, down to a few nanometres. Each pore is surrounded by an outer ring composed of eight protein subunits (red fluorescence). Examine the enlargement at the lower right-hand corner and see if you can identify an outer ring composed of eight protein subunits. Contrast the clarity of the STED nanoscopy image with the fuzzy image obtained using conventional confocal fluorescence microscopy. With a resolving power of only about 200 nm, the confocal technique cannot even resolve the separate nuclear pores, let alone resolve the detail of an individual pore.

ODD FACT

The term 'nanoscopy' has been introduced as a replacement for 'microscopy' when referring to images obtained using super-resolved techniques, such as STED. The prefix *nano-* means 'extremely small or minute', while *micro-* means 'very small'.

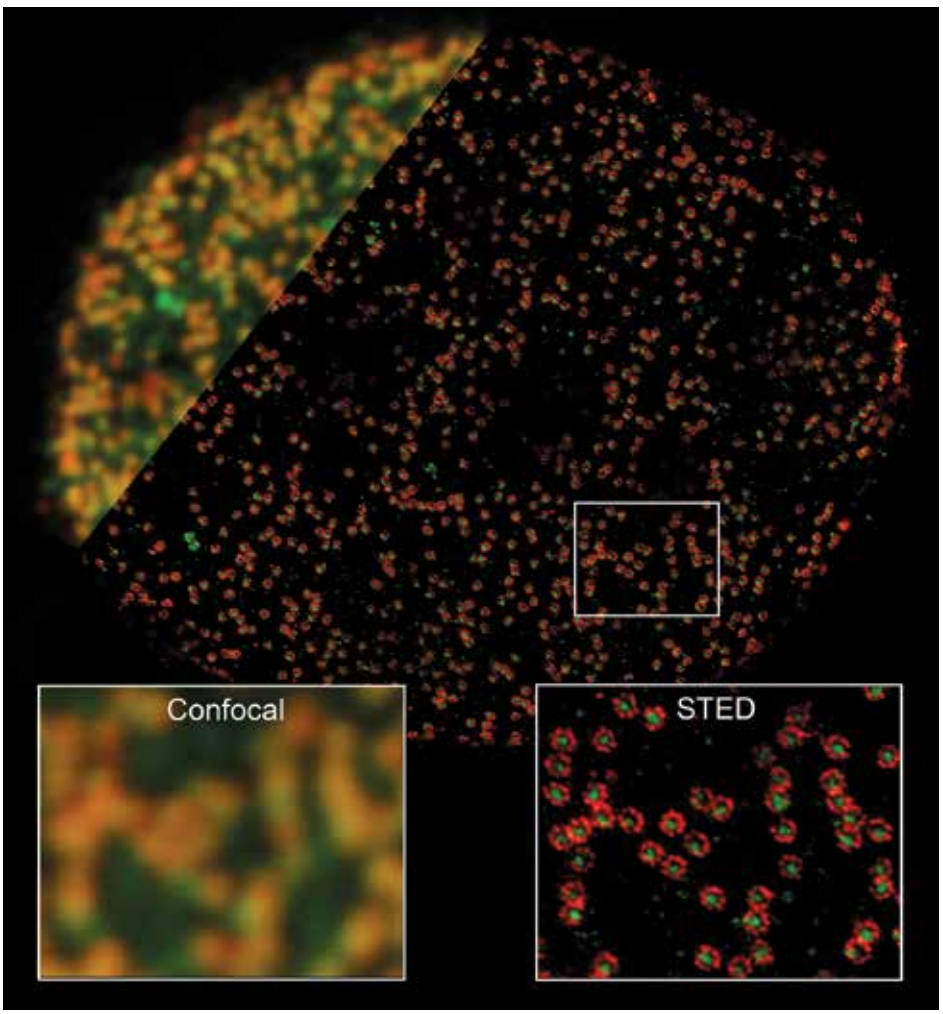


FIGURE 2.12 STED nanoscopy image of the nuclear pore complex in an intact nucleus. Note the clarity of the STED image in contrast to the 'fuzzy' and indistinct image obtained using conventional confocal fluorescence microscopy. Reproduced courtesy of Abberior Instruments GmbH/ Stefan W Hell (2014).

KEY IDEAS

- Cells are typically too small to be seen with an unaided eye.
- Instruments for viewing cells are various kinds of optical and electron microscopes.
- The maximum resolution of a microscope indicates the distance that two points must be separated in order to be distinguished.
- Fluorescence microscopy uses fluorescent probes that bind to cell structures and to proteins to reveal detail of the structure and function of cells.
- Scanning electron microscopes (SEM) reveal surface detail and texture.
- Transmission electron microscopes (TEM) reveal fine detail of cell ultrastructure.
- Recent developments include super-resolved fluorescence microscopy techniques that produce nanoscopic images.

QUICK CHECK

3 Given a choice of any kind of microscope, which kind might you choose to examine the following:
- **a** a living amoeba
- **b** the detailed ultrastructure of an animal cell
- **c** the surface of a layer of cells
- **d** the distribution of a specific protein in cells?

4 Identify whether each of the following statements is true or false.
- **a** A scanning electron microscope can be used to examine living cells.
- **b** The resolving power of a transmission electron microscope is much better that that of a light microscope.
- **c** All kinds of optical microscopes use visible light to illuminate the specimens to be viewed.
- **d** A microscope with a magnifying capability of several hundred thousand is likely to be a phase contrast microscope.

Ultrastructure of eukaryotic cells

The plasma membrane, the boundary of all living cells, was discussed in chapter 1. In this section we will explore the internal structure of plant and animal cells as examples of eukaryotic cells. We will explore the function of the various membrane-enclosed compartments present in both plant and animal cells, as well as the smaller number of cell organelles that are not enclosed by membranes. In addition, those cell organelles that are present in either plant or animal cells will be identified.

Plant and animal cells, like all eukaryotic cells, are characterised by the presence of a number of cell organelles enclosed in membranes (see figure 2.13). Remember that the presence of these membrane-enclosed organelles, in particular the nucleus, is the distinguishing feature of eukaryotic cells. The membrane-bound cell organelles found in plant and animal cells include the nucleus, mitochondria, the endoplasmic reticulum, the Golgi complex and lysosomes. These cell organelles are held in place by a 3D network of fine protein filaments and microtubules within the cell, collectively known as the **cytoskeleton** (see p. 74). Other cell organelles present in eukaryotic cells are *not* enclosed within membranes, for example, ribosomes and microtubules (see figure 2.13).

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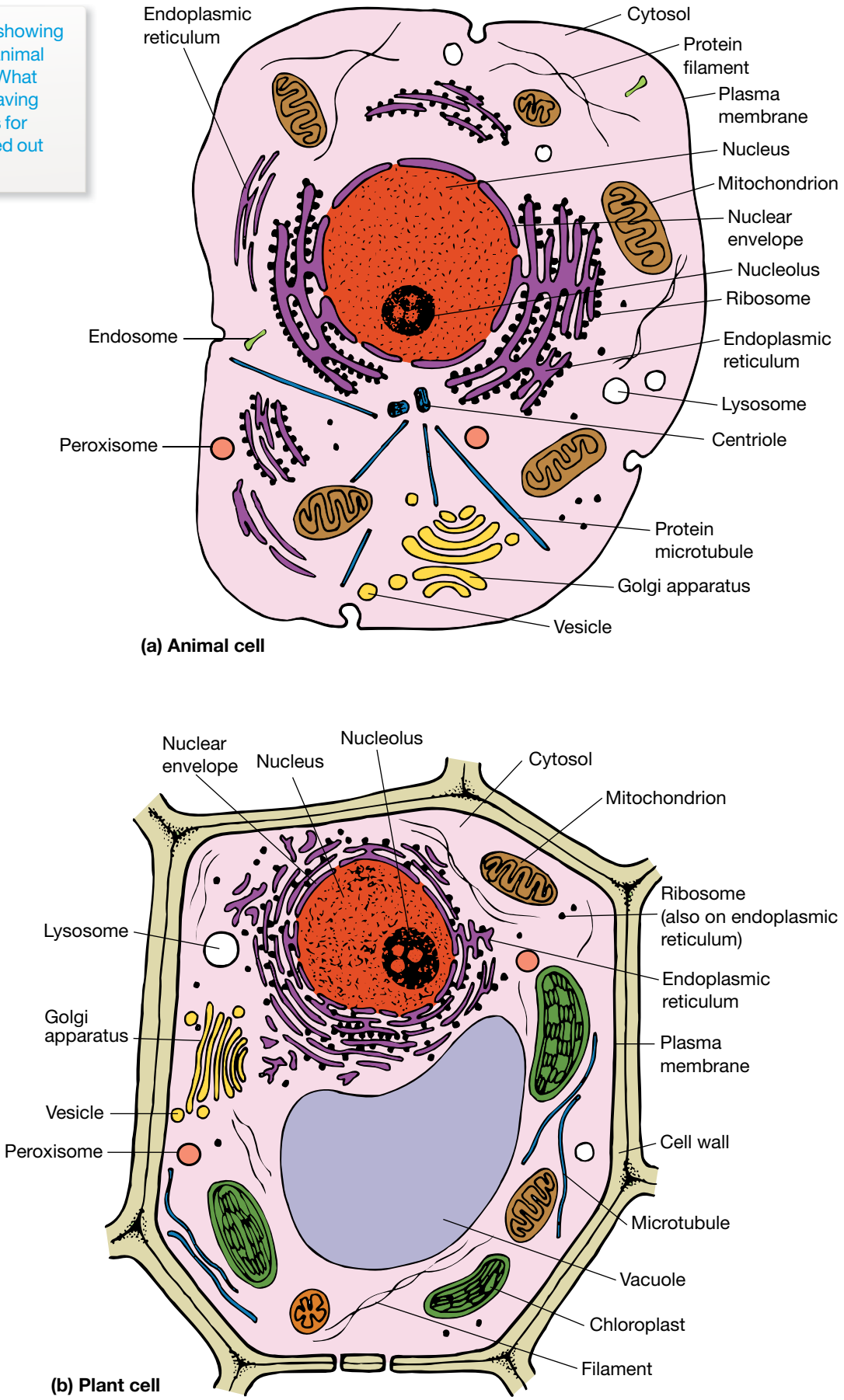
FIGURE 2.13 Diagram showing eukaryotic cells: **(a)** an animal cell and **(b)** a plant cell. What are the advantages of having separate compartments for different functions carried out by cells?



The cell organelles in plant and animal cells are located within a fluid region of the cell called the **cytosol** (shown in pink in figure 2.13). The cell organelles, *excluding* the nucleus, together with the cytosol form the **cytoplasm** of a cell.

Some cell organelles are present in plant cells, but *not* in animals cells:

1. In *some* plant cells membrane-bound organelles called **chloroplasts** may be seen.
2. In a mature plant cell a large central **vacuole** bound by a membrane is visible. A plant vacuole can take up to 80 to 90 per cent of the cell volume and it pushes the rest of the cell contents up against the plasma membrane (see figure 2.14a). Plant vacuoles are fluid-filled and are separated from the rest of the cytosol by the vacuole membrane, or **tonoplast**, that controls the entry and exit of dissolved substances into the vacuole As a result, the composition of the vacuole fluid is different from that of the cytosol. Plant vacuoles serve a number of functions, including storage of nutrients and mineral salts, and are involved in waste disposal (see discussion of lysosomes, pp. 68–70). Vacuoles may contain plant pigments, such as the anthocyanins that produce the purple and red colours of some flowers and fruits (see figure 2.14b).

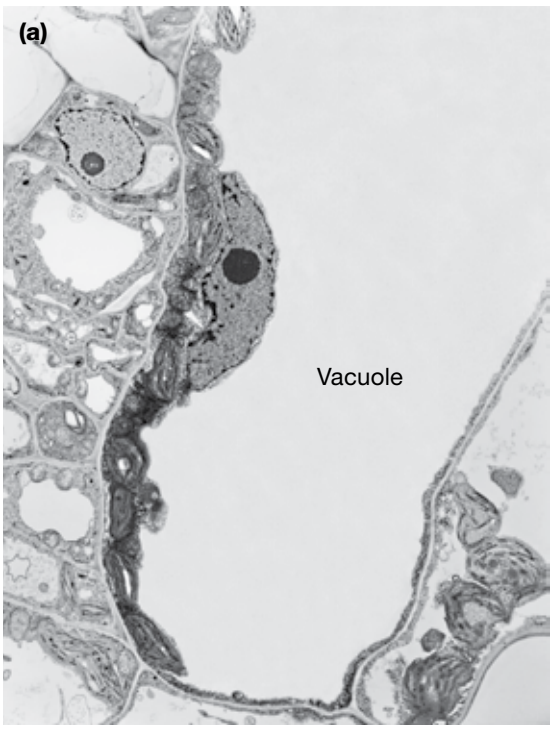


FIGURE 2.14 **(a)** TEM image of a mature plant cell showing its large vacuole. What separates the fluid contents of the vacuole from the rest of the cell contents? **(b)** The vacuole is the site of the anthocyanin pigments that give the red and purple colours to some fruits and flowers.

Cell walls

Let's move outside the plasma membrane to a structure that is present in some prokaryotic cells and in the all the cells of plants, algae and fungi, but *not* in animal cells. This is the **cell wall**.

The cell wall is located outside and surrounds the plasma membrane. The cell wall provides strength and support to cells and acts to prevent the over-expansion of the cell contents if there is a net movement of water into cells by osmosis. Cell walls are present in prokaryotic cells, in some protists and in all plant, algal and fungal cells. The presence of a cell wall is *not* a diagnostic feature that allows you to decide if a cell is prokaryotic or eukaryotic. This decision can only be made based on knowledge of the major component(s) in the cell wall.

Table 2.1 summarises the situation in prokaryotes and eukaryotes. Note that animal cells do not have cell walls and this absence serves to distinguish animal cells from all other eukaryotic cells.

TABLE 2.1 Composition of cell walls in various cell types

Type of organism	Major compound(s) in cell walls
prokaryote: most bacteria	peptidoglycan, a polymer composed of long strands of polysaccharides, cross linked by short chains of amino acids
prokaryote: most archaea	various compounds, including proteins or glycoproteins or polysaccharides; peptidoglycan *not* present
eukaryote: all fungi	chitin, a complex polysaccharide
eukaryote: all plants	cellulose in the primary cell wall; lignin in the secondary cell wall

Note: Bacteria of the genus *Mycoplasma* do not have cell walls. These parasitic bacteria are the smallest living organisms (just 0.1 µm, or 100 nm). Most are surface parasites growing on cells but some species, such as *M. penetrans,* are intracellular pathogens growing inside the cells of their hosts.

ODD FACT

Antibiotics, such as penicillin, stop some bacterial infections by disrupting the synthesis of bacterial cell walls. Because animal cells lack cell walls, antibiotics can be given to people to attack bacterial infections while leaving human cells unaffected. Would you expect penicillin to be useful against a *Mycoplasma* infection?

All plant cells have a **primary cell wall** made of fibrils of **cellulose** combined with other substances (see figure 2.15). The primary cell wall provides some mechanical strength for plant cells and allows them to resist the pressure of water taken up by osmosis (refer to figure 1.27, p. 30, which shows the difference in the behaviour of plant and animal cells in hypotonic environments). Cells with just a primary cell wall are able to divide and can also expand as the cells grow.

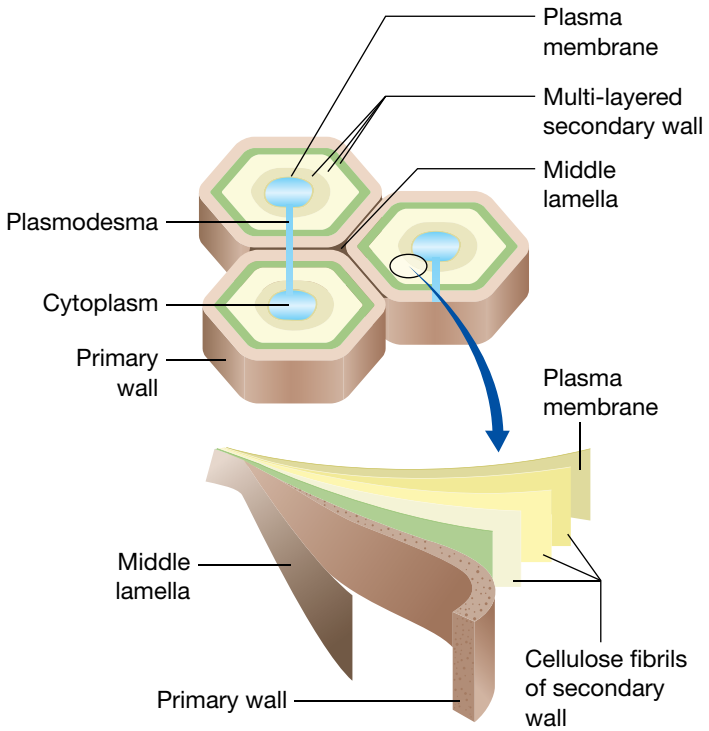


FIGURE 2.15 The primary cell wall of plant cells is made mainly of cellulose fibrils. Secondary cell walls that form in some cells of woody shrubs and trees are thicker and rigid because of strengthening by lignin. The middle lamella is a layer that forms between adjacent plant cells and this also contains lignin. Cytoplasmic connections exist between adjacent plant cells through pits in the cell wall. These connections are known as plasmodesmata.

Secondary cell walls develop in woody plants, such as shrubs and trees, and in some perennial grasses. Like primary cell walls, secondary cell walls are composed of cellulose. However, secondary cell walls are further strengthened and made rigid and hard by the presence of **lignin**, a complex insoluble cross-linked polymer. Secondary cell walls are laid down inside the primary cell walls, in particular in the various cells of the xylem tissue. As their secondary cell walls continue to thicken the cells die.

ODD FACT

Wood essentially consists of dead xylem cells, such as tracheids, vessels and fibres. The principal components of dry wood are cellulose (40%–44% of dry weight) and lignin (25%–35% of dry weight).

Secondary cell walls of dead xylem tissue create the 'woodiness' of shrubs and trees that gives increased mechanical strength to these plants, enabling them to grow high. Secondary cell walls give wood its shape and strength. Figure 2.16 is an SEM image of wood showing the various dead cells of xylem tissue that form the substance of wood.

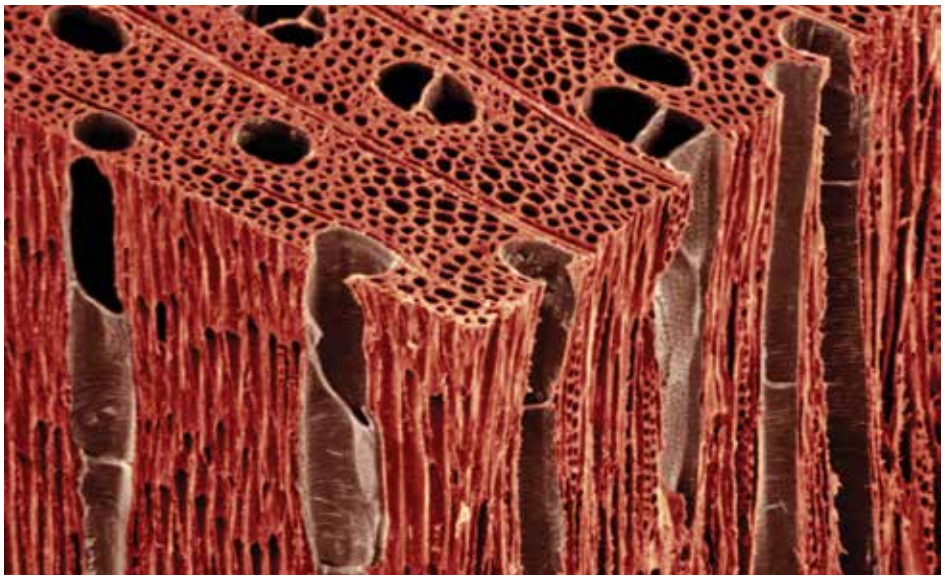


FIGURE 2.16 SEM image of a sample of hardwood. The wood is dead xylem tissue that consists mainly of the secondary cell walls including: (i) **tracheids**, small elongated cells that make up most of the wood; and (ii) **vessels**, larger cells but much fewer in number. Soft woods from conifer trees can be distinguished from hard woods because their wood lacks vessels.

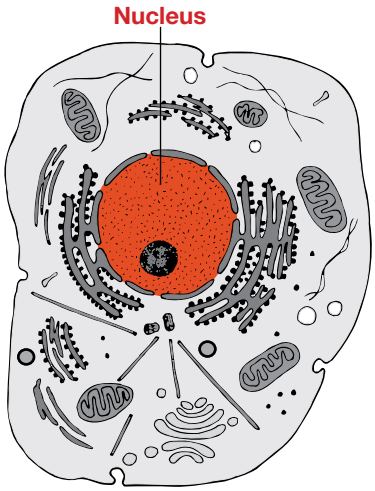


FIGURE 2.17 Fluorescence microscope image of eukaryotic cells. The nucleus in each cell appears as a fluorescent red body. What defines the shape of the nucleus? Based on this image, can you suggest whether this a cell from an animal or a plant?

Nucleus: the control centre

Cells have a complex internal organisation and are able to carry out many functions. The centre that controls these functions in the cells of animals, plants and fungi is the **nucleus** (see figure 2.17).

The nucleus is the defining feature of eukaryotic cells and it is a distinct spherical structure that is enclosed within a double membrane, known as the **nuclear envelope**. The nuclear envelope is perforated by protein-lined channels called **nuclear pore complexes** (NPCs) (see figure 2.18; also refer to figure 2.12). In a typical vertebrate animal cell, there can be as many as about 2000 NPCs that control the exchange of materials between the nucleus and the cytoplasm. Large molecules are transported into and out of the nucleus via the nuclear pore complexes. Molecules that move from nucleus to cytoplasm include RNA and ribosomal proteins, while large molecules that move into the nucleus from the cytoplasm include proteins.

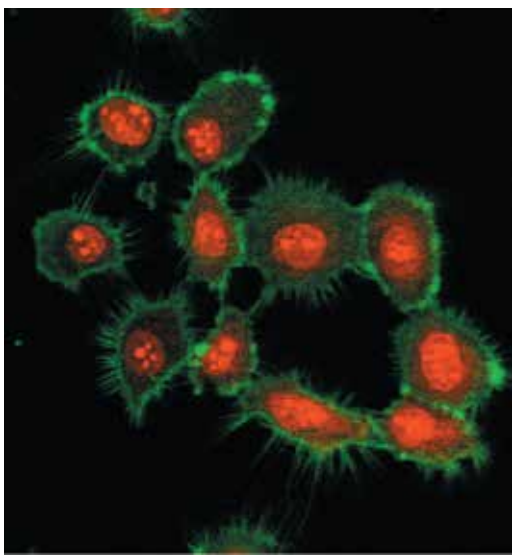


FIGURE 2.18 False coloured freeze–fracture TEM image of part of the nuclear envelope of a liver cell. The inner membrane (top blue) and the outer membrane (brown) are both visible. The rounded pores on the membrane allow large molecules to exit the nucleus and move into the cytosol. What large molecules might move from the nucleus to the cytosol?

A light microscope view reveals that the nucleus of a eukaryotic cell contains stained material called **chromatin** that is made of the genetic material **deoxyribonucleic acid (DNA)**. The DNA is usually dispersed within the nucleus. During the process of cell reproduction, however, the DNA becomes organised into a number of rod-shaped chromosomes. The nucleus also contains one or more large inclusions known as nucleoli (singular: **nucleolus**) that are composed of **ribonucleic acid (RNA)**. The nucleolus is not enclosed within a membrane. The function of the nucleolus is to produce the **ribosomal RNA** (rRNA) that forms part of the ribosomes (see below).

The nucleus houses the genetic material and the functions of the nucleus include:

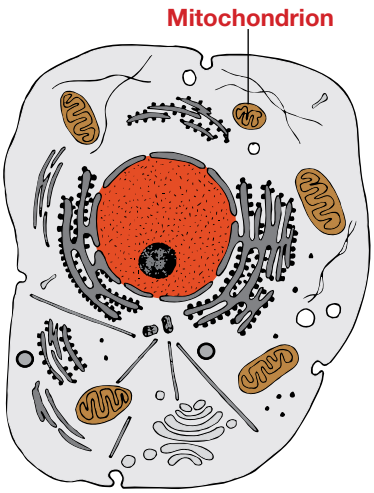
- control of DNA replication during cell division
- repair of the genetic material
- initiation of gene expression
- control of the metabolic activities of a cell by regulating which genes are expressed.

All cells have the same complement of DNA (except for reproductive cells), but the set of genes expressed in one type of cell differentiates these cells from cells of another type. For example, smooth muscle cells express the genes for contractile proteins, actin and myosin. These genes are silent in salivary gland cells that express the gene for the digestive enzyme, amylase. Both cells, however, express the genes concerned with essential life processes, such as those involved with cellular respiration.

Textbook diagrams typically show a cell as having a single nucleus. This is the usual situation, but it is not always the case. Some liver cells have two nuclei. Your bloodstream contains very large numbers of mature red blood cells, each with no nucleus. However, at an earlier stage, as immature cells located in your bone marrow, these cells did have a nucleus. Given the function of red blood cells, can you think of any advantage that the absence of a nucleus might give to them? Skeletal muscle is the voluntary muscle in your body that enables you to stand up or pick up a pen or kick a soccer ball. Skeletal muscle consists of long fibres that are formed by the fusion of many cells. Such structures contain many nuclei and are said to be multinucleate.

ODD FACT

The term ‘chromosome’ means ‘coloured body’. The fact that the cell of each species contains a definite number of chromosomes was first recognised in 1883.



Mitochondria: the energy-suppliers

Living cells are using energy all the time. The readily useable form of energy for cells is the chemical energy present in the compound known as **adenosine triphosphate (ATP)** (see figure 2.19). The supplies of ATP in living cells are continually being used and so must continually be replaced.

In eukaryotic cells, ATP production occurs mainly in the cell organelles known as **mitochondria** (singular: mitochondrion from the Greek, *mitos* = thread; *chondrion* = small grain). Mitochondria are *not* present in prokaryotic cells — their size alone would make this impossible (refer to figure 1.11, p. 11).

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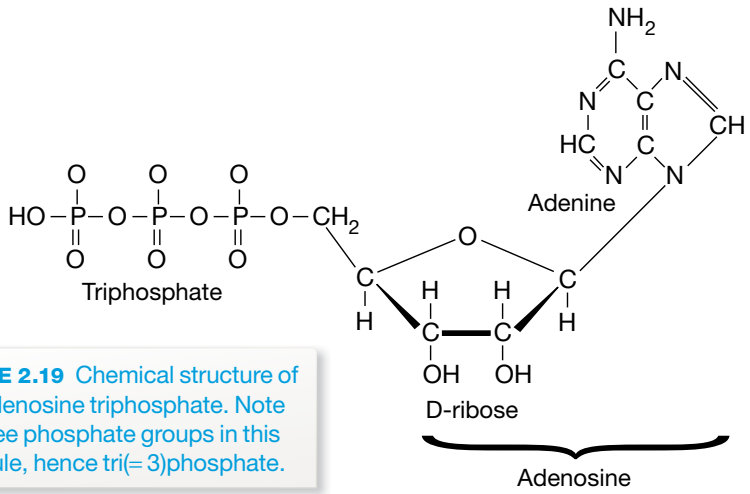


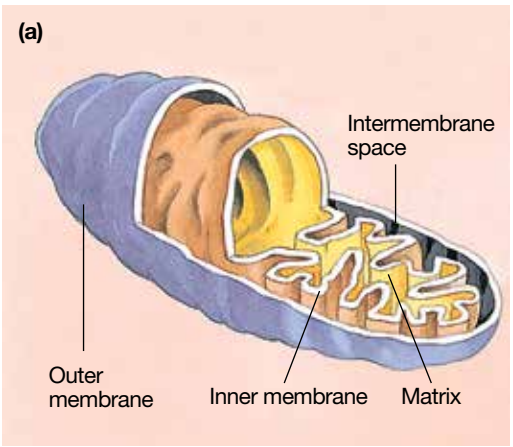
FIGURE 2.19 Chemical structure of ATP, adenosine triphosphate. Note the three phosphate groups in this molecule, hence tri(= 3)phosphate.

ODD FACT

Mitochondria were first recognised as cell organelles in 1890 by Richard Altmann, a German cytologist. He called them 'bioblasts', but they were re-named 'mitochondria' in 1898.

Plant and animal cells produce ATP in the process of **cellular respiration**, a series of biochemical reactions that, in the presence of oxygen, transfer the chemical energy of sugars to the energy in chemical bonds in ATP. ATP is the readily useable form of energy for cells. (This topic is covered in chapter 3.) Part of the process of cellular respiration occurs in the cytosol but this series of reactions (glycolysis) produces only a small amount of ATP. It is the stages of cellular respiration that occur in the mitochondria and make use of oxygen that produce the greatest amounts of ATP — more than 95 per cent — this is why mitochondria are often referred to as the 'powerhouses' of the cell.

Mitochondria cannot be resolved using a light microscope, but can easily be seen with an electron microscope. Each mitochondrion has a smooth outer membrane and a highly folded inner membrane (see figure 2.20). Note that this structure creates two compartments within a mitochondrion. Carriers embedded in the folds or cristae (singular: crista) of the inner membrane are important in cellular respiration (see chapter 3).



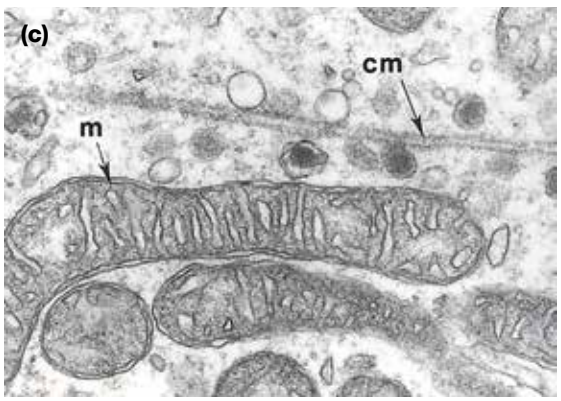


FIGURE 2.20 (a) Diagram of a mitochondrion showing its two membranes. Which is more highly folded: the outer or the inner membrane? **(b)** False coloured scanning electron micrograph of a section through a mitochondrion (pink) **(c)** TEM of a mitochondrion (78 000X); m = mitochondrion, cm = cell membranes (plasma membrane) of two adjacent cells

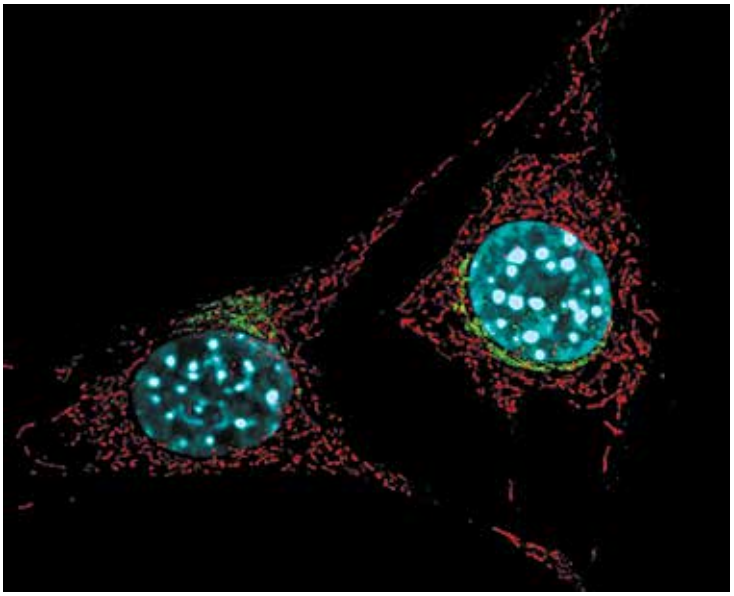


FIGURE 2.21 Living cells labelled with fluorescent probes that detect and bind to specific cell organelles. Mitochondria show red fluorescence, the Golgi complex shows green fluorescence and the DNA — the genetic material — fluoresces blue. Where are the mitochondria located in a cell? Where is the DNA located?

The number of mitochondria in different cell types varies greatly. In general, the more active the cell, the greater the number of mitochondria in that cell. For example, liver cells have one to two thousand mitochondria per cell. (Refer to table 1.2, p. 19 and check the relative volume of a liver cell that is occupied by its mitochondria.) In contrast, mature red blood cells have no mitochondria. The difference between these two cell types is that the liver is a vital organ and its cells carry out various functions related to digestion, immunity, and the storage and release of nutrients, all of which require an input of energy. Red blood cells, however, are effectively just bags of haemoglobin that are carried passively around the bloodstream. Relative to other cells, red blood cells have very low energy needs that can be met by fermentation, a less efficient process of ATP production.

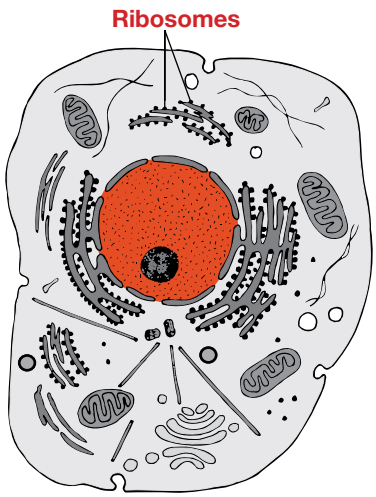
Figure 2.21 shows cells labelled with fluorescent probes that are specific for different cell organelles; note the large number of mitochondria (stained red). What does this suggest about the metabolic activity of these cells?

ODD FACT

It is estimated that about 40 per cent of the cytoplasmic space in heart muscle is occupied by mitochondria.

KEY IDEAS

- **Eukaryotic cells are partitioned into several compartments, each bound by a membrane, with each compartment having specific functions.**
- **In eukaryotic cells, the nucleic acid DNA is enclosed within the nucleus, a double–membrane bound organelle.**
- **The nucleolus is the site of production of RNA.**
- **Living cells use energy all the time, principally in the form of chemical energy present in ATP.**
- **Mitochondria are the major sites of ATP production in eukaryotic cells.**
- **The density of mitochondria in a cell reflects its energy needs.**



QUICK CHECK

5 Identify whether each of the following is true or false, giving a brief explanation where needed.
   - **a** A nucleus from a plant cell would be expected to have a nuclear envelope.
   - **b** Prokaryotic cells do not have DNA.
   - **c** A mature red blood cell has high energy needs and, in consequence, has large numbers of mitochondria.

6 What is the difference between the cytosol and the cytoplasm of a cell?

7 A cell has a cell wall. What conclusion can be drawn about the kind of organisms from which it came?

Ribosomes: protein factories

Cells make a range of proteins for many purposes. For example, development of human red blood cells in the bone marrow manufacture of haemoglobin, an oxygen-transporting protein; manufacture of the contractile proteins, actin

and myosin by the muscle cells; and manufacture of the hormone insulin and digestive enzymes including lipases by different cells of the pancreas.

Ribosomes are the site in the cell where proteins are made. It is on the ribosomes that amino acids are assembled and joined into polypeptide chains or proteins. The diameter of a ribosome is only about 0.03 µm. Because of their very small size, ribosomes can be seen only through an electron microscope (see figure 2.22a). However, ribosomes are present in very large numbers in a cell. Ribosomes in animal and plant cells are composed of about two-thirds RNA and one-third protein.

Within a cell, many ribosomes are attached to membranous channels known as the endoplasmic reticulum (see next section). Other ribosomes are found free in the cytosol. Proteins produced by ribosomes on the endoplasmic reticulum (see figure 2.22b) are generally exported from the cell. Proteins made by 'free' ribosomes are for local use within the cell.

ODD FACT

Ribosomes can join amino acids into a protein chain at the rate of about 200 per minute.

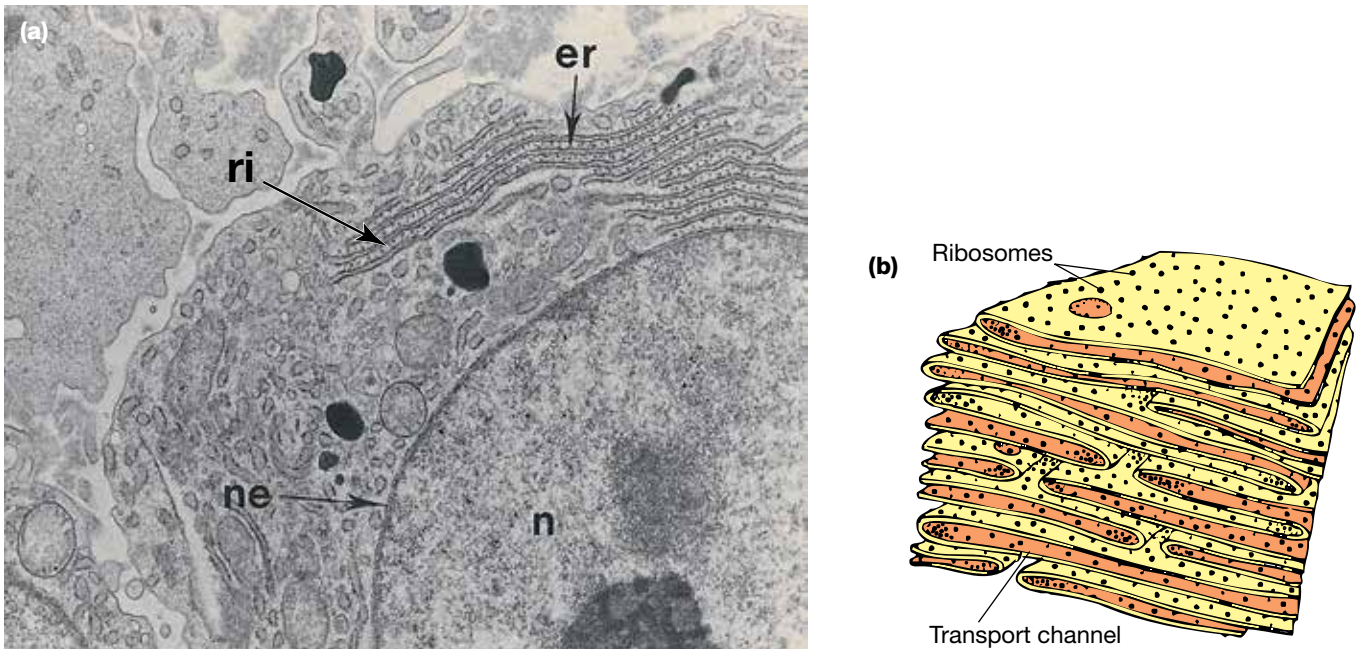
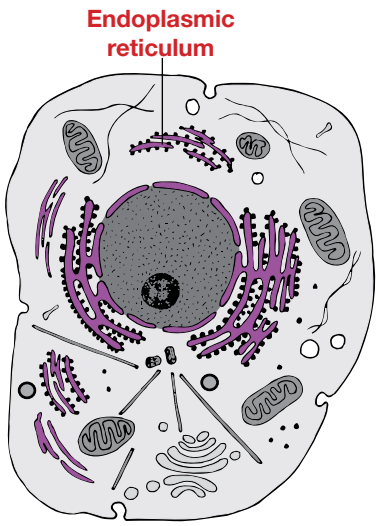


FIGURE 2.22 **(a)** TEM image of a section of cell showing the rough endoplasmic reticulum (er) with ribosomes (ri). Note also the nucleus (n) inside its nuclear membrane or envelope (ne). Ribosomes are only about 0.03 µm in diameter so they appear as tiny dots in this image. Are ribosomes enclosed in a membrane? **(b)** 3D representation of the endoplasmic reticulum with ribosomes



Endoplasmic reticulum: active channels

The **endoplasmic reticulum (ER)** is an interconnected system of membrane-enclosed flattened channels. Figure 2.23 shows part of the channels of the endoplasmic reticulum in a eukaryotic cell. Refer also to figure 2.22a. Where the ER has ribosomes attached to the outer surface of its channels, it is known as **rough endoplasmic reticulum**. Without

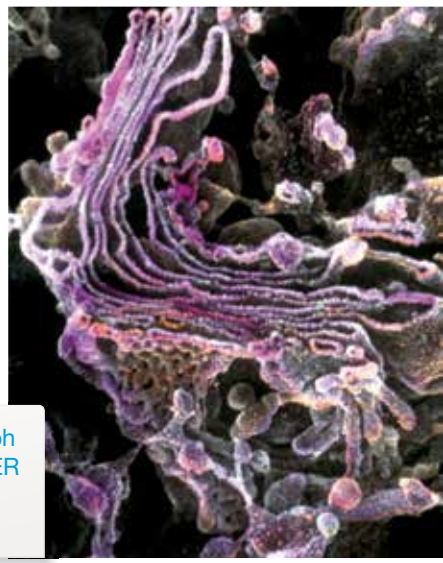


FIGURE 2.23 False coloured scanning electron micrograph of part of a eukaryotic cell showing the channels of rough ER (pink). Note the many tiny bead-like structures attached to the outside of the ER channels. What are these structures?

ODD FACT

An estimated 13 million ribosomes are attached to the rough ER in a typical human liver cell.

ribosomes, the term **smooth endoplasmic reticulum** is used. The rough ER and the smooth ER are separate networks of channels and they are not physically connected.

Both the rough ER and the smooth ER are involved in transporting different materials *within* cells, but they are not passive channels like pipes. **As well as their roles in internal transport within a cell, the rough ER and the smooth ER have other important functions**, as outlined below.

Rough ER

Through its network of channels, the rough ER is involved in transporting some of the proteins to various sites within a cell. Proteins delivered from the ribosome into the channels of the rough ER are also processed before they are transported. The processing of proteins within the rough ER includes:

- attaching sugar groups to some proteins to form glycoproteins
- folding proteins into their correct functional shape or conformation
- assembling complex proteins by linking together several polypeptide chains, such as the four polypeptide chains that comprise the haemoglobin protein.

ODD FACT

Smooth ER in liver cells can double its surface area when it is in 'detox' mode in response to the toxic effects of an overdose of barbiturate drugs or an alcoholic binge.

Smooth ER

The smooth ER of different cells is involved in the manufacture of substances, detoxifying harmful products, and the storage and release of substances.

For example:

- The outer membrane surface of the smooth ER is a site of synthesis of lipids; these lipids are then enclosed in a small section of the smooth ER membrane that breaks off and transports the lipids to sites within the cell where they are either used or exported from the cell.
- In cells of the adrenal gland cortex and in hormone-producing glands, such as ovaries and testes, the smooth ER is involved in the synthesis of steroid hormones, for example, testosterone.
- In liver cells, the smooth ER detoxifies harmful hydrophobic products of metabolism and barbiturate drugs by converting them to water-soluble forms that can be excreted via the kidneys.
- In liver cells, the smooth ER stores glycogen as granules on its outer surface (see figure 2.24) and breaks it down into glucose for export from the liver.

The importance of both rough and smooth ER in their various cellular functions is highlighted by the fact that, in an animal cell, about half of the total membrane surface is part of the endoplasmic reticulum.

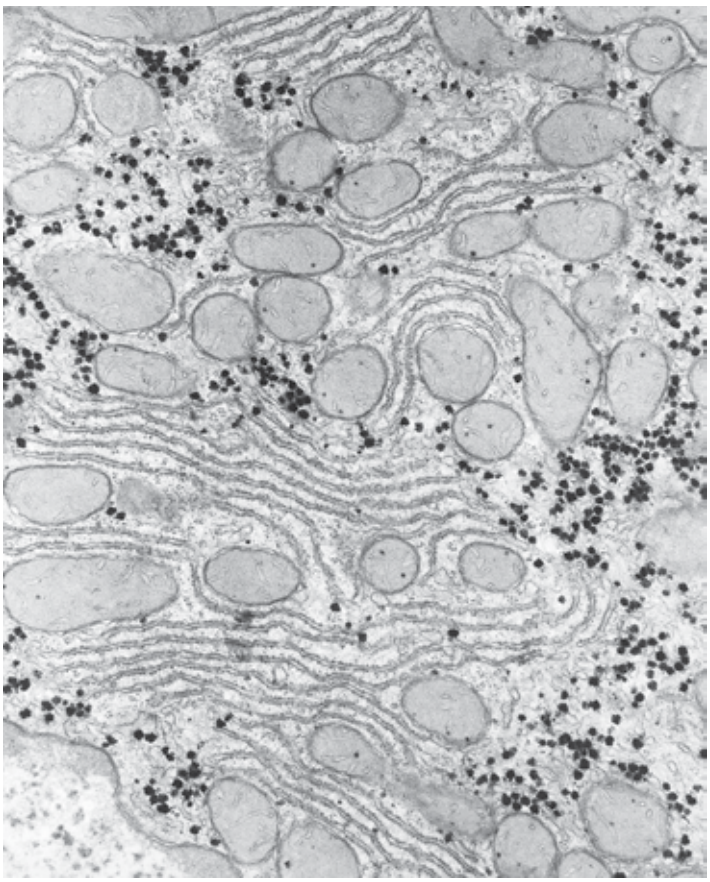
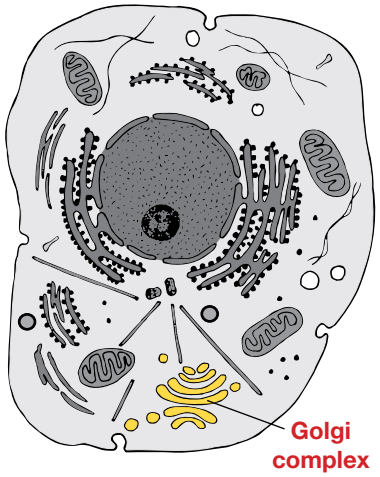


FIGURE 2.24 TEM image of an area of liver cell with an abundant supply of smooth ER (parallel membrane-lined channels). Dark clusters of glycogen particles (black dots) are visible around the smooth ER. Also visible are sections of mitochondria (large circular shapes).



Golgi complex: the exporter

Some cells produce proteins that are intended for use outside the cells where they are formed. Examples include the following proteins that are produced by one kind of cell and then exported (secreted) by those cells for use elsewhere in the body:

- the digestive enzyme pepsin, produced by cells lining the stomach and secreted into the stomach cavity
- the protein hormone insulin, produced by cells in the pancreas and secreted into the bloodstream
- protein antibodies, produced in special lymphocytes and secreted at an area of infection.

How do these substances get exported from cells? The cell organelle responsible for the export of substances out of cells is the **Golgi complex**, also known as the Golgi apparatus. The Golgi complex has a multi-layered structure composed of stacks of membrane-lined channels (see figure 2.25).

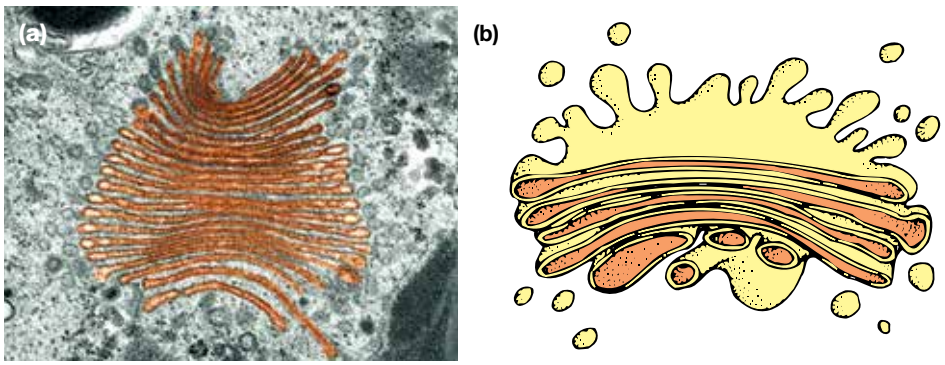


FIGURE 2.25 **(a)** False coloured TEM image of the Golgi complex (orange). Note the stacks of flattened membrane-lined channels with their wider ends that can break free as separate vesicles. **(b)** 3D representation of the Golgi complex. Note the vesicles breaking off from the ends of the Golgi complex membranes. What is their role?

ODD FACT

The Golgi complex is named after Camillo Golgi who, in 1898, first identified this cell organelle.

Proteins from the rough ER that are intended for export must be transferred to the Golgi complex. Figure 2.26 outlines the pathway followed. Because there is no direct connection between the membranes of the ER and the Golgi complex, the proteins are shuttled to the Golgi complex in membrane-bound

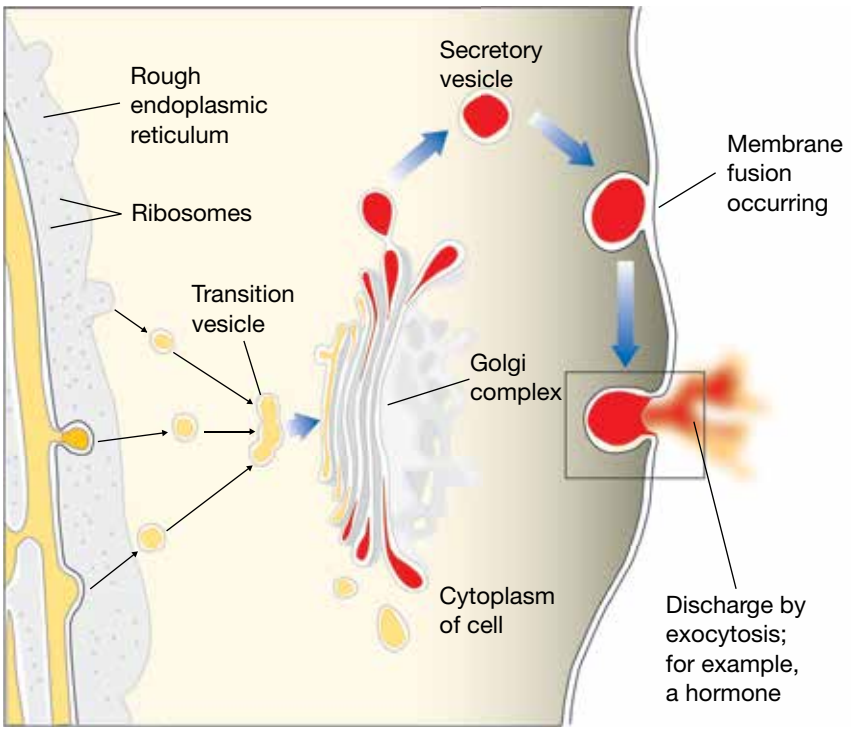


FIGURE 2.26 The secretory export pathway for proteins. Packages of protein are transferred from the rough ER in transition vesicles to the Golgi complex where they are taken in. From the Golgi complex, the secretory vesicles with their protein cargo move to the plasma membrane of the cell, merge with it and discharge their contents.

transition vesicles. The vesicles are taken into the Golgi complex where the proteins are concentrated and packaged into **secretory vesicles** that break free from the Golgi complex. The secretory vesicles move to the plasma membrane of the cell where they merge with it, discharging their protein contents. (Is this an example of exocytosis or endocytosis? Refer to chapter 1, pp. 38–9.) Lipids synthesised on the smooth ER and intended for export follow a similar pathway.

KEY IDEAS

- Ribosomes are cell organelles where proteins are manufactured.
- The endoplasmic reticulum (ER) is made of a series of membrane-bound channels.
- Rough ER is so named because of the presence of ribosomes on the external surface of its membranes.
- Rough ER is involved in processing of proteins and in their transport.
- Smooth ER lacks ribosomes and has several functions, including the synthesis of lipids and detoxifying harmful substances.
- The Golgi complex packages substances into vesicles for export from a cell.

QUICK CHECK

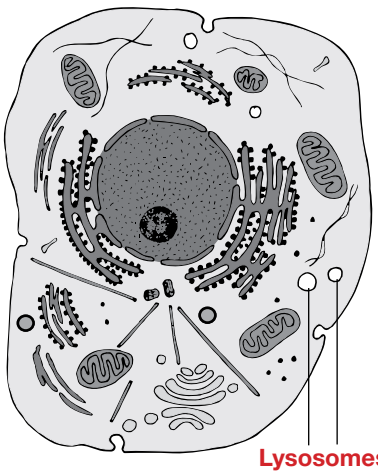
8 Identify whether each of the following is true or false.
- **a** The RNA of the ribosomes is made in the nucleolus.
- **b** Rough ER and smooth ER serve the same functions in a eukaryote cell.
- **c** The folding of a protein into its functional 3D shape takes place on the ribosomes.
- **d** Ribosomes are membrane-bound organelles that form part of the cell cytoplasm.
- **e** The channels of the Golgi complex are connected to those of the ER.

9 A scientist wished to examine ribosomes in a liver cell.
- **a** Where should the scientist look: in the nucleus or the cytoplasm?
- **b** What kind of microscope is likely to be used by the scientist: a light microscope or a transmission electron microscope? Explain.

10 List one similarity between rough ER and smooth ER.

11 Identify two differences between rough ER and smooth ER, one structural and one functional.

12 The liver is an important organ in detoxification of harmful substances. What organelle in liver cells is active in this process?



Lysosomes: the digestors

The cytoplasm of animal cells contains fluid-filled sacs enclosed within a single membrane, typically spherical in shape with diameters in the range of 0.2 to 0.8 µm. The fluid in these cell organelles contains a large number (about 50) of digestive enzymes that can break down carbohydrates, proteins, lipids, polysaccharides and nucleic acids. These lysosomal enzymes are only active in an acidic environment (pH about 4.8). These cell organelles are known as **lysosomes** (*lysis* = destruction; *soma* = body) (see figure 2.27) and they were first identified as cell organelles in 1955 by Christian du Dve, a Belgian cytologist.

A similar function is carried out in plant cells by vacuoles containing a similar range of enzymes to those in the lysosomes of animal cells. Some experts call these lysosome-like vacuoles, while others simply call them plant lysosomes.

FIGURE 2.27 High-resolution false coloured scanning electron microscope image of a lysosome (green) from a pancreatic cell. The material inside the membrane wall of the lysosome is material undergoing digestion. What causes this digestion? Note the surfaces of the nearby membranes of the endoplasmic reticulum (pink) that are covered with ribosomes. Is the ER in this image rough ER or smooth ER?

Functions of lysosomes include:

- digestion of some of the excess macromolecules within a cell. The excess material is delivered to the lysosome where it is broken down into small subunits by specific enzymes, such as proteins to their amino acid subunits and polysaccharides to their sugar subunits. The subunits are released from the lysosome into the cytoplasm where they can be re-used — an example of recycling at the cellular level.
- breakdown of non-functioning cell organelles that are old and/or damaged and in need of turnover — a process known as **autophagy** (from the Greek: *auto* = self; *phagy* = eating)
- breakdown of substances, such as bacteria, brought into the cell by phagocytosis (refer to chapter 1, p. 39).

Defects of the lysosome enzymes can occur. If an enzyme is defective, it can no longer digest the excess or unwanted substance that is the specific target of that enzyme. Instead, the substance accumulates in the lysosomes, causing a disruption of normal cell function. Disorders arising from defective lysosomal enzymes are called **lysosome storage diseases**. About 50 of these disorders have now been identified.

Plant vacuoles were once regarded as having a storage function only. Later studies (e.g. 'Barley aleurone cells contain two types of vacuoles: Characterization of lytic organelles by use of fluorescent probes', 1998) reported the existence of a second kind of plant vacuole containing hydrolytic (digestive) enzymes.

The first clue to the existence of lysosome storage diseases came from investigations by a Dutch pathologist, JC Pompe, into the unexpected death of a 7-month-old baby in 1932 from a disorder that is now known as **Pompe disease**. The postmortem showed that the baby had an enlarged heart and that the heart muscle and other tissues contained abnormal deposits of glycogen, a carbohydrate macromolecule. The next clue came in 1954, when this disorder was recognised as being a defect in the cellular metabolism of glycogen. Then came the discovery of lysosomes as a cell organelle in 1955. Finally, in the 1960s, scientists deduced that the abnormal deposits of glycogen in the tissues of persons with Pompe disease were the result of an absent or a defective enzyme in lysosomes that breaks down glycogen (see figure 2.28). Thus, Pompe disease became the first disorder to be classified as a lysosome storage disease. The defective enzyme in Pompe disease is acid maltase and its production is controlled by a gene on the number-17 human chromosome.

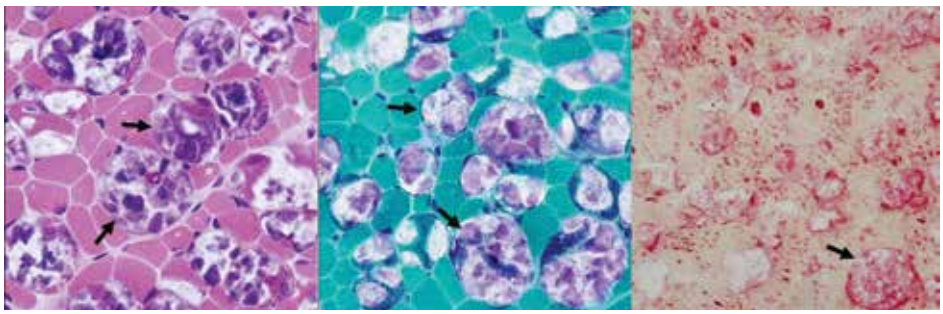


FIGURE 2.28 Light microscope images of samples of muscle tissue affected by Pompe disease. The left and middle images have been treated with different stains, while the image on the right has been treated to detect the presence of a particular lysosomal enzyme. All three images show the key feature of Pompe disease, namely the presence of many vacuoles containing glycogen (stained purple) that crowd the muscle fibres. The image on the right shows the presence of an enzyme that is present in lysosomes, indicating that these vacuoles are lysosomes.

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Pompe disease

ODD FACT

In 1932, the pathologist JC Pompe gave the name '*cardiomegalia glycogenica diffusa*' to the disorder that he was the first to identify. This disorder is now known as Pompe disease or acid maltase deficiency or glycogen storage disease II.

Other lysosome storage diseases are **Tay-Sachs disease** (first described in 1881), in which an abnormal accumulation of lipids occurs, and **Hurler syndrome** (first described in 1919), in which an abnormal accumulation of complex carbohydrates occurs. However, while these disorders were described and named as clinical entities at the times indicated above, their underlying causes were not identified until much later. For example, it was not until 1969 that Tay-Sachs disease was shown to be the result of a defect in one specific lysosomal enzyme, hexosaminidase.

Peroxisomes: breakdown sites

Another small cell organelle found in the cytoplasm of both plant and animal cells is the **peroxisome**. Peroxisomes were discovered in 1954 from electron microscopy studies of cell structure. They range in diameter from about 0.1 to 1.0 µm. Can you suggest why these cell organelles were discovered so much later than other cell organelles, such as mitochondria?

Peroxisomes have a single membrane boundary and contain a large number of enzymes; about 50 peroxisomal enzymes have been identified to date, including catalase and peroxidase.

Peroxisomes can be investigated in live cells using fluorescent fusion proteins targeted to this organelle (see figure 2.29).

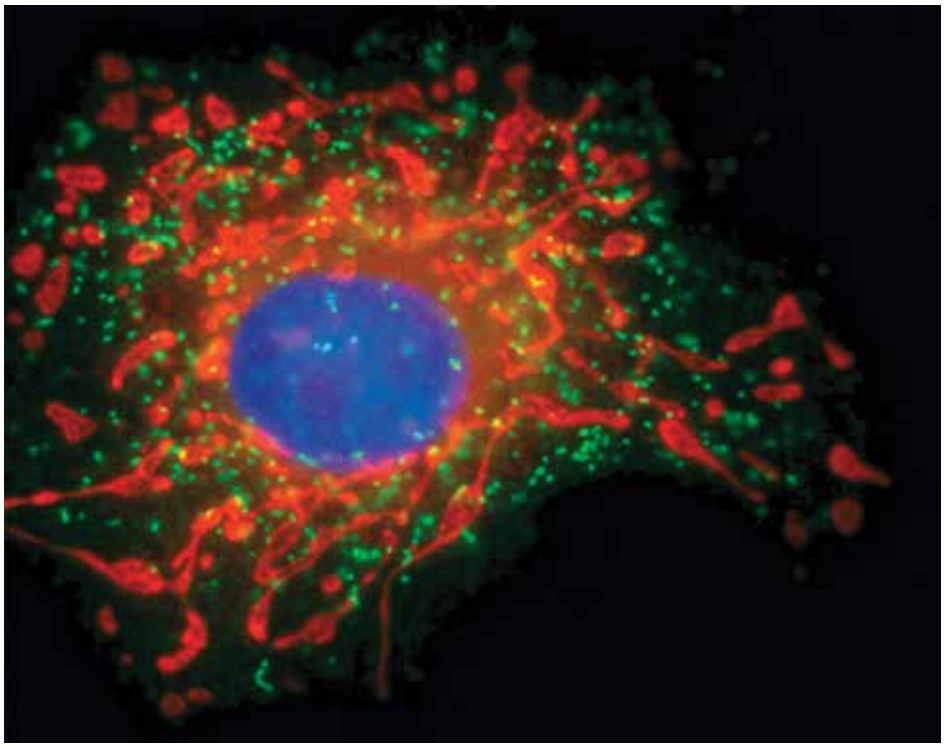

FIGURE 2.29 Peroxisomes made visible in a living cell with a fluorescent protein (green) that targets the peroxisomes. This image was made using CellLight® Peroxisome-GFP, BacMam 2.0. What does this image suggest about the importance of peroxisomes in living cells?

Peroxisomes carry out several functions in cellular metabolism, including the oxidation of fatty acids, an important energy-releasing reaction in some cells. Another role of peroxisomes is the breakdown of substances that are either toxic or surplus to requirements. For example, hydrogen peroxide (H_2O_2) is produced during normal cell metabolism. If it is not rapidly broken down, H_2O_2 poisons the cell. The peroxisome enzyme catalase breaks down hydrogen peroxide to water and oxygen, preventing its accumulation and toxic effects.

$$2H_2O_2 \xrightarrow{\text{catalase}} 2H_2O + O_2$$

Peroxisomes also break down long chain fatty acids. Normally, a specific transport protein on the peroxisome membrane brings long chain fatty acids across the membrane into the peroxisomes for breakdown. A defect in this transport protein causes the very rare disorder known as ALD (adreno-leuko-dystrophy). When this transport protein is defective, long chain fatty acids progressively accumulate in body cells, most particularly in brain cells. This accumulation results in the loss of the myelin sheaths that protect neurons and in the degeneration of the white matter of the brain. Childhood-onset ALD that occurs in boys is the most devastating form. You may have seen or heard of the 1992 film *Lorenzo's Oil* that told the story of Lorenzo Odone, a 6-year-old boy diagnosed with ALD, and his parents who developed an oil in an attempt to assist their son (see figure 2.30). This oil does not cure ALD but there is evidence that it may slow the appearance of ALD if administered before the onset of symptoms. Lorenzo died in May 2008, aged 30 years.

ALD has an incidence of about 1 in 17 000 newborns.

ODD FACT

Lorenzo's Oil is a combination of a 4:1 mix of oleic acid and erucic acid, extracted from rapeseed oil and olive oil.

FIGURE 2.30 Actor Nick Nolte in the role of Augusto Odone, father of Lorenzo, in the 1992 film *Lorenzo's Oil*

Chloroplasts: energy converters

Solar-powered cars have travelled right across Australia. The power for these cars is not the chemical energy present in petrol but the radiant energy of sunlight trapped and converted to electrical energy by solar cells. Use of solar cells is common in Australian households and can be seen in the solar cells on the roofs of houses.

Solar cells are a relatively new technology. However, thousands of millions of years ago, some bacteria developed the ability to capture the radiant energy of sunlight and to transform it to chemical energy present in organic molecules such as sugars. This ability exists in algae and plants. The remarkable organelles present in the cells of plants and algae that can capture the energy of sunlight function are the chloroplasts (see figure 2.31a). The complex process of converting sunlight energy to chemical energy is known as **photosynthesis**. Photosynthesis is discussed further in chapter 3.

Chloroplasts are relatively large cell organelles and, when present in a plant cell, can be easily seen using a light microscope. The green colour of a chloroplast is due to the presence of light-trapping pigments known as **chlorophylls**. Each chloroplast is enclosed in two membranes, termed an outer and an inner membrane. In addition, a third membrane is present internally and this is folded to create an intricate internal structure consisting of many flattened membrane layers called **grana**. The surfaces of the grana provide a large

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area where chlorophyll pigments are located. The region of fluid-filled spaces between the grana is known as the **stroma** (see figure 2.31b). (Chloroplasts also have other pigments and these will be examined in chapter 3, p. 100.)

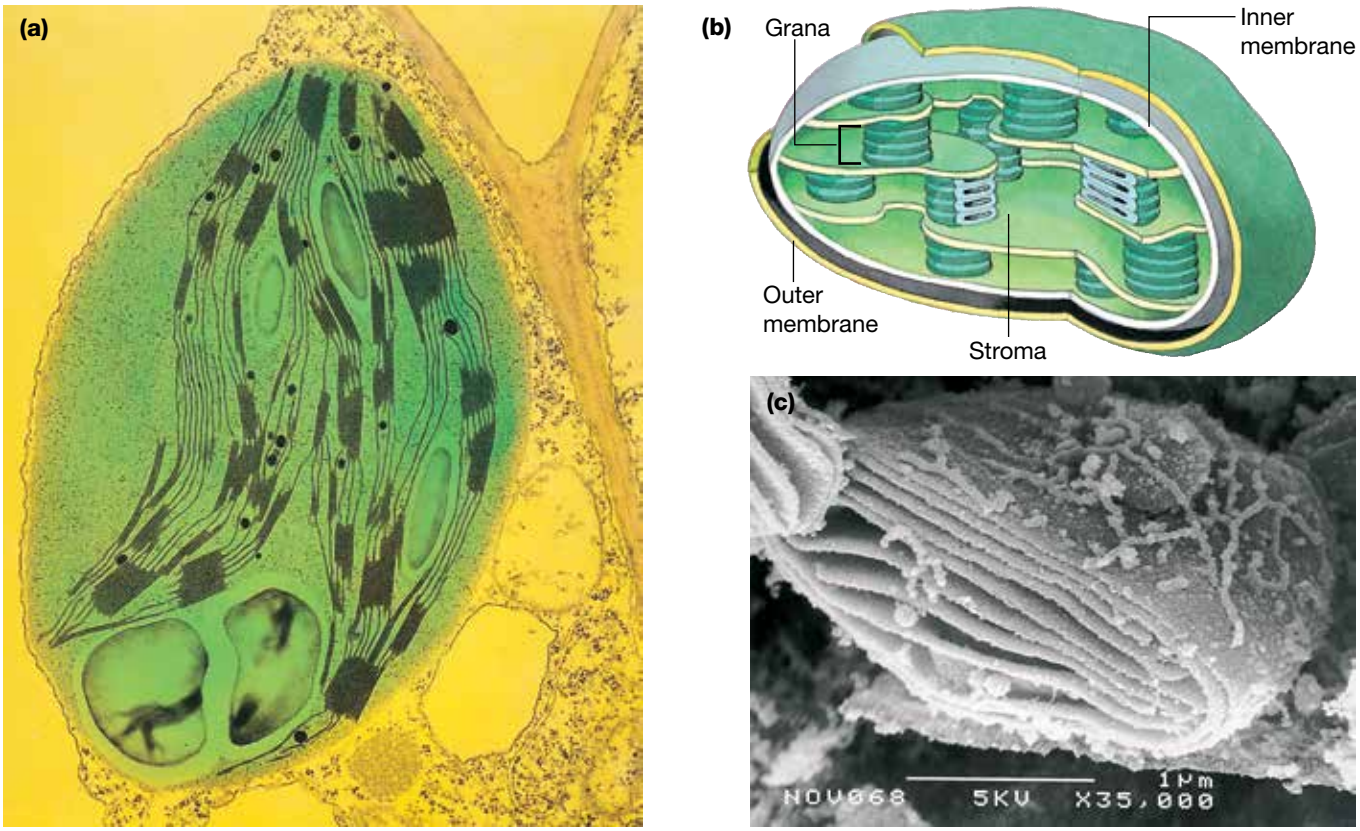


FIGURE 2.31 **(a)** Internal structure of a chloroplast showing the many layers of its internal membrane **(b)** 3D representation of a chloroplast **(c)** SEM (78 000X) image of a fractured chloroplast from the cell of a red alga (scale bar = 1 µm)

Chloroplasts are not present in *all* plant cells; they are found only in the parts of a plant that are exposed to sunlight, such as the cells in some parts of leaves (see figure 2.32) and in stems.

Flagella and cilia: moving around

For some unicellular eukaryotes, their ability to move depends on the presence of special cell structures. Look at figure 2.33. In the case of *Paramecium*, a eukaryotic unicellular protist, these structures are **cilia** (singular: cilium, from the Latin meaning 'eyelash'). In the case of *Euglena*, the structures are **flagella** (singular: flagellum, from the Latin meaning 'whip'). As well as their presence in these protists, cilia and flagella are also found in animals (but are very rare in plants).

FIGURE 2.32 False coloured SEM image of a section of a leaf. Sandwiched between the upper and lower leaf surfaces are the cells that contain chloroplasts. Chloroplasts are not present in the cells of the upper and lower surface of a leaf.

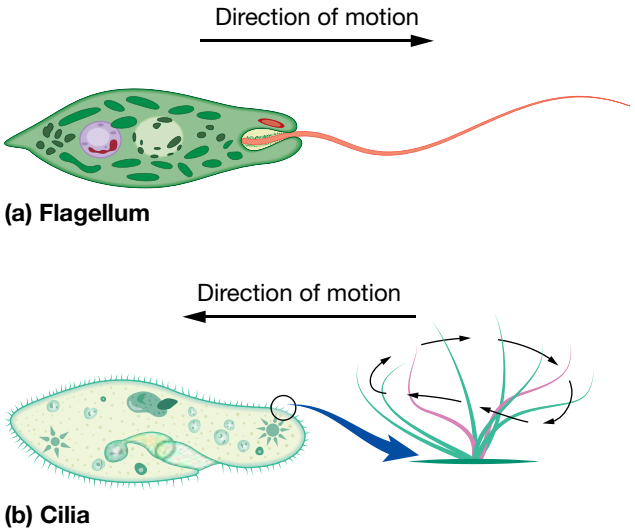


FIGURE 2.33
(a) Flagellum on *Euglena*
(b) Cilia on *Paramecium*

Cilia are shorter than flagella and multiple cilia can occur on a cell; for example, *Paramecium* is covered with several thousand cilia. Flagella are much longer than cilia and typically only one or sometimes two are present per cell. However, **eukaryotic cilia and flagella share the same basic structure**. Each cilium and flagellum is enclosed in a thin extension of the plasma membrane. Inside this membrane are **microtubules** arranged in a particular '9 + 2' pattern (see figure 2.34). Each microtubule is composed of 13 protein filaments forming a circular hollow tube.

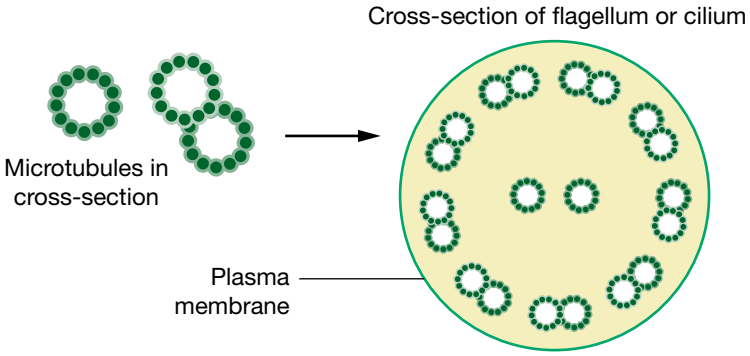


FIGURE 2.34 Cross-section through a eukaryotic cilium. Both cilia and flagella have the same arrangement of microtubules in their structure, with 9 paired microtubules in an outer ring and 2 central microtubules. A microtubule consists of 13 protein filaments that form a hollow tube.

Some eukaryotic animals are **sessile** (fixed to one spot) and live in aquatic habitats, for example, sponges and oysters. How do they feed? These organisms use their cilia to create water currents that bring oxygen and other substances, such as food particles, past them. Specialised cells then trap the food particles.

In the human body, the cells lining the trachea, or air passage, have cilia that project into the cavity of the trachea. Mucus in the trachea traps dust and other particles and even potentially harmful bacteria. The synchronised movement of the cilia moves the mucus up the trachea to an opening at the back of the throat. Cells lining the fallopian tubes also have large numbers of cilia (see figure 2.35). The beating of these cilia moves an egg from the ovary towards the uterus.

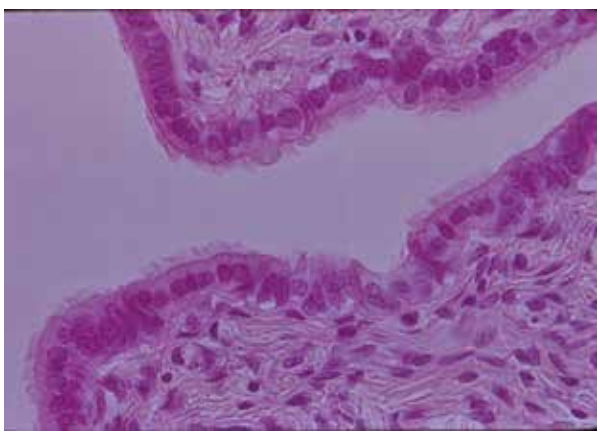


FIGURE 2.35 Cilia on the outer surface of cells lining the fallopian tubes. Are these cilia outside or inside the plasma membrane? *Clue:* Looks can be deceiving.

Human sperm are examples of human cells that have a flagellum that enables their movement. Sperm cells are the only human cells with flagella.

Cytoskeleton: the scaffold

Cell organelles are not floating freely like peas in soup. They are supported by the cytoskeleton of the cell. The cytoskeleton forms the 3D structural framework of eukaryotic cells. The cytoskeleton and its components are important to cell functioning because they:

- supply support and strength for the cell
- determine the cell shape
- enable some cell mobility
- facilitate movement of cell organelles within a cell
- move chromosomes during cell division.

Figure 2.36 shows the extent of the cytoskeleton within a cell. Different colours denote different components of the cytoskeleton.

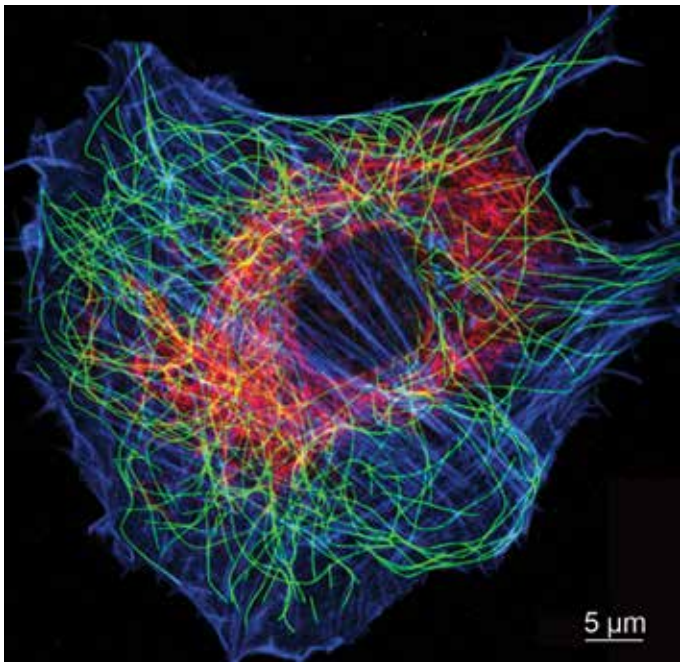


FIGURE 2.36 The cytoskeleton of the cell is a dynamic 3D scaffold in the cell cytoplasm. This fluorescent microscope image shows the extensive distribution of different coloured fluorescent probes, each targeted to a different component of the cytoskeleton.

The cytoskeleton has three components as shown in figure 2.37:

1. *Microtubules*. Hollow tubes, about 25 nm in diameter with an average length of 25 µm (but may be much longer); the walls of the tube are composed of chains of a spherical protein, tubulin (see figure 2.37a). Microtubules move material within cells and give cilia and flagella their structure and motion.
2. *Intermediate filaments*. Tough threads, about 10 nm in diameter, woven in a rope-like arrangement; composed of one or more kinds of protein, depending on cell type. For example, in skin cells, intermediate filaments are made of the protein keratin that is also found in skin and nails (see figure 2.37b). Intermediate filaments give mechanical support to cells.
3. *Microfilaments*. Thinnest of threads ranging from 3 nm to 6 nm in diameter; composed mainly of the spherical protein, actin (see figure 2.37c). Actin filaments are responsible for the movement of cells.

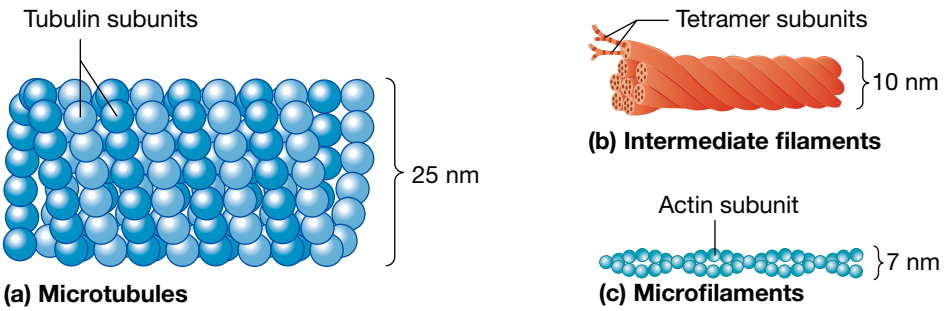


FIGURE 2.37 Components of the cytoskeleton in eukaryotic cells **(a)** Microtubule (side view above, top view below). Microtubules are built of the spherical protein, tubulin. **(b)** Side view of intermediate filament. Note the rope-like arrangement. **(c)** Side view of microfilament. The building blocks of microfilaments are the protein, actin.

KEY IDEAS

- Lysosomes are membrane-bound cell organelles whose functions include the breakdown/digestion of extracellular and intracellular material.
- The fluid within lysosomes contains large numbers of digestive enzymes.
- Peroxisomes are membrane-bound cell organelles that have several functions including the removal of toxic products of metabolism and the energy-releasing oxidation of long chain fatty acids.
- Chloroplasts are cell organelles, bound by a double membrane and containing chlorophyll on layers of an internal folded membrane.
- Chloroplasts can use the energy of sunlight to build organic molecules from carbon dioxide.
- Flagella and cilia have a similar structure and are concerned with movement, either of an organism or of fluids and other substances.
- The cytoskeleton of a cell is the 3D structural framework of eukaryotic cells that provides support for the cell organelles.

QUICK CHECK

13 Identify whether each of the following statements is true or false, giving a brief explanation where needed.
- **a** Chloroplasts are enclosed within a single membrane.
- **b** Peroxisomes carry out the oxidation of long chain fatty acids.
- **c** The enzyme catalase is one of the many enzymes present in peroxisomes.
- **d** Chloroplasts are present in all plant cells.
- **e** Fatty acids enter peroxisomes by simple diffusion.
- **f** The fluid within lysosomes contains about 50 digestive enzymes.
- **g** Cell organelles operate independently of each other.

14 Where in a plant cell would you find chloroplast-containing cells?

15 Identify one difference between cilia and flagella.

16 Identify one similarity between cilia and flagella:
- **a** in terms of structure
- **b** in terms of function.

17 What is the cause of Pompe disease?

18 In what cell organelle would you expect to find the following structures?
- **a** Stroma
- **b** Grana
- **c** Microtubules

Putting it together

Organelles within a eukaryotic cell do not act in isolation but have a high degree of interdependence.

Cell organelles interact in cell functioning

The cell is both a unit of structure and a unit of function. The normal functioning of each kind of cell depends on the combined and coordinated actions of its various organelles, including the plasma membrane, nucleus, mitochondria, ribosomes, endoplasmic reticulum, Golgi complex and peroxisomes. These cell organelles have a high degree of interdependence.

How many cell organelles are involved in the production of a specific protein for use outside the cell? Table 2.2 identifies the various cell organelles involved in this process.

studyon
Unit 1
AOS 1
Topic 1
Concept 5
Cell organelles
Concept summary and practice questions

TABLE 2.2 Cell organelles involved in producing a specific protein for use outside that cell

Structure	Function
plasma membrane	structural boundary that controls the entry of raw materials into the cell, such as amino acids, the building blocks of proteins
nucleus	organelle that contains the DNA which has the coded instructions for making the protein
ribosome	organelle where amino acid subunits are linked, according to DNA instructions, to build the protein
mitochondrion	organelle where ATP is formed; provides an energy source for the protein-manufacturing activity
endoplasmic reticulum	organelle that receives the protein from the ribosome and where the protein is folded into the correct shape and then transported to the next station
Golgi complex	organelle that packages the protein into vesicles for transport across the plasma membrane and out of the cell
peroxisome	organelle that detoxifies H_2O_2 produced in many metabolic reactions

ODD FACT

In 1908, the Russian scientist Mereschkowsky suggested that chloroplasts were once free-living bacteria that later 'took up residence' in eukaryotic cells.

The Endosymbiosis Theory

In her early academic career Lynn Margulis (1938–2011) wrote a paper relating to the origin of eukaryotic cells and submitted it for publication to scientific journals. This paper was rejected about 15 times before it was finally published in 1967, but even then its contents were largely ignored for more than a decade. Why? In her paper Margulis put forward the proposal that some of the cell organelles in eukaryotic cells, in particular mitochondria and chloroplasts, were once free-living prokaryotic microbes. She proposed that eons ago some primitive microbes were taken into another cell — perhaps by endocytosis — conferring an advantage on both the host cell and its ingested microbe. Fanciful? Keep an open mind for the moment. A host cell taking in a sunlight-trapping microbe would have a new source of energy; a host cell taking in an oxygen-using microbe would have a more efficient process of producing energy.

FIGURE 2.38 Lichens are a symbiotic association between an alga and a fungus. Here you can see different kinds of lichens.

The term 'symbiosis' (*syn* = together; *bios* = life) refers to an interaction between two different kinds of organism living in close proximity in a situation where often each organism gains a benefit as in, for example, the close association of a fungus and an alga that form a partnership called a lichen (see figure 2.38).

Endosymbiosis is a special case of symbiosis where one of the organisms lives inside the other. Margulis's proposal is now termed the **Endosymbiosis Theory**.

A few facts about mitochondria and chloroplasts for consideration:

- Both contain their own genetic material, arranged as a single circular molecule of DNA, as occurs in bacteria.
- Both contain ribosomes of the bacterial type that are slightly smaller than those of eukaryotes.
- Both reproduce by a process of binary fission as occurs in bacteria.
- Both have sizes that fall within the size range of bacterial cells.

In addition, genomic comparisons indicate that chloroplasts are most closely related to modern cyanobacteria; these are photosynthetic microbes that possess chlorophyll, enabling them to capture sunlight energy and use that energy to make sugars from simple inorganic material. Genomic comparisons indicate that mitochondria are most closely related to modern *Rickettsia* bacteria.

This evidence and ongoing biochemical and genetic comparisons support the view that mitochondria and chloroplasts share an evolutionary past with prokaryotes. The theory of endosymbiosis is now generally accepted as explaining in part the origin of eukaryotic cells, in particular the origin of their chloroplasts and mitochondria.

Endosymbiosis is not just a theoretical concept, we can see examples of endosymbiosis including:

- nitrogen-fixing bacteria that live in the cells of nodules on the roots of legumes, such as clovers
- single-celled algae that live inside the cells of corals.

As more and more evidence was identified in support the endosymbiosis theory, Margulis became recognised as an important contributor to the biological sciences and received several awards.

ORGANIC MOLECULES: ESSENTIAL BUILDING BLOCKS OF LIFE

Organic molecules are the building blocks of the structure of all known forms of life on planet Earth and they are the molecules that enable organisms to carry out the functions involved in 'being alive'. In December 2014, NASA's *Curiosity* rover made the first definitive detection of organic molecules on Mars. However, organic molecules can also be made by chemical reactions that don't involve life and there is not enough evidence to tell if the matter found by the *Curiosity* team came from ancient Martian life or from a non-biological process.

The major groups of organic molecules found in living organisms are **proteins**, **carbohydrates**, **lipids** and **nucleic acids**. The principal atom present in organic molecules is carbon (C), which forms the backbone of organic molecules. Carbon is linked most commonly to hydrogen (H) and oxygen (O). In addition, all proteins contain nitrogen (N), with some containing sulfur (S). Nucleic acids (DNA and RNA) always contain phosphorus (P). The molecular formulas for organic compounds simply show the numbers of each kind of atoms, with the order being C first, then H, and then any others in alphabetical order, for example, chlorophyll a ($C_{55}H_{72}MgN_4O_5$).

Some of organic molecules are large macromolecules made of smaller subunits joined together in a specific way. For example, the carbohydrates include large molecules, known as polysaccharides (*poly* = many; *saccharum* = sugar) that are built of many units of glucose or other simple sugars. Proteins are macromolecules built of one or more chains of amino acids. Figure 2.39 shows the four main groups of large organic molecules present in cells, and the subunits that form them.

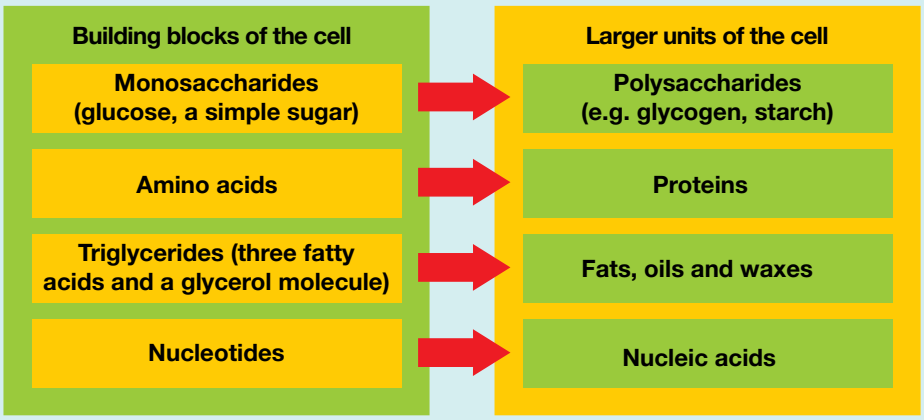
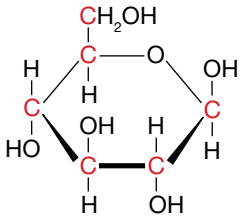
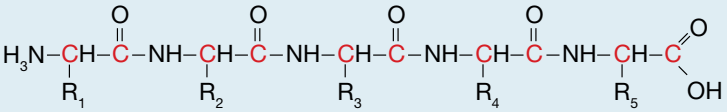
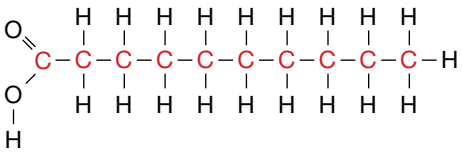
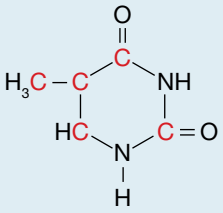


FIGURE 2.39 The building blocks of cells are small organic molecules such as sugars, amino acids, triglycerides and nucleotides. These small molecules can be assembled into large molecules that form the structure and play many roles in the functions of cells. Which subunits join to form proteins? What is the subunit of cellulose, a structural polysaccharide found in cell walls?

(continued)

Table 2.3 gives some examples of organic molecules. Do not worry about the details in column 3, just note the carbon chains or rings that form part of the backbone of these molecules.

TABLE 2.3 Carbon-based organic molecules in living organisms. Carbon atoms are shown in red: note their arrangement into chains or rings. In organic molecules, the carbon atoms are linked to other atoms, most commonly hydrogen and oxygen. Which types of organic molecule contain nitrogen bonded to carbon atoms?

Organic compound	Examples	Sample formula (part or whole molecule)
Carbohydrates • structural • functional	**cellulose** in plant cell walls **chitin** in cell walls of fungi **glycogen** (for energy storage in animal cells) **starch** (for energy storage in plant cells) **glucose** (for energy production)	 glucose
Proteins • structural • functional	**tubulin** of microtubules in cytoskeleton **actin** in human muscles **dynein** in cilia and flagella **amylase** enzyme in saliva **cytochrome oxidase** enzyme in mitochondria **carrier proteins** in the plasma membrane **catalase** enzyme in peroxisomes	 amino acid chain (polypeptide)
Lipids • structural • functional	**phospholipids** in plasma membrane **fats** in adipose tissue (for energy storage) **oils** in plant seeds (for energy storage)	 a fatty acid
Nucleic acids • both structural and functional	**DNA** of chromosomes **rRNA** of ribosomes	 thymine (T) one of the bases in DNA

In the polypeptide, the R groups are side chains that differ in the 20 amino acids. For example, the R groups include —H and —CH3 and —CH2-SH.

KEY IDEAS

- The Endosymbiosis Theory proposes that some cell organelles in eukaryotic cells, in particular mitochondria and chloroplasts, were once free-living microbes.
- Many lines of evidence exist in support of the Endosymbiosis Theory.
- Endosymbiosis is a special case of symbiosis where one organism lives inside the host organism.

QUICK CHECK

19 Identify whether each of the following statements is true or false.
- **a** The genomes of chloroplasts of eukaryotic cells are closely related to those of modern cyanobacteria.
- **b** Endosymbiosis occurred only in organisms on the ancient Earth.
- **c** Mitochondria are accepted as having once been free-living microbes.
- **d** Bacterial cells contain mitochondria.

20 What is the difference between symbiosis and endosymbiosis?

21 Identify two lines of evidence in support of the Endosymbiosis Theory.

BIOCHALLENGE

Exploring lysosomes

Where a question is marked with an asterisk (*), it will be helpful to refer to chapter 1.

Lysosomes

1 Lysosomes are little bags of digestive enzymes.
- **a** Approximately how many different enzymes are present in a lysosome?
- **b** What compounds can be digested by these lysosomal enzymes?

2 Lysosomes must maintain an acidic condition (about pH5) in their internal environment. In contrast, the pH in the cytosol is neutral (about pH7).
- **a** Why is this acidic environment within lysosomes necessary?
- **b** Suggest how this difference in pH between lysosomes and the cytosol might protect the cell from damage in the event of lysosomes rupturing and spilling their enzymes into the cytosol.

3* pH is a measure of the hydrogen ion (H^+) concentration in a fluid. In an acidic environment, the concentration of H^+ ions is far higher than the concentration in a neutral fluid. In fact, the concentration of H^+ ions in the lysosomes is about 100 times greater than that in the cytosol.

To maintain the acidic environment in the lysosome, there must be a constant replacement of the H^+ ions that steadily leak across the lysosome membrane down the concentration gradient into the cytoplasm (see figure 2.40).

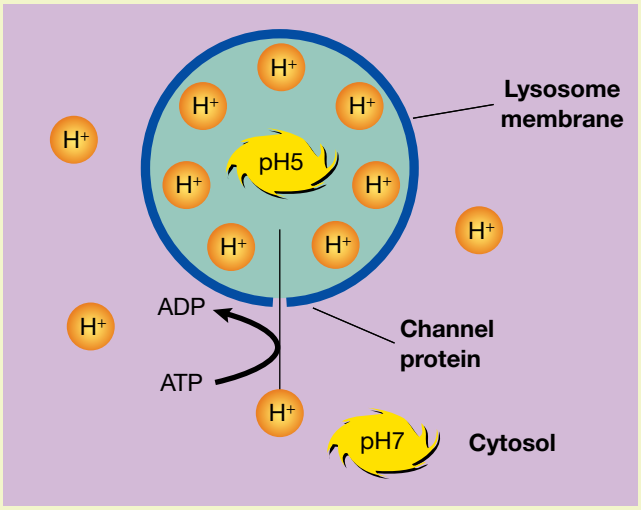


FIGURE 2.40 The acidic environment in a lysosome is maintained by the constant transport of H^+ ions into the lysosome from the cytosol.

- **a** In what direction is the gradient for H^+ ions: from cytosol to lysosome, or from lysosome to cytosol?
- **b** Identify the means by which H^+ ions are moved into lysosomes from the cytosol.

4
- **a** What name is given to the process shown on the left-hand side of figure 2.41?
- **b** What purpose does this process serve?
- **c** What name is given to the process shown on the right-hand side of figure 2.41?

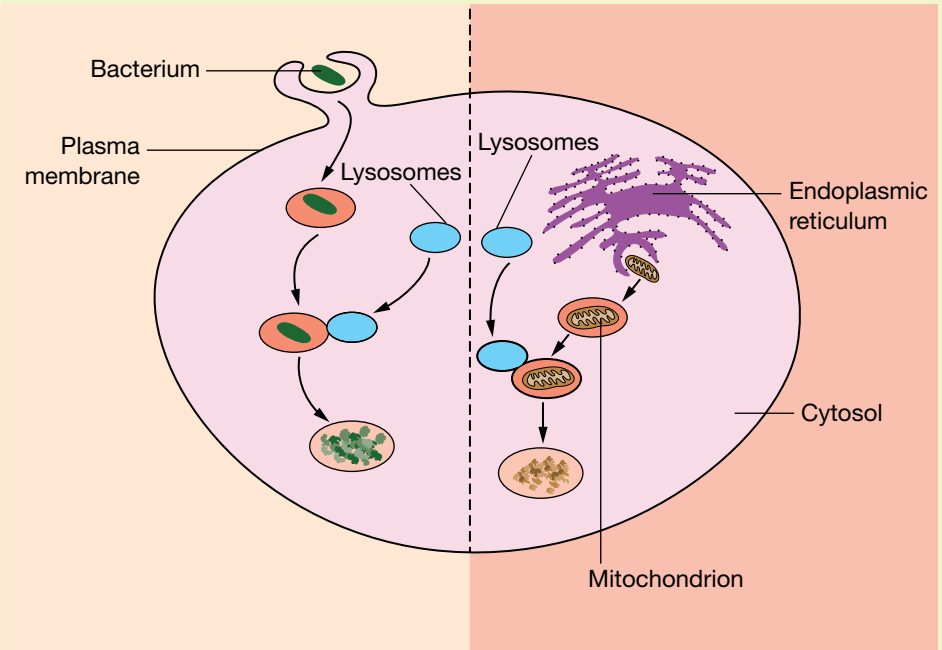


FIGURE 2.41 Lysosomes in phagocytosis and autophagy

Chapter review

Key words

adenosine triphosphate (ATP)
autophagy
carbohydrates
cell wall
cellular respiration
cellulose
chlorophyll
chloroplast
chromatin
cilia
cytoplasm
cytoskeleton
cytosol
deoxyribonucleic acid (DNA)
endoplasmic reticulum (ER)
endosymbiosis
Endosymbiotic Theory
flagella
fluorescence microscope
fossil
Golgi complex
grana
Hurler syndrome
laser scanning confocal microscope
light microscope
lignin
lipids
lysosome
lysosome storage diseases
microbial mat
microtubule
mitochondria
nuclear envelope
nuclear pore complex
nucleic acid
nucleolus
nucleus
peroxisome
phase contrast microscope
photosynthesis
Pompe disease
primary cell wall
proteins
proto-cell
resolution
resolving power
ribonucleic acid (RNA)
ribosomal RNA
ribosomes
rough endoplasmic reticulum
scanning electron microscope (SEM)
secondary cell wall
secretory vesicles
sessile
signs of life
smooth endoplasmic reticulum
STED nanoscopy
stroma
Tay-Sachs disease
tonoplast
tracheid
transition vesicles
transmission electron microscope (TEM)
vacuole
vessel

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map relating to the organelles observed in the cytosol of a plant cell. You may use other words in drawing your map.

2 **Applying your understanding** ➜
- **a** Identify five locations in a typical cell where membranes are found.
- **b** Describe how membranes in these various locations assist in the function of cells.

3 **Communicating understanding** ➜ Where are the following in a eukaryotic cell?
- **a** Control centre of a cell
- **b** Site of control of entry or exit of substances to or from a cell
- **c** Site of production of useable energy for a cell
- **d** Site of protein synthesis
- **e** Site of packaging for export of substances from a cell
- **f** Site of digestion of worn-out cell organelles
- **g** Site of breakdown of excess long chain fatty acids
- **h** Site of conversion of the energy of sunlight to the chemical energy of sugars

4 **Applying your understanding** ➜
- **a** List the following in order of decreasing size from largest to smallest.

  i Cell ii Tissue iii Mitochondrion
  iv Oorgan v Ribosome vi Nucleolus
  vii Nucleus
- **b** List the following in order from outside to inside a leaf cell.

  i Nuclear envelope ii Cell wall
  iii Plasma membrane iv Cytosol
  v Nucleolus

5 **Analysing information and drawing conclusions** ➜
Decide whether a particular cell is from a bacterium, a plant or an animal. Three observations are made as follows.

I Each cell contains ribosomes.
II Each cell tests positive for the presence of DNA.
III Each cell has a plasma membrane.

- **a** Consider each of the above observations in turn and indicate what conclusion is possible. Briefly explain.
- **b** A further observation is made:
  IV Each cell has mitochondria.
  Does this alter your conclusion from part (a)? Explain.
- **c** A final observation is made:
  V Only one cell has lysosomes.
  Does this alter your conclusion from part (b)? Explain.

6 **Communicating understanding** ➜
- **a** Identify two key features that would allow you to distinguish:
  i a plant cell from a bacterial cell
  ii an animal cell from a plant cell.

b Which evidence would be more robust in distinguishing a plant cell from an animal cell:
i the presence of chloroplasts
ii the presence of a cell wall? Explain.

7 Analysing information and drawing conclusions ➜ Suggest explanations for the following observations.
a Cardiac heart muscle cells have very high numbers of mitochondria.
b Cells of the skin oil glands that produce and export lipid-rich secretions have large amounts of smooth endoplasmic reticulum.
c Mature red blood cells cannot synthesise proteins.
d One cell type has a very prominent Golgi complex, while another cell type appears to lack this organelle.

8 Analysing information and drawing conclusions ➜ A scientist carried out an experiment to determine the time it took for a cell to manufacture proteins from amino acids. The scientist provided the cell with radioactively labelled amino acids and then tracked them through the cell to establish the time at which protein synthesis commenced. He monitored the cell 5 minutes, 20 minutes and 40 minutes after production started in order to track the proteins from the site of synthesis to a point in the cell from which they were discharged from the cell.

The scientist made an image of the cell at each of these times but forgot to mark each image with its correct time. The images are given in figure 2.42. Location of the radioactivity is shown by the green spots.

9 Discussion question ➜ The following quotation from the Biology Project website (www.biology.arizona.edu) is addressed to bacteria and expresses sympathy that:

'Eukaryotes have enslaved some of your "brethren" . . .'

a To what might this enslaving refer?
b Who are the 'brethren'?
c What use might the enslaved 'brethren' have served for the eukaryotes?
d Suggest possible benefits that the 'brethren' might have received in return.

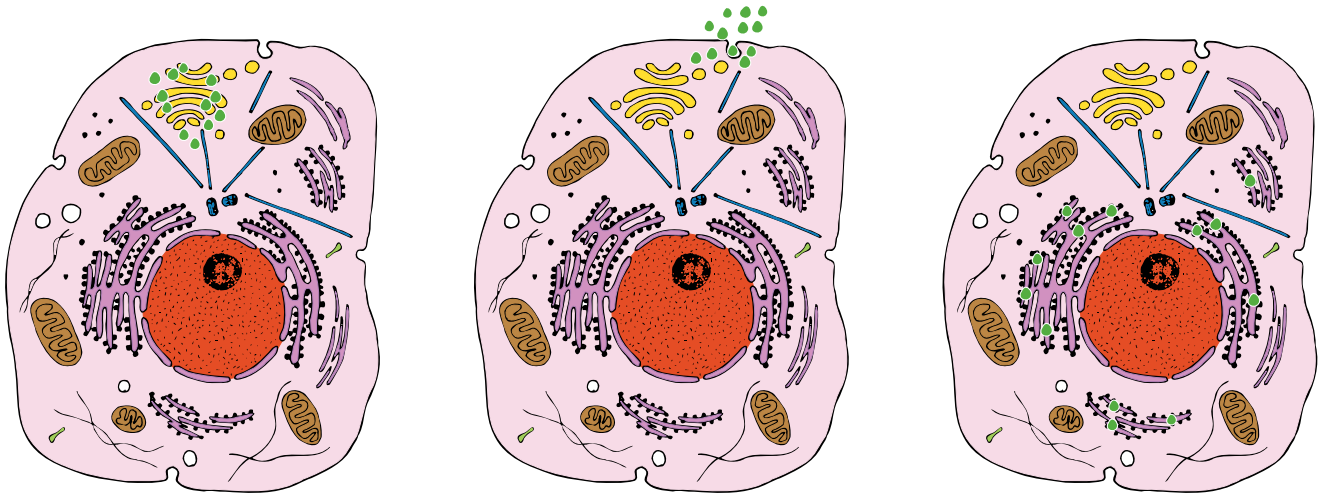


FIGURE 2.42 (a) Which cell corresponds to each of the particular times of viewing? List the correct order according to time of viewing. **(b)** On what grounds did you make your decision?

CHAPTER

3 Energy transformations

FIGURE 3.1 **(a)** The boy eating spaghetti is capturing the chemical energy of organic compounds in his food. This is how animals trap energy. **(b)** The fungi (*Trametes versicolor*) are capturing the chemical energy of organic compounds in dead wood. In this chapter, we will explore how living organisms capture external sources of energy, how they convert energy into a useable form for cell use and how they obtain the organic molecules that are the building blocks needed for their cellular structure and functioning.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- recognise that organisms must continually expend energy to sustain their living state
- understand that plants gain energy by capturing sunlight energy and transforming it to the chemical energy of sugars through the process of photosynthesis
- identify the inputs and outputs of photosynthesis
- understand that animals gain energy from the chemical energy of their food
- recognise the essential difference between autotrophy and heterotrophy
- understand the role of aerobic and anaerobic cellular respiration in the production of ATP.

Death at a nightclub

In the early hours of 27 January 2013, many young people were enjoying a night out at the *Kiss* nightclub in southern Brazil (see figure 3.2). The band was playing and, to add to the excitement, a band member set off a flare that was designed for outdoor use only. The flare hit the ceiling, igniting the insulating foam that lined the ceiling. The resulting fire spread through the ceiling, producing large volumes of thick smoke.

FIGURE 3.2 The front of the *Kiss* nightclub in Brazil following the tragic fire that caused the death of 245 people in January 2013. The front door was the only means of entry to and exit from the nightclub.

This fire resulted in the tragic deaths of 245 people, most aged from 18 to 30 years, with more than 630 persons injured. Contributing factors included overcrowding and the lack of emergency exits. Many young people were trapped. A small number died as a result of severe burns but most victims showed little evidence of physical burns and died as a result of smoke inhalation. Why was this smoke so deadly?

The soundproofing foam in the ceiling was synthetic polyurethane foam that had not been treated with a fire retardant. Polyurethane foams, such as plastics, synthetic upholstery and carpets, produce toxic chemicals when they burn. One of the chemicals produced is cyanide, in the form of hydrogen cyanide gas (HCN). As the fire progressed, the concentration of cyanide rapidly rose to lethal levels. The initial signs of cyanide toxicity, such as giddiness and excessive dilation of the pupils of the eyes, appear less than one minute after inhalation of the gas. Gasping, convulsions, loss of consciousness and death follow. The organs first affected by cyanide are those with the highest energy requirements, such as the brain, skeletal muscle and the heart.

ODD FACT

The Swedish–German chemist Karl Scheele (1742–86) was the first to isolate hydrogen cyanide gas in 1782. He recorded it as tasting like 'rotten almonds'. Cyanide poisoning was the cause of his death a few years later.

Why is cyanide a killer?

Have you ever wondered why you need to breathe? (Probably not!) But if you have, you might have thought that you breathe to get oxygen. But why do you need oxygen? The oxygen in every breath of air that reaches your lungs is carried by red blood cells to all cells of your body. Oxygen enters cells by diffusion and, from the cytosol, diffuses into the mitochondria. There, oxygen plays an essential role in one step in the process of **cellular respiration**.

Cellular respiration is a multistep process by which cells produce energy-rich ATP molecules for immediate use. Oxygen plays an essential role as an electron acceptor. Oxygen accepts electrons (e^-) and hydrogen ions (H^+) in a reaction that simply produces water:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

Cellular respiration is discussed later in this chapter (see p. 112).

Hard to believe, but this equation is the reason that you need to breathe! This reaction is catalysed by cytochrome oxidase, an enzyme located in the inner membrane of mitochondria.

When cyanide gas is breathed into the lungs, it is distributed via the bloodstream to all body cells. In cells, cyanide binds to the cytochrome oxidase enzyme and blocks the action of this enzyme, stopping oxygen from accepting electrons. This is like stopping the movement of one sprocket in a complex mechanism — a single block stops the movement of all the sprockets (see figure 3.3). If oxygen is prevented from acting as an electron acceptor, cellular respiration stops and the energy supply to cells stops. This leads to organ and system failure and death.

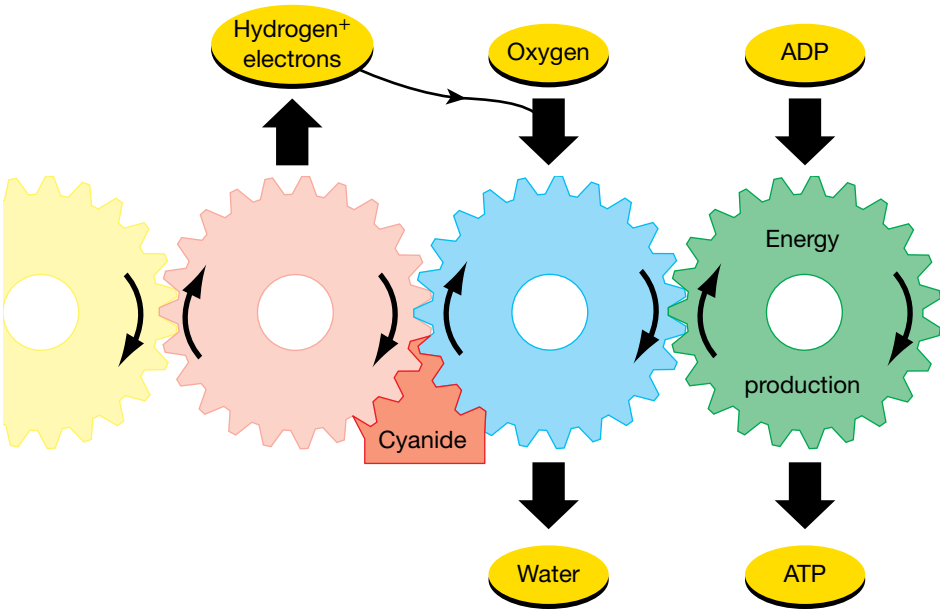


FIGURE 3.3 Energy production by cellular respiration is a multistep process that operates like a series of interconnected revolving sprockets. Block one sprocket and the whole mechanism stops. Likewise, blocking one step in cellular respiration stops energy production by cells. Cyanide acts like such a block.

ODD FACT

In a prison in Argentina in 1990, an inmate set a mattress alight in a confined space. The fire resulted in the deaths of 35 inmates and, in each case, the cause of death was found to be cyanide poisoning.

In cyanide poisoning the supply of oxygen to the cells is normal. Because the cytochrome oxidase enzyme is inhibited the cells are unable to use any oxygen. This condition is termed **histotoxic hypoxia** and it is like suffocating. However, breathing more deeply to get more oxygen is of no help because oxygen cannot function in people with cyanide poisoning.

Requirements for life

Survival of unicellular and multicellular organisms requires that certain conditions be met, namely that organisms can:

- access a source of energy from their environment
- obtain the organic molecules that are the building blocks needed for their structure and function
- access water that provides the aqueous medium of cells in which biochemical reactions can occur
- exchange gases with their environment
- remove waste products produced during cell metabolism.

For unicellular organisms, such as the prokaryotes, all these life-sustaining processes are achieved at the cellular level. Inputs to and outputs from microbial cells occur across the plasma membrane, including diffusion of gases, uptake of water by osmosis, active transport of substances and excretion of some wastes by exocytosis.

For multicellular organisms, life-sustaining processes involve cells that are organised into organs and systems. For example, in mammals, the exchange of gases involves the lungs of the respiratory system where oxygen is absorbed and carbon dioxide is expelled, and the removal of nitrogenous wastes involves the kidneys of the excretory system. In higher plants, water taken in by the roots is transported to all the cells via the vascular system. (These processes will be explored further in chapter 4.)

studyon

Unit 1
AOS 1
Topic 3
Concept 1

Energy intake
Concept summary and practice questions

Energy is needed for living

Living organisms use energy all of the time to drive the large number of chemical processes occurring in cells. To obtain energy for life-sustaining activities, organisms must be able to:

- capture energy from an external source in their environment
- convert this energy into the chemical energy of organic molecules for use by cells
- transfer energy produced in excess of immediate needs into organic molecules for storage.

Let's explore each of these ideas in turn.

External sources of energy

For an organism to stay alive, it must be able to capture energy from an external source in its environment. Consider the following eukaryotic organisms:

- a mountain ash tree (*Eucalyptus regnans*) in a temperate forest
- a green alga (*Ulva lactuca*) attached to rocks in shallow coastal seas
- a bracket fungus (*Trametes versicolor*) on a rotting log (refer to figure 3.1b)
- a copperhead snake (*Austrelaps superbis*) in vegetation around a swamp.

What are the external sources of energy that each organism can capture from its environment?

Energy exists in many different forms, including thermal, electrical, radiant and chemical energy (see the box, pp. 126–7). Wind blowing through your hair is motion energy, but this is not an energy source that you can use to keep your cells alive. Likewise, you might use the ultraviolet part of sunlight energy to get a tan (or sunburn if you don't use an appropriate sunscreen) but you cannot use this as a source of energy to keep your cells alive. Copperhead snakes may use thermal energy to raise their body temperature but cannot use this energy to drive energy-requiring reactions in their cells. On the other hand, a cheese sandwich is a source of chemical energy that assists you to stay alive. The cheese sandwich is of no use to a mountain ash tree, but the tree can make use of sunlight energy.

The two external sources of energy that can be captured and used by eukaryotic organisms are:

- the radiant energy of sunlight (sunlight energy)
- the chemical energy of organic molecules.

The type of organism determines which of these external energy sources can be captured (see figure 3.4).

FIGURE 3.4 The external source of energy for plants is sunlight energy. For animals it is the chemical energy of organic matter in their food. Can you identify the energy captures (actual and possible) in this image?

ODD FACT

One study found that the surface area of the leaves of orchard apple trees (*Malus domestica*) represented more than 80 per cent of the total surface area of the above-ground trees, with stems, branches and trunk making up the remainder.

Plants and algae capture sunlight energy

Plants and algae (seaweeds) capture the radiant energy of sunlight. The mountain ash tree in a temperate forest and the green alga attached to rocks in shallow coastal seas use sunlight energy as their external energy source.

Green leaves are the main organs that enable plants to capture sunlight energy. For algae, it is the flattened body (**thallus**) (see figure 3.5). A flattened shape provides a large surface area for this capture. In fact, much of the structure of the aerial part of terrestrial plants consists of leaves and the stems that support them.

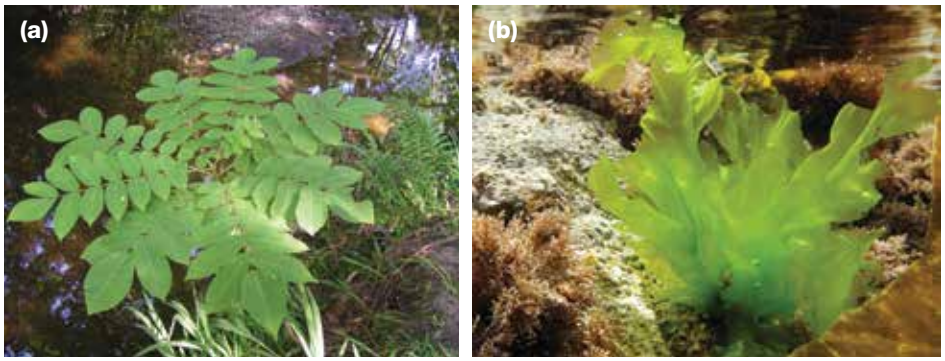


FIGURE 3.5 Plants and algae capture the radiant energy of sunlight. **(a)** Green leaves are the means through which plants capture the radiant energy of sunlight. Leaves are the major component of the visible surface area of plants. **(b)** The sheet-like body or thallus of this sea lettuce alga (*Ulva lactuca*) is just two cells thick. Effectively all of the surface area of this alga is involved in capturing the sunlight energy.

Animals and fungi capture chemical energy

All animals and fungi capture energy from their environment in the form of the chemical energy of organic molecules in their food. 'Food' for animals and fungi consists of the organic molecules of other organisms, living or dead, or their products. These organic molecules may be carbohydrates, lipids or proteins, or their subunits.

The term 'food' as perceived by a person might be a juicy hamburger, hot porridge, an ice-cream , apples or carrots. The food of other species might look quite unappetising to people, such as the cellulose in paper and the keratins in wool that are food for silverfish, the contents of the large intestine of humans that provide pre-digested food for pinworms (*Enterobius vermicularis*) and tapeworms (*Taenia solium*), hay that is food for cattle, live frogs that are the prey of copperhead snakes and the dead wood that is food for some fungi. In every case, 'food' is any organic substance that is a source of chemical energy which can be absorbed and utilised by an organism to provide energy for its cellular functions.

KEY IDEAS

- Living organisms use energy all the time and stopping that process for any extended period results in rapid death.
- Among the requirements for life is the ability of organisms to access a source of energy from their environment.
- Many different forms of energy exist.
- The only external sources of energy for eukaryotic organisms are the energy of sunlight and the chemical energy of organic molecules.
- The external energy source for plants and algae is sunlight energy.
- The external energy source for animals and fungi is the chemical energy of organic molecules.

QUICK CHECK

1 Identify whether each of the following statements is true or false.
   - **a** With cyanide poisoning, death results because the supply of oxygen to cells stops.
   - **b** The energy of sunlight is a useable source of energy for all eukaryotic organisms.
   - **c** Heat energy is a usable form of energy for cells.
   - **d** Organic molecules are a source of chemical energy.

2 List three different forms of energy.

Transforming energy to a useful form

To stay alive, living organisms capture energy from an external source in their environment. However, the energy captured from the environment may not be in a form that can be used by cells.

The sunlight energy captured by plants and algae is *not* a useful form of energy for cells. Sunlight energy is a diffuse form of energy that cannot be transported by cells or stored in that form in cells (see figure 3.6). If cells had to rely solely on sunlight energy for staying alive, darkness would be fatal since sunlight energy cannot be stored. In contrast, the chemical energy of organic molecules, such as glucose, is a dense form of energy that can easily be transported and stored, as either glycogen or starch, so that its energy can be drawn on at any time. Thus, plants and algae are faced with the challenge of converting the sunlight energy that they capture to the useable form of chemical energy. In this form, the energy can be transported within the organism and any energy in excess of immediate cell needs can be stored.

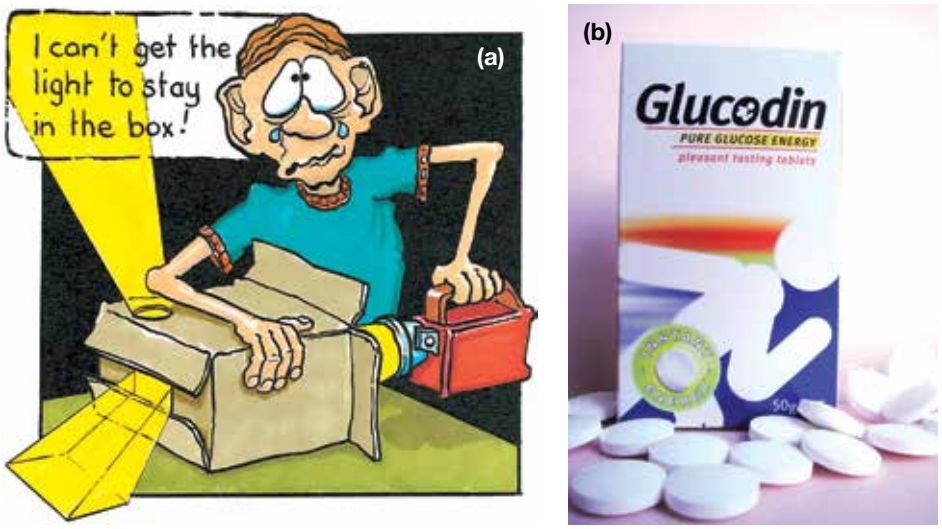


FIGURE 3.6 **(a)** The radiant energy of sunlight is a diffuse form of energy. In that form, sunlight can neither be transported nor stored. **(b)** Glucose tablets: much easier to put chemical energy into a package!

Table 3.1 shows the energy density of various organic molecules present in food and in some industrial fuels for comparison. Energy density is expressed as energy stored per unit mass (kilojoule per gram, kJ/g).

TABLE 3.1 Energy density of the organic molecules in various foods. Some fuels are included for comparison.

Type of molecules	Energy density(kJ/g)
Organic molecules of food	
sugars (e.g. glucose)	17
polysaccharides (e.g. starch, glycogen)	17
proteins	17
fats	37
Fuels	
carbon (in anthracite coal)	33
hydrocarbons (in petrol)	46
hydrazine (rocket fuel)	20
liquid hydrogen (rocket fuel)	142
Other	
water	0
alcohol (ethanol)	29

Plants transform sunlight to chemical energy

Plants and algae capture some of the sunlight energy that reaches the Earth's surface. They can convert sunlight energy to useful chemical energy through the process of **photosynthesis**. In this process, plants and algae transfer the energy of sunlight to glucose, an energy-rich organic molecule. To make glucose, plants and algae use the simple inorganic compounds of carbon dioxide and water (see figure 3.7).

The process of photosynthesis is explored later in this chapter (see pp. 102–5)

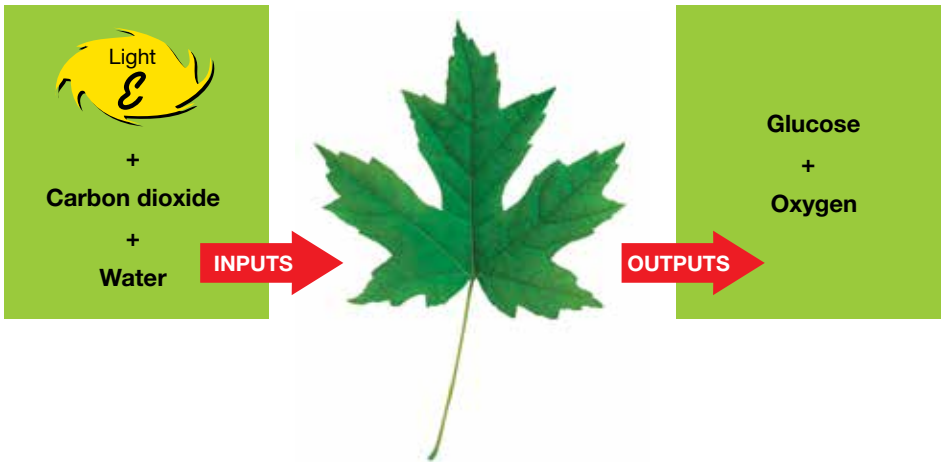


FIGURE 3.7 Summary of the inputs and outputs of photosynthesis. What energy transformation occurs in photosynthesis?

No need for energy conversion in animals

Transformation from radiant energy to chemical energy is not necessary in animals and fungi. The energy they capture from their environment is from the organic molecules of their food and this is already in the form of chemical energy.

However, for animals and fungi capturing an external source of chemical energy from organic molecules can pose challenges. In some cases, the target for capture may be highly mobile (the organic molecules of another animal) or difficult to find. Contrast this with the strategy for capturing sunlight energy — just expose a leaf or two to the sunlight.

Animals and fungi use many different strategies to capture the chemical energy of organic molecules, including:

- predation — hunting and killing live prey (see figure 3.8a)
- grazing — feeding on living plants without necessarily killing them (see figure 3.8b)
- scavenging — consuming dead animal matter (carrion) (see figure 3.8c)
- parasitism — feeding from another kind of organism without killing it (see figure 3.8d)
- filter feeding — trapping food particles from water (see figure 3.8e)
- saprotrophy — feeding on dead and decaying organic matter (refer to figure 3.1b).

FIGURE 3.8 Animals and fungi use various strategies to obtain the chemical energy of organic molecules in their food. **(a)** A praying mantis captures and kills its prey (a cricket) **(b)** Cattle (*Bos taurus*) are grazers that obtain energy by eating living plants (grasses). **(c)** The Tasmanian devil (*Sarcophilus harrisii*) is a scavenger that feeds on dead animals (carrion), such as road kill. **(d)** The parasitic fungus, wheat stem rust (*Puccinia graminis*) gains its nutrients from the stems of living wheat plants without killing them. **(e)** The humpback whale (*Megaptera novaeangliae*) is one of many filter feeders. Its baleen plates act as a sieve or filter that retains food while pushing out water.

ODD FACT

Sometimes, animals that eat food are not the ones that digest it. Hay-eating cattle have a community of bacteria, protozoa, fungi and yeasts living in the rumen of their stomachs. These rumen residents digest the insoluble cellulose of the hay, breaking it down into water-soluble simple sugars that can be absorbed by the cattle.

Although they do not need to transform their captured energy, animals and fungi have the challenge that their food is often composed of large insoluble organic molecules — proteins, carbohydrates and fats — that must be broken down into smaller, water-soluble subunits before they can be absorbed and used by cells. Digestive enzymes produced by animals and fungi carry out this function.

For animals, digestion typically occurs within the gut after food has been eaten (ingested). In contrast, fungi secrete digestive enzymes externally, so that digestion occurs outside their structure. So, fungi digest their food first and then 'eat' or absorb it, while animals eat their food and then digest and absorb it.

KEY IDEAS

- Chemical energy is a useful form of energy for cells because, not only can it be used, it can also be transported and stored.
- Sunlight energy is a diffuse form of energy that cannot be transported or stored.
- Organic molecules are dense forms of energy, but they differ in their stored energy concentrations.
- Plants and algae transform the sunlight energy they capture to the chemical energy of organic molecules, mainly glucose.
- Energy transformation is not required for the 'food' of animals and fungi.

QUICK CHECK

3 By what process do plants and algae transform sunlight energy to chemical energy?
4 Briefly explain why energy transformation is needed for the sunlight energy captured by plants.
5 How do fungi obtain the energy for living?
6 Which organic molecule could provide you with energy for living for a longer period: 10 g of sugars or 10 g of fat? Explain briefly.
7 Identify the key difference between predation and parasitism.
8 Identify whether each of the following statements is true or false.
a Plants transform sunlight energy to the chemical energy of glucose.
b Food eaten by animals must be transformed to chemical energy.
c Fungi do not need to digest their food.

ODD FACT

When a person goes on hunger strike, the energy needs of their cells must continue to be met. The person first exhausts their liver glycogen stores and then their fat stores. After this, they use proteins, such as their muscle tissue.

Chemical energy for living: immediate and stored

Organic molecules provide the chemical energy needed by cells to stay alive. The major organic molecules that supply energy to cells include ATP, glucose, glycogen (in animals), starch (in plants) and fats (see figure 3.9). These organic molecules have chemical energy stored in the bonds between their atoms, and this energy can be released for use in cells. Nucleic acids are essential to heredity and do not play a role in providing energy. Similarly, proteins are not normally used as a source of energy for cells. Proteins are a major component of the structure and the function of the human body, as seen in the actin and myosin of skeletal muscle, the collagen of bone and cartilage and the haemoglobin of red blood cells.

Chemical energy for immediate use by cells must be packaged in a form that:

- produces an immediate release of energy through a single-step reaction, rather than a slower multistep series of reactions
- releases energy in small amounts, rather than a larger amount that may be in excess of requirements.

The energy-rich molecule that meets these requirements is ATP (adenosine triphosphate).

Figure 3.9 shows the distribution of various energy-rich organic molecules in an average person. These organic molecules include one for instantaneous energy release for use by cells (ATP), one that provides a rapidly available reserve of energy (glucose), and others that serve as short-term (glycogen) and longer-term energy stores (fat) of chemical energy.

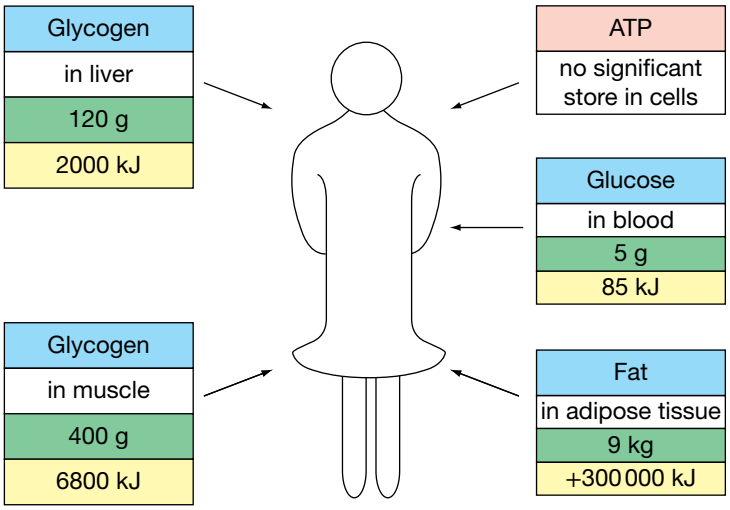


FIGURE 3.9 Energy compartments in an average adult. ATP is the immediate form of energy for use by cells. The other energy supplies in the various compartments differ in how rapidly their chemical energy can be accessed. What is the largest chemical energy store?

Let us look at each of these energy compartments.

Energy for immediate use by cells

The energy available for instantaneous use by the cells of all living organisms is the chemical energy of **adenosine triphosphate (ATP)**. ATP powers all the energy-requiring reactions that keep all organisms alive. The chemical energy of ATP is released in a single-step reaction in which one of its phosphate groups is removed in a process called **hydrolysis** (*hydro* = water; *lysis* = unfastening, releasing) (see figure 3.10).

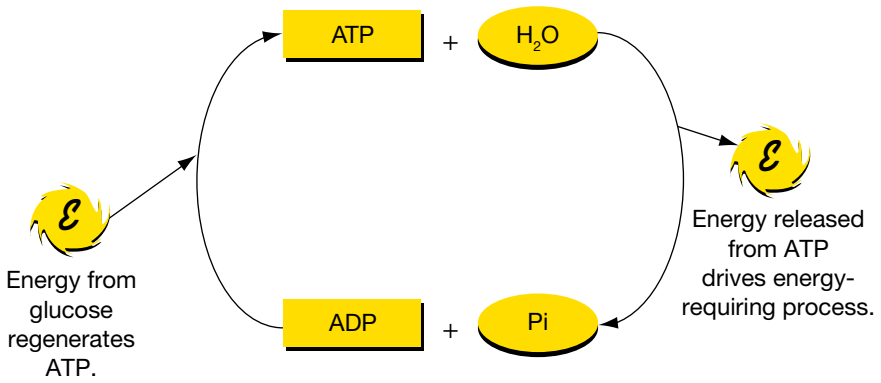


FIGURE 3.10 The ATP–ADP cycle. The chemical energy of ATP is released for use by cells when ATP is hydrolysed. ATP is regenerated from ADP in an energy-requiring reaction, with the energy coming from glucose.

Refer to figure 2.15 on page 63 to check the chemical structure of ATP.

ATP molecules are constantly being hydrolysed to supply the energy for the many energy-requiring metabolic activities of cells. Yet **at any stage, the supply of ATP molecules in cells is sufficient for only several seconds of activity.** There is no significant store of ATP in cells — only about 50 g (0.1 mole) in total at any one time in the entire human body. In a typical day, a person uses the energy of more than 100 kg of ATP. This means that the ATP molecules of a typical human adult are recycled several thousand times per day — this involves energy transfer from glucose.

Rapid release of energy for transfer to ATP

The chemical energy of glucose can be released and transferred to ATP. In the human body, glucose is transported in solution in the blood plasma to all cells. On average, people with normal blood sugar levels have about 5 g of glucose in total in their blood plasma — just a teaspoon (see figure 3.11).

FIGURE 3.11 Glucose is an energy-rich molecule. The chemical energy of one mole of glucose is about 2800 kJ. In comparison, the chemical energy of one mole of ATP is about 30 kJ.

Within cells, the chemical energy of glucose molecules is released in a series of oxidation reactions termed cellular respiration (see p. 112 for discussion). The chemical energy released from one molecule of glucose is sufficient to power the production of about 34 molecules of ATP. So, through the process of cellular respiration, the supply of ATP to cells is continuously replenished. (It was the last step in this process that was blocked in the victims of the *Kiss* nightclub fire.)

Stored energy for later use

Energy is stored in the cells of living organisms as the chemical energy of large organic molecules. Typically, storage molecules are insoluble in water.

Energy stores for quick access to more glucose

The organic molecules that act as stores of chemical energy in eukaryotes are **starch** (in plants and algae) and **glycogen** (in animals and fungi). Both starch and glycogen are **polysaccharides** (*poly* = many; *saccharum* = sugar) that are composed of thousands of glucose subunits. When needed, glucose can be readily released from these energy stores.

ODD FACT

The word 'glycogen' comes from *glyco* = glucose, sugar and *gen* = substance that produces. And that's exactly what glycogen can do — release its glucose subunits.

Glycogen is the rapidly accessed energy store in animals and fungi. In the human body, glycogen is stored mainly in the liver and skeletal muscle (see figure 3.12). Liver cells store a total of about 120 g of glycogen. Skeletal muscle has an average store of about 400 g, but this glycogen is available for muscle cells only. If you have not eaten for a while, your blood glucose levels begin to fall below the lower end of normal range. When this happens, glucose is mobilised from your liver glycogen stores. Similarly, when your blood glucose level rises after you have eaten, the excess glucose is shifted from the blood into storage as glycogen.

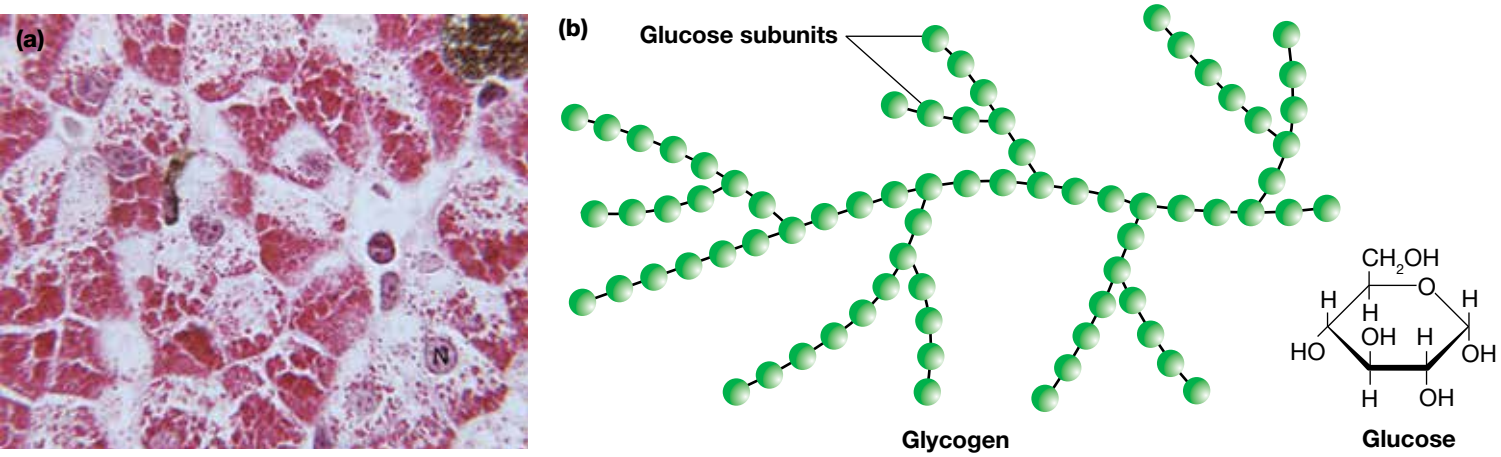


FIGURE 3.12 Rapid-access energy stores in animal cells are the chemical energy of glycogen. **(a)** Glycogen (stained purple) is present as granules in the cytosol of mammalian liver cells. **(b)** Glycogen is a polymer made of a very large number of glucose subunits.

Starch is the rapidly accessed energy store in the plant and algal cells. Starch is present in tubers such as potatoes, in some fruits such as bananas and in cereal crops such as wheat and corn (see figure 3.13).

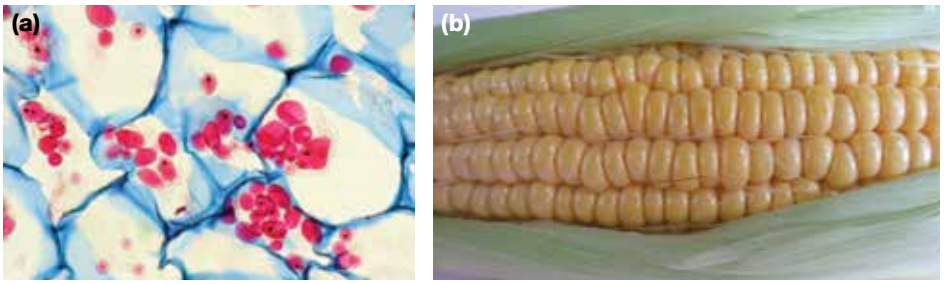


FIGURE 3.13 Energy is stored in the cells of plants and algae as the chemical energy of starch. **(a)** Starch grains (shown in red) in potato cells **(b)** Each kernel in an ear of corn contains more than 70 per cent starch.

Longer term energy store for slow release

Fats in the form of triglycerides are slower release energy stores in the human body. Fats provide the largest energy store in the human body. For a healthy adult male, stored body fat makes up an average of about 15 per cent of the body weight, while for healthy females the figure is about 25 per cent. On average, a well-nourished male has a store of about 9 kg of fat that can yield more than 300 000 kJ of energy.

Fat stores in humans are mainly in adipose tissue located under the skin and around the internal organs. Figure 3.14a and b shows an adipocyte, a cell specialised for the storage of fat. Figure 3.14c shows the structure of triglyceride fat — each molecule is composed of one glycerol molecule bonded to three fatty acid molecules. (Do not worry about the details of the formula, simply note that, like all organic molecules, each fatty acid has a carbon backbone.)

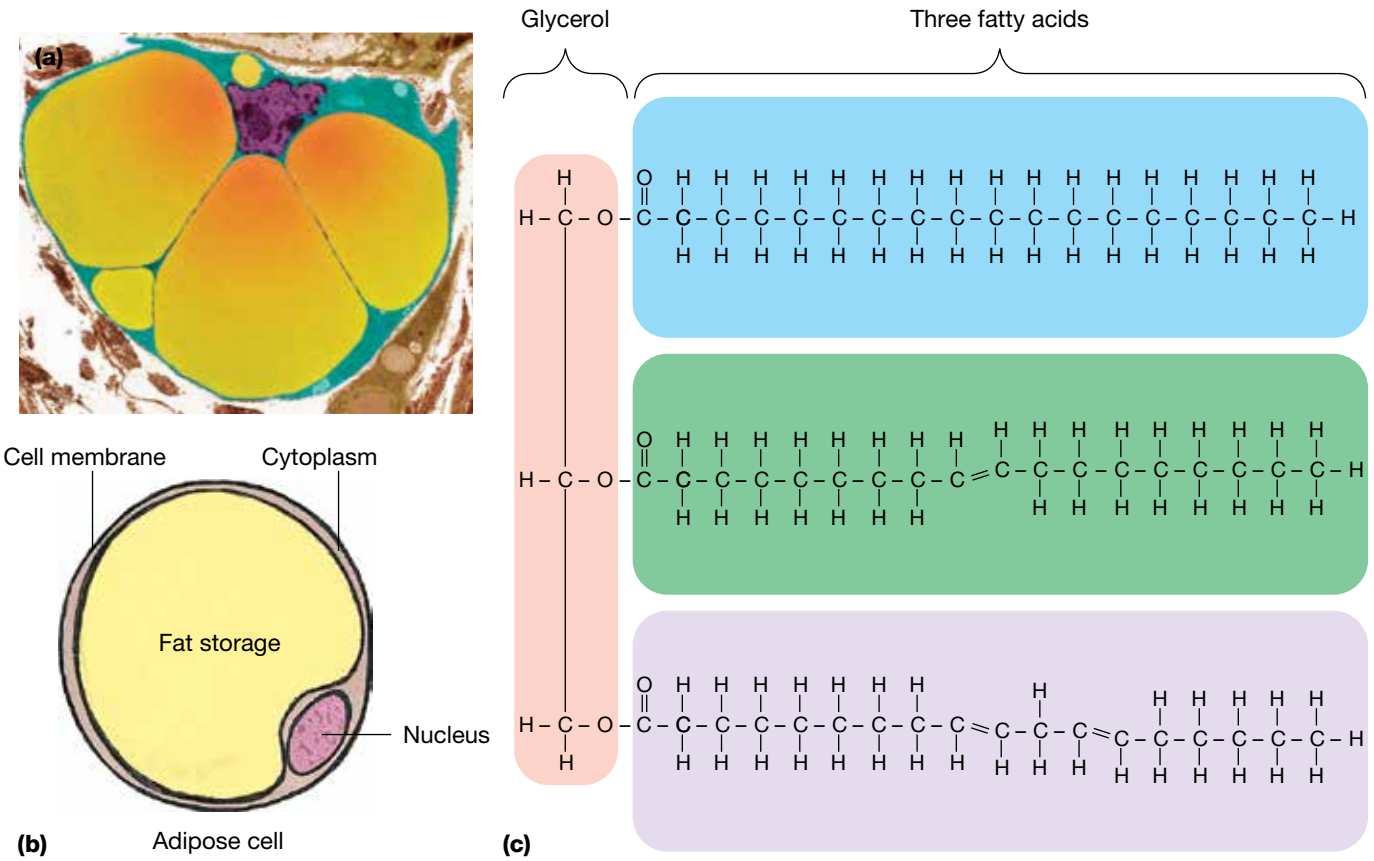


FIGURE 3.14 **(a)** Fat in a fat storage cell (adipocyte) in mammalian adipose tissue. This false coloured transmission electron micrograph shows fat droplets (yellow) and the cell nucleus (purple). **(b)** Diagram of an adipocyte **(c)** Example of a fat storage molecule. Note the carbon backbone of each of the three fatty acids and of the glycerol part of the triglyceride. Fatty acid components of fats are the major source of their chemical energy.

ODD FACT

Sweets are a source of glucose. In the human body, if glucose is present in excess in the blood, the excess is converted to glycerol for short-term storage. When the glycogen stores are full, excess glucose is converted to fat for longer term energy storage. So, too many sweets and too little exercise means fat deposits increase.

The energy of fats comes principally from its fatty acids. Palmitic acid is a fatty acid found in palm oil and animal fats, including meat, milk, cream and dairy products. When released, the chemical energy of one molecule of palmitic acid can supply the energy needed to produce about 130 molecules of ATP.

The chemical energy from fat stores is released after the glycogen stores in muscle and liver have been used. Energy release from fats occurs more slowly than from glycogen. Why? A longer time is required to remove fat molecules from storage, break them down into their fatty acids and glycerol components, and transport the fatty acids to cells where they enter a series of energy-releasing reactions.

Plants have energy stores in the form of fats and oils. Fats and oils are most commonly found in plant seeds (e.g. sunflower, linseed, castor bean and cacao beans (see figure 3.15)), in nuts (e.g. walnuts, peanuts and pecan nuts) and in fruits (e.g. olives and avocados).

Most of the energy stores of the human body are fats (refer to figure 3.9, p. 92). Why not store this energy as glycogen that provides faster access to glucose? Fats are a more dense energy store than glycogen (refer to table 3.1, p. 89). If the average energy store of 9 kg of fat in a 70 kg adult was replaced by an equivalent energy store as dry glycogen, the mass required would be about 20 kg. In fact, the replacement mass would be even greater because glycogen is not stored as dry glycogen but as hydrated glycogen.

FIGURE 3.15 Pods on a cacao tree (*Theobroma cacao*). Each pod contains 20 to 50 cacao beans. Fat extracted from the beans is used to make chocolate. *Theobroma* means 'food of the gods'.

Key role of glucose in energy transactions

The various organic molecules that are involved in the provision of energy to cells are interconnected. **Glucose is central to the various energy transactions.** Figure 3.16 shows the key role that glucose plays in the energy economy of cells.

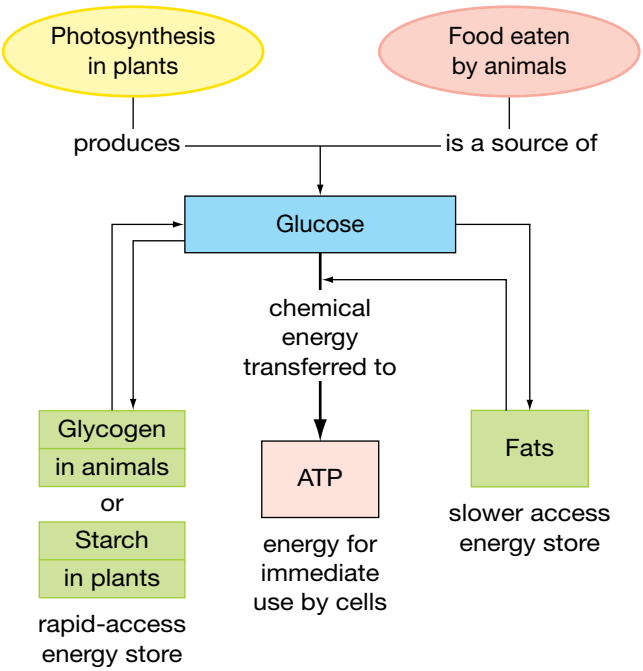


FIGURE 3.16 Central role of glucose

Plants produce glucose through photosynthesis and animals obtain glucose from their food. Glucose is oxidised in both plants and animals in the process of cellular respiration and the energy released is used to produce ATP. Excess glucose not needed for this purpose is converted to glycogen (in animals) or to starch (in plants) and is stored. Any glucose in excess of that is converted to fat for longer term storage. When glucose is required for ATP production, it can be rapidly accessed from the glycogen or starch stores.

KEY IDEAS

- The immediate source of energy for all cells is provided by ATP.
- Cells have no significant stores of ATP and it must constantly be replenished.
- Through the process of cellular respiration, glucose releases its energy to ATP production.
- Glycogen (in animals) and starch (in plants) are stores of glucose that can be rapidly released.
- In humans, fats are the largest energy store but their energy is released more slowly than the energy in glycogen.
- Glucose is central to the energy economy of cells.

QUICK CHECK

9 Identify whether each of the following statements is true or false.
- **a** The release of energy from glucose takes place through the process of photosynthesis.
- **b** Glycogen is an energy store in animal cells.
- **c** Starch molecules consist of large numbers of glucose subunits.
- **d** Fat stores are present in animal cells but not in plant cells.

10 Identify three different fates for glucose molecules in a cell.

11 Where is glycogen stored in the human body?

12 ATP could be described as 'a very busy molecule'. Briefly explain why this label is appropriate.

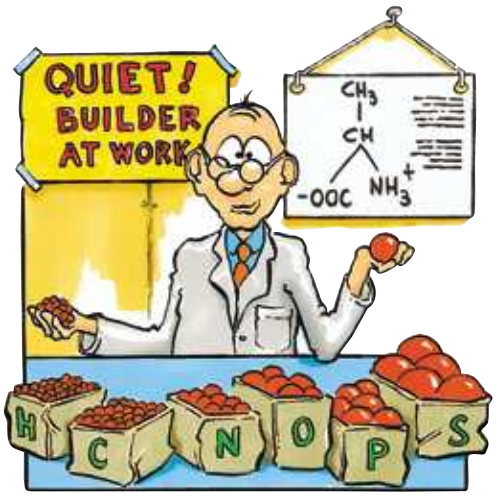


FIGURE 3.17 Organic molecules are built of carbon atoms that are linked to other atoms, mainly hydrogen and oxygen.

Organic molecules are needed for life

The non-living world around us is made of inorganic molecules. These inorganic molecules include liquids such as water (H_2O); gases such as oxygen (O_2), nitrogen (N_2) and carbon dioxide (CO_2); and inorganic solids, such as the mineral quartz (silicon dioxide (SiO_2)), the iron ore hematite (Fe_2O_3) and the aluminium ore bauxite (a mixture of minerals including gibbsite (Al_2OH_3)).

In contrast, living organisms are built almost exclusively of organic molecules and these molecules are also essential to allow them to function. The major groups of organic molecules are carbohydrates, proteins, lipids and nucleic acids (see the box, pp. 77–8). The distinctive feature of organic molecules is that they are composed of carbon (C) atoms, arranged as chains or as rings, and bonded to other atoms, mainly hydrogen (H) and oxygen (O). Other atoms, most often nitrogen (N), phosphorus (P) and sulfur (S), may also be present (see figure 3.17).

A key difference between various organisms is how they obtain the organic molecules that they need for living. This difference separates living organisms into two major groups: the heterotrophs and the autotrophs.

ODD FACT

Living organisms may have small amounts of inorganic molecules in their structure, such as the calcium hydroxyapatite mineral in human bones and the silica (H_4SiO_4) spicules in some sponges.

Heterotrophs need pre-formed organic molecules

Where do animals and fungi obtain the organic molecules that they need? The answer is not too surprising. These organisms trap chemical energy from their environment in the form of food. As well as providing them with chemical energy, the food of animals and fungi provides them with pre-formed organic molecules, including sugars, amino acids and fatty acids. From these organic molecules, animals and fungi can build larger organic molecules, such as proteins from amino acids, or can reorganise them in other ways. Animals and fungi *cannot* make the organic molecules they need from simple inorganic molecules.

Those organisms that must obtain pre-formed organic molecules through feeding are said to be **heterotrophs** (from Greek: *heteros* = other; *trophe* = food). Heterotrophs are also known as consumers. These pre-formed organic molecules come from the organic matter of living or dead organisms, in whole or part, or their organic products, for example, wool, nectar, pollen and honey.

Heterotrophs may be classified in various ways, for example:

- *range of food items*. As specialists, with foods restricted to one or a few items, or generalists that use a wider range of foods. The koala, for example, is a specialist feeder dining almost exclusively on the leaves of a small number of *Eucalyptus* species.
- *method of obtaining food*. As predators, parasites or decomposers (see some examples in figure 3.8, p. 90)
- *nature of their food*. As carnivores (eat other animals), herbivores (eat plants) or omnivores (eat both).

ODD FACT

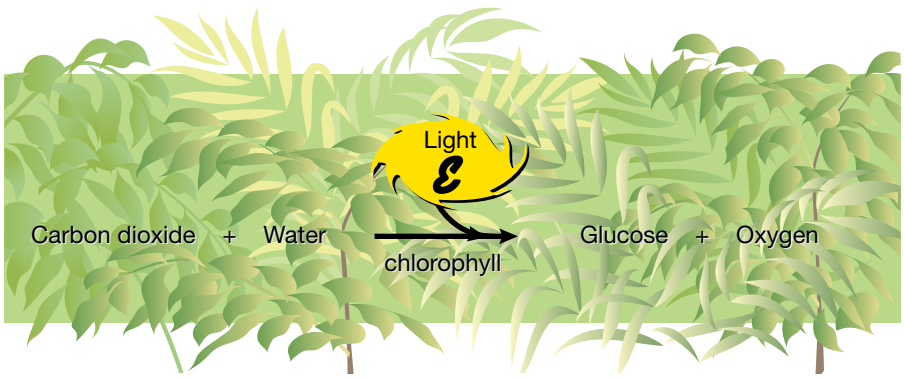
A champion generalist feeder might be the honey badger or ratel (*Mellivora capensis*). In one region of Africa, honey badgers were recorded as eating 60 different kinds of prey including insects, scorpions, snakes, birds, jackals, small crocodiles and antelope, as well as raiding beehives to eat honey and bee larvae.

Autotrophs build their own organic molecules

The sunlight energy captured by plants and algae provides them with energy, but it provides no substance. So, where do plants and algae obtain the organic molecules that they need? Plants and algae make all the organic molecules that they need from simple inorganic molecules — mainly carbon dioxide (CO_2) and water (H_2O) through the process of photosynthesis. Any other atoms required, such as nitrogen (N) and sulfur (S) come from inorganic salts, such as nitrates and sulfates in soil or water.

Organisms that can make their own organic molecules from inorganic raw materials are termed **autotrophs** (from Greek: *autos* = self; *trophe* = food). Autotrophic organisms obtain the carbon that is central to organic molecules from an inorganic source, carbon dioxide (see figure 3.18). Autotrophs are also known as producers.

FIGURE 3.18 Who is cheaper to feed? Autotrophs can build the organic nutrients that they need from carbon dioxide and water. Not so for heterotrophs.



A few plant species do *not* make organic molecules from carbon dioxide and water. These plants are parasites who live on other plant species and they must obtain pre-formed organic molecules from other organisms, called hosts. For example, the Australian dodder (*Cuscata australis*) attaches to its host plant

through a modified root. This modified root invades the transport tissues (xylem and phloem) of the host plant where it accesses both organic molecules, such as sugars, and water (see figure 3.19a). Because they are completely dependent on their host for nutrition, dodders are termed **holoparasites**. Such plants are classified as heterotrophs, not as autotrophs.

However, other parasitic plants are only partially dependent on their hosts. These plants have chlorophyll and can make some of their organic molecules, while obtaining the rest as pre-formed organic molecules from their hosts. Examples include mistletoes, which attach to the stems of their host plants and send out suckers that penetrate the sap-transporting phloem (see figure 3.19b), and the Christmas tree (*Nuytsia floribunda*), which attaches to the roots of its host. The Christmas tree is not an obvious parasitic plant because its attachments to the host are underground where it penetrates the roots of the host. These plants are termed **hemiparasites** and they do not fall neatly into the category of either autotroph or heterotroph.

FIGURE 3.19 **(a)** A dodder parasite (yellow) on the leaves of its plant host. The dodder attaches to the host using small suckers that penetrate the vascular tissue (xylem and phloem) of the stems and leaves of the host. What does the dodder obtain from this connection? (© State of Victoria, Department of Economic Development, Jobs, Transport and Resources 2007. Reproduced with permission) **(b)** A drooping mistletoe (*Amyema pendula*) on a host eucalyptus tree. Australia has about 90 species of mistletoe.

KEY IDEAS

- Organic molecules are essential for the structure and functioning of living organisms.
- Animals and fungi must obtain their supply of organic molecules as pre-formed organic molecules in their food.
- Organisms that must obtain their organic molecules pre-formed are termed heterotrophs.
- Plants and algae are generally able to make their own organic molecules from simple inorganic molecules, such as carbon dioxide and water, through the process of photosynthesis.
- Organisms that can make their own organic molecules from simple inorganic molecules are termed autotrophs.
- Some plants have a parasitic way of life, living either as holoparasites or hemiparasites.

QUICK CHECK

13 What is the distinguishing feature of a heterotroph?

14 An organism can make its own organic molecules using simple inorganic molecules. Does it qualify as a heterotroph?

15 Identify whether each of the following statements is true or false.

- **a** Holoparasitic plants are examples of autotrophs.
- **b** Heterotrophic animals need carbon dioxide to build their own organic molecules.
- **c** Organisms may be classified into autotrophs or heterotrophs depending on how they obtain their organic molecules.
- **d** Heterotrophic organisms use various strategies to access their food.

16 Organism X:

- **i** has chlorophyll and can build its own organic molecules from simple inorganic molecules
- **ii** supplements its supply of organic molecules from a host plant.

Identify whether each of the following statements is true or false in relation to organism X.

- **a** Based on statement (i) only, it may be concluded that organism X might be a plant.
- **b** Based on statement (i) only, it may be concluded that organism X might be an alga.
- **c** Based on statement (i) only, it may be concluded that organism X might be a fungus.
- **d** Based on statements (i) and (ii), it may be concluded that organism X is most probably a holoparasitic plant.

Radiant energy of sunlight

The sun is the source of radiant energy received by planet Earth. The use of sunlight energy by plants and algae is the basis of life on Earth. The energy of the sun is transported to Earth as waves of radiant energy across a distance of about 150 million kilometres. Nearly half of the sunlight energy that reaches Earth lies within the wavelength range of 400 to 700 nm; this is the visible light region of the spectrum violet to red (see figure 3.20). Sunlight energy also includes high-energy short-wavelength ultraviolet (UV) radiation (about 8%) that causes sunburn and skin cancers, and lower energy longer wavelengths including infra-red (IR) radiation.

Among the eukaryotic organisms, only plants and algae can capture sunlight energy. **The ability to capture solar energy depends on the presence of light-capturing pigments, principally chlorophylls, present in chloroplasts.** Of all the wavelengths of sunlight energy that reach Earth, only radiation within the visible light range (violet to red) can be used as a source of external energy by plants and algae. Their light-capturing pigments can absorb only particular wavelengths within the visible light range.

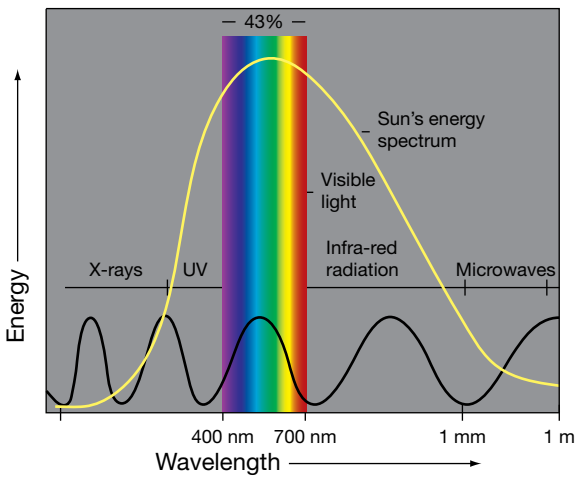


FIGURE 3.20 Energy spectrum of sunlight. Note that almost half (43%) of the energy of sunlight is in the visible section of the spectrum, with wavelengths from 400 to 700 nm, covering violet to red in the visible light spectrum. The shorter the wavelength, the higher the energy level of the radiation.

Pigments for capturing sunlight energy

Capturing sunlight energy depends on the presence of light-trapping pigments in cells. The major light-trapping pigments present in cells of plants and algae are the **chlorophylls** that give leaves and green algae their colour (see figure 3.21a). The chlorophyll pigments are embedded in the grana (flattened discs) that are part of the innermost membrane of chloroplasts (refer to figure 2.31, p. 72). In addition, other light-capturing pigments, termed **accessory pigments**, are found in plants and various algae. Accessory pigments capture sunlight energy and transfer the energy they absorb to the chlorophylls.

One group of accessory pigments are the **carotenoids**. Carotenoids are orange and yellow pigments that are also located on the membranes of the chloroplast grana. One carotenoid pigment is responsible for the colour of brown algae (see figure 3.21b). Another group of accessory pigments are the **phycobilins**; this group includes a blue pigment (phycocyanin) and a red pigment (phycoerythrin), both of which occur in red algae (see figure 3.21c). These phycobilin pigments are water-soluble and are found in solution in the stroma of chloroplasts.

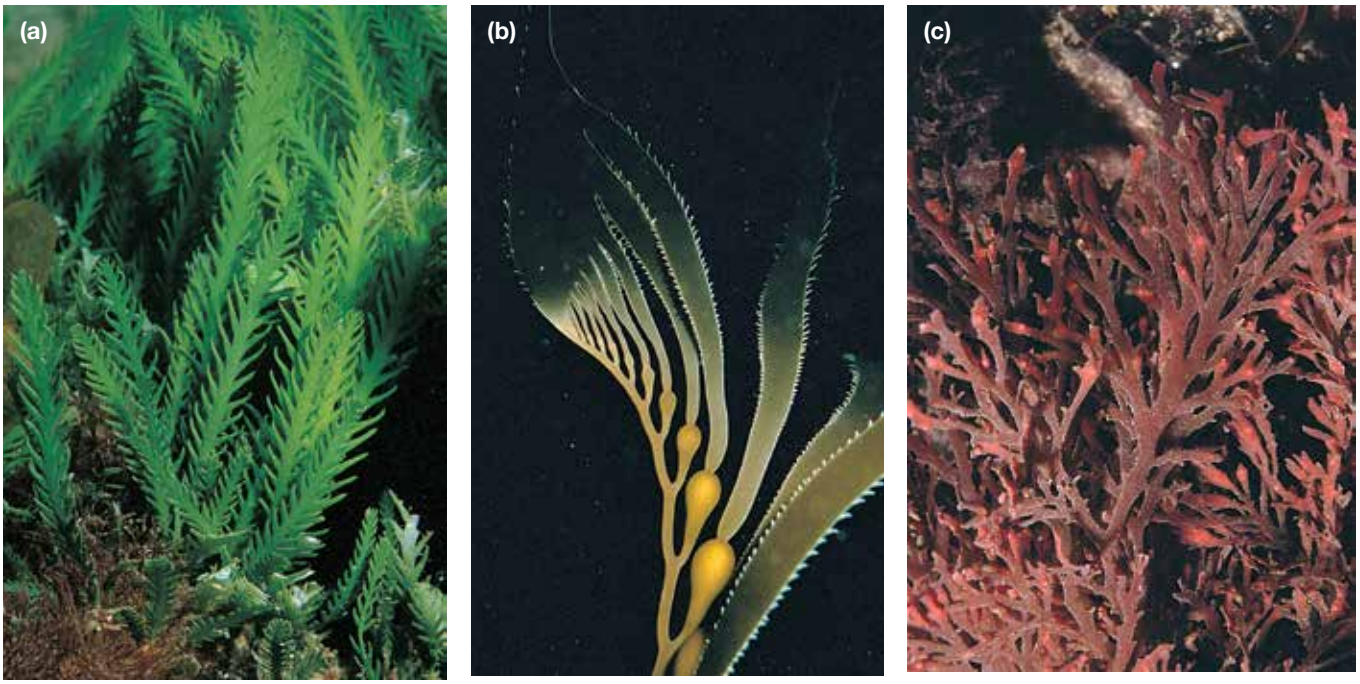
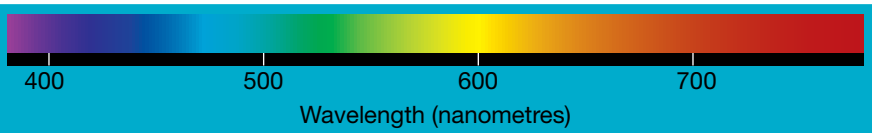


FIGURE 3.21 Different classes of algae (seaweeds) **(a)** A green alga (*Caulerpa remotifolia*) found at depths up to 10 m **(b)** A brown alga (*Macrocystis pyrifera*) also found at depths of up to 10 m; its brown colour is due to the presence of a carotenoid pigment, fucoxanthin (*fucus* = seaweed; *xanthos* = yellow) that masks the presence of its chlorophylls. **(c)** A red alga (*Callophyllis lambertii*) found at depths of up to 35 m

Table 3.2 identifies the major light-trapping pigments found in plants and algae. This table also shows typical values of the **absorption peaks** of each pigment. An absorption peak identifies the wavelength(s) at which a pigment is most effective in capturing sunlight energy. Note that the maximum absorption of the chlorophylls occurs in both the violet-blue and in the red regions of the visible spectrum. Note that the accessory pigments capture sunlight energy at wavelengths different from those captured by chlorophylls. The presence of accessory pigments enables plants and algae to capture more of the sunlight energy that chlorophylls alone can capture.

TABLE 3.2 Occurrence of various light-trapping pigments



Pigment	Colour	Organisms where found	Absorption peaks
chlorophyll a	green	all plants and all algae	violet-blue and orange-red
chlorophyll b	green	all plants and green algae	blue and orange-red
chlorophyll c	green	brown algae	blue and orange-red
chlorophyll d	green	red algae	violet-blue, blue and red
carotenoids	red, orange, yellow	all plants and various algae	blue and blue-green
phycocyanin	blue	red algae	yellow
phycoerythrin	red	red algae	blue and green

Note: The different colours of light-capturing pigments result from the wavelengths of light that they do *not* absorb, but instead reflect or transmit. (Phycocyanin and phycoerythrin belong to the phycobilin group of accessory pigments.)

ODD FACT

Carotenoids are present not only in leaves but also in other plant organs, such as ripening fruits and flower petals. One carotenoid (beta-carotene) gives carrots and sweet potatoes their orange colour, while another carotenoid (lycopene) gives tomatoes their red colour. These carotenoids are present, not in chloroplasts, but in plant cell organelles called chromoplasts (*chroma* = colour; *plast* = living).

The wavelengths of sunlight energy captured by plants and algae depend on the pigments present in their chloroplasts. The major chlorophylls — chlorophyll a and chlorophyll b — capture sunlight energy mainly in the violet-blue and the orange-red regions of the spectrum (see figure 3.22), but almost none in the green region. Instead, green light is mostly reflected from leaf surfaces, while the blue light and the red light are absorbed. This is why leaves are green! (What colour would plant leaves be if chlorophyll pigments absorbed the energy in the green and the red regions of the spectrum and reflected the blue light?)

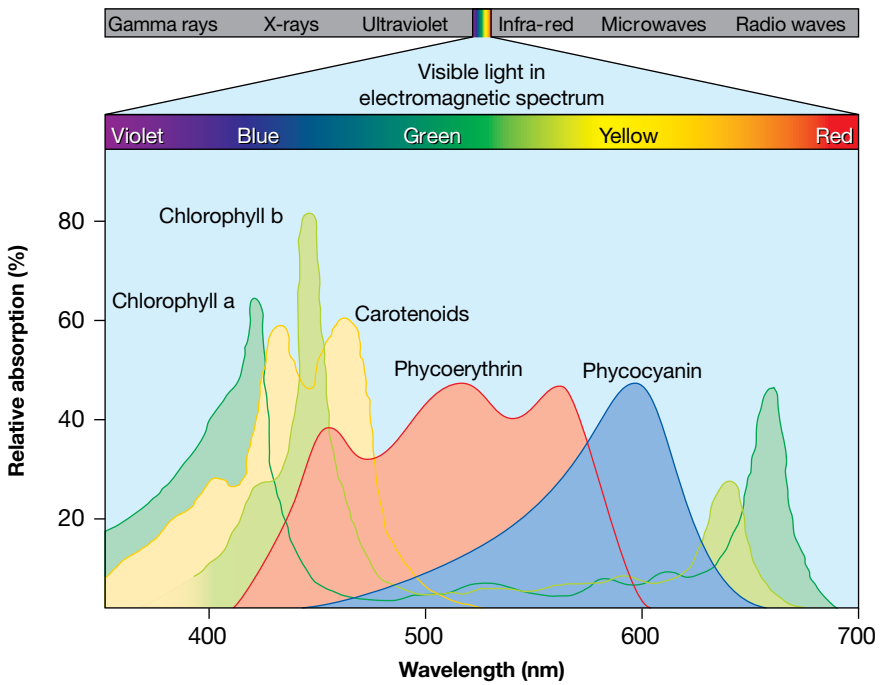


FIGURE 3.22 Absorption of light of various wavelengths for different plant pigments. Note that each of the chlorophyll pigments has two regions of maximum absorption of sunlight energy. Which pigment has its maximum absorption in the yellow region of the spectrum?

Chloroplasts in leaf cells contain both chlorophylls and carotenoids. Usually the carotenoids are present in lower amounts and are hidden by the green chlorophylls. During most of the year, chlorophyll production occurs to replace

FIGURE 3.23 Deciduous trees in early autumn show the presence of carotenoid pigments (yellows and orange) after chlorophyll replacement production slows and stops. Red colouration is from anthocyanin pigments that are also present in the leaves of some plant species.

chlorophyll molecules that are damaged or break down. In early autumn, however, before **deciduous** trees lose their leaves, their leaf cells stop producing chlorophyll. Before long, the chlorophyll has disappeared and the colours of carotenoids' pigments that are normally hidden are revealed, as well as any red anthocyanin pigments that may be present (see figure 3.23). Anthocyanins are water-soluble pigments found in the vacuoles of plant cells, and they are not involved in photosynthesis. Anthocyanin pigments are most apparent in the flowers and fruits of many flowering plants: the purples of pansies, eggplants and cherries; the blues of delphinium and blueberries; the reds of raspberries and red cabbages; and the range of colours (pink, red, orange, blue and purple) seen in petunias. What role might they play? (See Odd fact.)

ODD FACT

Because they absorb damaging UV radiation, it is postulated that anthocyanins may act as a sunscreen, protecting young leaves from damage. In flowers, anthocyanins play a role in attracting pollinators, and in fruits, the colour may attract fruit-eating animals that may disperse their seeds.

KEY IDEAS

- **Nearly half of the radiant energy of sunlight reaching Earth is in the visible light region of the spectrum (violet to red).**
- **The ability of plants and algae to capture sunlight energy depends on the presence of light-capturing pigments present in their chloroplasts.**
- **The most important light-capturing pigments are the chlorophylls that are found in all plants and algae.**
- **Accessory pigments capture sunlight energy at wavelengths that differ from those captured by chlorophylls.**

QUICK CHECK

17 Refer to table 3.2 and identify a possible capturer of sunlight energy for each of the following descriptions.
- **a** Has chlorophylls a and c in its chloroplasts
- **b** Has chlorophylls a and d in its chloroplasts
- **c** Has chlorophylls a and b in its chloroplasts

18 Refer to figure 3.22 and identify the following sunlight-capturing pigments:
- **a** Pigment A has absorption maxima in the blue and in the red region of the spectrum.
- **b** Pigment B has its major absorption in the green region of the spectrum.
- **c** Pigment C absorbs mainly in the yellow region of the spectrum.

19 Where are the chlorophylls located within a cell?

20 Student M asked 'Why bother with accessory pigments? Why not just have more chlorophyll molecules to capture sunlight energy?' Student N gave a reason why. What might student N have said?

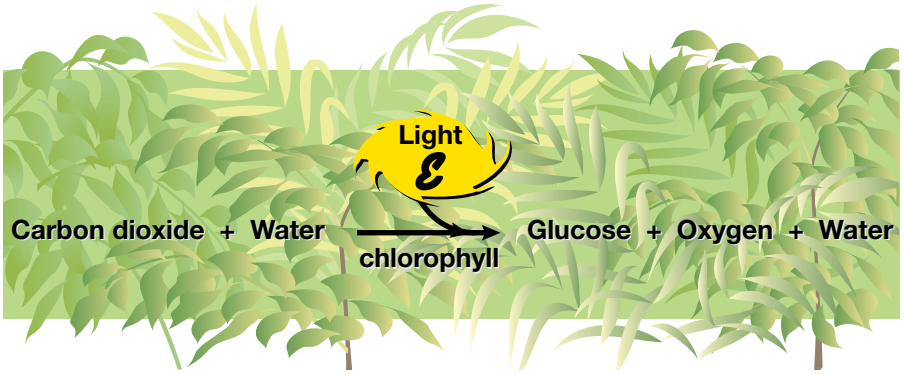
studyon
Unit 1 AOS 1 Topic 3 Concept 2
Photosynthesis Concept summary and practice questions

Photosynthesis: from sunlight to sugar

Plants and algae transform the energy of sunlight into the chemical energy of organic molecules, such as glucose, through the process of photosynthesis (*photo* = light; *synthesis* = putting together). Photosynthesis enables

autotrophs, such as plants and algae, to build simple inorganic molecules into the complex energy-rich organic molecules that they need for living.

Photosynthesis is the process by which autotrophs transform **sunlight energy** into the **chemical energy** of sugars, such as glucose. In a typical autotrophic organism, such as a terrestrial flowering plant, the complex series of reactions in photosynthesis can be summarised as follows:



The complete balanced equation for photosynthesis is:

$$6CO_2 + 12H_2O \xrightarrow[\text{light}]{\textbf{chlorophyll}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Note that water is both a reactant and a product in photosynthesis.

The photosynthesis equation is sometimes simplified to:

$$6CO_2 + 6H_2O \xrightarrow[\text{light}]{\textbf{chlorophyll}} C_6H_{12}O_6 + 6O_2$$

showing the net consumption of water only.

The chlorophylls that capture the sunlight energy are located on the grana membranes of chloroplasts (see figure 3.24). Typically, a photosynthetic cell has from 40 to 200 chloroplasts.

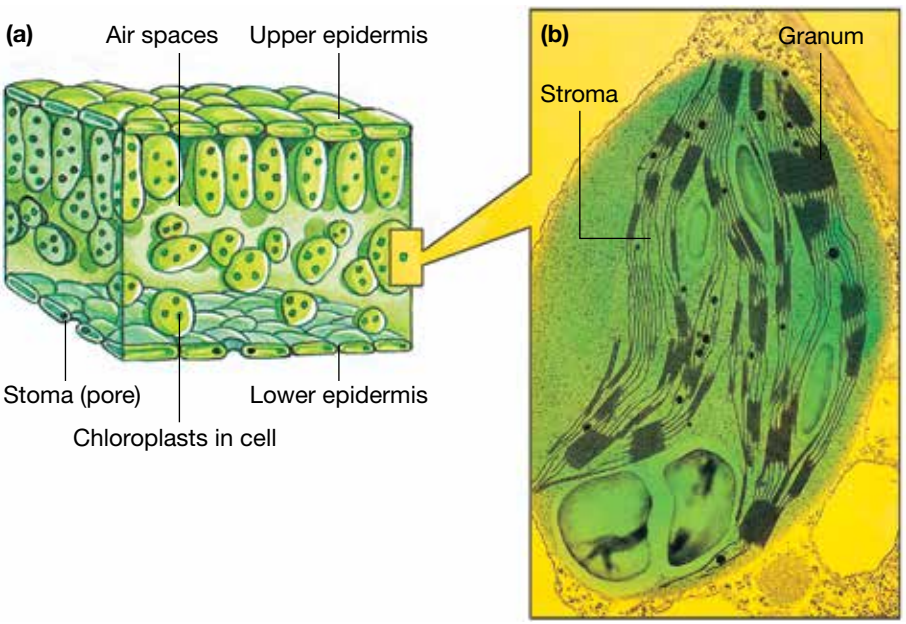
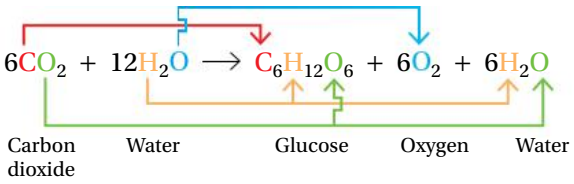


FIGURE 3.24 **(a)** Diagram showing features of a leaf. Note that chloroplasts are present only in cells inside the leaf and not in the cells of the upper and lower surfaces, except for guard cells that encircle the stomata. **(b)** Internal structure of chloroplast showing the membrane that is folded into stacks of flattened discs (grana) with chlorophylls (and accessory pigments) located on their surface

What happens to the atoms of the carbon dioxide and water molecules that are the inputs to photosynthesis? Check out the following image:



Water molecules are split by sunlight energy into hydrogen and oxygen atoms. What happens to the oxygen atoms from this splitting? Where do the carbon atoms go? Because oxygen is one of the products of photosynthesis, the type of photosynthesis carried out by plants and algae is referred to as **oxygenic** (oxygen-producing) photosynthesis.

Figure 3.25 shows the energy flow in photosynthesis. This starts with the capture of sunlight energy by chlorophyll in the chloroplasts that splits water molecules. Sunlight energy is transformed to chemical energy in energy-carrier molecules, including ATP. The energy from ATP is then used to build energy-rich glucose molecules.

The oxygen from the splitting of water that is released into the atmosphere is far from a waste product. This oxygen sustains all oxygen-dependent life forms on Earth and is an essential input to the process of aerobic cellular respiration (see p. 113).

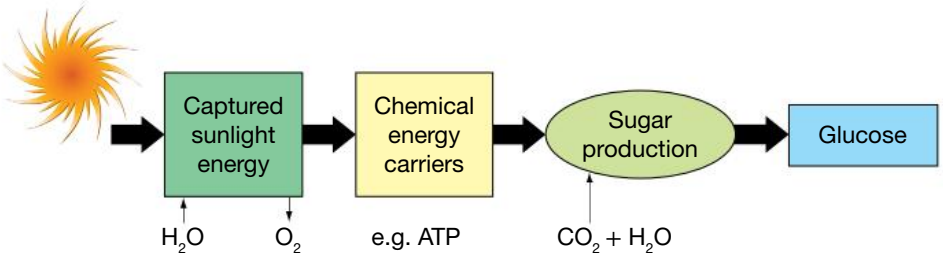


FIGURE 3.25 The energy flow in photosynthesis starts with the radiant energy of sunlight and ends with the chemical energy of glucose molecules. Where do these events occur?

Photosynthesis involves a series of chemical reactions. The details of the chemical reactions that occur during photosynthesis are far more complex than the equations shown here. In this book, we are not concerned with the details of photosynthesis, just its inputs, outputs and significance. Figure 3.26a is a simplified representation of photosynthesis showing the inputs and outputs of photosynthesis in a terrestrial plant. Examine this figure and note that:

- light energy is captured by the chlorophyll present in green leaves
- water comes from the soil
- carbon dioxide comes from the air
- glucose is built from carbon dioxide and water
- oxygen, derived from the water, is released into the air.

Figure 3.26b summarises the reactions occurring in chloroplasts.

The photosynthesis equation ends with the transformation of sunlight energy into the chemical energy of glucose. However, that is not the end of the story. Glucose provides the starting point for the production of other organic molecules needed by plants for maintenance and repair of their structure, for growth and for making enzymes and other organic molecules needed for them to function.

ODD FACT

When exposed to light, the first glucose molecules appear in leaf cells after about 30 seconds. Can you suggest what might be happening during that 30-second period?

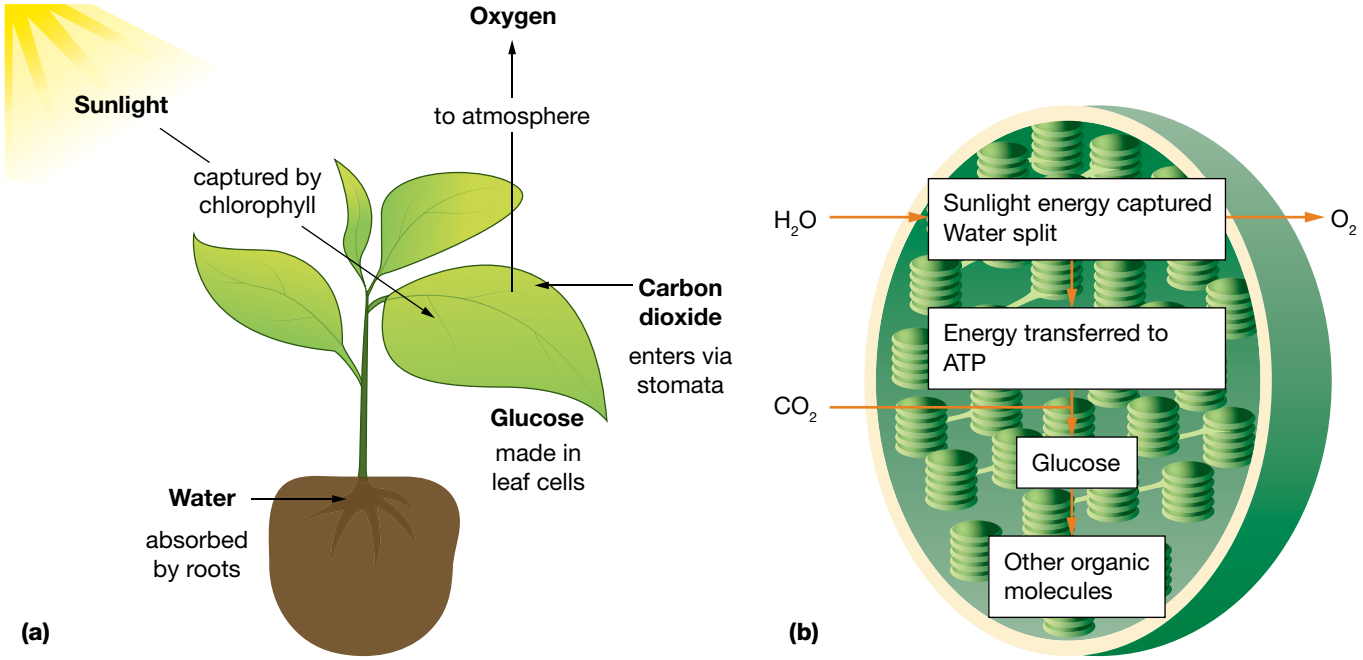


FIGURE 3.26 **(a)** Photosynthesis requires sunlight energy and the inputs of inorganic carbon dioxide and water to produce glucose. **(b)** Simplified diagram showing a summary of reactions occurring in the chloroplast during photosynthesis. Note that glucose is the starting point for the production of other organic molecules needed by plant cells.

Organic molecules made by plants are not used just by the plants that produce them. Organic compounds produced by plants and algae are the direct or indirect sources of food for virtually all heterotrophs (see figure 3.27). Organic molecules made by plants are used:

- directly as food by herbivores, such as a caterpillar that feeds on leaves, and by plant parasites, such as the powdery mildew fungus (*Uncinula necator*) that draws its nutrients from the tissues of grapevines
- indirectly by carnivores and by parasites that have animal hosts.

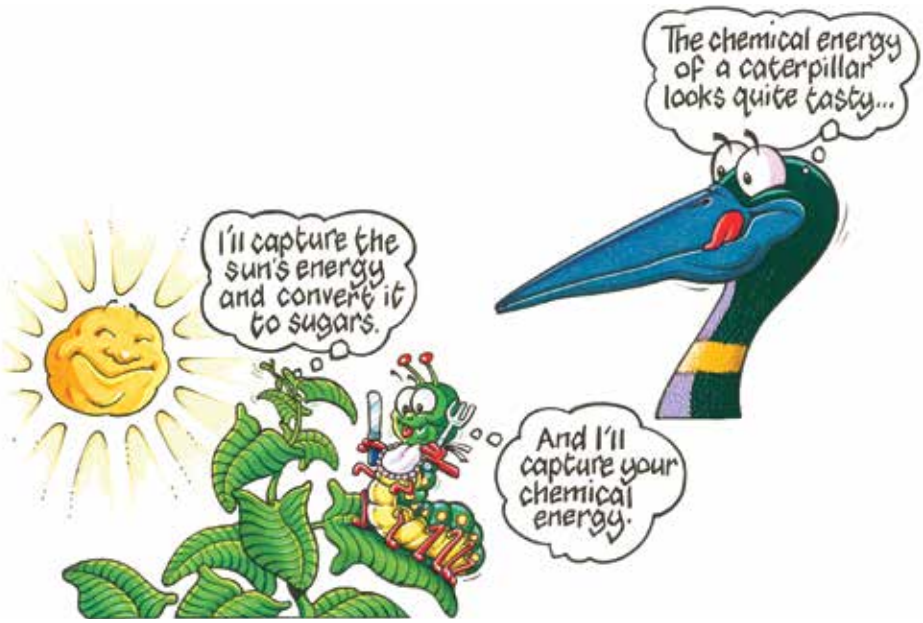


FIGURE 3.27 In photosynthesis, sunlight energy captured by plants is transformed to the chemical energy of organic molecules. This energy can flow directly to herbivores, such as leaf-eating caterpillars, and then indirectly to animals that feed on herbivores.

Plant structures to support photosynthesis

In this section, we will explore how the structure of terrestrial plants enables them to carry out photosynthesis and distribute the glucose produced by photosynthesis to all their cells. What structures and characteristics of leaves and other plant parts ensure a ready supply of the materials required for photosynthesis? Only the chlorophyll-containing cells of a plant produce energy-rich glucose for use by cells. So, how are photosynthetic products transported from leaves to all non-photosynthetic cells throughout a plant? Consider figure 3.28. The three regions of a plant we must consider are leaves, stems (or trunks, in the case of trees) and roots.

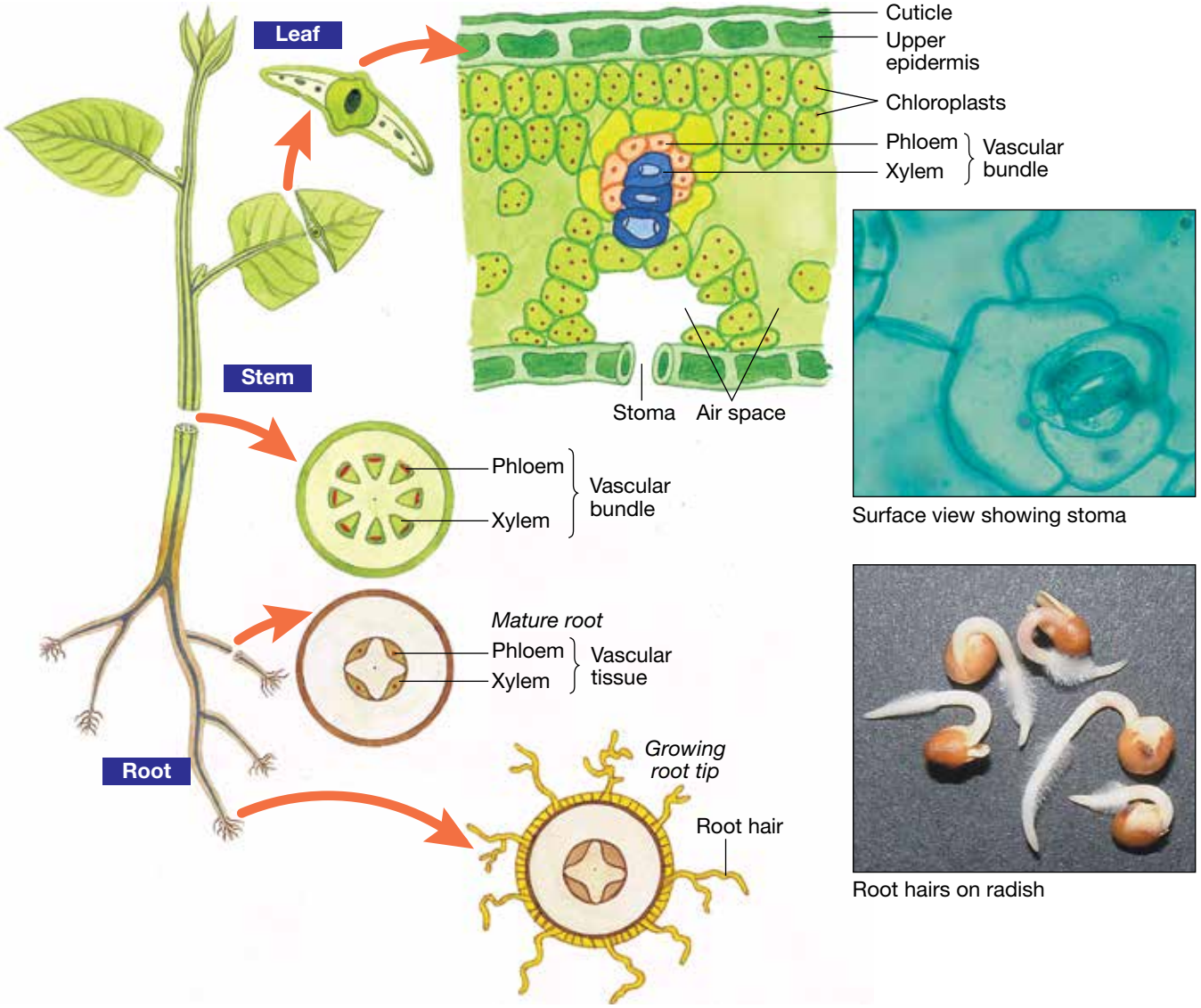


FIGURE 3.28 Leaves, stems and roots have structures that ensure the capture of light energy and the supply of water, mineral ions and carbon dioxide to photosynthetic cells of a plant. Note the cross-sectional view of each part of the plant.

Leaves

- The flat shape of leaves provides a large surface area exposed to sunlight.
- Each photosynthetic cell contains many chloroplasts with chlorophyll that traps the energy of sunlight.
- Pores, called stomata (singular: stoma) on the lower leaf surface provide the only access into the leaf for carbon dioxide from the air. The rest of the leaf is covered with a waxy impermeable cuticle that prevents water loss.

- The presence of internal air spaces in leaves enables the ready diffusion of carbon dioxide to photosynthetic cells in the leaf tissue.
- The vascular tissue contains xylem vessels to transport water to photosynthetic cells and phloem tissue to transport the products of photosynthesis from these cells to all other cells throughout a plant.

Stems

- Thick-walled xylem vessels give rigidity to a stem. How might this assist photosynthesis?
- Branching of stems allows layers of leaves to be positioned at different levels of a plant, hence increasing the total area available for capture of sunlight energy.
- Xylem vessels transport water and minerals from roots to all aerial parts of a plant.
- Phloem transports products of photosynthesis from photosynthetic cells to non-photosynthetic tissue throughout a plant. (Sugars are moved through the phloem as sucrose (cane sugar), not as glucose.)

Roots

- An extensive root system taps a significant volume of soil for water and mineral salts.
- In a region just behind the tip of each root, many of the external cells form outgrowths or long thin extensions called root hairs. These root hairs create a very large surface area for the absorption of water and dissolved minerals. (Root hairs are like an underground sponge that absorbs water.) By what process might water cross from the soil into the root hair cells?

These features of leaves, stems and roots enable a terrestrial plant to capture sunlight energy and access carbon dioxide from the air, water and soil that it requires to produce energy-rich glucose molecules through photosynthesis.

KEY IDEAS

- **Photosynthesis is the process in plants (and algae) by which they build glucose, an organic molecule, from inorganic starting materials, carbon dioxide and water.**
- **Sunlight energy is essential for photosynthesis and is captured by the chlorophyll in chloroplasts.**
- **Photosynthesis involves the transformation of sunlight energy to the chemical energy in glucose molecules.**
- **Sunlight energy splits water into hydrogen and oxygen.**

QUICK CHECK

21 Where in a cell is sunlight energy transformed to the chemical energy of organic molecules?

22 In photosynthesis, what is sunlight energy transformed to?

23 What are:
- **a** the inputs to photosynthesis
- **b** the outputs of photosynthesis?

24 What parts of a plant carry out the following functions?
- **a** Capture of sunlight energy
- **b** Transport of organic molecules made by photosynthesis to other parts of a plant
- **c** Absorption of water
- **d** Intake of carbon dioxide

25 Water is split into hydrogen and oxygen in photosynthesis. What happens to the oxygen atoms?

Living in darkness

For a living community to survive, it must include autotrophic (producer) organisms. Autotrophs capture an external source of energy from their environment and build energy-rich organic molecules, not only for their own use, but also for the heterotrophic (consumer) organisms in a community.

In the dark water column and on the floor of most oceans, there are no autotrophic organisms. Not surprisingly, fish and other consumers (heterotrophs) are rare and temporary visitors to these dark regions. Dead organisms and detritus occasionally drift down to the ocean floor from more shallow sunlit waters. This organic material provides nutrients for a temporary community of consumer organisms. (A real, but very occasional bonus is the carcass of a dead whale that can provide nutrients for heterotrophic organisms for years.)

However, while most of the ocean floor is lifeless, this is not always the case. Some regions of the ocean floor in perpetual darkness have thriving communities. Likewise, deep in caves and in subglacial lakes away from the reach of sunlight, living communities exist. Yet, no community can exist without producer organisms. The producers in these dark communities cannot be green plants, algae or phytoplankton that cannot survive without sunlight. What external energy sources might be available for autotrophs to trap and transform to chemical energy in these dark communities? (*Clue:* Oxidation reactions release energy.)

Let's look at some communities that exist in total darkness.

Subglacial Lake Whillans

Subglacial Lake Whillans in Antarctica (refer to chapter 1, pp. 3–6) is buried under more than 800 m of ice and is in total darkness. No sunlight energy to capture here! Yet, a thriving community of diverse microbes lives in its water and sediments. Microbes found in Lake Whillans include some bacterial species that capture energy released from the oxidation of reduced mineral compounds present in their environment. For example, *Thiobacillus* bacteria capture the energy released from the oxidation of sulfides to sulfates and use this energy to build glucose from inorganic carbon dioxide.

The process of using energy released from the oxidation of inorganic chemicals to build organic molecules from carbon dioxide is termed **chemosynthesis** (see figure 3.29). Both chemosynthetic and photosynthetic organisms are autotrophs that build complex organic molecules, such as glucose, from simple inorganic molecules such as carbon dioxide. Their difference is that they rely on different external sources of energy:

- Photosynthetic autotrophs (plants and algae) rely on sunlight energy.
- Chemosynthetic autotrophs (some bacteria and archaea) rely on chemical energy from the oxidation of reduced inorganic chemicals present in their environment.

Other microbes in the Lake Whillans community are heterotrophs that feed on organic molecules made by the chemosynthetic microbes.

ODD FACT

Chemosynthetic bacteria and archaea that use the chemical energy from the oxidation of reduced minerals to build glucose are also called lithotrophs (*lithos* = stone, rock; *trophe* = food) or 'rock-eaters'.

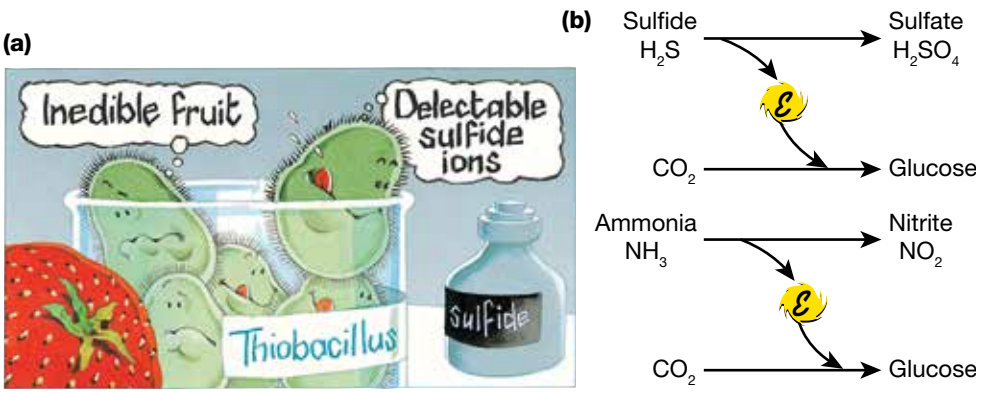


FIGURE 3.29 Chemosynthetic autotrophic microbes capture chemical energy from the oxidation of inorganic chemicals and use this energy to build complex organic molecules, such as glucose, from carbon dioxide. **(a)** Some chemosynthetic bacteria capture energy from the oxidation of sulfides. **(b)** Oxidation reactions used by chemosynthetic microbes include: (i) oxidation of sulfide to sulfate and (ii) oxidation of ammonia to nitrite.

The Movile Cave in Romania

The Movile Cave, discovered in Romania in 1986, is completely isolated from the surface and in total darkness. The cave was discovered accidentally when exploratory drilling revealed its existence. It is unusual because the water and gases inside the cave come from water and gases that rise into the cave from its floor, rather than seeping down from the surface; the cave receives little if any water percolating down from the surface. The cave was closed by Romanian authorities and only a few scientists have been given permission to go into the cave. Entry to the cave is by rope down narrow hand-cut shafts (see figure 3.30).

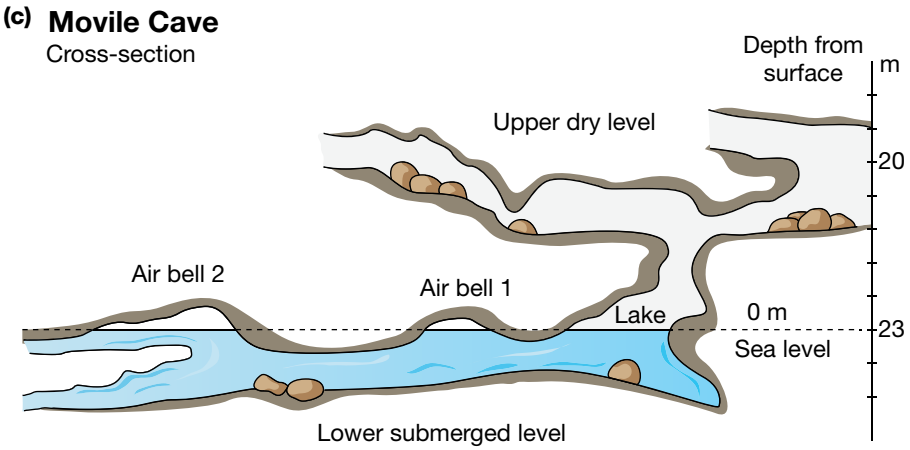


FIGURE 3.30 (a) Dr Alexandra Hillebrand-Voiculescu from the Institute of Speleology in Bucharest, Romania about to enter the hand-cut shaft that provides access to the Movile Cave. She is in a wetsuit because she will dive into the airbells in the cave that harbour the microbial mats. There is a lot of toxic hydrogen sulfide in the airbells and so she needs scuba gear. The light is so she can find her way around as it is completely dark in there. The orange ball is a football bladder that is used to sample the air in the airbells to find out how much methane is present. This provides a new interpretation of 'going to work in the laboratory'. **(b)** Professor Colin Murrell from the University of East Anglia at work in the cave. He is adding samples of isotopically labelled methane and methanol to samples of microbial mat and cave water in order to identify which microbes obtain their energy for living by consuming these substrates. **(c)** Diagram of Movile Cave (Images (a) and (b) courtesy of Colin Murrell)

ODD FACT

The various animals that live in the Movile Cave have no functional eyes, often lack pigments, but typically are richly equipped with tactile sensors, such as bristles, hairs and antennae. Can you suggest why?

The atmosphere in the Movile Cave is very different from the atmosphere that we breathe. The air in the cave has a lower concentration of oxygen, a higher concentration of carbon dioxide, and toxic gases including hydrogen sulfide, ammonia and methane are present in the air and water. A maximum of three people can enter the cave at any one time and can work there for one hour only.

Deep in the total darkness, the limestone walls of Movile Cave are coated with slimy films of bacteria, and deep pools of water on the cave floor are covered with floating mats of bacteria, termed **microbial mats**. These bacteria are chemosynthetic and obtain energy by oxidising inorganic molecules. Some oxidise hydrogen sulfide (H_2S) and others oxidise ammonia (NH_3). Other kinds of bacteria can oxidise methane (CH_4). They use energy from oxidation reactions to build inorganic carbon dioxide into complex organic compounds, such as glucose. This organic matter provides nutrients for the microbes themselves and also provides food for a variety of consumers that form part of the

living community in the cave. The consumer organisms in Movile Cave are unique invertebrate species adapted to life in complete darkness, and include species of earthworm, snail, centipede, spider and woodlouse.

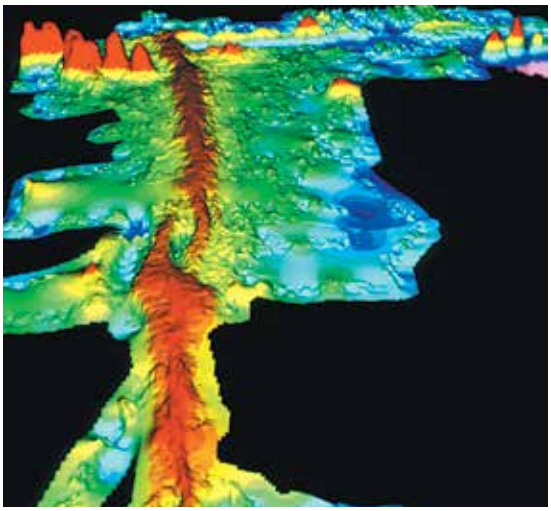


FIGURE 3.31 A false coloured image, obtained by sonar, of the ocean floor showing an extensive mid-ocean ridge

Deep-ocean hydrothermal vents

The ocean floor of the Atlantic and the Pacific oceans is a region of total darkness, crushing pressure and frigid temperatures. The floor of both oceans is crossed by **mid-ocean ridges**, where the ocean floor is shaped into valleys, cliffs and seamounts (see figure 3.31).

In the valley areas, new ocean crust is being formed as the plates of the Earth's crust spread apart. Here, cold sea water seeps into fissures in the Earth's crust and is heated by the underlying molten rock to temperatures up to 400 °C. The water reacts with the hot rock and dissolves minerals such as iron sulfide. Because the superheated mineral-rich water expands, it is forced upwards and emerges from outlets in the ocean floor known as **hydrothermal vents**. As the hot water (~350 °C) comes into contact with the surrounding frigid ocean waters (4 °C), minerals precipitate out of the solution and form 'chimneys' around the vent openings. One kind of hydrothermal vent, known as a 'black smoker', emits streams of dark acidic water from a chimney made mainly of iron sulfide (see figure 3.32). Could life exist in such an environment?

ODD FACT

The great water pressure at a depth of 2.5 km means that water will not boil until it reaches a temperature of about 450 °C.

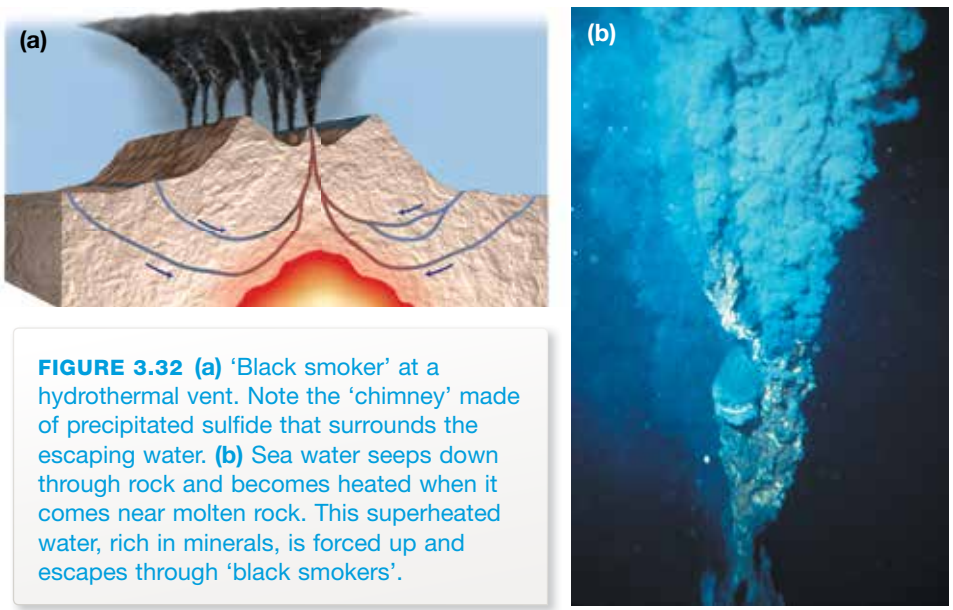


FIGURE 3.32 **(a)** 'Black smoker' at a hydrothermal vent. Note the 'chimney' made of precipitated sulfide that surrounds the escaping water. **(b)** Sea water seeps down through rock and becomes heated when it comes near molten rock. This superheated water, rich in minerals, is forced up and escapes through 'black smokers'.

In 1977, scientists discovered a fantastic abundance and high density of organisms around a hydrothermal vent about 2.5 km below the surface of the Pacific Ocean near the Galapagos Islands. The vent organisms included white clams, mussels, blind white crabs, shrimp and various kinds of worm.

The producers in deep-ocean hydrothermal vents are chemosynthetic bacteria that capture energy from the oxidation of chemicals, such as sulfides and hydrogen, and use that energy to make complex organic molecules from simple inorganic compounds. When a vent first forms, the ocean floor around the vent becomes covered with a thick mat of chemosynthetic bacteria that attracts various consumer organisms that feed on the bacteria (see figure 3.33).

FIGURE 3.33 A microbial mat coated in white sulfate material at a hydrothermal vent. The sulfate is produced by chemosynthetic autotrophic bacteria that form this mat. They capture energy from the oxidation of sulfides to sulfates. Chemosynthetic bacteria like these include *Sulfurimonas autotrophica.* What does the name of this bacterial species suggest?

KEY IDEAS

- Every living community must include autotrophic (producer) organisms that import energy and produce organic molecules from that energy.
- Oxidation of reduced chemicals is an energy-releasing reaction.
- Chemosynthesis involves the capture of energy from the oxidation of inorganic molecules and the use of this energy to build organic molecules, such as glucose, from inorganic carbon dioxide.
- Chemosynthetic autotrophs, such as bacteria and archaea, can capture the energy from the oxidation of inorganic chemicals in their environment.
- Chemosynthetic microbes are the autotrophic producers in communities living in extreme environments, including communities in complete darkness.

QUICK CHECK

26 Identify whether each of the following statements is true or false.
- **a** Chemosynthetic autotrophs rely on capturing chemical energy from their environment.
- **b** The oxidation of sulfides to sulfates is an example of an energy-releasing reaction.
- **c** Chemosynthetic microbes are examples of autotrophic organisms.
- **d** It is reasonable to predict that algae might be found in the water pools in the Movile Cave.
- **e** It is reasonable to predict that some photosynthetic bacteria might live in the waters of subglacial Lake Whillans.

27 List one difference between photosynthesis and chemosynthesis.

28 List one similarity of photosynthesis and chemosynthesis.

29 What is the essential difference between a photosynthetic autotroph and a chemosynthetic autotroph?

30 If the chemosynthetic autotrophs were removed from a deep ocean hydrothermal vent, predict, giving a reason, what might happen to the diverse community living around that vent.

Cellular respiration: energy transfer from glucose to ATP

studyon
Unit 1 AOS 1 Topic 3 Concept 3
Cellular respiration Concept summary and practice questions

All organisms require chemical energy for use *all the time* to drive energy-requiring life processes, such as making new organic molecules for growth, repair, movement, maintenance of internal conditions of cells within a narrow range and reproduction. For plants and algae, this chemical energy comes from glucose molecules made by photosynthesis. For animals and fungi, this chemical energy comes from the organic molecules, such as glucose, in their digested food.

However, the chemical energy in glucose must be transferred to the useable form of energy for cells: the chemical energy of ATP. ATP can release its chemical energy to drive the energy-requiring life processes of all organisms. Figure 3.34 shows some of the functions in the human body that use energy supplied by ATP.

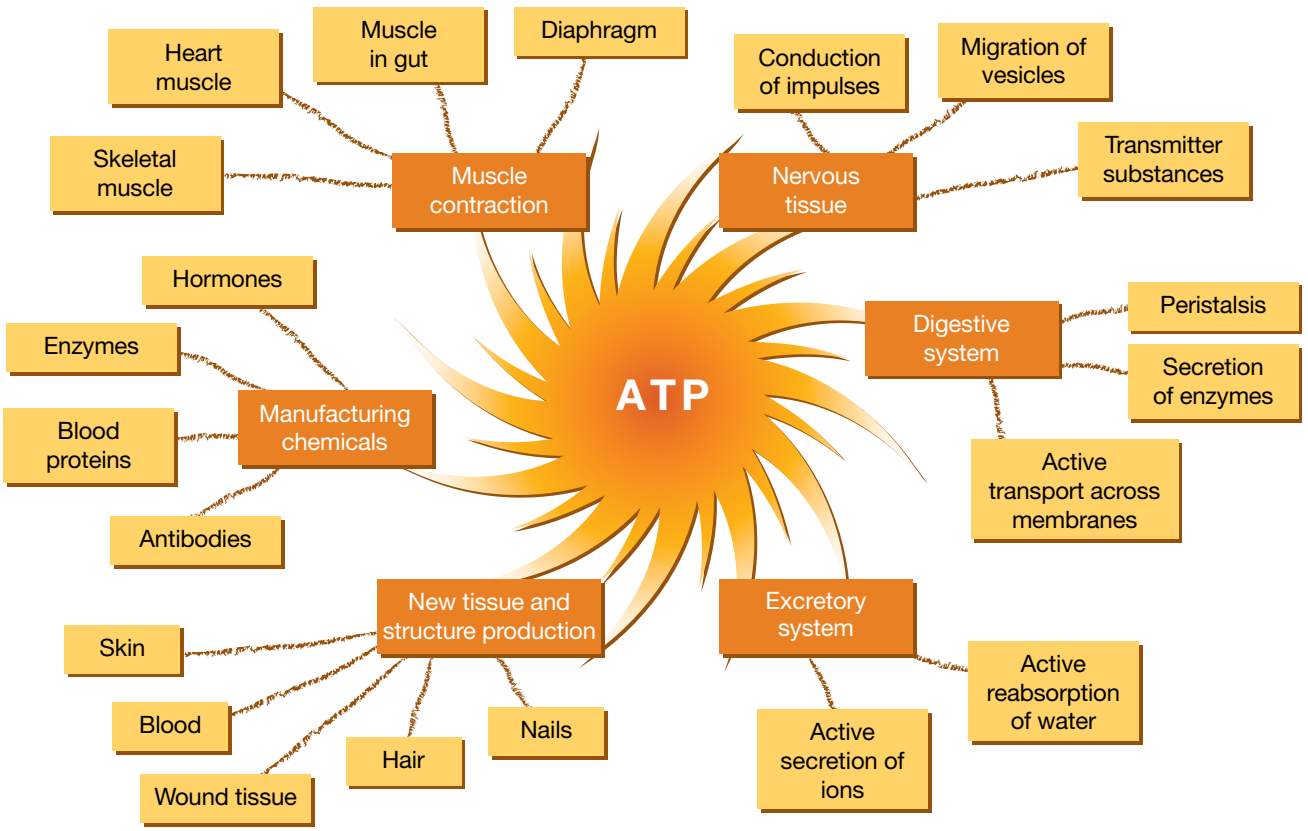


FIGURE 3.34 ATP is the source of energy for cells to carry out the many processes of living. This figure shows examples of cellular activities in the human body that are driven by energy released when ATP molecules release their energy upon being broken down to ADP.

Cells obtain the ATP they need through the process of cellular respiration. In cellular respiration, glucose molecules are progressively oxidised, under enzyme control, to carbon dioxide and water. This energy-releasing oxidation process is coupled (linked) to the energy-requiring process of ATP production. Refer to the box on pages 118–19 for more information about the coupling of energy-releasing and energy-requiring reactions. **Because of the continuous need for energy, cellular respiration occurs all the time in all living cells.**

Why not use glucose as the direct energy source for cells, rather than transfer its chemical energy to ATP? ATP is the ideal energy source for cellular processes because its chemical energy is released for use in a single-step instantaneous reaction. In contrast, the release of energy from glucose involves many steps and takes much longer. In addition, the amount of energy released by ATP is a small useful quantity (about 30 kJ/mole) compared to the relatively large amount of chemical energy contained in glucose (just under 3000 kJ/mole).

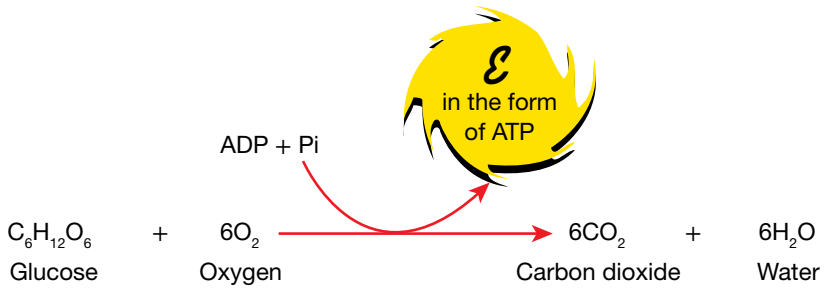
Cellular respiration: with or without oxygen

In most eukaryotic organisms, and in the cells of most tissues, cellular respiration can occur only if oxygen is available; this type of cellular respiration is termed **aerobic respiration**. For example, human heart muscle depends on aerobic respiration to provide the energy to sustain its muscular contractions that enable it to pump blood around the body. Under conditions of severe oxygen shortage, the heart's pumping action stops.

However, some organisms that live in oxygen-free (anoxic) environments, including some microbes and yeasts, must carry out cellular respiration in the absence of oxygen; this is termed **anaerobic respiration** (*an* = not, without; *aer* = air; *bios* = life) or **fermentation**. In addition, some organisms that rely on aerobic respiration may have particular tissues that can also carry out anaerobic respiration when oxygen supplies are inadequate, for example, your skeletal muscle tissue (see pp. 120–1). However, anaerobic respiration is not sufficient to maintain the function of heart muscle.

Aerobic respiration: making ATP in the presence of oxygen

In aerobic respiration, glucose molecules ($C_6H_{12}O_6$) are oxidised to produce carbon dioxide (CO_2) and water (H_2O). This is an energy-releasing, or **exergonic**, process and the energy released is used to produce ATP. The following equation is a highly simplified summary of aerobic respiration:



Oxidation reactions release energy, such as when wood burns in a fire. When it burns, the organic material in wood combines with oxygen from the air, producing carbon dioxide, water and, importantly, energy, mainly in the form of heat energy. Glucose can also be burned or oxidised in air (see figure 3.35a), forming carbon dioxide and water. However, burning glucose in a frying pan is an uncontrolled single-step oxidation reaction that releases the chemical energy of glucose in one burst, mostly as heat energy. The complete oxidation of one mole of glucose releases about 2800 kJ of energy.

In aerobic respiration in cells, glucose is also oxidised to carbon dioxide, but this does *not* occur as a single-step reaction, as shown in the equation above. Instead, aerobic respiration consists of a series of enzyme-controlled reactions that release the chemical energy of glucose in small quantities. Much of the energy released in these reactions is transferred to ATP, instead of being transformed to heat energy and lost (see figure 3.35b).

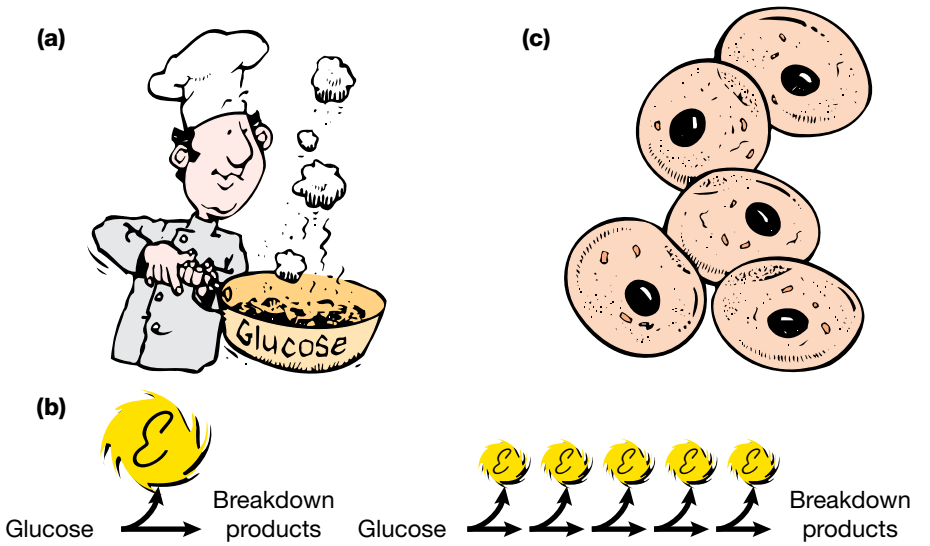


FIGURE 3.35 (a) The single-step uncontrolled oxidation of glucose releases a large amount of energy, mainly as heat energy. **(b)** In cells, the controlled release of energy in many small steps allows energy to be released in smaller amounts that can be used to drive ATP production.

ODD FACT

For the mathematically minded only! How much ATP might be formed from the complete oxidation of glucose? Energy from glucose is 2800 kJ/mole, but at 40 per cent efficiency this is reduced to about 1120 kJ. Each mole of ATP requires 30 kJ. So, energy from one mole of glucose might drive the production of about 37 mole of ATP. (In fact, 34 ATP is the generally accepted value.)

When oxygen is not present, glucose undergoes a process termed anaerobic respiration.

The efficiency of aerobic respiration is about 40 per cent; this means that normally about 40 per cent of the chemical energy of glucose is transferred to ATP and about 60 per cent is lost as heat energy. In mammals and birds some of this heat is trapped by insulating layers of fat, fur or feathers that assist in maintaining their core body temperatures.

Aerobic respiration: what happens where

Aerobic respiration is a complex multistep process that involves more than 20 enzyme-controlled reactions. You do not need to know the detail, just the big picture:

- Glucose (with 6 C atoms) is oxidised to carbon dioxide and water.
- One intermediate product in this pathway is pyruvate (with 3 C atoms).
- A total of about 34 molecules of ATP are produced for each starting molecule of glucose.

The reactions in aerobic respiration occur in order in three different locations within a cell, so they may be grouped into three sets as shown in figure 3.36.

1. The first set of reactions of aerobic respiration occurs in the cell cytosol. In this set of reactions, known as **glycolysis** (*glyco* = glucose; *lysis* = unfastening, releasing), glucose ($C_6H_{12}O_6$) molecules are broken down into two molecules of pyruvate ($C_3H_4O_3$). The energy released is transferred to produce two molecules of ATP. In the presence of oxygen, pyruvate molecules are actively transported from the cytosol into the inner compartment (matrix) of the mitochondria where aerobic respiration is completed (sets 2 and 3). (If oxygen is not present, the pyruvate stays in the cytosol and undergoes fermentation.)
2. The second set of reactions occurs in the fluid matrix of mitochondria where the enzymes involved are located. (This set of reactions is termed the **Kreb's cycle**, named after Hans Krebs (1900–81), the scientist who identified the many complex reactions involved in this cycle.)
3. The final set of reactions of aerobic respiration is termed the **electron transport chain**. These reactions take place on the inner membrane of the mitochondria where electron acceptors are located. The final electron acceptor in this chain is oxygen. You may recall the cyanide gas produced in the *Kiss* nightclub fire blocked this process (refer to p. 84).

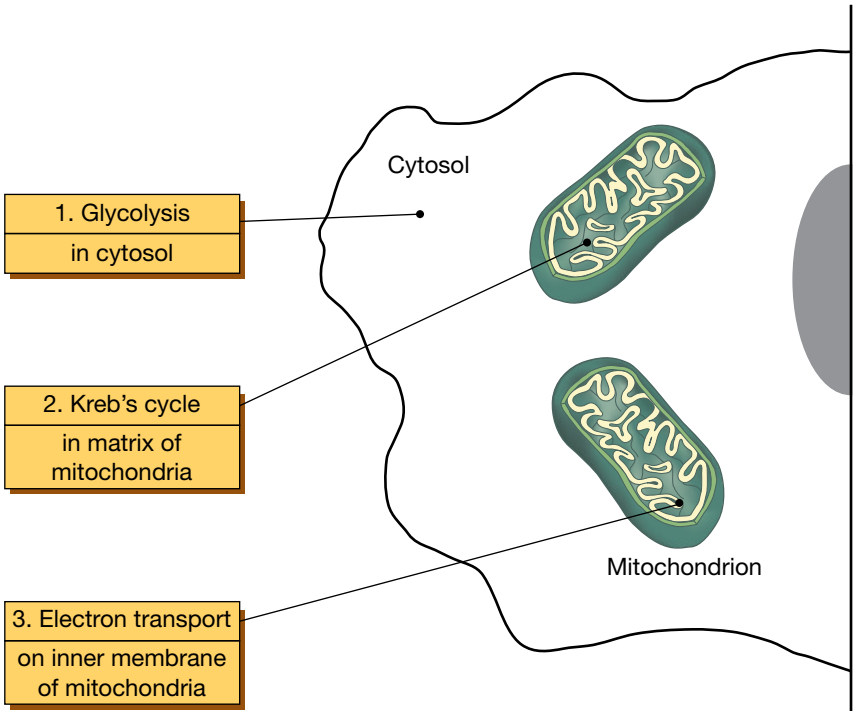


FIGURE 3.36 The many reactions of aerobic cellular respiration take place in different locations within a eukaryotic cell. The first set (glycolysis) occurs in the cytosol, the second set in the mitochondrial matrix and the final set on the inner membrane of mitochondria. (Cell diagram, not to scale)

The two sets of reactions that occur in the mitochondria (2 and 3) produce about 32 ATP molecules and are the major source of ATP production in cells. Once formed, the ATP leaves the mitochondria via the ATP channel for immediate use within the cell. Figure 3.37 shows a summary of these three sets of reactions in aerobic respiration. The pathway of a molecule of glucose through aerobic respiration is shown by the black arrows. Remember that in this process, the chemical energy of glucose is transferred to 34 molecules of ATP.

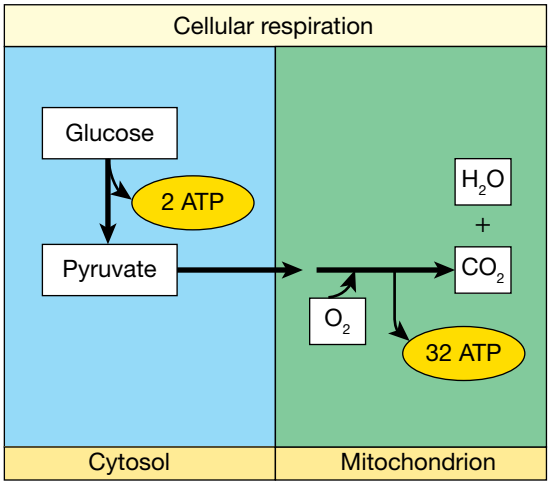


FIGURE 3.37 Summary of aerobic respiration. The black arrows show the aerobic respiration pathway of a glucose molecule to pyruvate and then to carbon dioxide.

Measuring rates of aerobic respiration

Various human tissues have different energy requirements. For example, heart muscle uses energy at a much higher rate than skin cells. The same tissue may differ in its energy requirements at different times — more energy is needed for skeletal muscle during vigorous exercise than when resting. Rates of respiration can be measured in various ways. One method of comparing rates of aerobic respiration is to measure the rate of oxygen use (see table 3.3).

The rate of aerobic respiration under various conditions can be identified by measuring oxygen consumption. Figure 3.38 shows an athlete having her

oxygen consumption measured under various conditions of exercise. By gradually increasing the intensity of exercise, the athlete's maximum rate of oxygen consumption can be measured.

FIGURE 3.38 Measuring oxygen consumption of an athlete at various levels of exercise. What would be expected to happen to her oxygen consumption as her activity level increases?

Table 3.3 shows the rates of oxygen consumption in various organs of an adult male.

TABLE 3.3 Oxygen consumption rates in various tissues of a human adult (male)

Tissue	Oxygen consumption (mL/100 g tissue/minute)
skeletal muscle (resting)	1
skeletal muscle (contracting)	50
skin	0.2
liver	2
brain	3
kidney	5
heart muscle (resting rate)	8
heart muscle (during heavy exercise)	70
rest of body	0.2

Source: Adapted from RE Klabunde, *Cardiovascular Physiology Concepts* 2nd ed., Lippincott Williams & Wilkins, 2011.

The average value of oxygen consumption for the resting body as a whole is 0.4 mL per 100 grams of body tissue per minute. This value corresponds to 300 mL/minute for a 75-kilogram person at rest. During exercise, this figure may rise more than ten-fold to 4000 mL/minute. This increased oxygen use is required for increased ATP production through aerobic respiration, especially in muscle tissues. Changes to meet this increased need for oxygen include:

- increased heart rate (beats per minute)
- increased volume of blood pumped at each heart contraction
- increased breathing rate
- increased blood flow to lungs.

Not surprisingly, the muscle of the heart that is responsible for most of these changes has a very rich blood supply itself to ensure plenty of oxygen is available to it; heart muscle also has very large numbers of mitochondria to produce ATP through the process of aerobic respiration.

It is also possible to measure the rate of aerobic respiration in the cells of various tissues and organs by looking at glucose consumption. This is one means of assessing the extent of damage to a person's heart muscle after a heart attack (a coronary occlusion or myocardial infarction).

The heart has a high oxygen demand for ATP production by aerobic respiration (refer to table 3.3). As it contracts, heart muscle transforms chemical energy of ATP to kinetic energy.

When one or more of the coronary arteries becomes blocked by a clot, the oxygen supply to a region of the heart is interrupted, heart function is affected and damage to heart tissue occurs. Treatment required depends on the extent and the permanence of the damage.

If the region of heart muscle affected by the blockage is still alive, the damage may be reversed. In such cases, bypass surgery may be done to restore the blood supply to the region. (In bypass surgery, the blocked area of the coronary artery is bypassed.) If the affected region of heart muscle has died, this damage is permanent. In such cases surgery to restore the blood supply to the affected area is of no use and exposes the patient to unnecessary risk.

It is important to be able to distinguish whether the damaged area consists of living or dead heart tissue. Can this be done? A non-invasive technique known as **positron emission tomography (PET)** can make this distinction. PET can obtain an image of glucose uptake and use by the heart. When damaged areas of the heart are still alive, they can take up and use glucose. Figure 3.39 shows the PET image of glucose use for two patients. Uptake and use of glucose is shown by the various colours. Red indicates the regions of heart muscle with the highest uptake of glucose. Then, in order of decreasing glucose uptake, are regions of yellow, then green, then blue. Dead areas of heart tissue neither take up nor use glucose and appear black. In which patient would surgery to restore the blood supply to the damaged tissue be of greater value?

Tomography from Greek:
tomos = cutting; *graphos* = writing

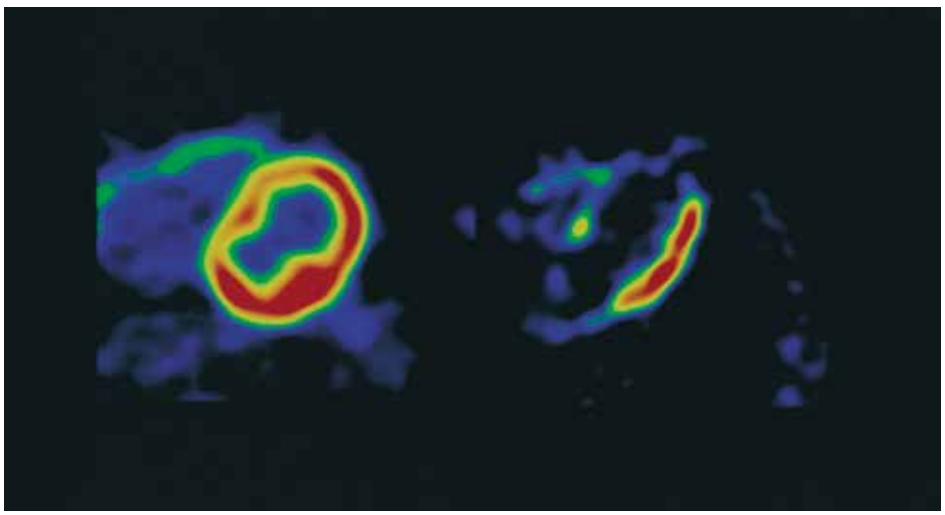


FIGURE 3.39 PET images showing uptake and use of a form of glucose (18 fluoro-deoxyglucose, or 18 FDG) by the heart tissue of two persons following heart attacks. Regions of living tissue are indicated by colours. The image on the left shows a complete coloured outline, which indicates that the heart tissue of that person is alive. The image on the right shows that in the second person a significant portion of the heart tissue has died.

ENERGY TRANSFERS INVOLVE COUPLING OF REACTIONS

In living organisms, energy-releasing reactions do not occur as isolated reactions. Energy is not simply released into cells; rather each energy-releasing reaction is coupled or paired with an energy-requiring reaction. Figure 3.40a shows an example of a physical coupling. To move the carriage uphill an input of energy is needed. The train engine can release energy. Only when the carriage is coupled to the train engine can it be moved uphill. Left uncoupled, the carriage goes nowhere.

Likewise, energy-requiring reactions in cells can occur only because they are coupled to energy-releasing reactions. For example, in aerobic respiration energy released from the oxidation of glucose is coupled to the production of ATP (see figure 3.40b). In turn, the release of energy from ATP is coupled to the many energy-requiring reactions in cells, including active transport across plasma membranes, synthesis of proteins and muscle contraction for movement.

The coupling of reactions is normally tightly controlled. The rate of cellular respiration is determined by the availability of ADP to capture the energy released from the oxidation of glucose.

Some chemicals can uncouple the energy-releasing reactions of aerobic respiration from the production of ATP. When uncoupling occurs, the uptake of oxygen by cells and energy production occurs in an uncontrolled manner and none of the energy is captured as chemical energy of ATP. Instead, the energy is released as heat energy, resulting in an increase in body temperature. For example, the venom of some snakes and the toxins of some pathogenic bacteria act as uncoupling agents. When people have certain bacterial infections, the fever they experience is due to the uncoupling effect of the toxin released by the bacteria.

Uncoupling agents can kill

Other chemicals that act as uncoupling agents include dinitrophenol (DNP), used in the manufacture of pesticides. In the 1930s in the United States, DNP was marketed as a weight-reducing agent. (Can you suggest why?) The numerous deaths that occurred in people taking DNP led to its being banned as 'extremely dangerous and not fit for human consumption.' However, in spite of being banned for human consumption, DNP remains available on the internet, often labelled

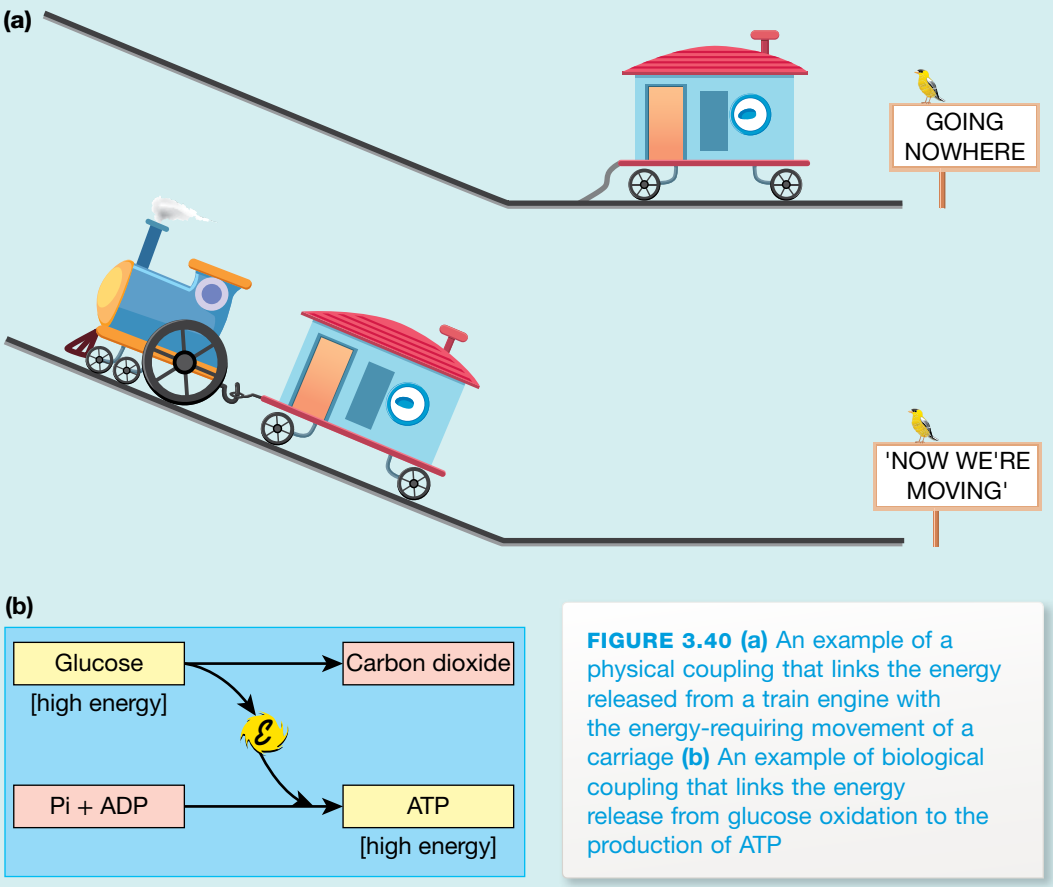


FIGURE 3.40 (a) An example of a physical coupling that links the energy released from a train engine with the energy-requiring movement of a carriage **(b)** An example of biological coupling that links the energy release from glucose oxidation to the production of ATP

as 'fat burning pills'. In Britain in the period from September 2012 to June 2013, four young people died from DNP obtained via the internet that they self-administered for the purpose of losing weight.

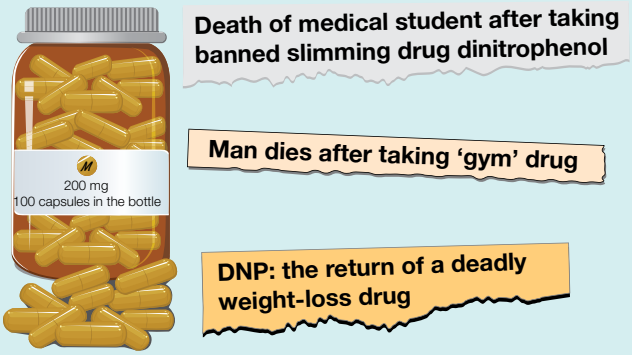


FIGURE 3.41 Headlines tell the story of the dangers of DNP.

DNP acts by inhibiting the ATP synthase enzyme that is located on the inner wall of the mitochondria. When DNP is present in cells, aerobic respiration of glucose proceeds, but DNP uncouples the energy-releasing reactions from the energy-requiring reactions that produce ATP. This uncoupling means that more energy from glucose is released as heat energy. This in turn leads to an increase in the rate of aerobic respiration in order to meet the need for ATP by cells, and results in weight loss. Depending on the amount taken, the uncoupling action of DNP can produce an increase in body temperature (hyperthermia). The early signs of hyperthermia include excessive sweating, an increase in breathing rate and an accelerated heart rate. If the hyperthermia becomes uncontrolled, it can lead to multi-organ failure and death.

Uncoupling for survival

Uncoupling of energy-releasing and energy-requiring reactions does have a survival value in very young human babies and those of other mammals, and also in hibernating mammals. Uncoupling is an important means of preventing the dangerous fall in body temperature (hypothermia) that is a major cause of death of very young babies. Shivering is one mechanism to produce body heat. Very young mammals and hibernating mammals cannot shiver to produce body heat. This is where their brown fat tissue plays an important role.

About 5 per cent of the weight of newborn human babies consists of brown fat tissue, located mainly in their upper backs and necks (see figure 3.42). Brown fat differs from the more common yellow fat of adipose tissue (refer to figure 3.14, p. 94). More importantly, the mitochondria in cells of brown fat tissue contain an uncoupling protein, known as thermogenin (*thermo* = heat; *genesis* = beginning).

FIGURE 3.42 Distribution of major reserves of brown fat in a very young baby

The thermogenin protein is usually inactive. If a baby's temperature falls, thermogenin is activated by fatty acids released from the brown fat in response to a hormone signal. Thermogenin starts the oxidation of these fatty acids and, because this reaction is uncoupled, most of the energy produced is released as heat energy. This heat production raises the baby's body temperature back to within the normal range.

KEY IDEAS

- Aerobic respiration can occur only in the presence of oxygen.
- In aerobic respiration, glucose is oxidised to carbon dioxide and water.
- Aerobic respiration begins in the cytosol where glucose is broken down to pyruvate in a process termed glycolysis that does not require oxygen.
- The energy released from glycolysis is 2 ATP molecules for each starting molecule of glucose.
- If oxygen is present, pyruvate is transported into the mitochondria where aerobic respiration is completed.
- The energy released from reactions in the mitochondria is transferred to the production of 32 molecules of ATP.
- Cells of different human tissues vary in their rates of aerobic respiration.
- Rates of aerobic respiration by cells may be measured using either their consumption of oxygen or their uptake of glucose.

QUICK CHECK

31 What are the inputs to aerobic respiration?
32 What are the end products of aerobic respiration?
33 Where in a cell do the following reactions take place?
  a The initial breakdown of glucose to pyruvate glycolysis
  b The major production of ATP
34 Which human tissue has the greater rate of aerobic respiration: kidney or skin?
35 What change occurs in the rate of aerobic respiration by heart muscle when a person changes from resting to strenuously exercising?

Anaerobic respiration: making ATP without oxygen

Anoxic environments are environments where oxygen is absent; these include marshes, deep ocean waters, so-called 'dead zones' of water and sediments of coastal seas, lower regions of the gut (away from the gut wall) and rock crevices deep in the Earth's crust. Some microbes live only in anoxic conditions and oxygen is toxic to them. These microbes are termed **obligate anaerobes**. Parts of multicellular organisms may survive in anoxic environments, such as plant roots in waterlogged soils.

In conditions where oxygen is not available, organisms carry out a process of anaerobic respiration to obtain the energy that they need to stay alive. Anaerobic respiration is the breakdown of glucose in the **absence of oxygen**, and the energy released is used to produce ATP. The yield of ATP from the anaerobic respiration is far less than that from aerobic respiration but, because fewer reactions are involved, the ATP is produced more rapidly.

Some organisms live in environmental conditions where oxygen shortages may occur from time to time, such as a tidal flat. These organisms are termed **facultative anaerobes** and include various molluscs that can switch between aerobic and anaerobic respiration as oxygen concentrations fluctuate.

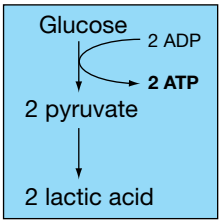
Anaerobic respiration in skeletal muscle

Specific tissues of some organisms have the capacity to carry out anaerobic respiration under conditions when the supply of oxygen to that tissue is inadequate. This ability enables cells of these tissues to continue functioning for short periods by producing ATP under conditions of oxygen shortage.

ODD FACT

The bacterium *Clostridium tetani*, the causative agent of tetanus, is an obligate anaerobe. Its inactive spores are present in soil but if they get into the human body via a deep puncture wound where oxygen is absent, the bacteria multiply in the anoxic conditions and produce their damaging toxin.

For a comparison of aerobic and anaerobic respiration, see table 3.4 on page 122.



ODD FACT

Some bacteria carry out lactic acid fermentation to obtain their energy for living. Yoghurt making depends on one type of these bacteria, *Streptococcus thermophiles*. The lactic acid produced by these bacteria curdles the casein protein of milk converting it from liquid to semi-solid.

In anaerobic respiration in skeletal muscle, each glucose molecule is broken down to two molecules of pyruvate — just as in aerobic respiration. In the absence of oxygen, an enzyme in human skeletal muscle converts pyruvate to lactic acid. This type of anaerobic respiration is called **lactic acid fermentation**. The chemical energy released in lactic acid fermentation can drive the production of two molecules of ATP (see simplified equation on the left).

On the Serengeti grasslands of Africa, a cheetah (*Acinonyx jubatus*) stalks a young Thomson's gazelle (*Eudorcas thomsonii*). Once it nears its intended prey, the cheetah breaks from the grass in an explosive burst of speed. The startled gazelle likewise starts running, not in a straight path, but frequently zigzagging. The top speed of a cheetah (more than 100 km/hour) is faster than that of a gazelle (about 80 km/hour). However, if she cannot catch the gazelle within a distance of about 100 metres, the cheetah must give up the chase, stop and rest. Why?

Initially as she stalks her prey, the cheetah's muscles use ATP from aerobic respiration. The sudden highly intense activity of the chase means that the cheetah cannot breathe fast enough and her heart cannot pump hard enough to supply the oxygen needed for aerobic respiration. The cheetah now depends on ATP from anaerobic respiration. Soon, the build up of lactic acid changes the pH in her muscles, inhibits enzymes and produces muscle fatigue. She cannot run further. She stops and pants rapidly — her breathing rate can reach 150 breaths a minute (see figure 3.43). Any gazelle that escapes a cheetah's pursuit owes its life to the fact that anaerobic respiration can operate for a short period only before muscle fatigue sets in. At the highest intensity muscular activity, such as sprinting, anaerobic respiration has a duration of less than 1 minute before muscle fatigue hits.

FIGURE 3.43 After the chase, the cheetah is hot and her breathing rate is high: up to 150 breaths per minute. She is panting to rebuild the oxygen supplies to her muscles.

For a person at rest or during moderate activity (60–80% of the maximum heart rate), aerobic respiration can supply the ATP needed by skeletal muscle. Activities such as power walking, jogging, distance cycling and marathon running can be sustained for long periods by the ATP supplied through aerobic respiration.

In contrast, during periods of intense muscular activity involving short bursts of power or speed, the oxygen supply to muscles is not sufficient to maintain aerobic respiration. Under these circumstances, muscles can be powered by the ATP produced by anaerobic respiration. (The 100-metre sprinters can run their races without breathing.)

However, the lactic acid produced through anaerobic respiration in muscle tissue affects the pH of the muscles and causes muscle fatigue, so that the muscles cannot continue contracting and the athlete is forced to stop. An athlete may even collapse (see figure 3.44). When strenuous exercise stops, athletes

ODD FACT

After intense exercise ends, the lactic acid built up in muscle tissue is carried away in the bloodstream to the liver where it is converted to glucose; this is the reverse of the lactic acid fermentation pathway.

breathe very heavily to restore their oxygen supply and their circulatory system removes the lactic acid from their muscle tissue. When the oxygen supply to their muscles returns to normal, anaerobic respiration stops and the muscle requirements for ATP are met again through aerobic respiration.

FIGURE 3.44 This athlete is exhausted. Her muscles are fatigued and have stopped contracting.

Skeletal muscle also has a store of **phosphocreatine (PCr)** as another energy source. Phosphocreatine can produce some ATP by transferring its phosphate group to ADP as follows:

$$ADP + PCr \rightarrow ATP + Cr$$

This reaction provides ATP for only about 15 seconds of muscle activity.

Athletes in different sports rely on aerobic and anaerobic sources of energy to differing degrees. The 100-metre sprinters can run their races without breathing as they can use anaerobic respiration. In contrast, marathon runners use aerobic respiration. Table 3.4 shows the approximate relative contributions of the various sources of ATP for athletes in various sporting events. Immediate ATP availability and anaerobic respiration are important sources of energy for short-duration events. For distances over 200 metres, the longer an event is, the greater the dependence on aerobic respiration. Physiological characteristics of an athlete are also important; for example, the rate at which an athlete can take in, transport and use oxygen is a factor in success.

TABLE 3.4 The relative contributions of different energy systems for a range of sports

Approximate relative contributions of the different energy systems to the needs of an athlete			
Sport	**Phosphocreatine**	**Anaerobic/lactic**	**Aerobic**
100-metre swim	+ + + + +	+ +	+
1500-metre swim	+	+ +	+ + + + +
100-metre sprint	+ + + + + + +	+	0
400-metre sprint	+ + + +	+ + +	+
weightlifter	+ + + + + + +	+	0
cross country	0	+	+ + + + + + +
marathon	0	+	+ + + + + + +
hockey	+ + + +	+ +	+ +

Anaerobic respiration: making bread and wine

In human skeletal muscle tissue, the end product of anaerobic respiration is lactic acid. Other kinds of organism produce different end products because they possess different enzymes in their cytosol. For example, anaerobic respiration in yeast *(Saccharomyces cerevisiae)* produces ethanol, an alcohol.

Anaerobic respiration in yeasts is called **alcoholic fermentation**. During this fermentation, glucose is broken down to pyruvate, which is then broken down to carbon dioxide and ethanol. The amounts of ethanol and carbon dioxide produced vary with different strains of yeasts and different environmental conditions. The energy yield from one molecule of glucose that undergoes fermentation is two molecules of ATP (see simplified equation on the left).

Glucose
2 ADP
2 ATP
2 pyruvate
2 ethanol + $2CO_2$

Baker's yeast is used in bread making. The conditions in the dough are anaerobic. Kept in the warmth, yeast cells multiply and produce carbon dioxide gas, causing bread dough to rise and giving bread its 'holey' texture (see figure 3.45). The alcohol produced by baker's yeast is driven off during the baking of the bread.

Yeasts are also used to produce the alcohol contained in beers, distilled spirits and wines. In wine-making, grapes are crushed to release the juice that contains sugars. Yeasts are added to this fluid and fermentation occurs, producing alcohol. When the alcohol concentration reaches about 12 per cent (v/v), this kills the yeast cells and fermentation stops (see figure 3.46).

FIGURE 3.45 What process caused this bread to rise and gave it a 'holey' texture?

FIGURE 3.46 The alcohol in these wines results from anaerobic respiration by yeast cells of the sugars present in crushed grapes. What other name is given to this process? Does it require the presence of oxygen or not? White wines result when the juice of crushed grapes is used; red wines result when the juice, skins and stems of the grapes are used.

Distillation is a process that reduces the water content of a fluid.

ODD FACT

When fermentation of grape juice occurs in a sealed bottle, sparkling wines, such as champagne, result. The carbon dioxide that forms during fermentation dissolves under pressure and is released when the bottle is opened.

Beer is made in a process known as brewing. To brew beer, barley grains that are sprouting are mashed with water, the resulting mixture is boiled with hops to give colour, taste and aroma. Fermentation starts after brewer's yeast is added.

Spirits are produced by fermenting various products, such as fruit juice (brandy), molasses (rum) and barley grains (whisky). Spirits are distilled to increase the alcohol content in the final product to about 40 per cent (v/v).

Comparing anaerobic and aerobic respiration

Figure 3.47 shows a simplified representation of cellular respiration in people. The starting point for both aerobic and anaerobic respiration is glucose that is broken down to pyruvate in the cytosol. When oxygen is not available (anaerobic respiration), pyruvate is fermented to lactic acid. When oxygen is available (aerobic respiration), pyruvate moves to the mitochondria and is broken down to carbon dioxide and water.

ODD FACT

Parrots get drunk when they eat rotting or fermenting fruit. Parrots have been reported as 'flying upside down and doing barrel rolls'.

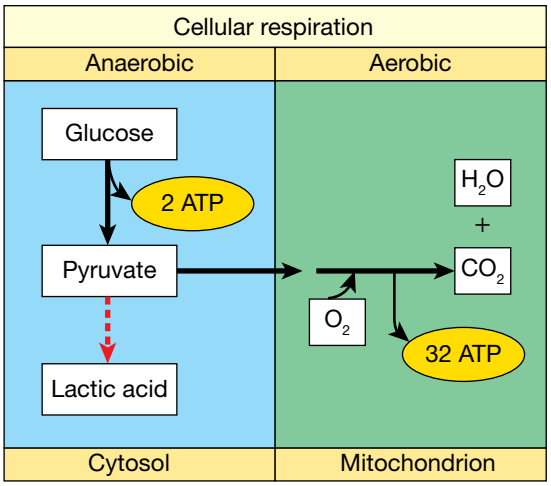


FIGURE 3.47 A highly simplified version of cellular respiration, both aerobic and anaerobic. Note that both aerobic and anaerobic respiration start with the same set of reactions (glycolysis) in the cytosol that produce pyruvate from glucose. This does not require oxygen. Oxygen is needed in the final reactions in the mitochondria. The red arrow shows what happens if oxygen if not present.

Apart from the presence or absence of oxygen, other differences between aerobic and anaerobic respiration are shown in table 3.5. The end products of anaerobic respiration differ for various kinds of organisms and are due to the presence of different enzymes in the various organisms.

TABLE 3.5 Comparison of two types of cellular respiration

Anaerobic respiration (fermentation)	Aerobic respiration
oxygen not required	oxygen essential
very rapid ATP production	slow rate of ATP production
can be sustained over a short time only in people: the higher the intensity of exercise, the shorter the duration	can be sustained indefinitely provided oxygen and glucose available
less efficient energy transfer	more efficient energy transfer
2 ATP produced per molecule of glucose input	34 ATP produced per molecule of glucose input
various end products: • lactate and water (human skeletal muscle) • ethanol and carbon dioxide (yeasts) • butyl alcohol (some bacteria, e.g. *Clostridium acetobutylicum*) • vinegar (acetic acid bacteria, e.g. *Acetobacter acetii*)	end products: carbon dioxide and water

Rate of energy release

The rate of energy release from glucose in anaerobic respiration occurs about 100 times faster than in aerobic respiration. Aerobic respiration involves more reactions and oxygen must be transported from the lungs via the bloodstream to the tissues. Fewer reactions are involved in anaerobic respiration and no oxygen transport from lungs to tissues is required.

Efficiency of ATP production

Aerobic respiration is more efficient than anaerobic respiration. In aerobic respiration, glucose is fully oxidised to carbon dioxide — no more chemical energy can be extracted — and the yield is 34 ATP molecules from each glucose molecule. In anaerobic respiration, just 2 ATP molecules are generated for each glucose molecule that is partially oxidised. (The lactic acid still has a store of chemical energy).

Duration of energy release in humans

Aerobic respiration can continue as long as the body has access to glucose and oxygen. Anaerobic respiration can only continue for a short period until the change in pH of cells inhibits enzymes and muscle fatigue sets in.

The photosynthesis and respiration cycle

Photosynthesis and cellular respiration are interrelated. The process of photosynthesis creates chemical energy stores by building energy-rich glucose from carbon dioxide and water. The process of cellular respiration releases energy by oxidising glucose to carbon dioxide and water. The energy released in this oxidation is transferred to ATP.

Figure 3.48 shows the relationship between photosynthesis and aerobic respiration. The carbon dioxide and water that are the products of aerobic respiration are used in photosynthesis. Likewise, the glucose and oxygen that are the products of photosynthesis are used in aerobic respiration.

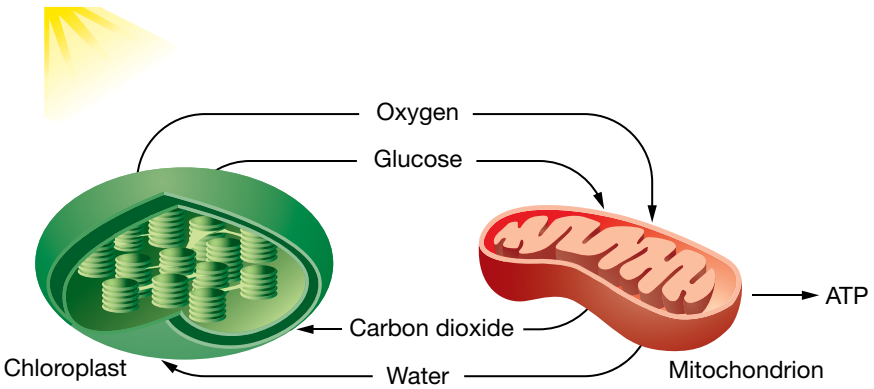


FIGURE 3.48 Relationship between photosynthesis and aerobic respiration. The outputs of photosynthesis in chloroplasts are inputs to aerobic respiration. The outputs of respiration from mitochondria are inputs to photosynthesis.

KEY IDEAS

- Anaerobic respiration occurs in the absence of oxygen.
- Anaerobic respiration begins with the breakdown of glucose to pyruvate.
- The final product(s) in anaerobic respiration depend on the different enzymes present in various organisms.
- In human skeletal muscle tissue, pyruvate is converted to lactate during anaerobic respiration.
- In yeasts, pyruvate is converted to an alcohol (ethanol) and carbon dioxide.
- The energy yield from anaerobic respiration is two molecules of ATP per molecule of glucose.

QUICK CHECK

36 What are the inputs to anaerobic respiration?
37 What are the end products of anaerobic respiration in human skeletal muscle?
38 Why do human muscle cells produce lactate during anaerobic respiration while yeast cells produce an alcohol and carbon dioxide?
39 What produces the 'holes' in a slice of bread?

ENERGY IN VARIOUS FORMS

Energy can exist in various forms and these can be classified as either kinetic energy (the energy of motion) or potential energy (stored energy). Figure 3.49 shows the various forms of energy.

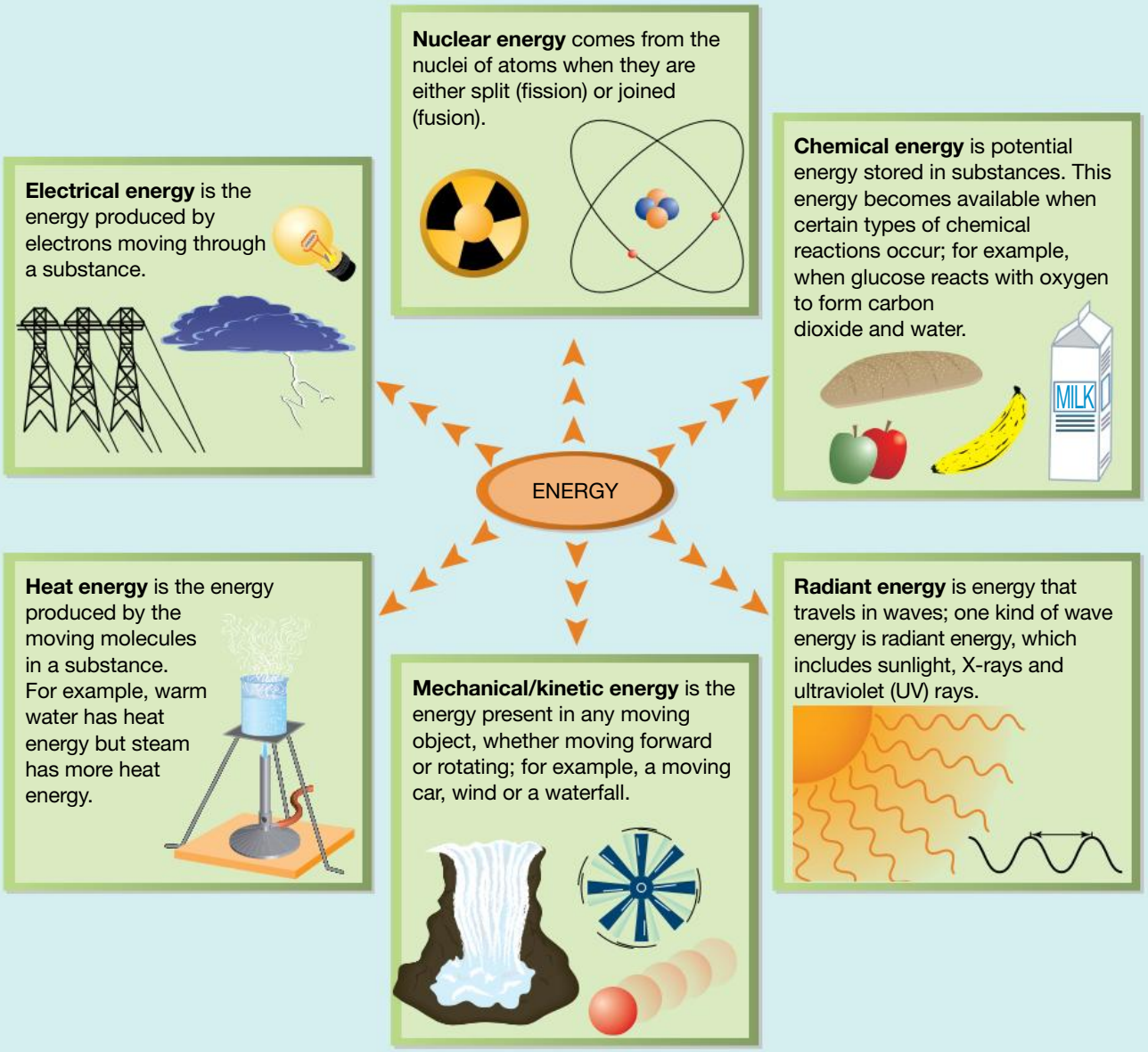


FIGURE 3.49 Some of the main forms of energy. Animal cells can make use of chemical energy only for staying alive, while plant cells can utilise radiant energy.

Energy can be transformed from one form to another (see figure 3.50), but energy cannot be created or destroyed. Transformation of energy from one form to another is typically not 100 per cent efficient. Efficiency is a measure of how much of the input energy is converted into the desired energy output. For example, wind turbines convert about 45 per cent of the motion energy of the wind into electrical energy with the rest (about 55 per cent) appearing as heat.

FIGURE 3.50 Energy transformations **(a)** Photovoltaic solar panels transform energy of sunlight to electrical energy. **(b)** Turbines at Australia's first wind farm at Crookwell, NSW, transform the motion energy of wind to electrical energy. **(c)** Leaves transform the radiant energy of sunlight to the chemical energy of sugars.

Examples of energy transformations in living organisms include:

- *transformation of the chemical energy of ATP to the mechanical energy of movement*. This movement may be either at the cellular level, for example, the beating of cilia on cells that line your windpipe (trachea), the whip-like motion of the flagellum of unicellular *Paramecium* or the contraction of smooth muscle cells in your gut lining as food is moved along your small intestine. Or this movement may be that of a whole organism, such as the pursuit of a cheetah chasing its prey, a person cycling along a street or a butterfly flitting from flower to flower.
- *transformation of chemical energy to the thermal energy of heat*. This conversion occurs in the mitochondria of brown fat tissue that is present in human babies and in hibernating mammals. Generation of heat is an important source of body heat for babies and hibernating mammals because they cannot generate body heat by shivering.
- *transformation of radiant energy of sunlight to the chemical energy in sugars, such as glucose*. The most important transformation of all, this occurs during the process of photosynthesis in plants, algae and some microbes including cyanobacteria, and provides both the energy and the organic molecules required for the survival of almost all life on Earth. Under optimal conditions, this transformation occurs at efficiencies up to 34 per cent.

BIOCHALLENGE

Photosynthesis is a complex process that supports almost all life on Earth. Knowledge of this process did not occur as a result of a single experiment. Rather, the findings of many scientists over centuries contributed to our understanding of photosynthesis. In this Biochallenge you can explore some of these findings.

FIGURE 3.51 Jan van Helmont wonders about the source of the increase in mass of a plant as it grows.

In the 1600s, Jan van Helmont (1580–1664), a Dutch doctor, planted a small willow cutting weighing 2.27 kg in a large pot filled with 90.7 kg of dry soil. He placed the pot in the ground and covered it with a perforated plate so that he could water the cutting and air could circulate, but that soil could neither be lost from nor added to the pot.

Over a 5-year period, van Helmont regularly watered his plant and watched it grow into a sizeable tree. At the end of that time, van Helmont removed the entire plant from the pot and re-weighed it. He removed all the soil from the pot, dried it and re-weighed it. His findings are shown in table 3.6.

TABLE 3.6 Van Helmont's experimental results

	Start of experiment	End of experiment
mass of plant	2.27 kg	74.39 kg
mass of dry soil	90.7 kg	just under 90.32 kg

1 **a** What change occurred in the mass of the plant?
b What approximate change occurred in the mass of the soil?

2 From his experiment, van Helmont concluded that the increase in plant mass over the 5-year period:
i did *not* come from the soil, but
ii must have come from the water that he supplied to the plant.

Discuss with your classmates whether each of van Helmont's conclusions (i) and (ii) above is:
a a reasonable conclusion
b a correct conclusion.

3 The increase in the mass of a plant during growth results from photosynthesis. What occurs during photosynthesis that could produce an increase in plant mass?

4 One factor that van Helmont did not take into consideration as a possible source of the increase in mass of a growing plant was the air. Little was known about the composition of air in the 1600s. However, in the 1770s, a Dutch biologist, Jan Ingenhousz (1730–79) carried out some simple experiments showing that:
- when plants were illuminated, they released oxygen
- the release of oxygen was from only the green tissues of the plant
- when plants were put in the dark, the release of oxygen stopped
- when plants produced oxygen, they used up carbon dioxide.

Ingenhousz's various findings added to the knowledge about photosynthesis. Take each of Ingenhousz's findings in turn and, using your knowledge of photosynthesis, re-state each finding in a more up-to-date form.

Chapter review

Key words

absorption peak
accessory pigment
adenosine triphosphate (ATP)
aerobic respiration
alcoholic fermentation
anaerobic respiration
autotrophs
carotenoids
cellular respiration
chemical energy
chemosynthesis
chlorophyll
deciduous
electron transport chain
exergonic
facultative anaerobe
fats
fermentation
glycogen
glycolysis
hemiparasite
heterotrophs
histotoxic hypoxia
holoparasite
hydrolysis
hydrothermal vent
Kreb's cycle
lactic acid fermentation
microbial mat
mid-ocean ridge
obligate anaerobe
oxygenic
phosphocreatine (PCr)
photosynthesis
phycobilin
polysaccharide
positron emission tomography (PET)
starch
sunlight energy
thallus

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map. You may use other words in drawing your map.

2 **Developing explanations and communicating ideas** ➜ Arterial blood is normally bright red because of the oxygen present in the red blood cells. Blood in the veins is purple because this blood has given up its oxygen to cells. In a person affected by cyanide poisoning, the venous blood is bright red, rather than its usual purple colour. Suggest a possible explanation for this observation.

3 **Applying knowledge in a new context** ➜ A person in hospital after major surgery who cannot eat may be put on an intravenous drip of a saline solution that contains the sugar glucose.
   - **a** What is a possible reason for the inclusion of glucose?
   - **b** Could a polysaccharide made of many subunits of glucose be used in this drip instead of glucose? Briefly explain your decision.

4 **Demonstrating understanding and communicating ideas** ➜ Considering the statement 'Organic compounds produced by plants, directly or indirectly, are the source of "food" for all heterotrophs', a student observed 'When I eat a lamb chop, I'm not eating plants, so that statement is false.' Do you agree with this student. Briefly explain.

5 **Demonstrating knowledge and understanding** ➜ Figure 3.52 shows the IVANPAH solar thermal plant in the Mojave Desert in California, USA. The total solar collection area for this plant consists of more than 300 000 garage–door sized mirrors over an area of more than 14 km^2. These computer-controlled mirrors concentrate heat from the sun, focus it on a central boiler at the top of a 140-metre-high tower, where the heat boils water creating high-pressure steam that is piped to turbines where electricity is generated. This technology is different from the photovoltaic solar panels on house roofs that capture the radiant energy of sunlight and convert it directly to electricity.

FIGURE 3.52 The IVANPAH solar thermal plant showing the computer-controlled mirrors arranged around the central tower that houses a boiler

   - **a** Identify some of the energy conversions that occur at the IVANPAH solar thermal plant.
   - **b** The mirrors at this solar thermal plant are computer-controlled. Can you suggest why this is required?
   - **c** In terms of the number of energy conversions, which of these two technologies — solar thermal and photovoltaic — is more similar to photosynthesis?
   - **d** Give two examples of energy conversions in living organisms.

6 Demonstrating skills of analysis and synthesis ➜ Cornelius van Niel (1897–1985), a Dutch microbiologist, carried out experiments on particular bacteria, known as purple sulfur bacteria. He found that, like green plants, these bacteria could capture sunlight energy to produce glucose and to do this they required a source of carbon dioxide (CO_2), just like plants. These bacteria carried out a process of photosynthesis. The remarkable finding made by van Niel was that these bacteria did not require water (H_2O) to produce glucose from carbon dioxide, but instead made use of hydrogen sulfide (H_2S).

The process of photosynthesis in plants is shown in the following equation:

$$\underset{6CO_2}{\text{carbon dioxide}} + \underset{12H_2O}{\text{water}} \longrightarrow \underset{C_6H_{12}O_2}{\text{glucose}} + \underset{6O_2}{\text{oxygen}} + \underset{6H_2O}{\text{water}}$$

a Consider the above information and write the equation that shows the process of photosynthesis in purple sulfur bacteria.
b Are purple sulfur bacteria an example of a chemosynthetic organism? Explain.

7 Interpreting information and communicating ideas ➜ After following a careful program of exercise and diet a person lost 2 kg.
a Suggest from which energy compartment this 2 kg of material probably came.
b Suggest what might have happened to the molecules concerned.

8 Applying understanding ➜ Figure 3.53 represents a group of photosynthesising cells in a leaf. The arrows represent compounds entering and leaving the leaves. Explain which compounds the input arrows and the output arrows could represent when the cells are in:
a bright sunlight
b darkness.

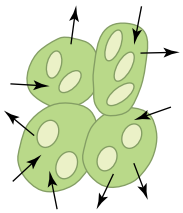


FIGURE 3.53

9 Demonstrating knowledge ➜ Identify the following.
a The gas that is taken up from the atmosphere in photosynthesis
b The gas that is released from cells in aerobic respiration
c The gas that is essential for aerobic respiration
d The gas that is the product of photosynthesis in green plants
e The gas that gives bread its 'holey' texture

10 Interpreting and analysing information ➜ The complete balanced equation for photosynthesis in green plants and algae is:

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_2 + 6O_2 + 6H_2O$$

a Oxygen is a product of photosynthesis (on the right-hand side of the equation). Look at the reactants on the left-hand side of this equation and identify the *possible* sources of this oxygen.

Before the 1930s, the accepted view was that the oxygen came from the carbon dioxide. However, during the 1930s, the hypothesis was first proposed that the oxygen came from the water input. (Your answer to part (a) should have identified these two possible sources of the oxygen.)

The challenge was to test these alternative hypotheses. In the 1940s, two scientists, Samuel Rubin (1913–43) and Martin Kamen (1913–2002) used a heavy isotope of oxygen(^{18}O) for this purpose. (Isotopes are different forms of the same element; almost all atmospheric oxygen is the lighter ^{16}O isotope.) They set up two experiments:

Experiment 1. A plant provided with heavy isotope labelled carbon dioxide ($C^{18}O_2$) and unlabelled water (H_2O).

Experiment 2. A plant provided with heavy isotope labelled water ($H_2{}^{18}O$) and unlabelled carbon dioxide (CO_2).

The results of these experiments are shown in figure 3.54.

b What conclusions may be drawn from the results of these two experiments?
c In experiment 1, what happened to the heavy isotope of oxygen?

11 Applying understanding and communicating ideas ➜ Cellular respiration in two different species of bacteria, P and Q, was examined. It was found that, during cellular respiration species P always produced carbon dioxide (CO_2) and water (H_2O), while species Q always produced ethanol (C_2H_2OH) and carbon dioxide (CO_2).

From these observations, what conclusions may reasonably be drawn about:
a the mode of cellular respiration in these two bacterial species
b the possible environmental conditions in which these two species live?

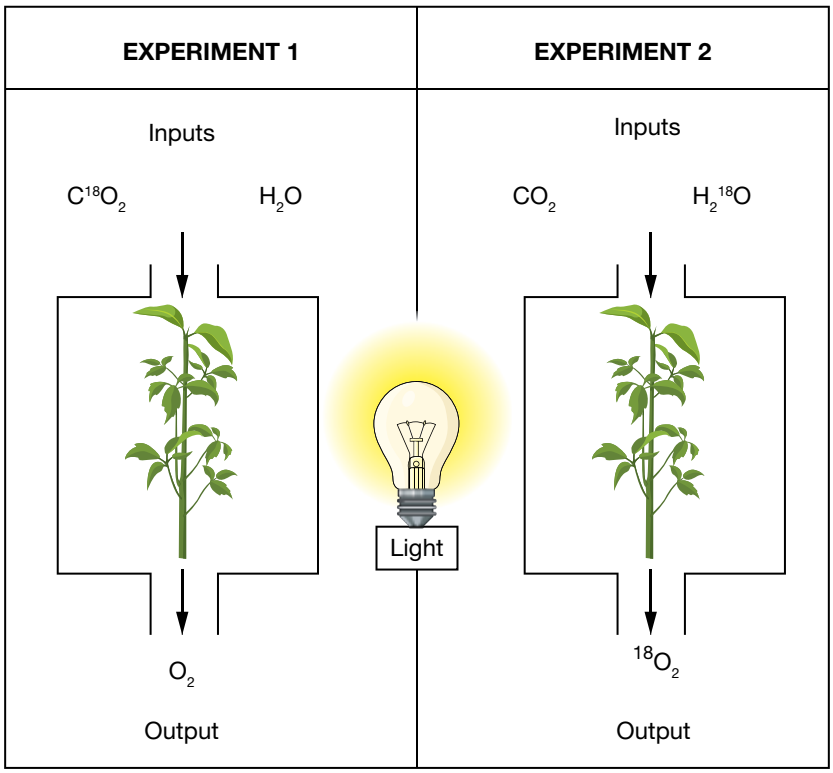


FIGURE 3.54

12 **Comparing and contrasting concepts** ➜ Identify two key differences between the processes of:
- **a** photosynthesis and cellular respiration
- **b** aerobic and anaerobic respiration
- **c** photosynthesis and chemosynthesis.

13 **Demonstrating knowledge and understanding** ➜ Identify whether each of the following statements is true or false. Where you identify a statement as false, re-write it in the biologically correct form.
- **a** Photosynthesis produces oxygen while cellular respiration uses oxygen.
- **b** Photosynthesis produces glucose while cellular respiration uses glucose.
- **c** Photosynthesis uses carbon dioxide while cellular respiration produces carbon dioxide.
- **d** Photosynthesis occurs only in plants while cellular respiration occurs only in animals.
- **e** Photosynthesis occurs only in sunlight and respiration occurs only in the dark.

14 **Analysing information, demonstrating understanding and communication** ➜ Suggest possible explanations in biological terms for each of the following observations.
- **a** The maximum alcohol content of wines cannot exceed about 12 per cent.
- **b** All that is needed for making alcohol is sugar, water and yeast.
- **c** Riding a bike at a leisurely pace on a flat surface can be sustained all day, but riding at speed uphill can be sustained for only a short period before you need to rest.
- **d** A weightlifter is using heavy weights in short bursts for a competition. As he continues in the competition, his muscles begin to fatigue.
- **e** In autumn, the leaves of many trees turn red or yellow.
- **f** Dead or dying tissue can be distinguished from living tissue by comparing their uptake of glucose.
- **g** The oxygen consumption of skeletal muscle tissue in a resting condition increases greatly during vigorous activity.

15 **Demonstrating knowledge and understanding** ➜ The oldest grapevine *(Vitis vinifera)* in the United Kingdom was planted at Hampton Court Palace in 1769 (see figure 3.55a overleaf). The sign next to the vine is shown in figure 3.55b.
- **a** What role do the vine leaves serve in photosynthesis?
- **b** What role do the roots of the vine serve in photosynthesis?
- **c** How do substances move around the vine from the sites where they are either produced or taken in to other sites where they are needed?
- **d** Suggest why the area under the vine is kept clear of other plants.

FIGURE 3.55 (a) The Hampton Court grapevine **(b)** The sign at the base of the vine

16 Using and applying knowledge → Figure 3.56 shows a native marsupial mammal, the fat-tailed dunnart (*Sminthopsis crassicaudata*). Note the tail that gives this animal its common name.

FIGURE 3.56 Fat-tailed dunnart

a Suggest a possible role for this fat in the tail.
b What would happen to the tail if the fat were to be replaced by glycogen that stored the same amount of energy?

CHAPTER

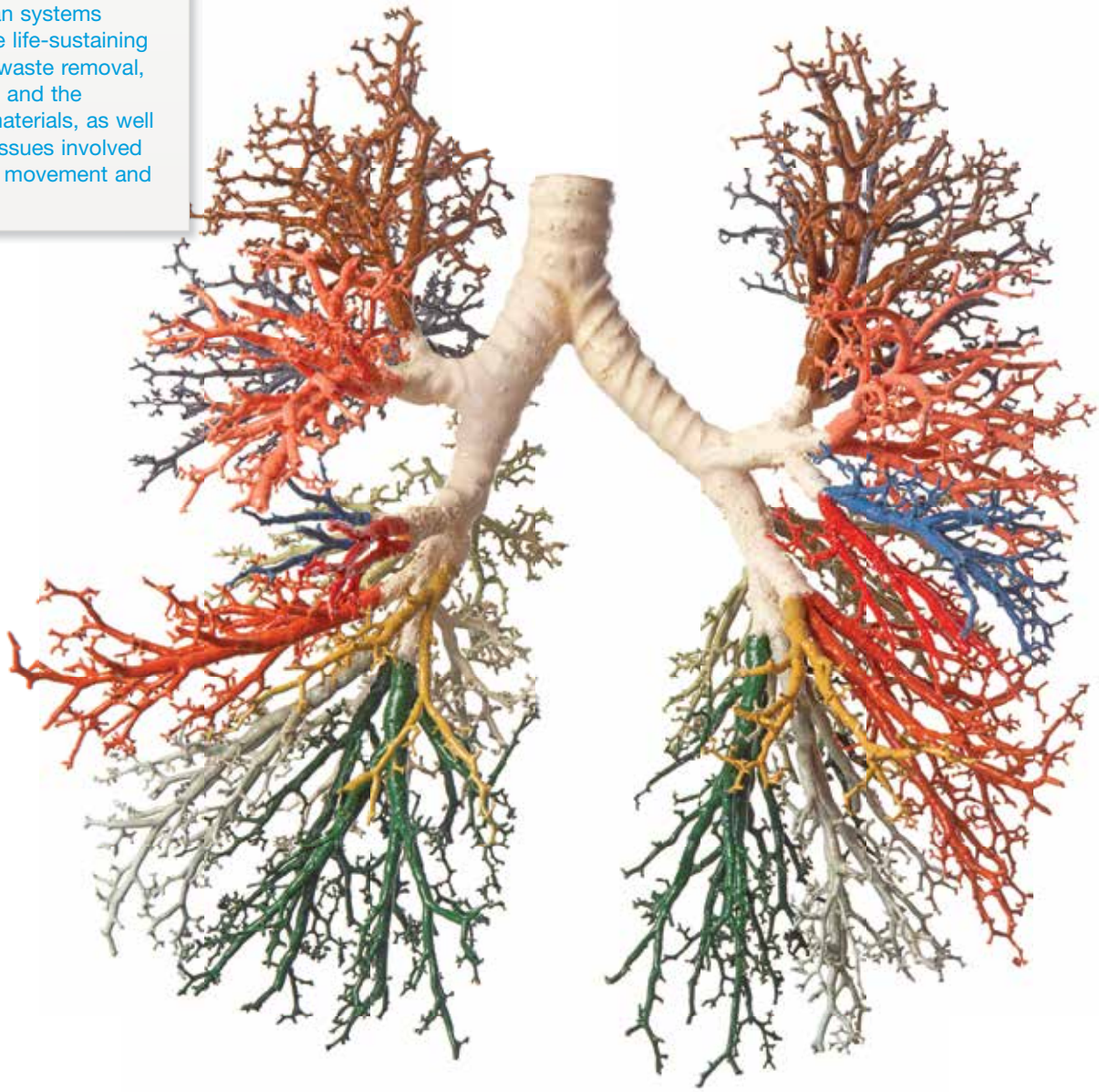
4 Staying alive: systems in action

FIGURE 4.1 This image shows the airways that form the so-called bronchial tree of a vertebrate lung. The other tissue of the lung has been removed. These airways carry air from the upper airways in the head to the areas of the lungs where gas exchange occurs. In this chapter we will examine how cells are organised into tissues, organs and systems, and will explore the mammalian systems involved in the life-sustaining processes of waste removal, gas exchange and the transport of materials, as well as the plant tissues involved in the uptake, movement and loss of water.

KEY KNOWLEDGE

This chapter has been designed to enable you to:

- develop understanding of the organisation of specialised cells into tissues, organs and systems
- gain knowledge of the contribution of various tissues in vascular plants to the uptake, transport and loss of water
- gain knowledge of how various mammalian systems are organised to serve particular functions
- recognise the interdependence of operation of mammalian systems
- give examples of system malfunctions, including causes and consequences.



Dialysis to stay alive

Susan was a healthy adult but she began experiencing health problems that were worsening progressively. She became easily fatigued, lacked stamina, experienced bouts of nausea and vomiting, suffered from shortness of breath, and found it difficult to concentrate. Susan's blood pressure rose to high levels, her face, legs and ankles became swollen, and she was producing abnormally small volumes of urine. Blood tests on Susan showed that she had severe chronic kidney disease. Kidneys are vital organs that carry out many functions, including the removal of nitrogenous wastes from the blood. The most common causes of **chronic kidney disease**, which account for about half of all cases, are high blood pressure and diabetes.

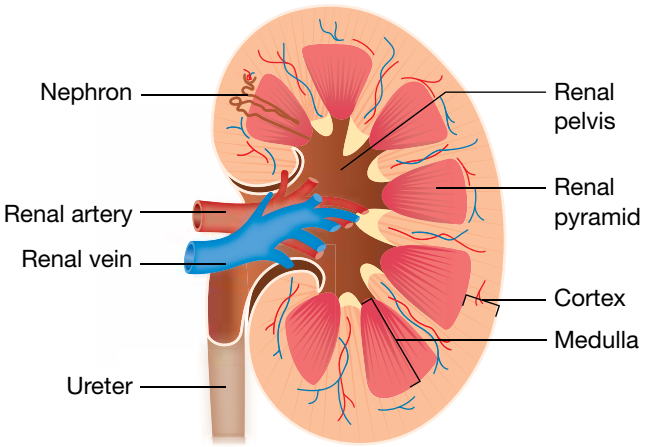


FIGURE 4.2 Gross anatomy of kidney showing the renal artery that supplies the kidney with about one litre of blood per minute, the renal vein that returns blood from the kidney and the ureter that carries urine from the kidney. Note the nephron (shown magnified), which is the basic functional unit of the kidney, with each kidney averaging about one million nephrons. Urine produced by all these nephrons reaches the renal pelvis and drains into the ureter.

Kidney health can be identified by estimating the rate at which the kidney nephrons remove wastes from a person's blood. Nephrons are the basic functional units of the kidneys and each kidney contains a large number of nephrons, ranging from 200 000 to more than 2 million (see figure 4.2). Blood from the body flows into a tight cluster of capillaries known as a **glomerulus** (plural = glomeruli) in each nephron. Here, water and small soluble molecules are filtered from the blood and pass into the nephron. Red blood cells and large molecules do not cross from the blood into the capsule.

The average rate of filtration (known as glomerular filtration rate (GFR)) in a healthy young adult is about 120 mL or more per minute. This means that each hour a total of more than 6 litres of liquid is filtered from the blood — this is equivalent to filtering more than the total blood volume of a human adult. Of course, you do not produce urine at the rate of more than 6 litres per hour. We will see later in this chapter (p. 171) that most of this filtrate is returned to the bloodstream but without the nitrogenous waste and other toxic or excess substances. Susan's GFR was estimated at 25 mL per minute, a sign of severe chronic kidney disease.

Susan's kidneys were diseased and were becoming less and less efficient in their functions, namely:

1. filtering nitrogenous wastes (N-wastes) from the blood that result from the breakdown of proteins
2. maintaining the normal balance of water by removing excess fluid from the body
3. maintaining the normal balance of electrolytes in the blood, in particular sodium and potassium
4. maintaining the acid–base balance of the blood
5. producing renal hormones.

These hormones are **calcitriol**, which increases calcium levels in the blood and contributes to bone strength, and **erythropoietin**, which controls the production of red blood cells. Can you match any of Susan's symptoms (listed in the first paragraph) to her impaired kidney functions?

Susan was advised to manage her diet carefully by limiting intake of fluids; avoiding salty foods and foods high in potassium, for example, fruits such as bananas, avocados, stone fruits and starfruit, and vegetables such as potatoes and tomatoes. Can you suggest why these limitations might be needed?

Unfortunately, Susan's kidney function continued to deteriorate and she reached a condition termed **end stage kidney disease**. At this time, Susan's

In a strict and narrow sense, the kidneys are part of the *urinary* system that removes nitrogenous wastes. More commonly, this system is referred to as the *excretory* system and this will be done in this book. Excretion in mammals also involves the respiratory system that removes a gaseous waste, carbon dioxide.

GFR was less than 15 mL per minute and she commenced a process termed **haemodialysis**. To undertake haemodialysis, Susan attended a dialysis centre three times a week, with each visit lasting 4 to 5 hours. During these sessions, Susan's blood was passed through a dialysis machine that replaces some of the functions of her diseased kidneys, in particular the removal of N-wastes, excess fluid and electrolytes, and other chemicals. Susan also received medication to replace the hormones that her diseased kidneys were unable to produce. The medication is injected into the return dialysis tubing that delivers her blood back to her body.

Being on haemodialysis was a life-saver for Susan. Without haemodialysis:

- nitrogenous wastes from the breakdown of proteins would build up in Susan's blood causing her tiredness and nausea
- excess fluid in her blood would raise her blood pressure to harmful levels and also cause swelling
- abnormally high concentrations of electrolytes in her blood would have negative effects, such as excess sodium ions that would elevate her blood pressure and excess potassium ions that can result in a decrease in heart muscle activity.

Without haemodialysis Susan would have died, possibly within several weeks.

Dialysis treats the major symptoms of kidney failure but it does not cure kidney failure; it simply treats some of the major symptoms.

Because of the time required for haemodialysis, this life-saving treatment may negatively affect a patient's family life and working life; it can limit social life and the choice of holiday destinations. (Why?) Susan was very fortunate that, after several years on haemodialysis, her father decided to become a living donor for her after tissue typing showed a good match between them. (We can maintain good health with just one working kidney.) This generous gift from her father meant that Susan received a kidney transplant. Because the transplant was successful, Susan no longer needed to undergo haemodialysis and instead required regular medical check-ups to ensure her new kidney continued to function well. To prevent rejection of her transplanted kidney, Susan must take immunosuppressant (anti-rejection) drugs for the rest of her life.

Susan's case is an example of the serious consequences of organ and system failure. The kidney is the major organ of the excretory system. The deterioration of Susan's kidney function created more and more serious negative impacts on Susan's health and, without medical intervention and the technology of kidney dialysis, she would not have survived for long. Susan's treatment by dialysis greatly improved her health and she assisted this process by adhering to the dietary restrictions imposed on her. The kidney transplant that Susan received from her father gave her a healthy kidney with normal functions. Kidney transplantation is a powerful example of how surgical intervention can alleviate organ failure.

ODD FACT

The dialysis machine was invented by a Dutch physician, Wilhelm Kolff, in 1943. During the Nazi occupation of Holland, Kolff used available bits and pieces, including sausage skins, tin cans and a washing machine, to build the first crude kidney dialysis machine. With refinement, it saved the first life in 1945.

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Healthy eating for haemodialysis

Haemodialysis in action

In haemodialysis, blood is continuously taken from the body; typically it is taken from a specially prepared vein in the arm that is directly connected to an artery. The blood is pumped through a dialyser that removes toxic wastes including urea, excess fluids and excess mineral ions from the blood.

Figure 4.3a shows Carlos Pizzorna undergoing his regular dialysis treatment at Epworth Hospital under the supervision of Karyn Jones, Head of the Dialysis Unit. Figure 4.3b shows the dialysis machine to which his blood supply is connected. Key components of the dialysis machine include the pump to move the blood from Carlos to the dialyser, an air trap, the dialyser where the blood is filtered and purified, and the dialysate fluid delivery system with its inflow pressure monitor. The screen display of the dialysis machine (see figure 4.3c)

shows the data collected about the blood when it is outside the body (arterial and venous pressures) and about the dialysate solution (inflow pressure to dialyser). At any time during dialysis, about 250 mL of blood are outside the body and in the dialysis machine. (The total volume of blood is about 5 litres in adult males and about 3.5–4 litres in adult females.)

FIGURE 4.3 **(a)** Carlos Pizzorna undergoing haemodialysis at the Dialysis Unit at Epworth Hospital **(b)** A dialysis machine **(c)** The screen display of a dialysis machine shows data relating to the flow of blood when it is outside the body and to the dialysate solution. (Images courtesy of Epworth Dialysis Unit (Head Karyn Jones) and Carlos Pizzorna)

An important part of the dialysis machine is the hollow fibre dialyser (see figure 4.4a and b). Blood enters the dialyser at the red end, passes through hollows within these fibres and exits at the blue end. Inside the dialyser are thousands of very thin hollow fibres whose walls have microscopic pores (see figure 4.4c). The dialysate solution is purified water mixed with bicarbonate and acetic acid. The dialysate solution enters the dialyser near its base and flows around the fibres, coming very close to, but not making direct contact with, the blood. The dialysate solution is separated from the blood by the thin walls of the fibres that are like semipermeable membranes. Three processes are involved in the operation of the dialyser:

1. *Osmosis.* Excess water moves from the blood by osmosis into the dialysate solution.
2. *Diffusion.* Dissolved solvents, including urea, a nitrogenous waste, and other substances in excess in the blood diffuse down their concentration gradients from the blood into the dialysate.

3. *Ultra-filtration*. The volume of fluid removed from the patient is directly controlled by varying the pressure gradient that exists between the blood and the dialysate solution. Fluid moves from a region of higher pressure to a region of lower pressure. The blood side in the dialyser is under positive pressure because the blood is being pushed through the dialyser by the pump. The dialysate side is under negative pressure because the dialysate solution is being pulled from the dialyser.

The used dialyser solution loaded with nitrogenous wastes, such as urea and creatine, excess electrolytes and excess fluid exits the dialyser. The purified blood with a normal water balance and electrolyte concentration and free of nitrogenous wastes is returned to the body.

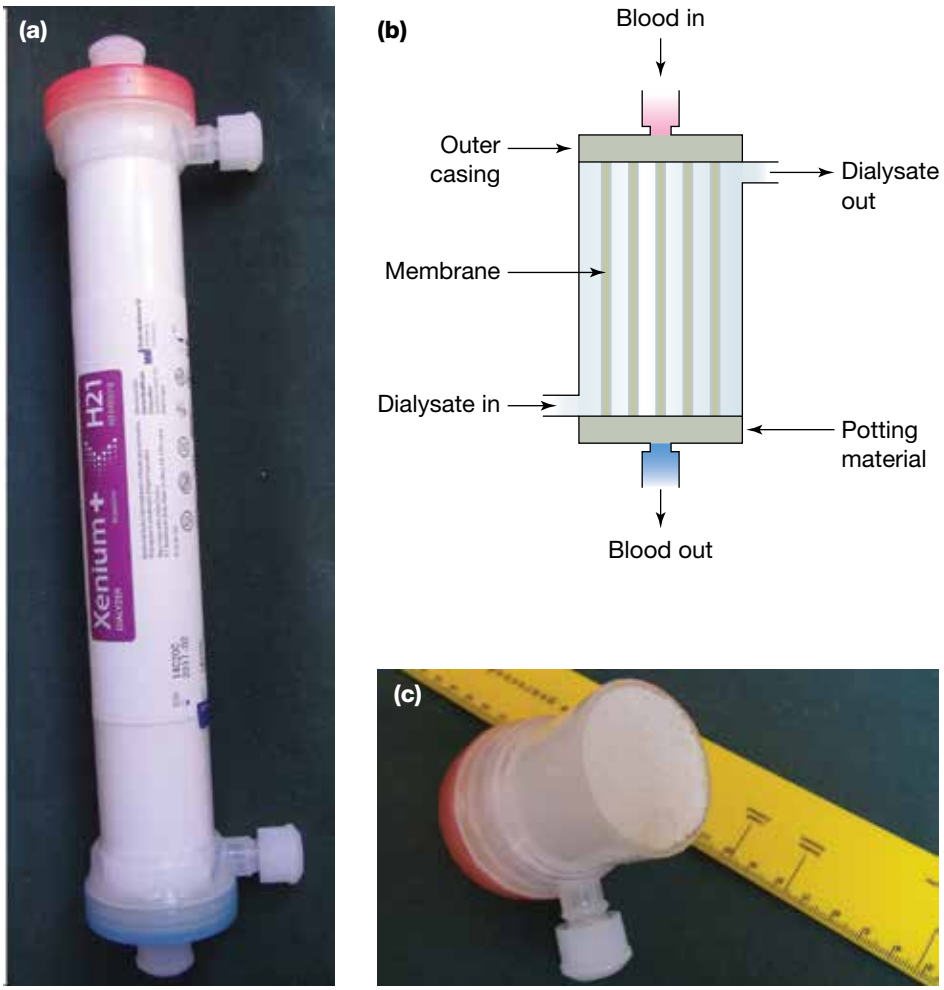

FIGURE 4.4 **(a)** Photo of the hollow-fibre dialyser, or artificial kidney, that is the hub of the haemodialysis equipment. The patient's blood enters the dialyser at the red inlet, passes through the membrane-bound hollow fibres and exits at the blue outlet. The inlet and outlet of the dialysate solution are on the side. **(b)** Simplified diagram showing the structure of the dialyser — only a few of the hollow fibres with their semipermeable membrane walls are shown. **(c)** A cross-section of the dialyser showing the very large numbers of thin hollow fibres through which blood is pushed. This large number of fibres greatly increases the surface area available for exchange between the blood and the dialysate solution. (Images (a) and (c) courtesy of Epworth Dialysis Unit (Head Karyn Jones))

The excretory system is examined further in this chapter, see pages 163–5.

The major symptoms of kidney failure can be treated by dialysis, either haemodialysis and, less commonly, peritoneal dialysis. Peritoneal dialysis makes use of the lining of the abdominal cavity, called the peritoneum, that has a rich blood supply. The dialysate is introduced through a tube (catheter) into the abdominal space around the intestines. The fluid is left there for up to 6 hours, during which wastes and excess substances pass from the blood in the peritoneal vessels into the dialysate fluid. The fluid is then drained from the abdominal space via the catheter. New fluid is introduced and the cycle starts again.

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Keeping kidneys healthy

Later in this chapter, we will explore examples of some human systems: excretory, respiratory and circulatory. But first, let's examine how cells become organised into tissues, tissues into organs and organs into systems.

KEY IDEAS

- Removal of nitrogenous wastes is an essential life-sustaining process in living organisms.
- In humans, the kidney is an essential organ for several functions, importantly the excretion of nitrogenous wastes.
- When kidneys fail, as in end stage kidney disease, dialysis can replace the major kidney functions.
- Kidney transplantation is another possible treatment for end stage kidney failure but depends on the availability of a matched living donor or a matched cadaver kidney.

QUICK CHECK

1 In addition to the removal of nitrogenous wastes, what are two important functions of the kidney?
2 List three symptoms of kidney failure.
3 Identify whether each of the following statements is true or false.
   a Whole blood moves into the kidney tissue where wastes are removed.
   b Kidney function can be assessed by measures such as glomerular filtration rate.
   c As soon as kidney function shows the first signs of failing, a person would begin dialysis.
   d Haemodialysis involves blood transfusions.

Levels of organisation

For much of the geological history of Earth, its inhabitants were unicellular organisms, living separately or in a group. The box on pages 139–40 provides a clue as to how multicellularity might have first evolved in groups of unicellular organisms.

Being multicellular allows organisms to have cells that specialise in form and function so that they can perform various functions that serve the needs of the whole organism. For multicellular animals, these functions might relate to movement, food capture, reproduction or defence. In a multicellular plant, these functions might relate to the capture of sunlight, cell division or transport of nutrients. So, the cells of multicellular organisms show a division of labour among their cells. However, a specialised cell of a multicellular organism performs fewer functions but has lost the ability for independent living, in contrast to the single cell of a unicellular organism that can perform all the functions needed to stay alive.

Beyond that, in some multicellular organisms, groups of specialised cells may be organised into tissues that perform a specific function. By working together as part of a tissue, these cells can support each other. Then different tissues may become organised into an organ that carries out a key function. Finally, organs can become arranged into a coordinated system that performs a major life-sustaining function for a multicellular organism. So, to have a system, such as your blood circulatory system, you must have organs. To have organs, you must have tissues. To have tissues, you must have specialised cells. To have specialised cells, you must be multicellular.

UNICELLULAR TO MULTICELLULAR

The first organisms on Earth were unicellular microbes that emerged at least 3.6 billion years ago. Unicellular organisms can carry out all the metabolic processes necessary for living. Each of these single cells is capable of an independent existence. It can trap the energy it needs and convert it to a useable form, can build complex macromolecules from simple building blocks, is self-mobile, can maintain its internal environment and can reproduce. Unicellular bacteria and archaea were the sole occupants of this planet for more than a billion years. The first simple multicellular organisms probably appeared on Earth about 2 billion years ago. The oldest evidence of multicellularity comes from fossils of *Grypania spiralis*, probably a coiled alga, dated at 2.1 billion years old (see figure 4.5).

FIGURE 4.5 Fossil impressions of *Grypania spiralis*, found in an ancient rock formation in Michigan, USA. These are the oldest possible multicellular organisms found thus far and date from 2.1 billion years ago. These coils were probably algae, each measuring about 2 mm by 10 or more mm.

How, after more than a billion years of unicellular life thriving on Earth, might multicellular organisms have emerged? Some scientists propose that the answer may lie in the advantages of cooperative living, a situation where cells benefit more from living together than they would from living independently.

Evidence of simple cooperative living is apparent in the living communities that form microbial mats. Different kinds of microbes occupy different layers in a microbial mat, their position depending on conditions at particular levels within the mat, such as temperature, nutrient availability, pH and light conditions (see figure 4.6). Individual bacteria in a microbial mat have some of the advantages of multicellular life in so far as their living conditions are more stable within the mat than outside it. Based on fossil evidence, this type of cooperative living among microbes was happening as early as about 3.6 billion years ago (refer to page 48).

FIGURE 4.6 A microbial mat along an outflow channel from Pinwheel Geyser in Norris Geyser Basin, Yellowstone National Park, USA. Note the different colours of the different microbial species. (Image courtesy of Carrine E Blank, PhD, Department of Geosciences, University of Montana)

However, cooperative living is not multicellularity. Cells in a microbial mat can move away from the mat and live independently. Multicellularity exists when cells in a group of cells are interdependent, with the group consisting of different cell types specialised for various roles that serve the entire group of cells (e.g. reproduction, energy production, motion). In becoming specialised, individual cells lose their ability to live independently. What event might have triggered the appearance of multicellularity?

Multicellularity had its beginnings in cooperative living, a situation where individual cells lived in close physical proximity and gained some benefit from living together that they would not have had when living as independent single cells. However, the benefit was not essential for life — it might be seen as a convenience — and the cells still retained their ability to live independently. Individual microbes

(continued)

may well have moved to and from cooperative living and independent living as circumstances changed, finding the situation best suited to their individual survival and reproduction. Multicellularity would not have developed under these circumstances.

A team of scientists led by Dr Eric Libby from the Santa Fe Institute in the United States proposed that the multicellular way of life resulted from a mutation that produced an inherited trait that was beneficial, but only for cells living in a cooperative group setting, and not for single cells.

The scientists labelled this trait as a 'ratchet mechanism' to describe an important aspect of its operation. Ratchets allow movement in one direction only. Likewise, the only direction in which a trait that acts as a ratchet mechanism can move a group of communal living organisms is toward multicellularity. Such a trait gives a selective advantage to cells in the multicellular setting and acts against cells living independently. With this trait, the behaviour of shifting between cooperative and individual living would be disadvantageous.

A trait operating as a ratchet mechanism to make cells in a group rely more on each other would strongly favour multicellular living. For example, such a trait might produce a division of labour among cells in a cooperative group, so that some cells produced one essential compound while others produced a different essential compound. In this case, the cells living in the group would have more advantages than if they lived apart.

Division of labour is the distinctive feature of multicellularity. An example of an early expression of multicellularity is seen in *Volvox* sp., a fresh water alga that lives as a colony and has a cellular level of organisation, that is, it has no tissue or organs (see figure 4.7). A *Volvox* colony consists of a large number of cells: up to 50 000 cells arranged as a hollow sphere. The cells are held together by an extracellular matrix or 'glue' that the colony produces, and the cells are connected by thin strands of cytoplasm. Some of the cells of *Volvox* are specialised for reproduction, while most are specialised for the functions of energy production (by photosynthesis) and locomotion. These latter cells move the colony in a coordination manner by the synchronised beating of their flagella, acting as a single multicellular organism.

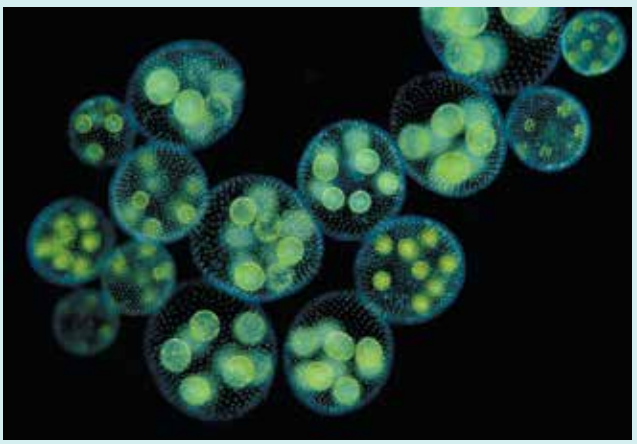

FIGURE 4.7 Photomicrograph of *Volvox* colonies. A colony can consist of up to 50 000 cells and ranges in size from 0.1 to 6.0 mm in diameter. The ancestors of *Volvox* are estimated to have transitioned from the solitary life of a unicellular alga to colonial life about 200 million years ago.

The increasingly complex levels of organisation of multicellular organisms are as follows:

- cell level — different types of cells present, but no further organisation
- tissue level — different tissues present, but not aggregated into organs
- organ level — several organs present, but not arranged into systems
- system level — organs present and organised into systems.

The animal kingdom includes animals whose structures range from simple multicellular animals organised at the cellular level to very complex animals, such as mammals, that are organised at the levels of tissues, organs and systems.

Organisation at the cellular level

The simplest level of organisation for a multicellular organism is the cellular level that shows the presence of specialised cells, but no tissues, organs or systems. The cellular level of organisation is seen today in simple animals, such as sponges.

Sponges have a simple structure organised at the cellular level (see figure 4.8a). Their body structure consists of two cell layers separated by a layer of non-cellular gel material. A few specialised cell types are present in sponges including:

- *cells with pores (porocytes)*. These tubular cells form the outer layer of a sponge and water can pass through the pores to the internal cavity of the sponge.
- *collar cells with a flagellum*. These cells line the inner chamber of a sponge. The beating of their flagella creates the incoming water currents and any tiny food particles are trapped by the collar cells.
- *amebocytes*. These mobile cells within the cell layers distribute food to other cells and play a role in reproduction.

Water and wastes leave the sponge via a single large opening (see figure 4.8b). Sponges do not have any internal organs, they have no tissues and no circulatory, nervous or digestive systems. The relative simplicity of the structure of sponges is illustrated by the fact that it is possible to disaggregate a sponge into its individual cells. If kept alive, within weeks the various cell types will re-aggregate into the original sponge structure.

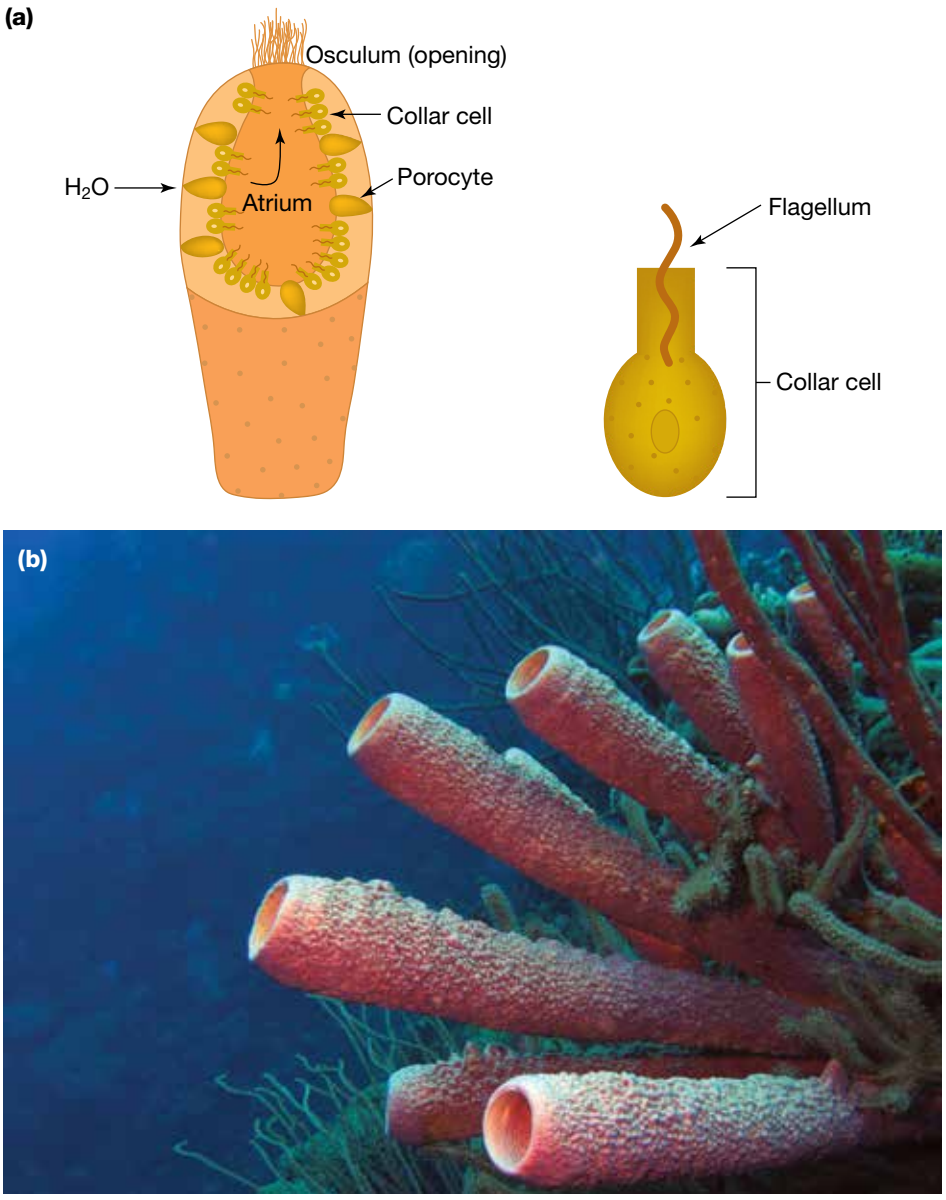

FIGURE 4.8 Sponges are the simplest animals organised at the cellular level only: no tissues, no organs, no systems, just some specialised cells. **(a)** Diagram showing the body structure of a sponge **(b)** Living sponges. Note the single large opening. Is this an entry or an exit point for water?

Organisation at higher levels: tissues, then organs and systems

Over the passage of geological time, multicellular animals became more complex. They developed more cell types and these cells became organised into tissues. A tissue forms when cells of one similar type act in a coordinated manner to carry out a specific function. So, a tissue is an aggregate of similar cells arranged to perform a common function.

The first animals to show the tissue level of organisation were the group of animals that includes jellyfish (see figure 4.9), anemones and corals. The distinctive feature of jellyfish is the presence of stinging cells used for defence and the capture of prey. They have tissues, such as the muscle tissue that pulsates their bell-shaped body and powers their swimming and nerve tissue, but they have no organs or systems.

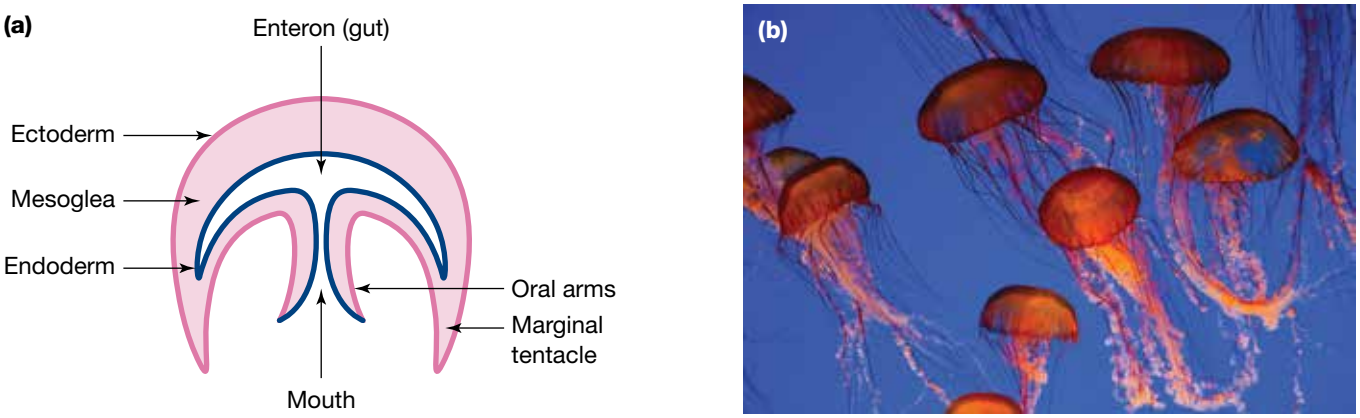

FIGURE 4.9 **(a)** Diagram of the body plan of a typical jellyfish with its two cell layers, ectoderm and endoderm, separated by a non-cellular jelly layer, the mesoglea. Note the single body opening (mouth) for the intake of food, the disposal of wastes and the release of reproductive cells. **(b)** Note the many fine marginal tentacles and the thicker oral arms that are covered with stinging cells for defence and for capturing prey; in some species these oral arms may reach lengths of up to 40 m.

studyON
Unit 1 AOS 1 Topic 4 Concept 1
Cellular specialisation
Concept summary and practice questions

Next to appear were organs. The organ level of organisation is seen when different kinds of tissue aggregate to form a discrete organ that has a specific function. It is generally accepted that organs first appeared in the group of animals, called flatworms, that includes parasites, such as tapeworms and flukes, as well as free-living marine flatworms. Flatworms have a three-layer body plan, and they show the presence of several organs including stomach, eyespots and excretory organs, but they have no circulatory or respiratory systems.

The system level of organisation is seen in the more complex animals. Among the first to show organisation at the system level were the group of animals, known as annelids, that includes earthworms and polychaetes (marine worms). These animals have a large number of cell types that are organised into tissues, organs and systems:

- They have a three-layer body pattern, and a tube-within-a tube structure with a mouth at one end for food intake and an anus at the other end for waste removal.
- They have a digestive system that includes organs such as a crop, a gizzard and an intestine.
- They have a nervous system that consists of various organs — a brain at the head end from which extends a central nerve cord that runs the length of the body.
- They have a closed circulatory system with a heart and blood vessels, but they lack a respiratory system.

A summary of the levels of organisation in multicellular organisms is shown in figure 4.10.

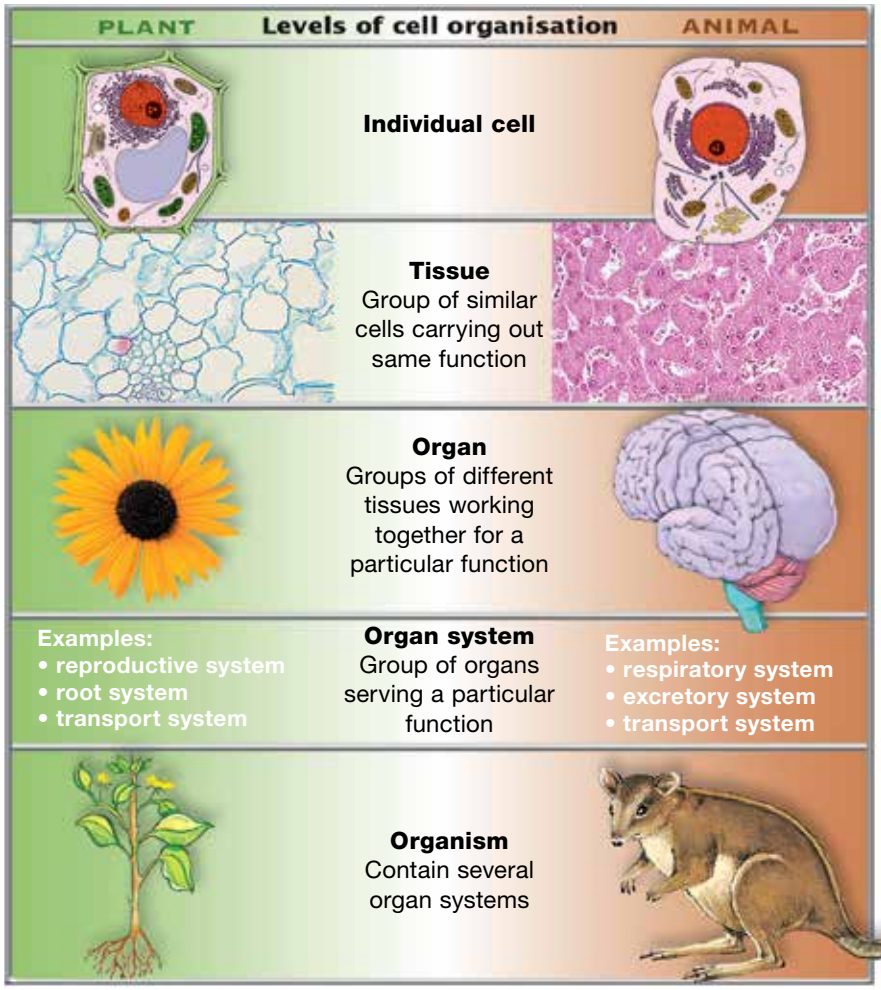

FIGURE 4.10 Similar cell types group together to form a tissue. Aggregates of different tissues form an organ. Various organs work together to carry out a major function as a system.

KEY IDEAS

- Multicellular organisms have specialised cells used to perform different functions that serve the needs of the whole organism.
- Multicellular organisms can have different levels of organisation of their cells.
- The levels of organisation, in order of increasing complexity, are cellular, tissue, organ and system.
- Tissues are aggregates of one kind of specialised cell that serves a general role.
- Organs are aggregates of various tissues that act in a coordinated manner to carry out a specific function.
- Systems are groups of various organs acting in cooperation to carry out a major life-sustaining function.
- The earliest animals in the geological record show a cellular level of organisation only, while later animals show organisation at the tissue levels, then organ level and then system level.

QUICK CHECK

4 Identify whether each of the following statements is true or false.
   a Sponges have a more complex organisation of cells than jellyfish.
   b An animal with a tissue level of organisation would not be expected to have organs or systems.
   c A unicellular prokaryote could show a tissue level of organisation.
   d Organs are more complex in their structure than tissues.

5 Animal M has tissues, but no organs, while animal N has organs, but no systems:
   a What is the highest level of organisation shown by each animal?
   b What kind of animal might animal M be?
   c What about animal N?

studyon
Unit 1 AOS 1 Topic 4 Concept 2
Tissues and organs
Concept summary and practice questions

Mammalian tissues, organs and systems

You are a member of a group of animals known as mammals. Mammals have a highly complex organisation with tissues built into organs and organs arranged into systems, such as the immune, endocrine, musculoskeletal and respiratory systems. This complexity of organisation is possible because of a large number of different cell types, each specialised for a particular function, that mammals possess. For example, you and other mammals have hundreds of different cell types, each specialised for a particular function, and these are organised into tissues, organs and systems. In this section, we will use a human being as an example of a mammal.

Tissues in mammals

In mammals, as in other animals, four major kinds of tissues are recognised:

1. **Epithelial tissues** cover flat surfaces, for example, the outermost layer of your skin. They line cavities in the body that have a connection to the external environment, for example, the lining of your bladder, lungs and gut (see figure 4.11a).
2. **Muscle tissues** are capable of contraction and movement, for example, your heart, the muscles of your arms and the muscles within your gut (see figure 4.11b).
3. **Connective tissues** bind and support body structures, for example, the loose connective tissue that holds the outer layers of the skin to the underlying muscle layers, the fibrous connective tissue of your bones and cartilage, your adipose tissue (see figure 4.11c) and the fluid tissue of your blood.
4. **Nervous tissues** are made of different kinds of nerve cells (neurons) that can receive external stimuli and transmit nerve impulses. Nerve tissue is found in your brain and spinal cord and includes cells (neuroglia) that support nerve cells. An example of nervous tissue is the retina of your eye.

The further classification of these four major tissue groups is shown in figure 4.12. Your various organs contain several or all of these different types of tissue. How many different tissues might be present in an organ such as your eye?

You may recall from chapter 1, pages 14 to 16, that the surface-area-to-volume-ratio (SA:V) of a cell is important in determining the cell's efficiency in moving materials across its membrane to supply the needs of a cell and in removing wastes from the cell. A tissue consists of an aggregation of many specialised cells. The exchange of materials between the cells of a tissue and their environments has the potential to be far more efficient if the tissue is made up of many small cells rather than fewer larger cells. But the potential for efficiency of small cells becomes a reality only if the cells of a tissue are close to a mechanism that can deliver required materials to and remove waste materials from those cells.

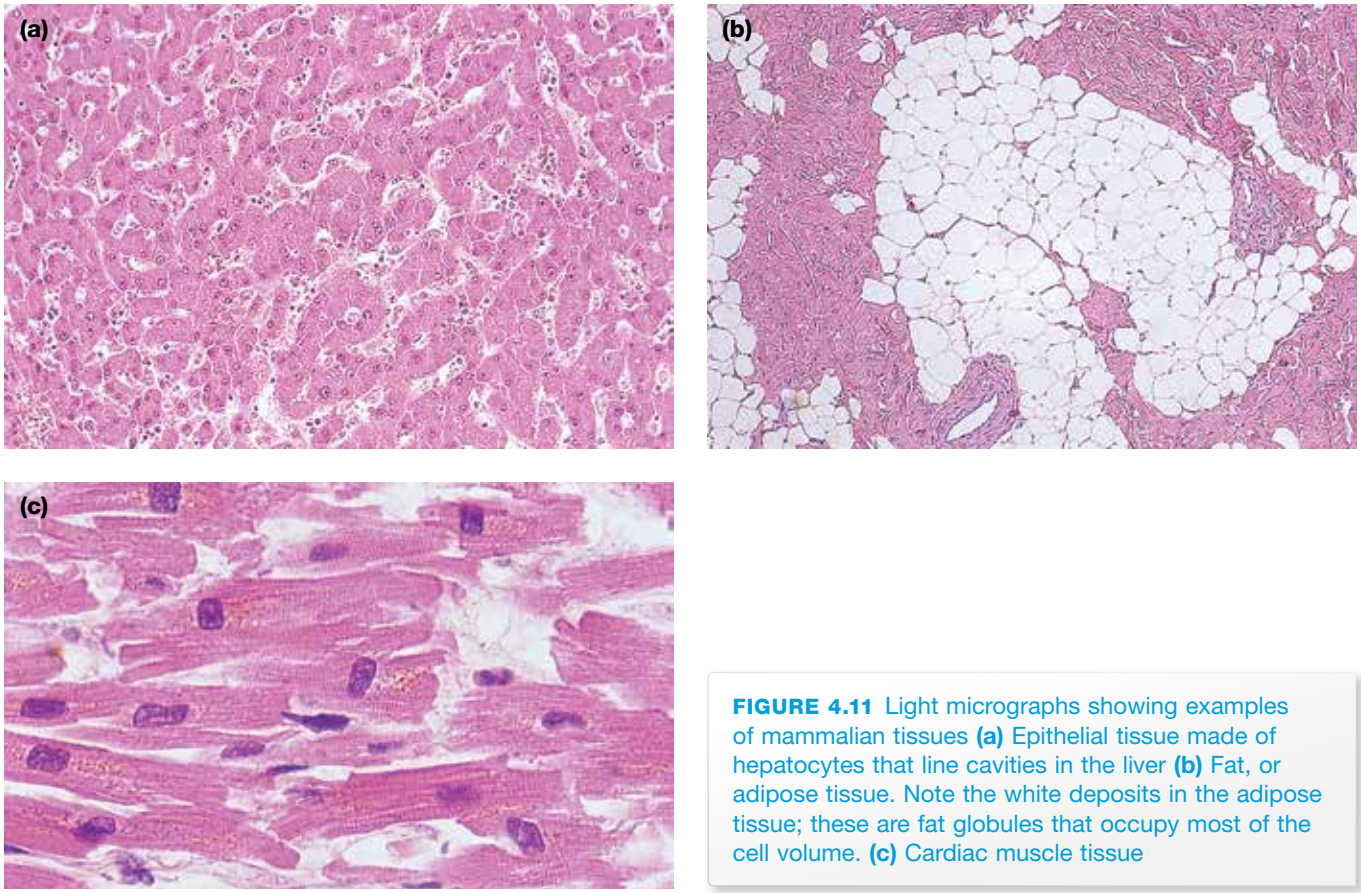

FIGURE 4.11 Light micrographs showing examples of mammalian tissues **(a)** Epithelial tissue made of hepatocytes that line cavities in the liver **(b)** Fat, or adipose tissue. Note the white deposits in the adipose tissue; these are fat globules that occupy most of the cell volume. **(c)** Cardiac muscle tissue

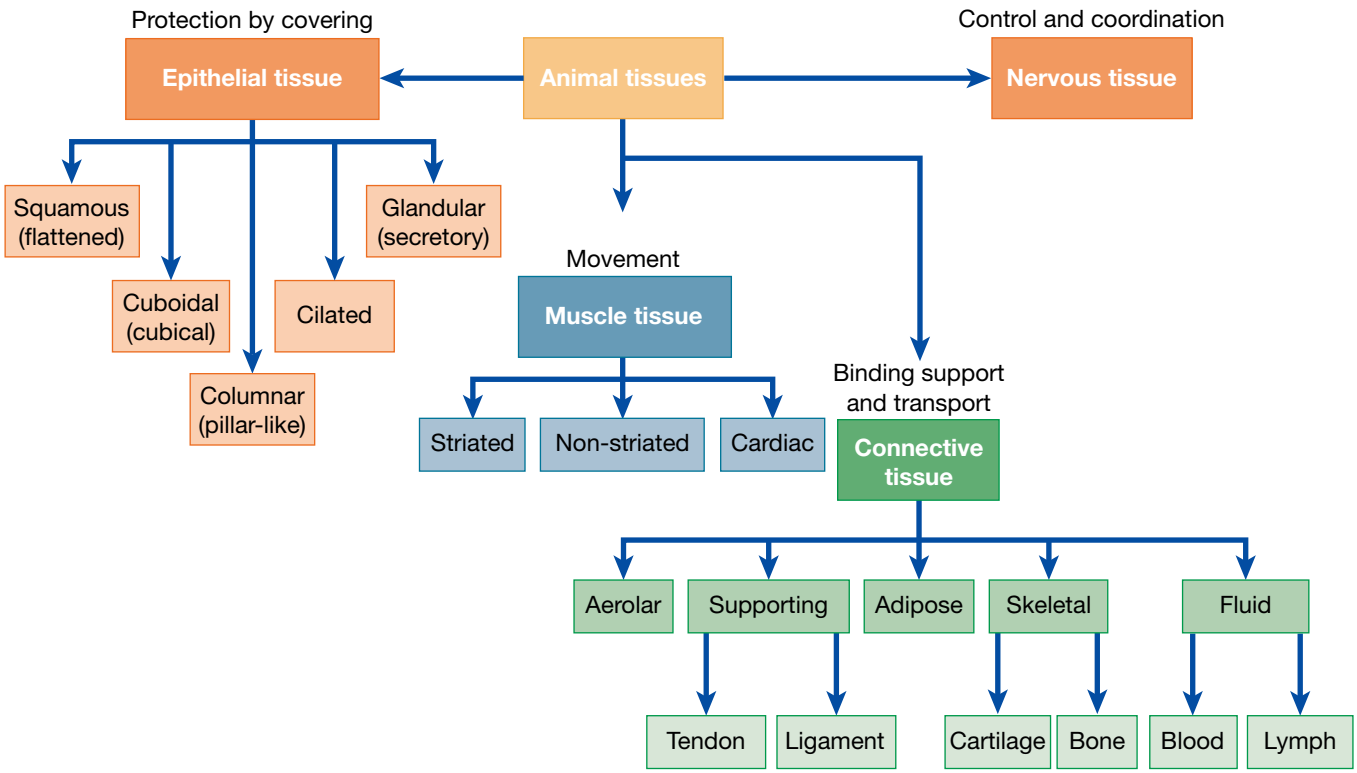

FIGURE 4.12 A classification scheme of the four major tissues in mammals. What is an example of an epithelial tissue? Where would you find skeletal tissue?

A tissue composed of a mass of small cells *without* a delivery system is like a single large cell of comparable volume. Such a cell mass acts like one large cell with a small SA:V ratio such that the surface area exposed to the extra-cellular environment cannot efficiently service the combined cell volume (see figure 4.13a). In contrast, a tissue composed of a mass of cells *with* a delivery system has a greater surface area to service the needs of the combined cell volume and so will do this more efficiently (see figure 4.13b). In mammals, the delivery system is the blood circulatory system that delivers oxygen and nutrients to cells and removes metabolic wastes.

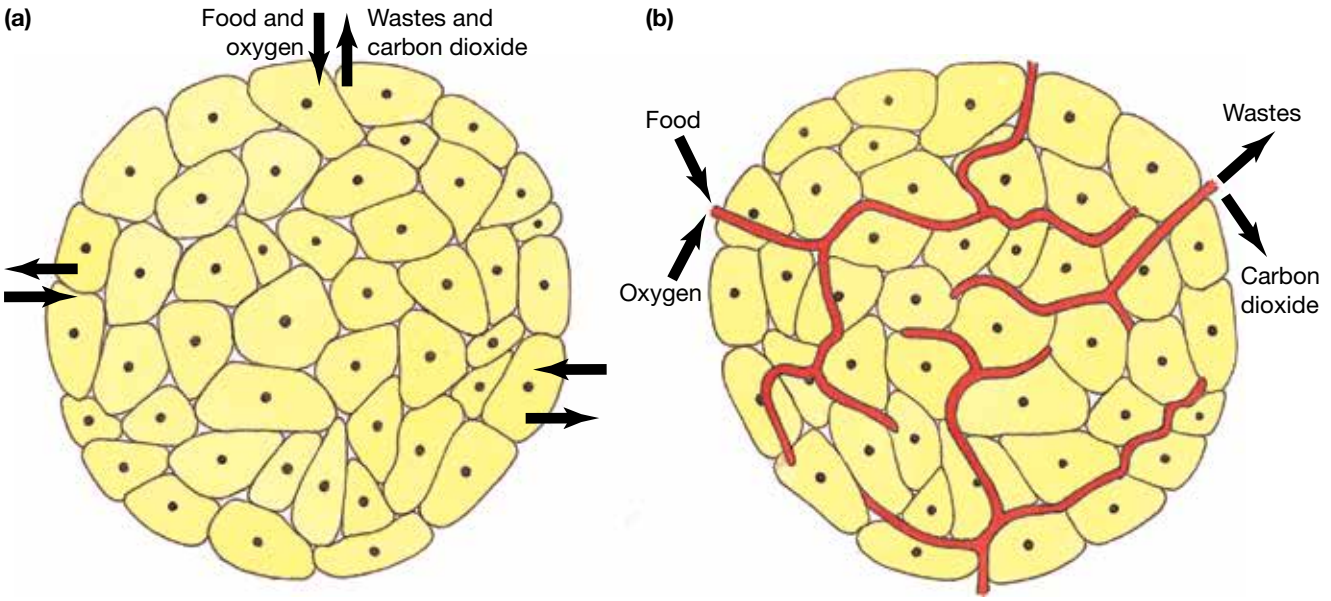

FIGURE 4.13 **(a)** In the absence of a delivery system, the innermost cells of a solid tissue will be inefficient in obtaining needed materials from and getting rid of wastes to the extra-cellular environment. **(b)** A solid tissue with a delivery system can efficiently service the needs of all its cells, including the innermost cells.

Mammalian organs: several tissues, one organ

In multicellular organisms, groups of different tissues work together to perform a particular function. A collection of such tissues is called an **organ**. Your heart is an organ, your brain is an organ, your lungs are organs and your kidneys are organs. Each organ is composed of several different kinds of tissue, each of which makes an essential contribution to the specific function of the organ.

Your stomach is an organ. Tissues of your stomach include an epithelium that lines the inner chamber of the stomach, smooth muscle cells within the stomach wall that allow the stomach to expand and blood vessels that supply nutrients to and remove wastes from the cells (see figure 4.14).

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Unit 1
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Body systems
Concept summary and practice questions

Mammalian systems: many organs, one major function

The aggregation of many organs into one major function is called a system (or an organ system). Each system carries out major life-sustaining functions including:

- The digestive system contains various organs that work together to ensure the food you eat is digested and that the nutrients it contains are in a form that can be absorbed. Your digestive system contains organs such as your teeth, oesophagus, stomach, intestines and liver (see figure 4.15).

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Concept 9
Heterotrophs: Digestive system
Concept summary and practice questions

- The excretory (urinary) system contains various organs that work together to remove nitrogenous wastes from the body. Your excretory system contains organs such as your kidneys, ureters, bladder and urethra (see figure 4.35, p. 164).
- The circulatory (cardiovascular) system includes the heart, arteries, veins, capillaries and blood.
- The respiratory system includes the larynx, pharynx, trachea, bronchi, and lungs (see figure 4.47, p. 175).

Other mammalian systems include the immune system, the nervous system, the endocrine system, the skeletal system, the muscular system, the reproductive system, the lymphatic system and the integumentary (skin) system.

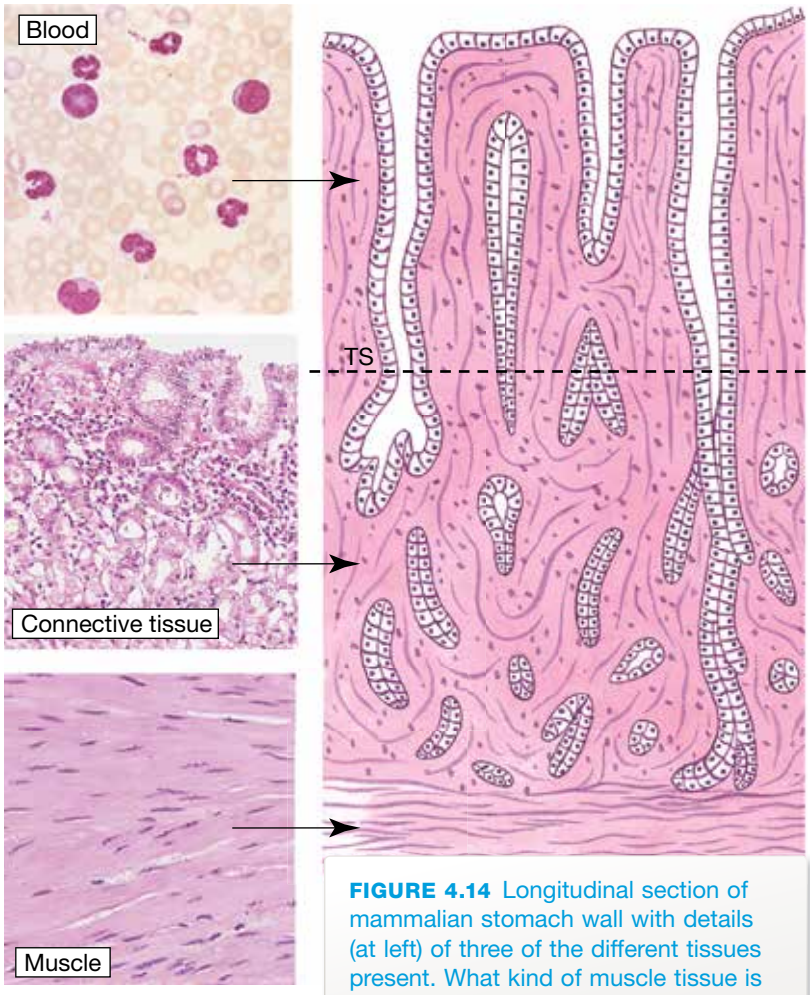

FIGURE 4.14 Longitudinal section of mammalian stomach wall with details (at left) of three of the different tissues present. What kind of muscle tissue is present in the stomach wall?

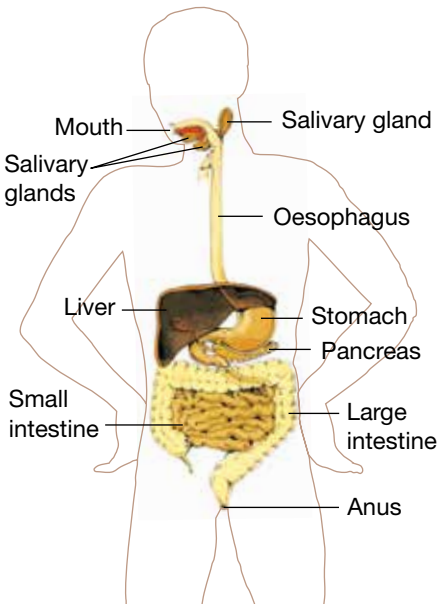

FIGURE 4.15 The main organs of the human digestive system. What is an organ system?

Systems do not operate in isolation

Each system in a mammal has a major function that it carries out to sustain the life of the mammal. However, systems do not act in isolation; instead they are interconnected and rely on each other. To perform its role, a system depends on the operation of all other systems. For example, the excretory system cannot carry out its key role of excreting N-wastes unless there is a functional circulatory system to transport N-wastes from all cells to the kidneys of the excretory system. No system can operate unless their cells receive the nutrients produced by the digestive system that are then transported to the cells by the circulatory

system. Can you identify another interaction between the circulatory system and some other mammalian systems?

The blood circulatory system has important interactions with all other mammalian systems because it is the transport system that moves substances in solution to and from all cells. The circulatory system interacts with other systems as follows:

- with the digestive system, by transporting nutrients produced by the digestive system to the cells of all systems
- with the respiratory system, by transporting oxygen from the lungs to the cells of all systems for use in aerobic respiration and by transporting carbon dioxide from all cells back to the lungs for excretion
- with the urinary system, by transporting N-wastes from all cells to the kidneys of the urinary system for excretion
- with the endocrine system, by transporting hormones released by the glands of the endocrine system to their sites of action throughout the body
- with the immune system, by transporting the white blood cells (leucocytes) to sites of infection where they produce antibodies.

TABLE 4.1 Some examples of interactions between the nervous system (brain and spinal cord of the central nervous system, the sense organs and the sensory nerves of the peripheral nervous system) and other mammalian systems

System	Some organs of system	Examples of interactions with the nervous system
respiratory system	lungs	brain monitors blood gas levels and breathing rate lungs are source of oxygen for brain
skeletal system	bones	brain controls muscles and so regulates position of skeleton skull and spine protect brain and spinal cord
circulatory system	heart, blood vessels	brain regulates blood pressure and heart rate cardiovascular system delivers nutrients and oxygen to cells of nerve tissue
excretory (urinary) system	kidneys, bladder	brain controls urination bladder sends sensory information to the brain
digestive system	mouth to anus	brain controls muscles for eating and for elimination digestive system sends sensory information to the brain

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Interactivity
Digestive system
int-3030

KEY IDEAS

- Mammalian tissues can be classified into four major types.
- Cells within a tissue mass need a delivery system for the supply of nutrients and the removal of wastes.
- Mammalian organs are composed of several different tissues.
- Many systems sustain the life of a mammal.
- Systems do not act in isolation but have a dependence on each other.

QUICK CHECK

6 Identify four systems that sustain the life of a mammal.

7 Identify whether each of the following statements is true or false.

- **a** The mammalian heart is an example of a tissue.
- **b** The lining of the human bladder is an example of an epithelial tissue.
- **c** The digestive system includes many organs, for example, the pancreas.
- **d** To carry out its major function, a mammalian system depends on the operation of other systems.

8 Classify each of the following as a tissue, an organ or a system:

- **a** heart
- **b** human liver
- **c** kidneys
- **d** layer of fat surrounding the kidney.

9 Given an example of each of the following.

- **a** An interaction between the excretory system and the circulatory system
- **b** A tissue that could be found in the human stomach
- **c** An organ of the excretory system
- **d** An interaction of the skeletal system with the nervous system

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Unit 1 AOS 1 Topic 4 Concept 5

Heterotrophs: Circulatory system
Concept summary and practice questions

Circulatory system of mammals

The **blood circulatory system** is the transport system for the mammalian body. The circulatory system is responsible for the transport of oxygen and nutrients to cells and for the transport of N-wastes from cells to the kidney and the transport of carbon dioxide waste from cells to the lungs. The circulatory system provides the link between the external environment and cells.

What are the characteristics of this system that facilitate its functions? The blood circulatory system is the mechanism that delivers nutrients and oxygen to all cells of a multicellular organism. The circulatory system consists of:

- the heart, a muscular pump that provides the force that moves the blood
- the vessels — arteries, arterioles, veins, venules — that form the channels through which blood moves to and from tissues and their cells
- the capillary networks that provide the sites where material can be exchanged between the blood and the cells.

We will consider the circulatory system of humans, which is a system typical of all mammals.

Until the seventeenth century the popular belief was that blood was consumed by the body as fast as it was produced. In 1628 Dr William Harvey of St Bartholomew's Hospital in London published his manuscript *De Motu Cordis* (On the Motion of the Heart), which was the first to argue that blood constantly circulates around the body. Harvey's experiments allowed him to deduce that blood leaves the left side of the heart and is pumped to all parts of the body, excluding lungs, before it returns to the right side of the heart. From there it goes to the lungs and back to the left side of the heart, from where it is once again pumped around the body. Blood travels through the heart twice during each circulation of the body: once after circulating through the pulmonary system (the lungs) and once after circulating through the remaining parts of the body (figure 4.16).

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Interactivity
Circulatory system
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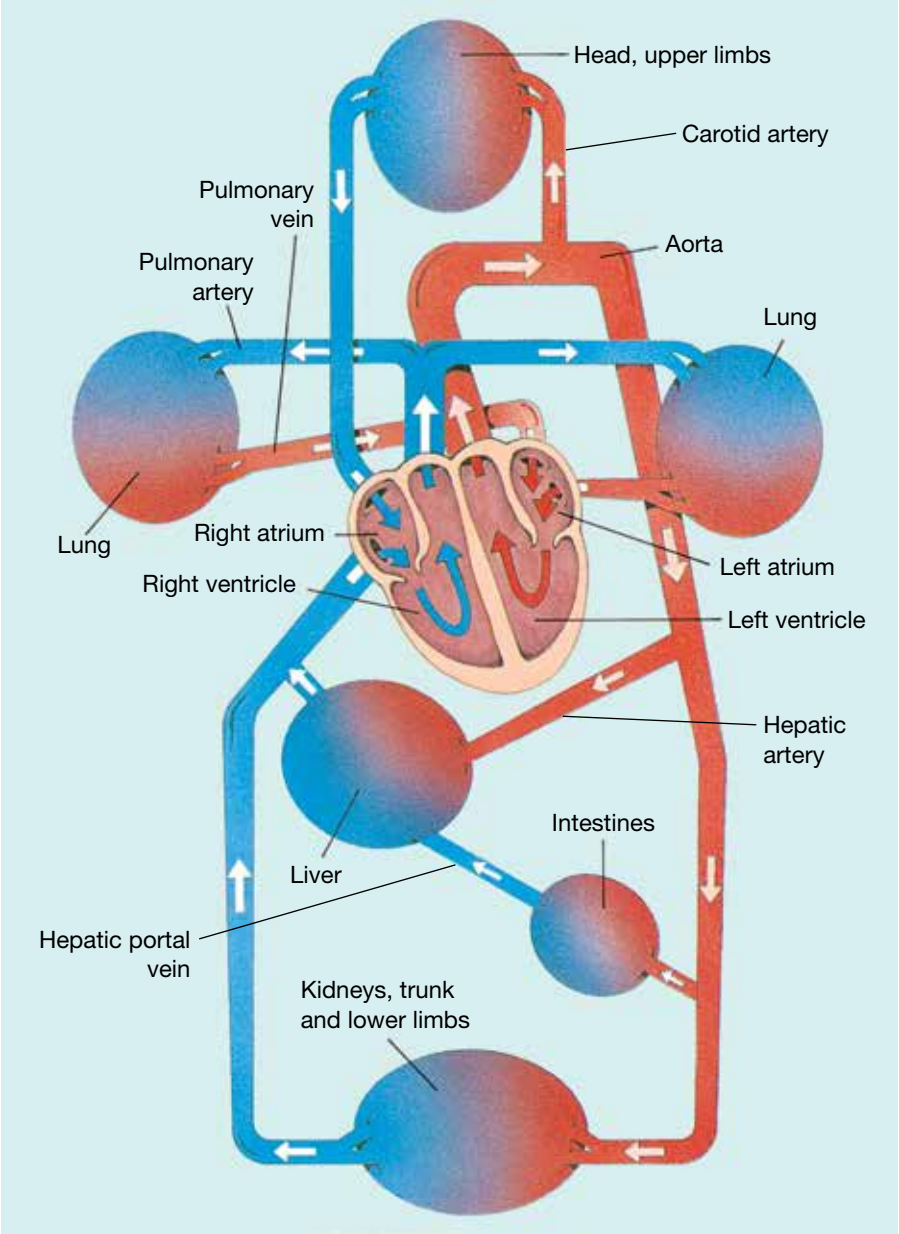


FIGURE 4.16 Main routes for blood circulation. Arrows within vessels indicate the direction of blood flow. Arteries branch into smaller vessels called arterioles, then capillaries. From capillaries, blood flows through venules into veins and is transported back to the heart. Red indicates oxygenated blood and blue indicates deoxygenated blood. All arteries except one carry oxygenated blood. Which one is the exception?

Components of blood

Blood is about 55 per cent plasma, which is itself about 90 per cent water. The remaining 10 per cent of plasma is made up of the various compounds and molecules dissolved in the water part (see table 4.2). The materials transported by plasma and the significance of each are summarised in table 4.3.

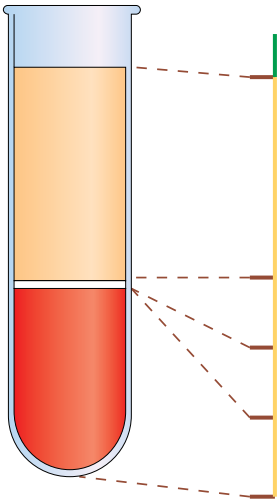


TABLE 4.2 Composition of human blood

Component	Approximate %	Function
plasma (about 91% water, 7–8% dissolved plasma proteins and other molecules)	55	• suspends blood cells • contains substances that stabilise pH and osmotic pressure, promote clotting and contribute to immune response • transports nutrients, waste carbon dioxide and other substances
white blood cells	< 0.1	• destroy foreign cells and debris • act in immune response
platelets	< 0.01	• aid in clotting of blood • aid in inflammation
red blood cells	45	• transport most of the oxygen and some carbon dioxide

TABLE 4.3 Materials transported by plasma and the significance of each

Component of plasma	Significance
water	solvent for non-cellular materials in blood; suspends cellular components
nutrients: • glucose • fatty acids • amino acids • vitamins	supply: • source of energy for cell • building material for renewal of cell components
nitrogenous waste and carbon dioxide	produced during metabolism and must be removed from cells and the body
oxygen	small amount carried in solution
plasma proteins such as: • albumin • globulins • fibrinogen	 • bind hormones and fatty acids • antibodies — react with foreign material • acts in blood clotting
ions such as: • sodium • chloride • potassium • calcium • magnesium • bicarbonate	contribute to a variety of actions such as: • stabilising pH • osmotic balance • regulation of permeability of plasma membranes
hormones	transported from sites of manufacture to particular target cells or organs around the body

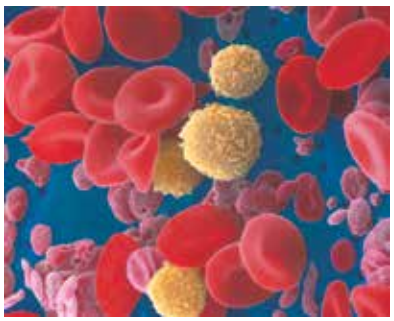


FIGURE 4.17 Photomicrograph of human blood. Note the many red blood cells, white blood cells (yellow) and platelets (pink). Platelets are specialised fragments of larger cells.

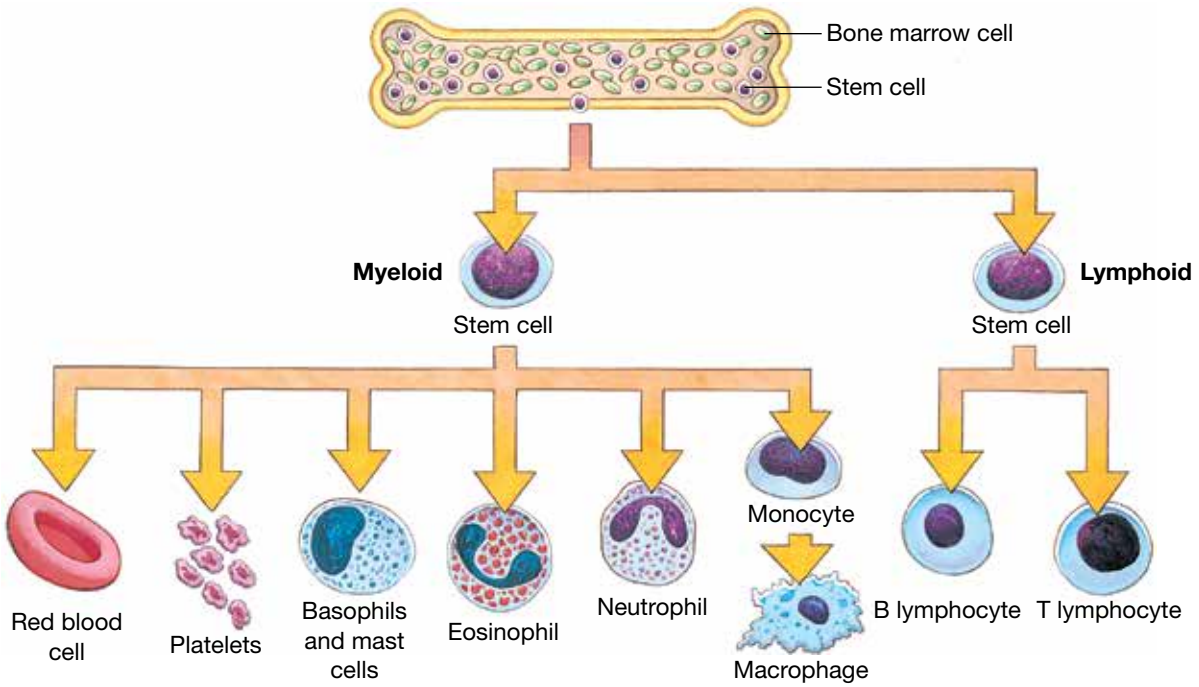
Blood cells

Blood contains three different kinds of cells (figure 4.17). These are red blood cells, also called **erythrocytes**, white blood cells, also called **leucocytes**, and platelets.

The three kinds of cells found in the blood are derived from special cells, called **stem cells**, in bone marrow. This is summarised in figure 4.18.

Red blood cells

Red blood cells contain haemoglobin, a red iron-containing protein that readily combines with oxygen to form oxyhaemoglobin. This is the form in which the vast majority of oxygen is transported to all cells of the body.



Cell type	Red blood cell or erythrocytes	Platelets	White blood cells or leucocytes
Function	Transport oxygen and to a lesser extent carbon dioxide	Important in blood clotting	Active in defence against infection and in the immune system
Number (per mm^3 of blood) in healthy person	Typical male: 5.4×10^6 Typical female: 4.8×10^6	250 000 to 500 000	5000 to 7000
Survival time in healthy person	About 120 days	About one week	May survive for several days. If person has an infection may survive for only a few hours.

FIGURE 4.18 All blood cells develop from special cells, called stem cells, in bone marrow. Stem cells continually reproduce by mitosis and then differentiate.

ODD FACT

The blood volume of an average adult male is 5–6 L compared with 4–5 L in an average adult female.

Males generally have a higher metabolic rate than females and so have a greater need for energy and hence oxygen. The blood of a male carries about 10 per cent more red blood cells than the same volume of blood in a female.

White blood cells

The function of white blood cells is to combat infection. They can move out of the bloodstream — in much the same way as amoebas move — through connective and epithelial tissues (refer to figure 1.21, p. 22). Many white blood cells are phagocytic, which means that they ingest bacteria and other foreign material.

Platelets

Platelets are specialised fragments of larger cells and play an important role in the clotting of blood when damage occurs to blood vessels.

What can go wrong?

The various blood cells play important roles in the human body. Unfortunately disorders can arise that affect the blood cells, for example, aplastic anaemia and leukaemia.

Aplastic anaemia

Aplastic anaemia is a condition affecting the blood in which the bone marrow ceases to produce sufficient numbers of new blood cells to replace those that are damaged or dying. In aplastic anaemia all blood cells are lacking (in contrast to anaemia, a condition in which only red blood cells are deficient in numbers).

Aplastic anaemia is most commonly an acquired condition, although there is a rarer hereditary form. The causes of acquired aplastic anaemia include exposure to toxic chemicals or radiation and viral infections, but in many cases the cause is unknown. Blood transfusions are used to treat aplastic anaemia and, in severe cases, bone marrow transplants may be used.

Leukaemia

Leukaemia (*leukos* = white) is a cancer that affects the bone marrow so that it produces large numbers of abnormal white blood cells that enter the bloodstream. These white blood cells do not die as rapidly as normal white blood cells and do not perform the normal functions of white blood cells, so they crowd out the normal blood cells, interfering with the functions of the normal blood cells. Various forms of leukaemia exist: acute lymphocytic leukaemia (ALL), which affects the lymphoid cells, is the most common leukaemia in young children; chronic lymphocytic leukaemia (CLL) is the most common leukaemia seen in older adults, more commonly in men than in women. Acute forms of leukaemia develop more rapidly than chronic forms.

Risk factors for leukaemia include exposure to chemicals such as benzene, exposure to radiation and smoking. Treatments for leukaemia, depending on its type and rate of progress, may include chemotherapy, radiation therapy and stem cell transplants.

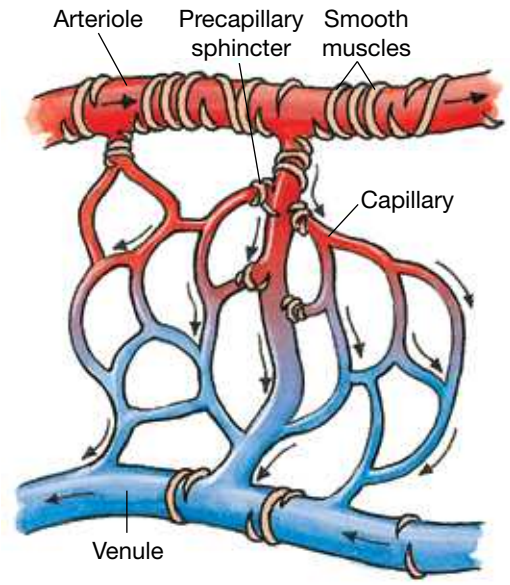


FIGURE 4.19 A capillary bed branching from an arteriole and ultimately feeding into a venule. Note the smooth muscle cells, called precapillary sphincters, that regulate blood flow through the capillary network.

Vessels to transport blood

Blood is transported around the body in three different kinds of blood vessels. These are the larger vessels (arteries and veins), which are linked by the smallest of blood vessels (capillaries).

Arteries

Arteries are thick-walled vessels that carry blood away from the heart. Arteries branch into smaller and smaller arteries. The smallest arteries are called arterioles. Arteries have thick walls to withstand the pressure of the blood as it is pumped from the heart but their walls are far too thick to allow the ready movement of materials and gases between blood and tissue cells. A much thinner barrier is required if diffusion is to occur. As arterioles enter tissues, they branch into microscopic vessels called capillaries (see figure 4.19).

Although the flow of blood into capillary networks is controlled by arterioles, additional control occurs through the contraction of smooth muscle cells that act as sphincters in the networks (see figure 4.19).

Capillaries

Capillaries are thin-walled vessels between 5 and 8 μm in diameter. Their walls are one cell thick and materials either pass through these cells or pass between the cells as they leave or enter the blood (see figure 4.20).

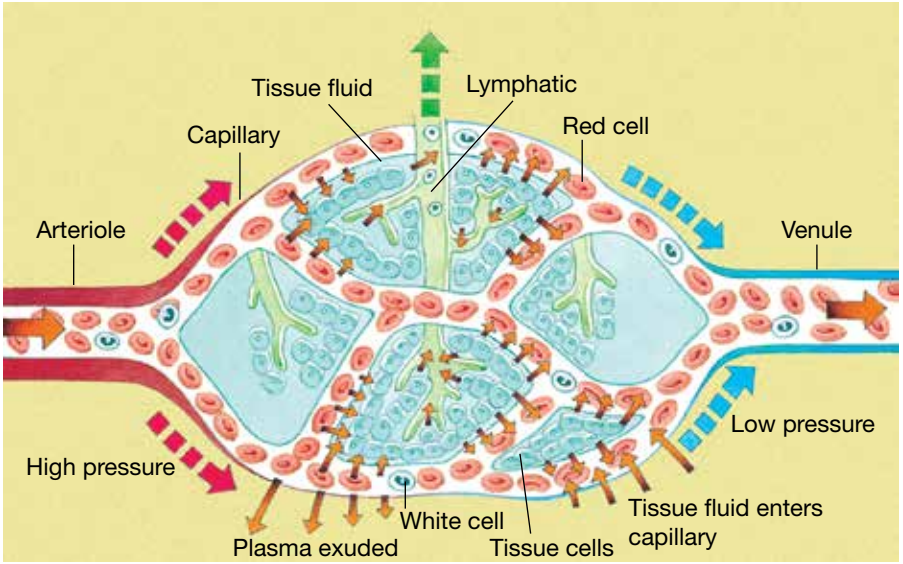


FIGURE 4.20 The relationship between blood capillaries, tissues and lymphatics. The diagram also indicates the movement of material between capillaries and tissue cells.

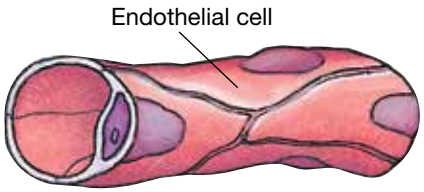


FIGURE 4.21 The wall of a capillary is made of a single layer of flattened endothelial cells.

Refer to the drawing and cross-section of a capillary in figures 4.21 and 4.22. Oxygen diffuses through the endothelial cells into surrounding tissue fluid and cells. Oxygen moves down a concentration gradient. Carbon dioxide makes the reverse journey, also down a concentration gradient. Water and small water-soluble molecules, such as glucose and inorganic ions, diffuse through gaps between the endothelial cells. Some proteins leave the capillaries through endothelial spaces or across the cells in vesicles. Most protein stays in the blood vessels. Phagocytic white blood cells can squeeze between endothelial cells.

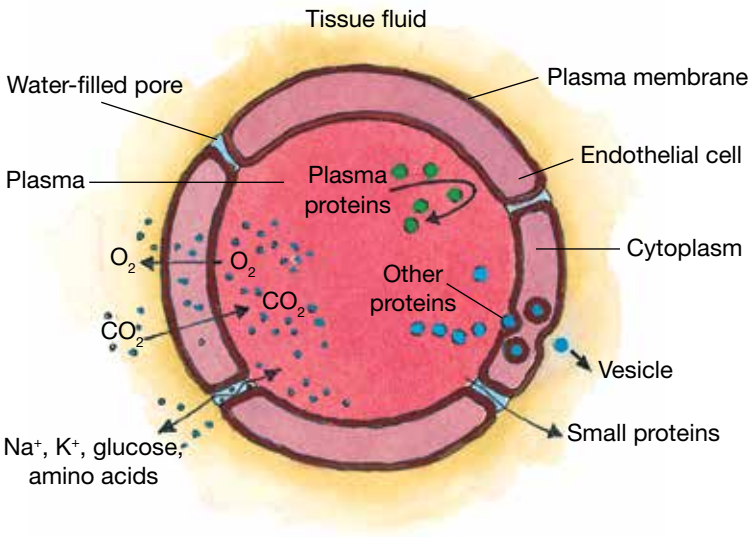


FIGURE 4.22 Cross-section through a capillary. Note the different ways in which different materials leave and enter a capillary.

Veins

Blood moves from the capillaries into venules, which combine to form larger vessels called veins. These are relatively thin-walled vessels that transport blood back to the heart (see figure 4.23).

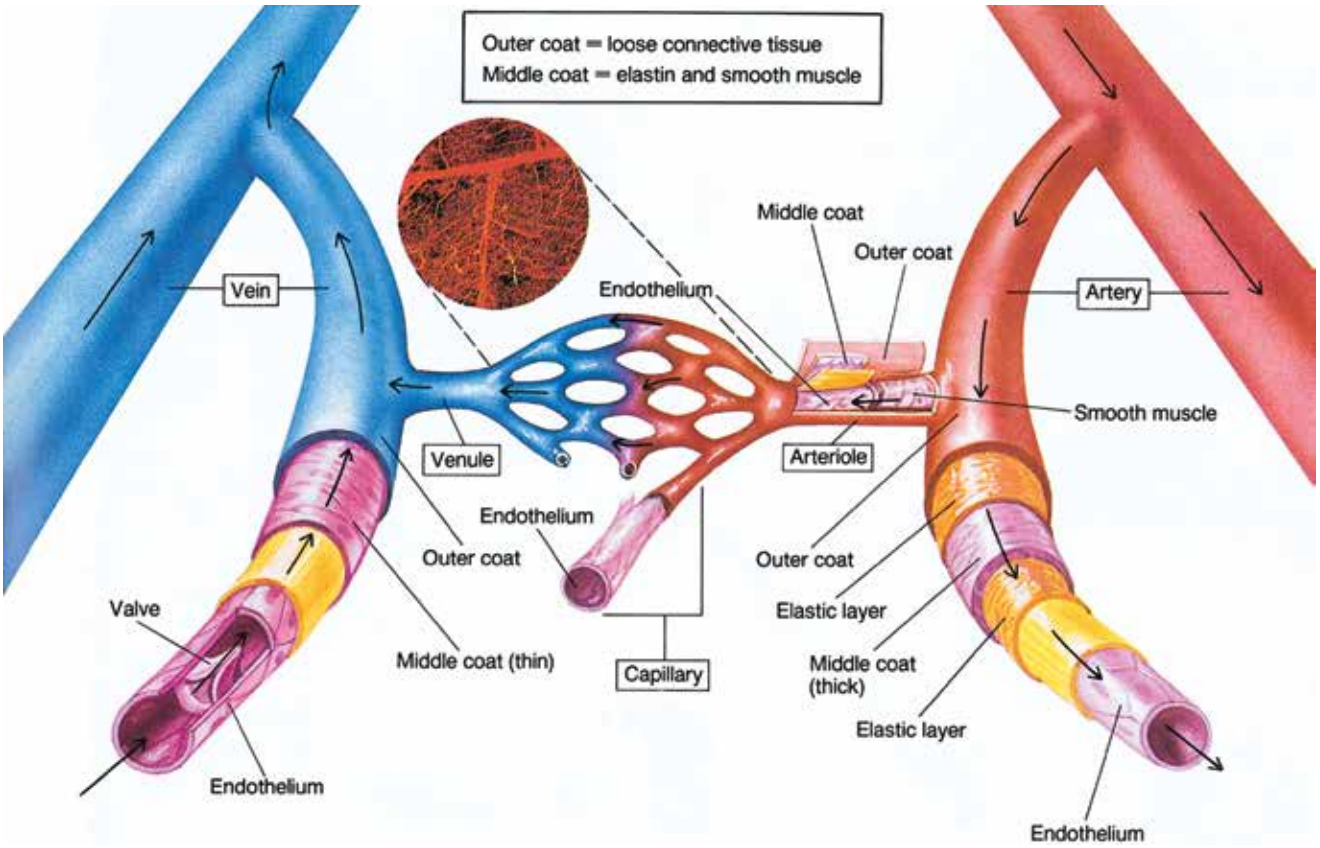
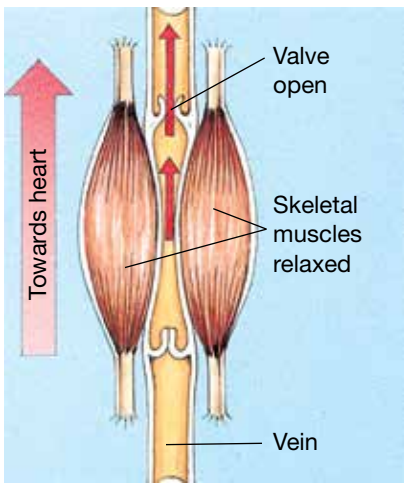


FIGURE 4.23 Note the differences in structures of the walls of the five different kinds of blood vessels: artery, arteriole, capillary, venule and vein. In what way is the structure of each kind of vessel related to its function?

Blood in veins is under lower pressure than blood in arteries because it has travelled further from the heart. Veins have valves that prevent backflow of blood (see figure 4.24).

Contraction of muscles near veins also helps squeeze the veins and move the blood towards the heart.



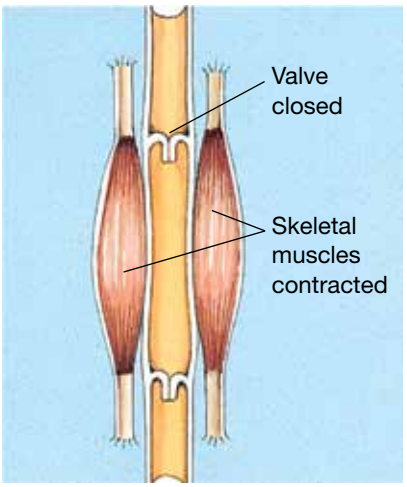


FIGURE 4.24 Valves in veins prevent a backflow of blood in those vessels. The contraction of muscle alongside the vessels helps to move the blood towards the heart.

What can go wrong?

The blood vessels form the channels through which blood flows around the body. Conditions affecting the blood vessels include **aortic aneurysms** and **atherosclerosis**.

Aortic aneurysm

An aneurysm is a balloon-like bulge in the wall of the aorta (see figure 4.25) that results from the force of the blood being pumped through the aorta. This force either splits the wall of the aorta (called a dissection) or completely bursts the wall (called a rupture). An aortic aneurysm may occur either in the chest or in the abdomen.

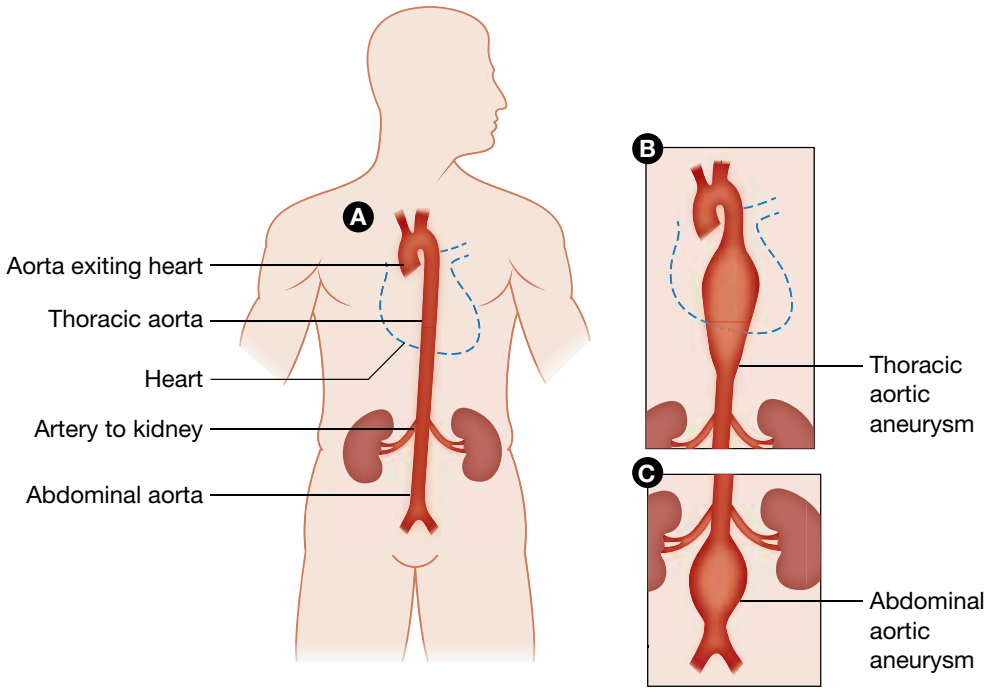


FIGURE 4.25 An aortic aneurysm is a balloon-like swelling of the aorta that may occur in the chest or in the abdomen. An aneurysm may be either a dissection of the aorta or a rupture of the aorta.

ODD FACT

Aneurysms may occur in other blood vessels, including those in the brain. If such an aneurysm ruptures, it can cause a stroke.

In a dissection of the aorta, the wall of the aorta splits allowing blood to accumulate between the layers of the wall of the aorta. (Refer to the right-hand side of figure 4.23 to see the layers of an artery wall.) In a rupture of the aorta, the aorta wall bursts, allowing blood to leak into the body cavity.

The major risk factors for an aneurysm are high blood pressure, hardened arteries (atherosclerosis) and smoking. Physical injury may cause an aortic aneurysm. In addition, certain inherited diseases of the connective tissue increase the risk of an aortic aneurysm.

Atherosclerosis

Atherosclerosis is a condition that results when the arteries become clogged with a fatty substance, known as plaque or atheroma. Plaque is a mixed collection of cholesterol, cells and debris that builds up *within* the inner lining of arterial walls. The build-up of plaque in affected arteries causes them to harden and to narrow, restricting and even blocking blood flow. Atherosclerosis is the major cause of cardiovascular diseases, that is, diseases of the heart and blood vessels. Figure 4.26 shows a normal artery, contrasted with an artery with extensive plaque.

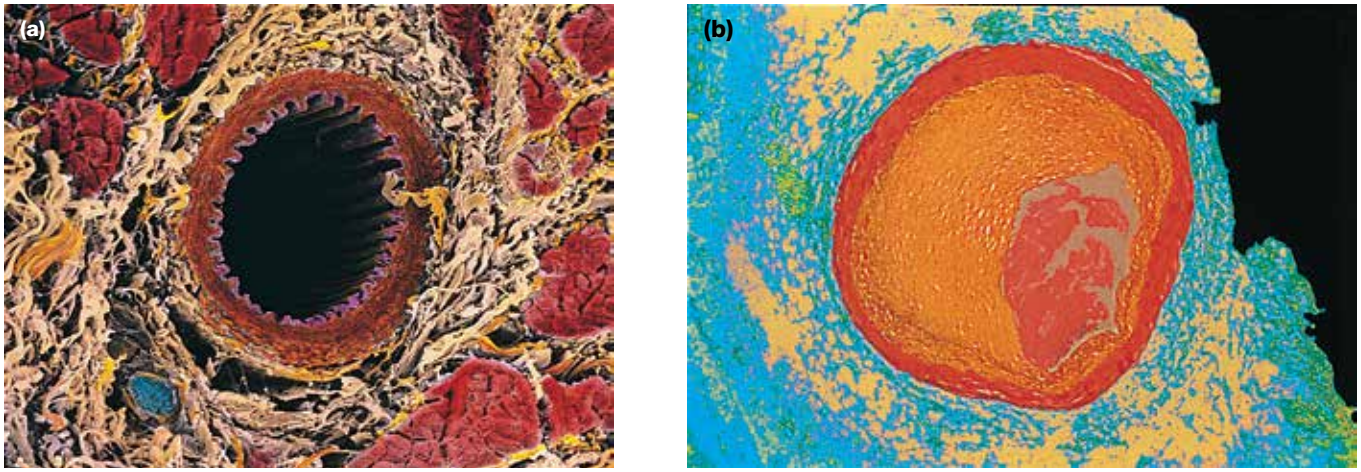


FIGURE 4.26 Cross-section of human arteries **(a)** The interior of a normal human artery **(b)** Deposits of plaque in an artery showing the condition known as atherosclerosis. The open area for the blood is confined to the ovoid shape (shown in red), while the plaque (shown in orange) is occluding most of the artery.

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Unit 1 | AOS 1 | Topic 4 | Concept 6

Organ and system failure: heart attack
Concept summary and practice questions

Plaque can build up in the inner lining of the coronary arteries of the heart and, if it blocks the blood supply to the heart, this can result in the death of heart muscle in the affected region, a condition known as a heart attack (myocardial infarction). If a similar event occurs in one of the arteries of the brain this can cause a stroke.

Large-scale population studies have identified nine major risk factors for atherosclerosis; these are smoking, elevated cholesterol, high blood pressure, diabetes, excess alcohol intake, poor diet, stress, physical inactivity, and obesity. Reducing risk factors through lifestyle changes will not remove plaque but will reduce the risk of strokes or heart attacks; likewise medications that lower cholesterol and blood pressure will also reduce these risks.

KEY IDEAS

- Blood is an important transporting tissue.
- The blood of mammals is made up of several different components.
- Arteries are thick-walled vessels that transport blood away from the heart.
- Veins are relatively thin-walled vessels that transport blood to the heart.
- Arteries and veins are connected by networks of arterioles, very thin-walled vessels called capillaries and venules.
- Nutrients and oxygen diffuse from capillaries into tissue fluid then into surrounding tissue cells.

QUICK CHECK

10 What is the function of red blood cells, white blood cells and platelets?
11 Name two components that are transported in solution by the plasma.
12 Why do arteries have thicker walls than veins?

The heart

Blood must be continually on the move — to collect oxygen from the lungs, to collect nutrients from the intestines, to transport the nutrients and oxygen to all the tissues of the body, and to carry carbon dioxide and other wastes away from cells to those specialised regions where they are disposed of by the body. **The heart is the pump that keeps the fluid moving.**

The heart can be thought of as two pumps joined together (see figure 4.27). The right side of the heart receives blood from the head and other parts of the body and pumps it to the lungs. Because the blood has come from tissues, it will be relatively low in oxygen and high in carbon dioxide.

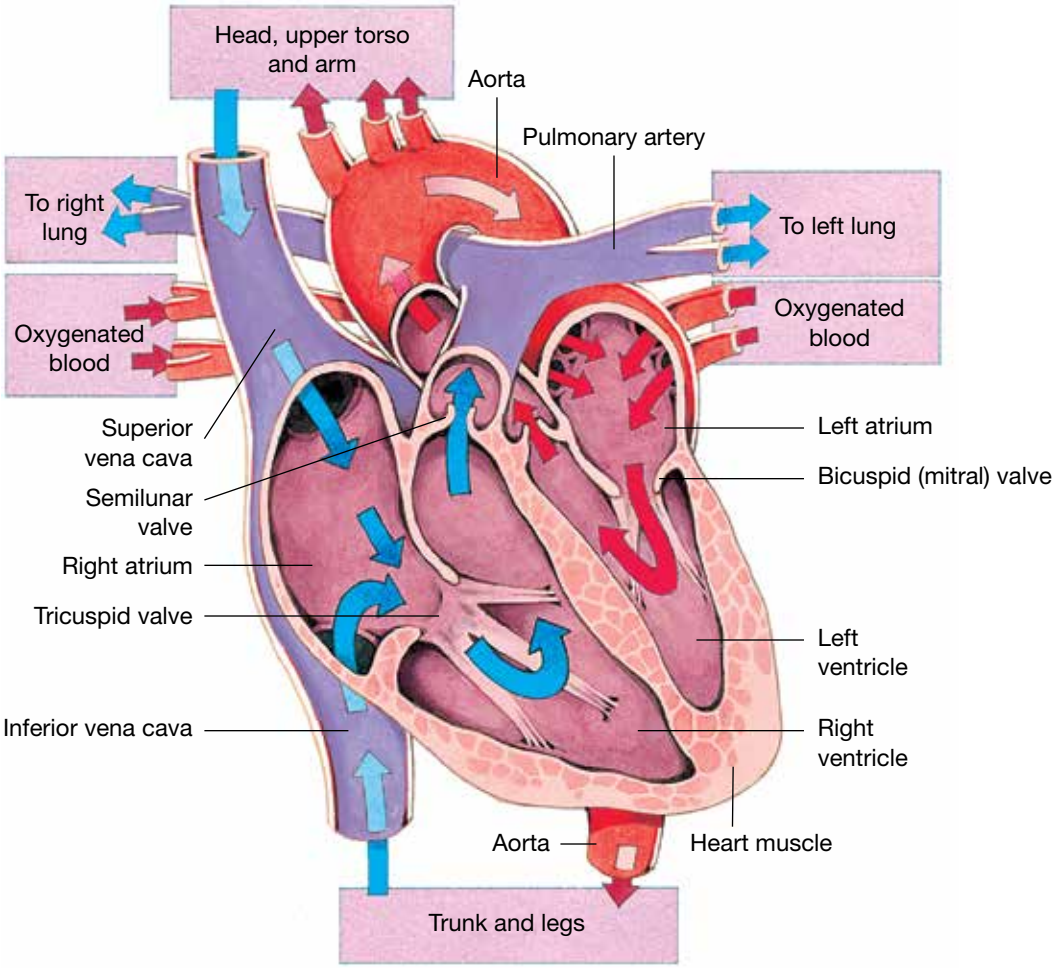

FIGURE 4.27 The human heart is typical of mammals. The pressure generated when the muscle of the thick wall of the ventricles contracts forces blood from the heart to the lungs and other parts of the body. Valves in the heart prevent backflow of blood into the atria when the heart contracts.

In the lungs, carbon dioxide is released from the blood. Oxygen is absorbed from the air in the lungs and combines with the haemoglobin of the red blood cells.

The left side of the heart receives blood from the lungs and pumps it to all other tissues of the body via the main artery known as the **aorta**.

A force from behind is the main factor responsible for the continual movement of blood. A beating heart provides this force. **If a heart stops beating, blood stops flowing.**

Inside the heart

The right and left sides of the heart are separated by the septum, a muscular wall. **Each side of the heart has two chambers,** an **atrium** and a **ventricle**. After blood moves into the atrium on the right side of the heart, it is squeezed into the right ventricle. The walls of the atria are relatively thin because not much cardiac muscle is required to move blood from an atrium into a ventricle.

The right ventricle pumps blood into the **pulmonary artery**. The muscular wall of the ventricle is quite thick because it must pump the blood with sufficient force for it to get to the lungs and back to the heart again. Blood is prevented from moving back into the atrium when the ventricle contracts by valves that separate the two chambers. The valves are flaps of muscle tissue that close over when blood moves out of the ventricle. As the heart relaxes between beats a valve in the pulmonary artery prevents backflow of blood into the right ventricle.

Prior to birth, there is a hole in the septum between the right and left atria. If this hole does not close at birth a baby is said to have a hole in the heart and may require surgery to close it.

Blood travels from the lungs via the **pulmonary veins** to the heart and enters the left atrium. It is squeezed into the left ventricle from where it is pumped out through the aorta to other parts of the body. Valves preventing the backflow of blood are located between the left atrium and ventricle and the left ventricle and aorta.

What can go wrong?

Blocked heart vessels

Blood vessels can become blocked or narrowed, for example, by plaque. Blockages can occur in the coronary arteries that supply blood to the heart muscle and, if the blood flow is interrupted, the region of heart muscle supplied by that artery can be damaged and may die.

Several interventions are available to treat blocked coronary arteries. One such intervention is **coronary bypass graft surgery**, which is used if the damage to one or more of the coronary arteries is severe (see figure 4.28). This is a surgical procedure in which the blocked part of a coronary artery is bypassed by grafting another blood vessel above and below the blocked segment of the coronary artery. The number of bypass grafts depends on the severity of the blockage and the number of coronary arteries affected (see figure 4.29). The blood vessel that is used in the graft comes from another part of the patient's body, most commonly a vein from the leg (the saphenous vein) or, less often, an artery from the inner chest wall (the internal mammary artery). Once in place, the graft re-establishes a normal blood flow to the affected region of the heart and supplies it with essential oxygen and nutrients.

FIGURE 4.28 3D electron beam tomography (EBT) scan showing a heart with a coronary artery bypass graft — the narrow vein running from lower right to top left. The vein, usually taken from the patient's leg, bypasses obstructions in the arteries to enable blood to flow freely again to the aorta.

Another intervention to address blockages or narrowing of coronary arteries is **coronary angioplasty**. This is a nonsurgical technique, used to remove an obstruction in a coronary artery (see figure 4.30). It is performed under local anaesthetic and generally requires only a short stay in hospital. A long, narrow, hollow tube (catheter) is inserted into an artery through a small incision, generally in the groin. X-ray images on a screen are used to guide the catheter up through the aorta to the heart arteries until the blockage is reached. A thinner catheter, tipped with a miniature deflated balloon, is guided through the first catheter until the balloon is in the blockage area. The balloon is inflated and deflated several times. The plaque is pushed against the artery wall and the artery is widened slightly. A fine metallic mesh tube, called a stent, is then inserted into the artery to prevent the artery wall from collapsing. The stent remains inside the artery and within a few weeks the natural lining of the artery grows over it.

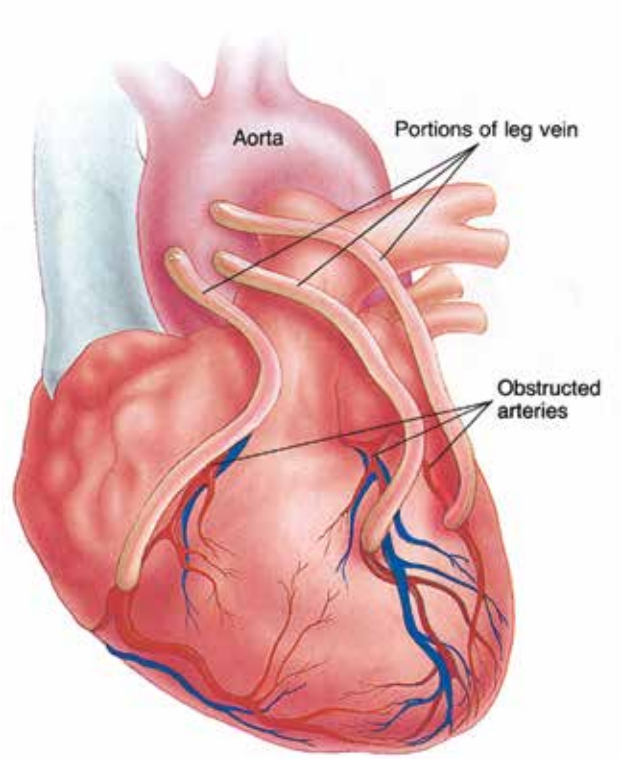

FIGURE 4.29 Heart showing a triple bypass required due to three blocked arteries

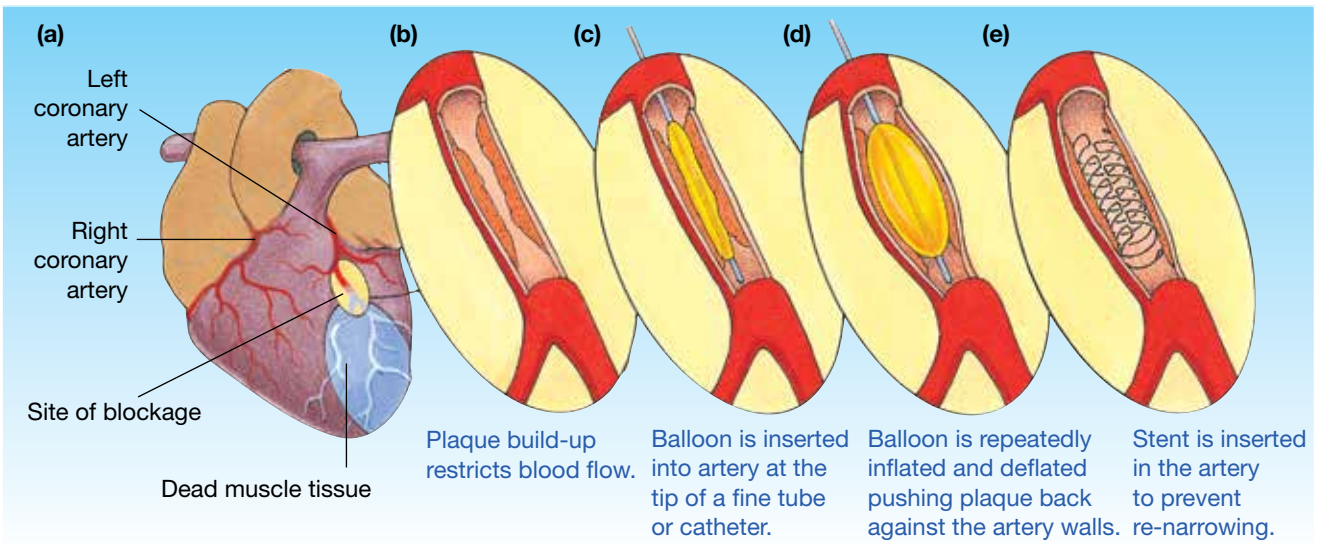

FIGURE 4.30 **(a)** If a coronary artery becomes blocked, heart muscle close to the blocked vessel may die. **(b)** The blockage is due to the build-up of fatty deposits (atherosclerosis or plaques). **(c)** A balloon at the tip of a fine tube, or catheter, is inserted into the artery and when it reaches the blocked area it is repeatedly inflated **(d)** and deflated. The artery widens and the plaque is pushed against the artery wall. **(e)** A fine metallic mesh tube, called a stent, prevents a re-narrowing of the artery at the previously restricted area.

Note the difference in diameter of the coronary artery before and after angioplasty as shown in figure 4.31.

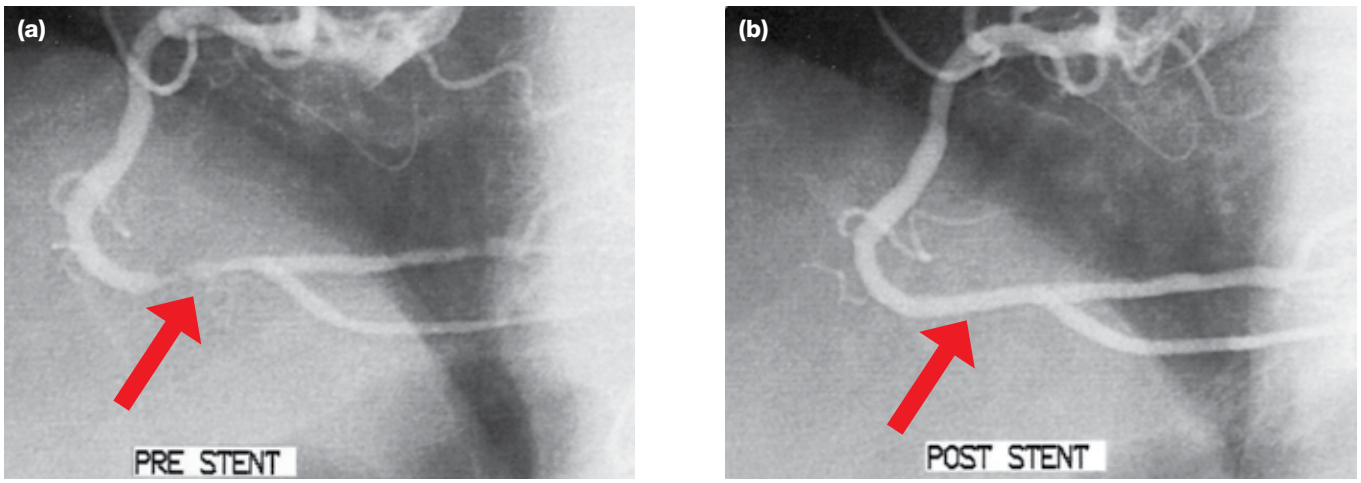

FIGURE 4.31 Image of a coronary artery: **(a)** before and **(b)** after angioplasty. Special dyes are used to observe the flow of blood. This patient had a heart attack 10 days before having angioplasty. He was discharged from hospital two days after the procedure. Arrows show affected segments.

Hypertrophic cardiomyopathy

Another heart condition is **hypertrophic cardiomyopathy (HCM)**, the most common cause of heart-related sudden death in young people aged less than 30 years, including athletes. These deaths often occur during or after physical activity.

HCM is a disorder in which the muscle of the heart becomes thickened and less elastic. Most often, the thickening occurs in the muscular wall that separates the left ventricle from the right ventricle. This thickening has a number of effects: it prevents the heart muscle from relaxing fully so that the heart does not fill fully with blood on each cycle, it may obstruct the blood outflow from the heart, it can cause mitral valve leakage (see figure 4.32) and it may lead to an irregular heartbeat (arrhythmia) or even a heart attack. Persons with HCM are advised to refrain from vigorous physical activity or sudden intense activities such as weightlifting.

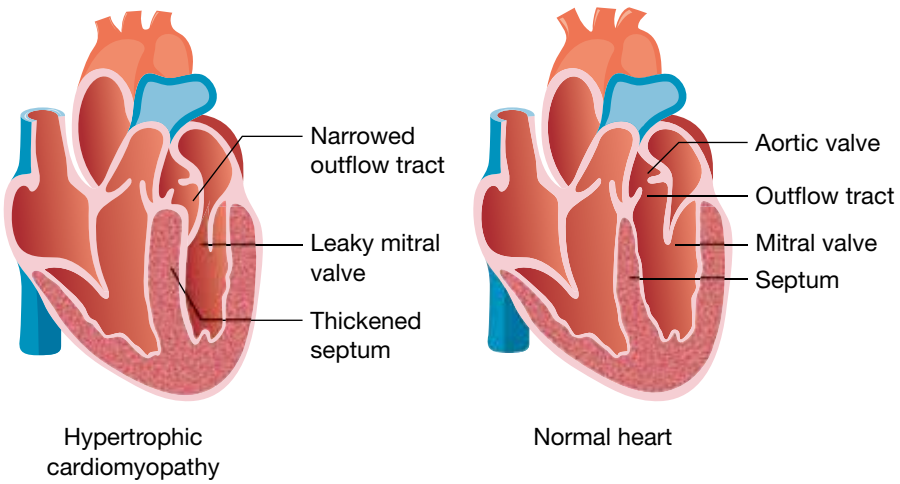

FIGURE 4.32 HCM usually causes a thickening of the muscle wall that separates the left and right ventricles. This thickening, in turn, results in a narrowing of the blood outflow channel and damage to the mitral valve, resulting in leakage.

HCM is the most common genetic cardiovascular disease and most cases of HCM are due to this inherited familial form. Some cases of HCM are not inherited but are acquired, either as a consequence of high blood pressure or from an unknown cause.

ODD FACT

Fibrosis is a type of scarring. Fibrotic, or scar, tissue shows an accumulation of fibroblast cells with an abnormal deposition of extracellular material.

The Baker IDI Heart and Diabetes Institute in Melbourne is a world leader in the area of cardiac magnetic resonance (CMR) imaging. Read the Biologist at work about how this technology is being used by Professor Andrew Taylor, Head of Clinical Imaging, and his research team in studies of cardiac fibrosis. Cardiac fibrosis is a condition in which fibrotic tissue replaces the normal healthy muscle tissue of the heart, leading to abnormalities of heart structure and function. The occurrence of cardiac fibrosis is not specific to HCM. However, a positive correlation has been found between the amount of fibrosis and the degree of ventricle wall thickening in HCM. The identification of the amount of cardiac fibrosis is a pointer to the severity of HCM.

BIOLOGIST AT WORK

Professor Andrew Taylor

I am a cardiologist, currently working full time at The Alfred Hospital, Melbourne in the Heart Failure and Heart Transplant Unit, and at the Baker IDI Heart and Diabetes Research Institute. In addition to directly looking after patients with advanced heart disease, I spend a lot of my time in cardiac imaging, a field of medicine that has advanced greatly over the last decade. While the mainstay of heart imaging has been cardiac ultrasound (known as echocardiography), new technologies have emerged that enable higher resolution imaging of the heart, and are capable of demonstrating tissue characteristics that could not be identified with echocardiography.

FIGURE 4.33 Professor Andrew Taylor of The Alfred Hospital and the Baker IDI Heart and Diabetes Institute. At his left is the CMR imaging equipment.

CMR imaging has evolved into a standard cardiac test and each year we perform close to 1000 of these tests at the Alfred (see figure 4.33). The strength of CMR is that, in addition to providing better image quality than echocardiography, it can also provide information on cardiac tissue, such as the presence of cardiac scarring, oedema, inflammation or fatty infiltration. Figure 4.34 demonstrates cardiac scarring due to a prior heart attack, which is one of the most common abnormalities CMR is used to identify. Our group has utilised CMR imaging in numerous research studies and demonstrated important relationships between cardiac scarring and adverse outcomes in heart failure, including worsening of symptoms, and even sudden death.

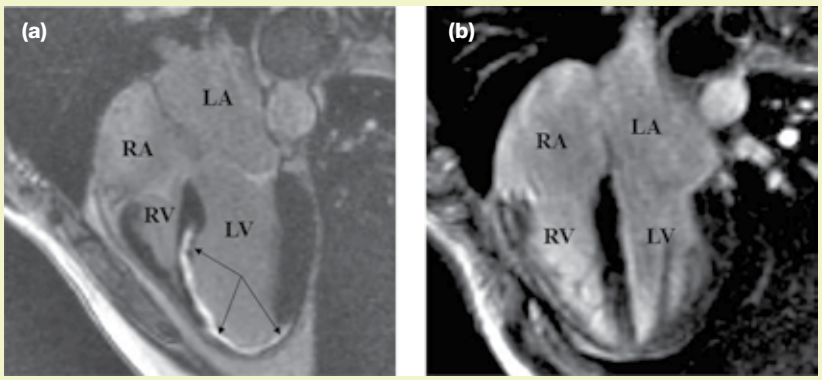

FIGURE 4.34 **(a)** Magnetic resonance image (MRI) of the heart of a patient following a heart attack. Note the extensive scarred heart muscle (arrowed). The contrast between the healthy and the scarred tissues of the heart has been made more apparent by the use of a gadolinium contrast medium that is retained in the damaged heart tissue. LV (left ventricle), RV (right ventricle), LA (left atrium), RA (right atrium). **(b)** Image of the heart of a healthy volunteer

I first studied medicine at university for 6 years to get my basic degree, and after that undertook

4 years of practical training as a medical resident and registrar. Following this I completed a further 3 years of advanced training in cardiology to become accredited as a cardiologist. I then spent another 3 years completing a PhD and a further year working in Berlin where I learned all about the then-new technology of CMR. When I returned to Melbourne in 2003 I established the CMR service at the Alfred, which is one of only a handful of high volume CMR services in Australia.

While becoming a qualified cardiologist was a fairly long road, it has been an exciting and stimulating path. Recently, I have needed to revisit the mathematics from my high school years, as this is important in understanding CMR physics as well as biostatistics, which is essential for the research that I take part in. I now supervise a number of PhD students and am constantly amazed at the high quality of junior doctors and researchers who are coming through the system.

KEY IDEAS

- The heart acts as a pump to maintain a rhythmic circulation of the blood.
- Various technologies can assist in the diagnosis and treatment of disorders affecting various components of the circulatory system.
- The risk of some disorders can increase due to particular personal behaviours.
- Capillaries have walls just one cell thick and are the sites where exchange of materials between the blood and nearby cells can occur.

QUICK CHECK

13 What component of the circulatory system is affected by the following disorders?

a Leukaemia
b Hypertrophic cardiomyopathy
c Aortic aneurysm

studyon
Unit 1 AOS 1 Topic 4 Concept 10
Heterotrophs: metabolic waste and toxin removal
Concept summary and practice questions

The excretory (urinary) system

Living organisms carry out life-sustaining chemical reactions all the time. However, some of these reactions generate products that are toxic, or are in excess of immediate needs but cannot be stored or they can become harmful if they accumulate. As a consequence, these unwanted, excess or toxic metabolic products must be removed in a process known as **excretion**.

For unicellular organisms, such as microbes and some protists, wastes are excreted from their cells through a process of simple diffusion across their plasma membranes to their external environment. For simple animals, such as sponges, diffusion is also their means of excreting wastes. However, as animals became more complex in structure, the ability to excrete wastes depends on special organs and systems. In the case of mammals, one of these systems is the excretory (urinary) system for the excretion of N-wastes, mainly urea. The other major waste product produced by mammals is carbon dioxide, which is excreted by another system, the respiratory system. The principal organs of the human excretory system are shown in figure 4.35, which summarises the function of each part.

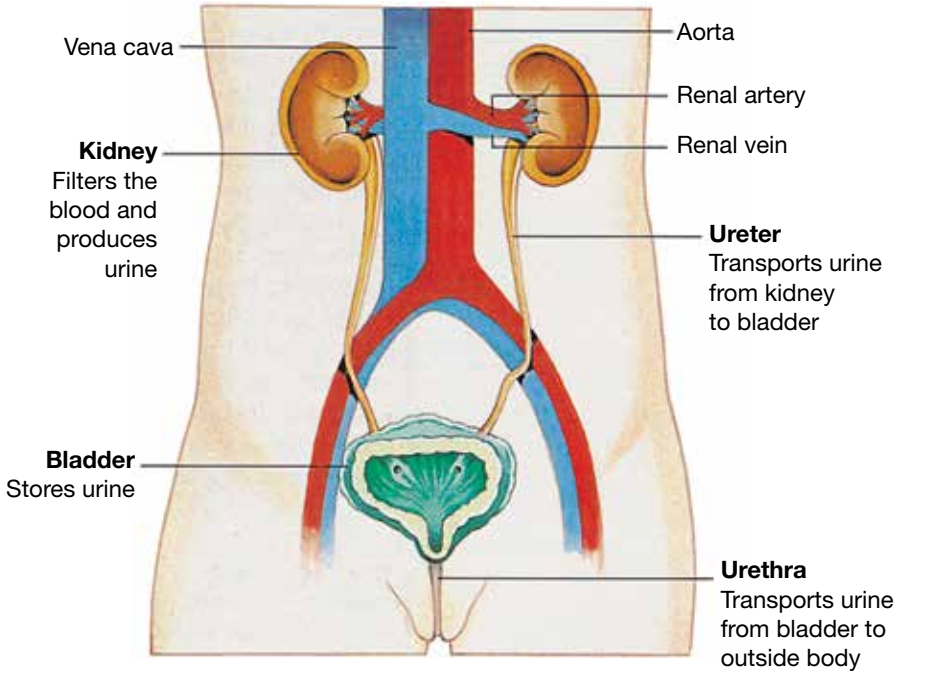

FIGURE 4.35 The kidneys are vital organs that form part of the excretory (urinary) system. Kidneys produce urine that is transported via the ureter to the bladder for storage. From there, it passes through the urethra and is excreted by the body, carrying with it many wastes and other substances that are present in excess or are unneeded.

In this section, we will explore the system responsible for the excretion of N-wastes in mammals. This system is also responsible for ensuring a balance between water gained by the body and water lost. But first, what is the source of these N-wastes?

ODD FACT

Estimated average requirements (EARs) for dietary protein vary by gender and age. For 14- to 18-year-old girls, the EAR is 35 g protein per day, while boys in the same age range have an EAR of 49 g per day.

Sources of N-wastes

For mammals, the major source of the N-wastes they excrete is their dietary proteins. Proteins are essential nutrients that mammals obtain from the food that they eat; foods rich in proteins include fish, meat, eggs, milk, cheese, yoghurt, nuts, grains and the dried seeds of peas and beans (see figure 4.36).

FIGURE 4.36 Proteins are an essential part of the human diet. The percentage of proteins in these foods varies with skinless chicken breast and filet steak (about 28 g protein/100 g), poached salmon (about 21 g/100 g), boiled egg (about 12 g/100 g), almonds (about 17 g/100 g). Fresh beans have low levels of protein but their dried seeds and those of other legumes are very rich sources of protein. Likewise, milk has some protein but its concentrated products such as cheese (about 25 g/100 g) and yoghurt are richer sources of protein.

The proteins in food are broken down into their amino acid subunits through digestion. After absorption into the body, these amino acids are used to build a mammal's own proteins as part of growth and repair. In addition, the proteins of the body are continually being broken down and resynthesised in a process called protein turnover. **However, amino acids in excess of these requirements cannot be stored.**

What happens to excess amino acids? Simply excreting excess amino acids as such would throw away molecules that contain useful chemical energy. Instead, in mammals excess amino acids are transported to the liver where they are 'dissected' into two parts. Figure 4.37 shows a simplified summary of how excess amino acids are treated in mammals. The N-containing part of each amino acid is removed as ammonia (NH_3). The remaining part, known as a carbon skeleton, is used as a source of energy, either by aerobic respiration or by conversion to glucose. The removal of the nitrogen-containing part from an amino acid is a process termed **deamination**. The ammonia that is produced by deamination in liver cells is immediately converted to urea, and this is the form in which most N-wastes of mammals are excreted.

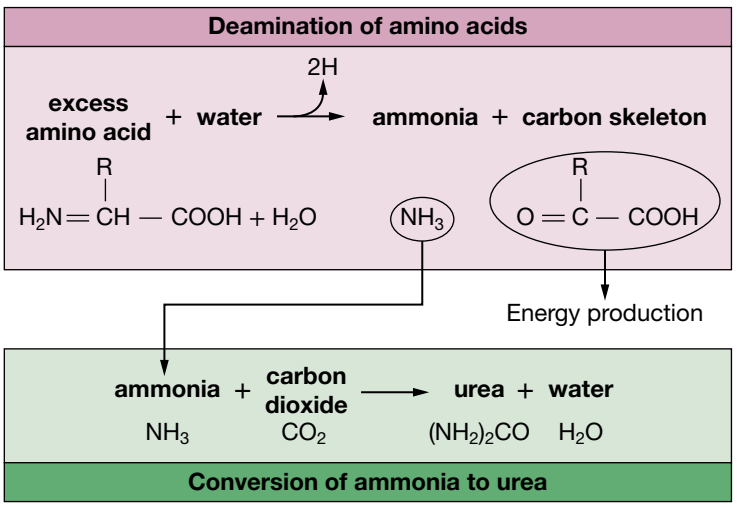

FIGURE 4.37 Excess amino acids are transported to the liver where they are deaminated — this is like a 'dissection' in which the N-containing part of the amino acid is removed as ammonia (NH_3). In mammals, the ammonia is then converted to urea for excretion from the body. The carbon skeleton that remains can be used for energy production.

Deamination of excess amino acids is the major source of N-wastes in mammals. Other N-wastes come from the breakdown of nucleic acids into their nucleotide subunits and from metabolic activity of skeletal muscle that generates creatine and its derivative, creatinine.

Some animals excrete N-waste as unchanged ammonia. Other animals expend energy to convert ammonia to other excretory products, either urea or uric acid. For example, all birds convert ammonia to uric acid for excretion, while all mammals convert ammonia to urea for excretion. The conversion of ammonia to urea or to uric acid for excretion requires an input of energy. Why bother? Is this a waste of energy? The following box will help you think about these questions.

WHY UREA? WHY NOT AMMONIA?

The form in which N-wastes are excreted depends on the availability of water in the environment in which the animal lives, and on the enzymes that it possesses. Table 4.4 outlines the different properties of the three major forms of N-wastes. Of the three excretory products, which has the highest energy cost of production? Which is the most efficient in conserving water? Which is the most toxic? Which N-waste removes the most nitrogen per molecule?

TABLE 4.4 Types of N-wastes excreted by various animal groups

Ammonia (NH_3)	Urea (CH_4N_2O)	Uric acid ($C_5H_4N_4O_3$)
highly toxic	100 000 times less toxic than NH_3	non-toxic
production in liver cells	production in liver cells	production in liver cells
requires least energy	requires more energy	requires most energy
excretion of one molecule removes one N atom	excretion of one molecule removes two N atoms	excretion of one molecule removes four N atoms
very highly soluble in water	good solubility in water	insoluble in water
requires lots of water for excretion: 500 mL needed for excretion of 1 g nitrogen	requires less water for excretion: 50 mL needed for excretion of 1 g nitrogen	requires least water for excretion: 10 mL needed for excretion of 1 g nitrogen
excreted as very dilute urine	excreted as more concentrated urine	excreted as a white semi-solid paste
rapid excretion rate	slower excretion rate	slowest rate of excretion
seen in most aquatic invertebrates, larval amphibians and most freshwater fish	seen in all mammals, sharks, land turtles and adult amphibians	seen in birds, insects, arthropods, some reptiles (lizards, snakes) and land snails

Ammonia

Ammonia is highly toxic (see figure 4.38) and very soluble in water. Because of its toxicity, ammonia must be excreted rapidly from cells and must be diluted in large volumes of water. Note that the excretion of just one gram of N-wastes (in the form of ammonia) requires about half a litre of water. For this reason, the only animals that can excrete N-wastes as ammonia are animals that live in a watery environment, such as aquatic invertebrates.

FIGURE 4.38 Ammonia is a toxic gas. In aqueous solution, it is called liquid ammonia. Its toxic effects can result from breathing ammonia gas or swallowing liquid ammonia.

Urea

The situation for terrestrial animals differs from that of aquatic animals. A constant challenge for animals living in a terrestrial environment is to prevent dehydration by minimising water loss from their bodies. Mammals, for example, excrete their N-wastes mainly as urea and not as ammonia. Advantages of urea are that it is far less toxic than ammonia and its excretion requires far less water than ammonia, which means excreting urea conserves water. However, the conversion of ammonia to urea requires energy:

ammonia + carbon dioxide + 3 ATP → urea + water + 2ADP + AMP

Uric acid

Other animals such as birds, insects and many reptiles excrete their N-wastes as uric acid. The advantages of uric acid are that it is non-toxic and its excretion requires very little water as uric acid is excreted as a semi-solid white paste (see figure 4.39). A key advantage of uric acid is that the developing embryos of birds and reptiles are sealed inside eggs with shells that are permeable only to gases. The N-wastes of these embryos are excreted as insoluble, harmless uric acid crystals that can be safely stored inside the egg. However, the conversion of ammonia to uric acid involves a very complex series of energy-requiring reactions, so this conversion is costly in energy terms; in fact, each molecule of uric acid formed from ammonia requires the energy of 8 ATP molecules.

FIGURE 4.39 Part of a colony of cormorants along the coast of France. Note the extensive white uric acid droppings produced by these birds.

Some animals switch the kind of N-waste that they excrete as their lifestyles change. For example, amphibians such as frogs and toads excrete ammonia when they are tadpoles that live fully in water. As adults living partly on land and in water, frogs and toads excrete their N-wastes as urea. However, some amphibians remain totally aquatic all their lives, for example, the African clawed frog (*Xenopus laevis*), an inhabitant of rivers, lakes, ponds and swamps (see figure 4.40). This frog continues to excrete its N-wastes as ammonia as an adult.

FIGURE 4.40 The African clawed frog (*Xenopus laevis*) lives in water both as a tadpole and as an adult. In what form does it excrete its N-wastes as a tadpole? As an adult frog?

ODD FACT

The masses of uric acid excrement produced by large colonies of seabirds is termed *guano*, and it has been mined for use as an agricultural fertiliser. Currently, fertilisers produced by industrial processes have largely replaced the use of guano as a fertiliser.

KEY IDEAS

- **The major source of N-wastes in mammals is excess amino acids derived from the proteins in their diet.**
- **In mammals, amino acids in excess of requirements cannot be stored.**
- **Excess amino acids undergo a process of deamination that removes their N-containing part, leaving the carbon skeleton.**
- **The ammonia that is produced by deamination in mammals is immediately converted to urea.**
- **In mammals, urea is the form in which most of their N-wastes are excreted.**
- **Other animals excrete their N-wastes either as ammonia or uric acid, depending on the availability of water in their external environment and on the type of egg they produce.**

QUICK CHECK

14 What is the major source of N-wastes in mammals?

15 What are the three major forms in which N-wastes may be excreted by animals?

16 Identify whether each of the following statements is true or false.

- **a** Deamination is the process of removal of nitrogen-containing groups from amino acids.
- **b** The carbon skeleton product from deamination of amino acids is excreted.
- **c** Amino acids in excess of needs cannot be stored by animals.
- **d** The main form in which mammals excrete N-wastes is ammonia.
- **e** Ammonia is more toxic than uric acid.
- **f** More water is required for the excretion of urea than for uric acid.

Human excretory system

All mammals depend on an excretory system to remove N-wastes. The circulatory system transports metabolic wastes (except carbon dioxide) from all body cells to the kidneys for excretion. As a result, the kidneys have a very rich blood supply, which highlights their importance as organs of waste removal. For a person at rest, their kidneys receive blood via the renal artery at the rate of just over one litre per minute. This represents about 25 per cent of the total output of the heart even though the kidneys represent less than 0.5 per cent of the body mass. In contrast, the brain receives about 15 per cent, the heart about 3 to 5 per cent and the skin about 5 per cent of the output of the heart. (Would these figures be expected to change, for example, during vigorous exercise?)

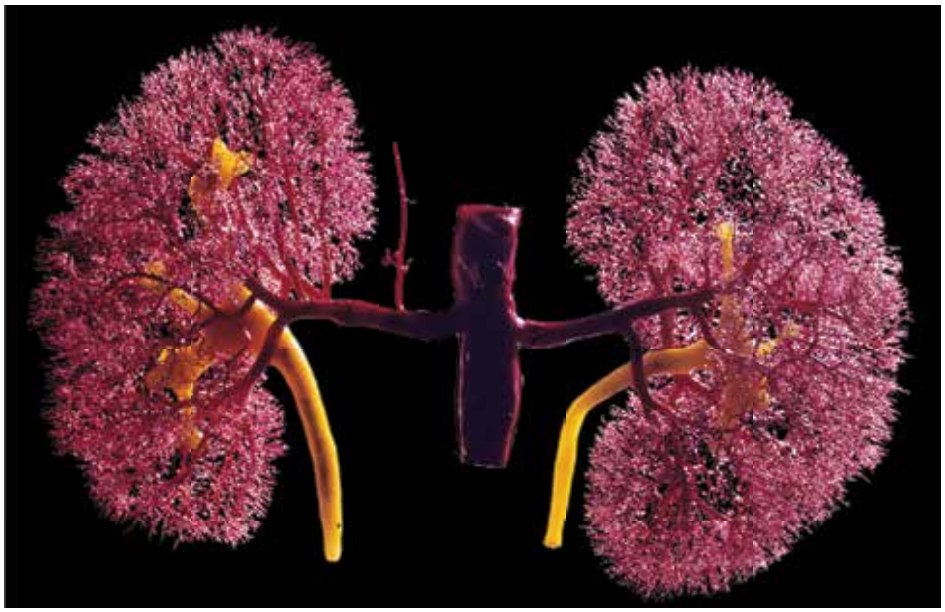

FIGURE 4.41 A resin cast showing the rich blood supply of the kidney. Note the two renal arteries (purple), branching from the aorta, that supply blood to the kidney. The network of blood vessels within the kidney includes the clusters of capillaries (glomeruli). Urine produced by the kidney leaves via the two ureters (yellow) and travels to the bladder.

Urine is the fluid through which N-wastes are excreted from a mammal. Wastes are highly concentrated in the urine, relative to their concentration in the blood. For example, the concentration of urea, the major N-waste, in the blood of a healthy human adult lies in the range of 2.0 to 8.0 mmol /L. The concentration of urea in human urine can reach a maximum of about 880 mmol/L.

Kidneys

You have two kidneys. They are flattened bean-shaped organs, about 11 cm long, 5 to 7.5 cm wide and about 2.5 cm thick. Each kidney weighs about 150 g, and they are located on each side of the spine, partly protected by the rib cage and embedded in a mass of fat for protection. Kidneys are vital organs; you would survive for only a few days without them, although you can live with only one functioning kidney.

Kidneys are adapted for filtering wastes from the blood. They also excrete hormones and other substances such as vitamins that would otherwise build up in the body. Kidneys also maintain a correct balance of ions in the blood by excreting those that are in excess. This maintains the pH (or degree of acidity) of the blood.

A thin layer of cells, the capsule, surrounds each kidney.

The outermost layer of kidney tissue is the cortex, a granular-looking layer that extends into the second, striated layer, the medulla (see figure 4.42a).

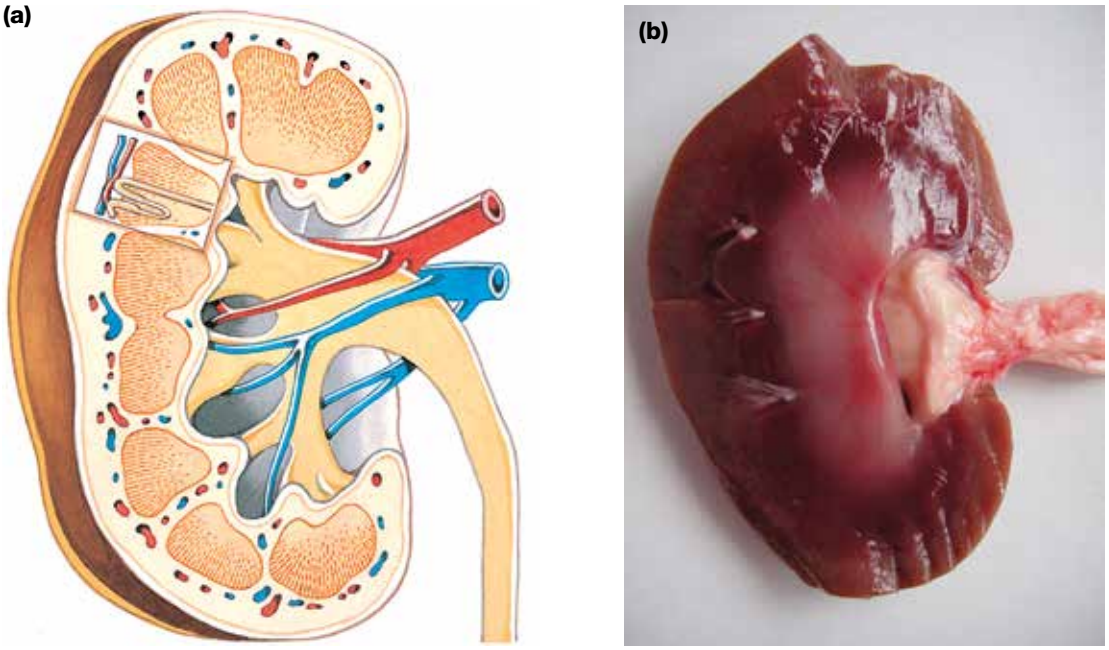

FIGURE 4.42 The mammalian kidney **(a)** Diagram of longitudinal section through a mammalian kidney showing some features of its internal structure **(b)** Longitudinal section through a sheep kidney. The glomeruli and Bowman's capsules are located in the darker outer cortex of the kidney. The lighter inner medulla shows distinctive striations and is the region where the U-shaped portions of the tubules are concentrated. The fatty tissue at the centre right protects the blood vessels that enter and exit from the kidney as well as the ureter, the tube that transports urine to the bladder.

The basic functional unit of the vertebrate kidney is the **nephron** (see figure 4.43; also refer to figure 4.2, p. 134). The processes of filtration and reabsorption in the nephrons enable the composition of body fluids, including blood and tissue fluids, to be maintained or regulated within narrow limits. If there is too much of a compound in the blood, it can be removed via the kidney. The artery that enters the kidney, the renal artery, branches in much the same way as any other artery into arterioles and finally branches into capillaries. Each human kidney has a large number of nephrons, the total ranging from 200 000 to about 2 million. Each nephron consists of a cluster of capillaries, called a glomerulus, and a long tubule that shows clearly defined regions (see figures 4.43 and 4.44). The glomeruli give the cortex its granulated appearance. One end of the tubule, known as **Bowman's capsule** (see figure 4.43), forms a thin-walled container around the glomerulus; this is where the filtrate from the blood enters the tubule. The other end of the nephron joins a collecting duct; this is the duct that carries the modified filtrate, known as urine, to the ureter. Note that part of the tubule, the **loop of Henle** (see figure 4.43), is U-shaped and extends into the medulla of the kidney. The loops of Henle give the medulla a striated appearance.

ODD FACT

It has been estimated that the total length of all nephrons in an individual is about 85 km.

The arteriole that leaves the capillaries of the glomerulus forms another capillary network around the tubules. These are known as the **peritubular capillaries** (*peri* = around). This is the site where materials are exchanged between the bloodstream and the filtrate in the tubules in the processes of reabsorption and secretion.

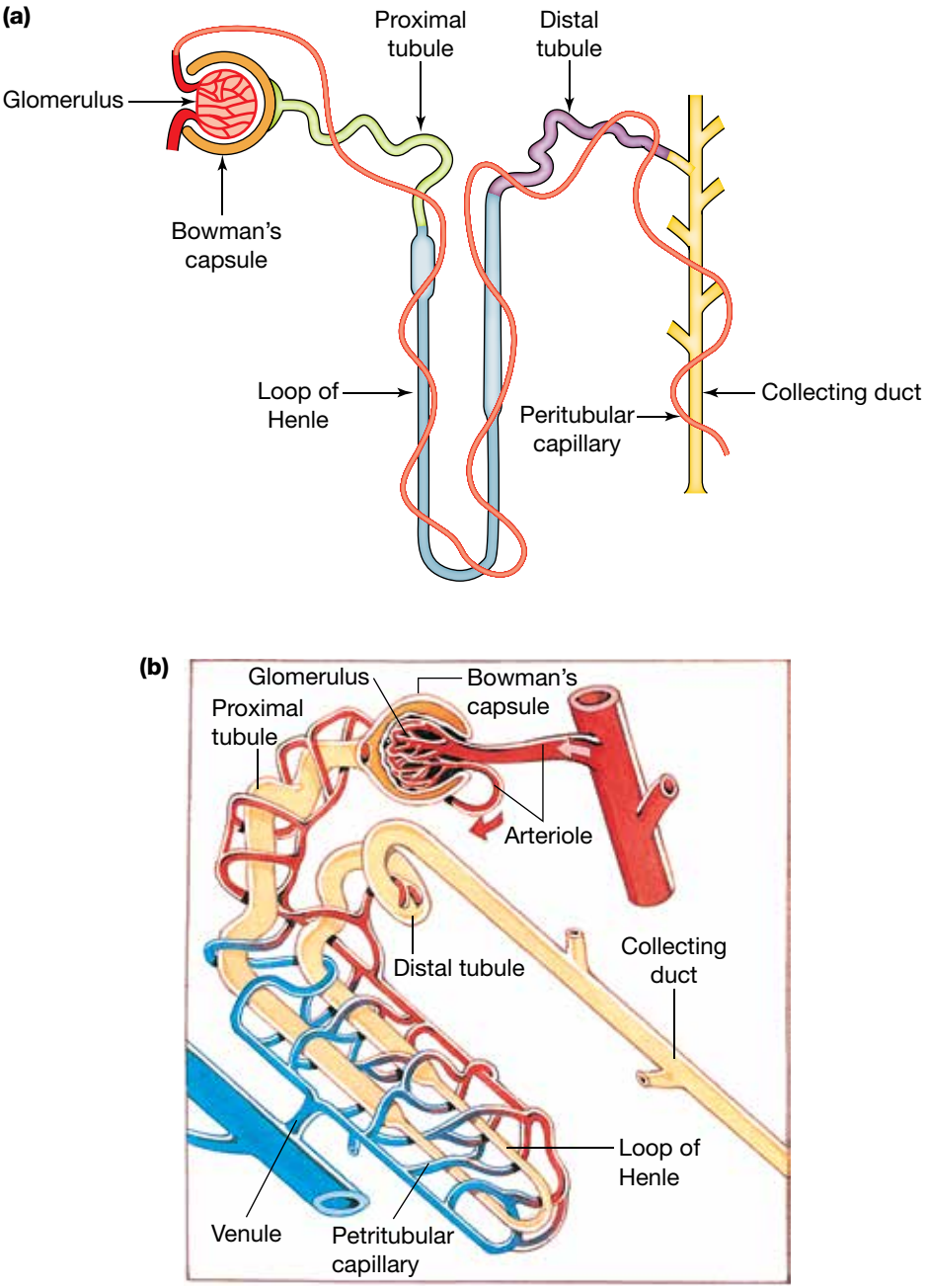

FIGURE 4.43 Kidney nephron **(a)** Simplified diagram of kidney nephron **(b)** Detailed structure of a nephron. Each nephron has five parts: Bowman's capsule, the proximal tubule, the Loop of Henle, the distal tubule and the collecting duct. Note the associated blood vessels: the glomerulus and the peritubular capillaries that wind around the rest of the kidney tubule. This intimate contact of tubule and capillaries enables material to be exchanged between the filtrate in the nephron tubule and the blood.

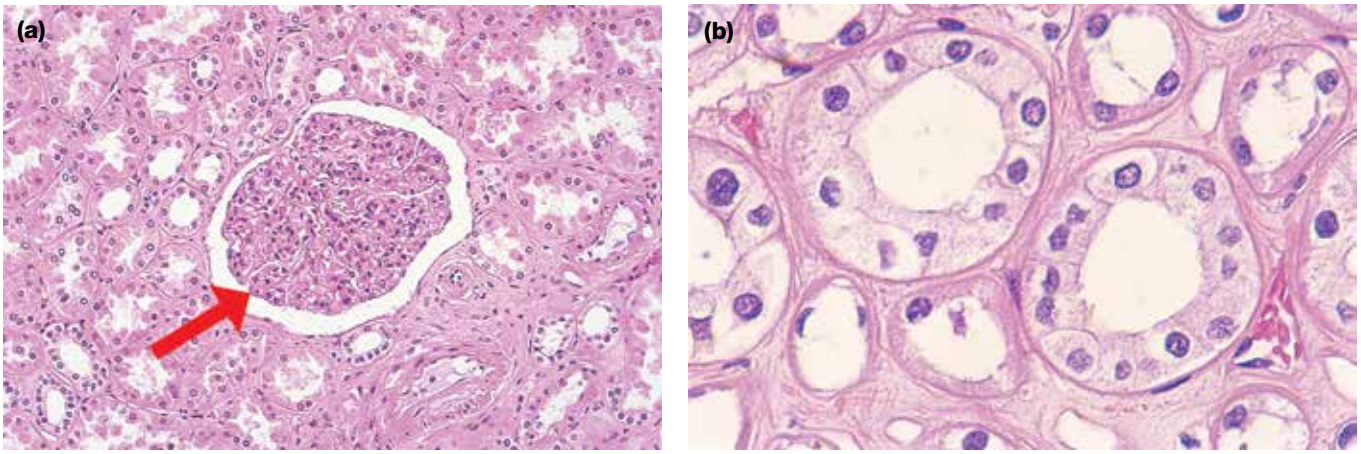

FIGURE 4.44 Photomicrographs of kidney tissue **(a)** Section through the kidney showing a glomerulus (arrowed) within a Bowman's capsule. Filtrate from the blood passes into the space within this capsule. Surrounding the glomerulus and Bowman's capsules are cross-sections through kidney tubules. **(b)** Transverse section at higher magnification showing a cross-section of several kidney tubules. What would be found within the tubules of a functioning kidney?

Making urine

In a 24-hour period, the volume of filtrate produced is about 180 litres, and in the same period the volume of urine produced is about 1 to 2 litres, a reduction of almost 99 per cent. So, in its passage through the nephron tubules, most of the filtrate is reabsorbed. The reabsorption involves processes of active transport of ions and some organic molecules, such as glucose. The reabsorption of water is by passive diffusion down the concentration gradient created by the reabsorption of ions. The average change in the volume of filtrate as it passes through the nephrons is shown in table 4.5. At the end, it is termed urine. In which region of the kidney tubule does most of the reabsorption of water occur?

TABLE 4.5 Average change in volume of filtrate in its passage from Bowman's capsule to the end of the collecting duct of the nephron

Location	Percentage of original filtrate present
Bowman's capsule	100
end of proximal tubule	20
end of Loop of Henle	14
end of distal tubule	5
end of collecting duct	1

Note: The percentage changes are given as average figures.

ODD FACT

Cats excrete urine that is more concentrated than that of humans. If cats are fed food with high levels of magnesium and drink little water they may develop bladder stones from crystals of magnesium and the urethra may become blocked. This is called feline urologic syndrome (FUS) and can be fatal if it is not treated. Both sexes suffer from the condition but males are more likely to have a blocked urethra. This condition can be minimised by ensuring that cats have access to fresh water.

Formation of urine

Waste materials are filtered from the blood in the coiled capillaries that form the glomerulus. Note that the arteriole leaving a glomerulus has a smaller diameter than the arteriole entering a glomerulus. This means that the blood in the glomerular capillaries is under pressure. Because blood is under pressure, substances are forced through the glomerular walls and into the Bowman's capsule. About one-fifth of all plasma that passes through a glomerulus is filtered through the capsule into the tubule. In a healthy kidney, proteins and other large macromolecules, as well as the blood cells, do not leave the blood. The filtrate that moves into the kidney tubule from the glomerulus contains water, N-wastes, nutrients, such as glucose, and salts. Obviously some of these compounds can be used by the body and need to be re-absorbed from the tubule fluid into the bloodstream in some way (see figure 4.45).

As fluid moves along the tubules, useful compounds that have been filtered out in the glomerulus, such as glucose, are reabsorbed into the capillaries that wind around the tubule (refer to figure 4.44b). In some cases this reabsorption occurs by a process of diffusion, while other compounds are actively transported against a concentration gradient (see figure 4.45).

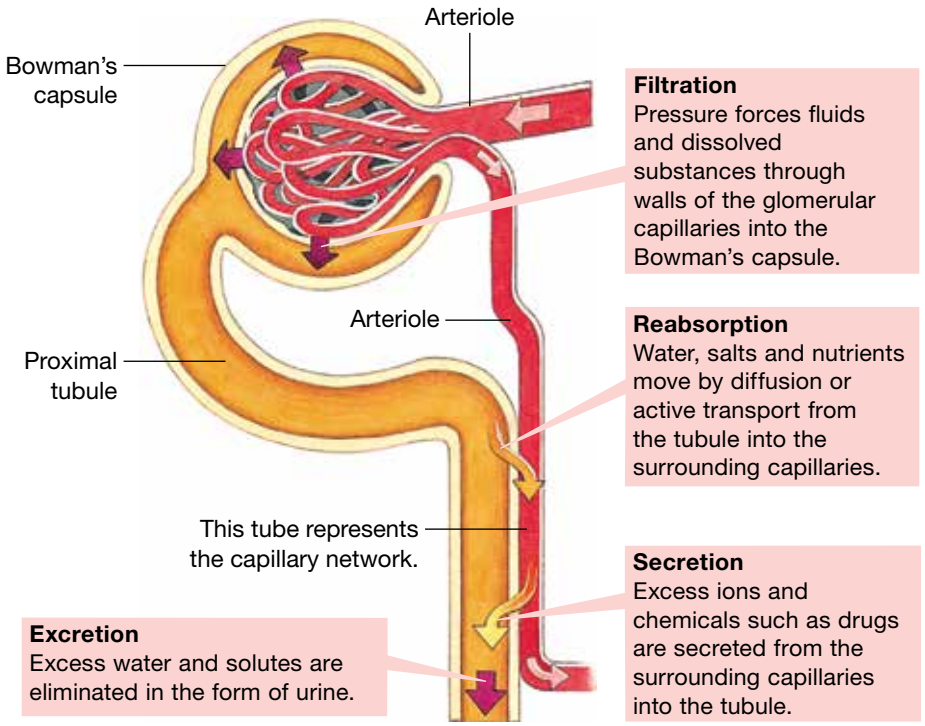

FIGURE 4.45 Summary of urine formation in mammals. Material forced through the glomerulus into the Bowman's capsule passes along the tubule of the nephron. Some material and much of the water is reabsorbed from the nephron tubule by the blood; other material is added to the filtrate in the tubule.

In addition, some compounds are added to the filtrate from the bloodstream by a process called **secretion**, in particular, pharmaceutical drugs such as penicillin. Some ions are also secreted. The secretion of ions helps the body control the pH or acidity of blood and other tissues. As hydrogen ions are secreted into the tubule, sodium ions are displaced from the fluid and reabsorbed by the body.

The fluid that reaches the end of the nephron tubule is urine. Because of the reabsorption that has taken place along the tubules, only about one per cent of the fluid that is filtered by the glomeruli actually leaves the kidney.

The composition of a person's urine, how much is produced and its pH depend on the body needs of that person. For example, a diet high in protein leads to higher concentrations of N-wastes in the urine. If a person is on medication of some kind, that material may be found in urine. High doses of vitamin C result in that vitamin being found in the urine. A person of average health on a mixed diet produces 1200–1500 mL urine daily. The composition of this is shown in table 4.6.

TABLE 4.6 The composition of urine from a person of average health on a mixed diet

Component	Percentage
water	95
solids, including:	5
• urea	2
• uric acid	0.03
• ammonia	0.05
• creatinine	0.1
• sodium	0.6
• chloride	0.6

Mammals produce **hypertonic** urine. Hypertonic urine contains a higher concentration of solutes than are present in the body fluids of the same animal. Other animals, such as freshwater bony fish and amphibians, produce **hypotonic** urine. Hypotonic urine contains a lower concentration of salts than do the body fluids of the same animal.

The urine is carried away from each kidney by the ureter. Each of these tubes is about 25–30 cm long and has a diameter of just over 1 cm at its widest part.

Two ureters, one from each kidney, transport the urine to the bladder, a muscular bag that stores the urine until it leaves the body. The urine is transported from the bladder to outside the body by the urethra.

In summary, the key functions of kidney nephrons are (see figure 4.46):

1. *Filtration of the blood.* Filtration occurs at the glomerulus where the filtrate from the blood is forced into the Bowman's capsule. The average filtration rate in a healthy adult is up to 180 litres per 24 hours. Yet the average amount of urine

produced by a person in a 24-hour period is only 1 to 2 litres. Clearly, something else happens in the kidney and this is the process called reabsorption.

2. *Reabsorption*. Reabsorption is the process by which water and other substances are removed from the tubule fluid and returned to the bloodstream. Reabsorption occurs mainly in the proximal tubules. Useful substances, including water, glucose and electrolytes, such as Na^+ ions, Cl^- ions and potassium ions are transported from the filtrate back into the peritubular capillaries.
3. *Secretion*. Secretion is a process of active transport of substances including drugs and ions from the blood in the peritubular capillaries into the fluid in the distal tubule. Substances that are secreted include drugs (e.g. penicillin and morphine) and some ions such as hydrogen ions that are important for acid–base (pH) balance.

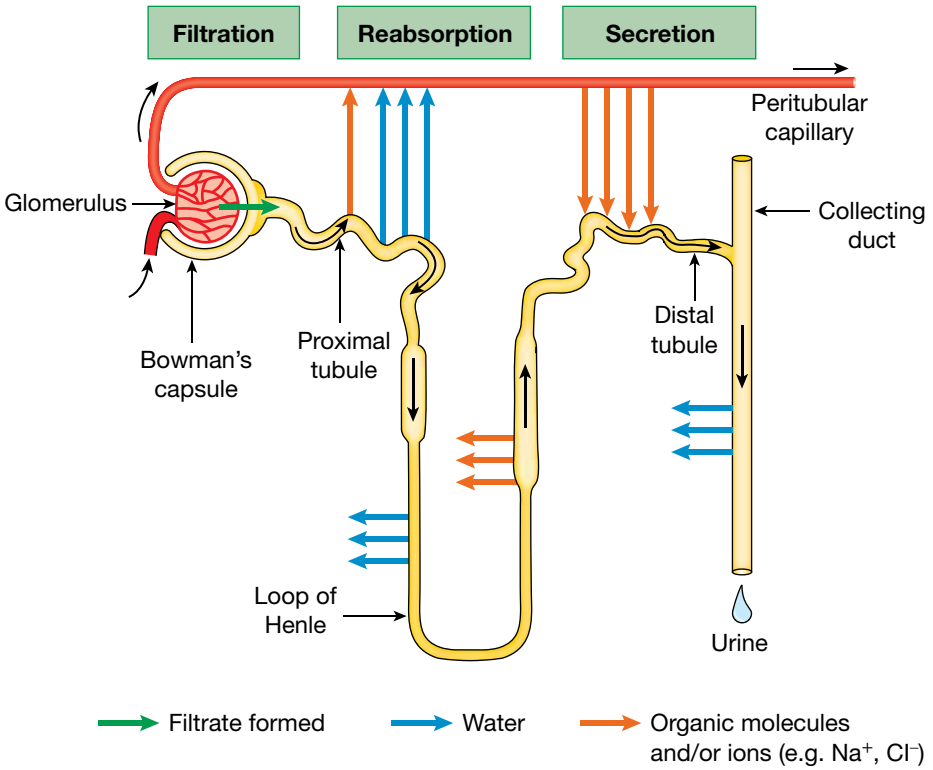

FIGURE 4.46 Stylised and simplified diagram showing the structure of a nephron and the key functions of its various sections of the tubule: glomerular filtration, tubular reabsorption and tubular secretion. Filtrate from the capillaries of the glomerulus passes into the space within the Bowman's capsule. The filtrate with toxic, excess and unneeded substances then passes along the nephron tubules. Water and useful substances (organic molecules and ions) are reabsorbed from the filtrate at various points along the tubule and returned to the bloodstream at the peritubular capillaries. Additional substances (drugs and other ions) are also removed from the blood and added to the kidney filtrate by a process of secretion.

The final volume of urine produced at the end of the collecting duct is given by the following equation:

$$\text{volume of urine} = \text{volume filtered} - \text{volume reabsorbed} + \text{volume secreted}$$

or

$$\text{excretion} = \text{filtration} - \text{reabsorption} + \text{secretion}$$

The excretory system provides an example of how organs (kidneys, ureters, bladder and urethra) can be combined to form a working system that carries out a major life-sustaining function in a mammal. Systems do not operate in isolation; the excretory system is dependent for its operation on the circulatory system.

What can go wrong

Problems with kidneys and kidney function are the major causes of issues in the excretory system:

1. *End stage kidney disease.* Kidney failure of varying degrees can occur, with the most serious condition being end stage kidney disease. In the introduction to this chapter (p. 134), this condition was discussed as was the use of haemodialysis to replace some of the defective kidney functions.

2. *Kidney stones*. Another condition that can affect the mammalian excretory system are kidney stones, also termed renal calculi. Kidney stones are hard crystalline deposits made of minerals and acid salts that form in the kidney. From there, stones can pass to other parts of the urinary system or may stay lodged in the kidney. Kidney stones can be produced if the urine volume is decreased making the urine more concentrated. This can occur if a person becomes dehydrated. The mineral most commonly found in kidney stones is calcium oxalate (in about 70% of cases). Other minerals include calcium phosphate (10%) and uric acid (5–10%).

KEY IDEAS

- In unicellular microbes, protists and the simplest animals, wastes are removed by a process of simple diffusion across the plasma membrane.
- Animals with complex multicellular structures use specialised tissues, organs and systems for waste removal.
- In mammals, the excretory system is responsible for removing N-wastes from the blood and plays a role in water balance.
- The mammalian excretory system consists of several organs, with the principal organ being the kidneys.
- The functional unit of the kidney is the nephron.
- End stage kidney disease is a serious and life-threatening condition.
- Haemodialysis is a medical intervention that can replace some of the defective kidney functions.

QUICK CHECK

17 What is the main excretory product found in human urine?

18 Identify whether each of the following statements is true or false.

a Drugs are among the substances that are secreted into the tubules of the kidney nephrons.

b Reabsorption of substances occurs by both passive diffusion and active transport.

c The concentration of urea in the blood is equal to its concentration in the urine.

19 Identify a medical intervention that can be used in end stage kidney disease.

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Unit 1 AOS 1 Topic 4 Concept 7

Heterotrophs: respiratory system
Concept summary and practice questions

Mammalian respiratory system

Aerobic respiration produces essential energy in the form of the chemical energy of ATP. The following equation shows that another product is carbon dioxide:

$$\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy (ATP)}$$

For those organisms, both autotrophs and heterotrophs, that depend on aerobic respiration for their supply of energy, oxygen is an essential reactant that must be supplied to every cell. The carbon dioxide produced by aerobic respiration is not needed by heterotrophs, and is a waste product that must be excreted.

Animals that depend on aerobic respiration for staying alive must have a means of obtaining oxygen for supply to all their cells and a means of removing carbon dioxide from their cells. This is the essence of gas exchange: oxygen in and carbon dioxide out.

For unicellular microbes and protists, these needs can be met by simple two-way diffusion across their plasma membrane. Simple animals such as

sponges and jellyfish also rely on gaining oxygen and losing carbon dioxide by diffusion into and out of their body cells. Complex and larger multicellular animals, however, have specialised tissues, organs and systems where the oxygen they require can be taken into the body and the carbon dioxide waste can be removed; this is the role of the organs of the respiratory system. In addition, these animals typically use a transport system, such as the blood circulatory system, to distribute oxygen that enters the body to all its cells and to carry waste carbon dioxide away from its cells.

The surfaces where gas exchange occurs are specialised respiratory surfaces. In mammals, these surfaces are within the lungs and they have a number of features, including:

- having a large surface area
- being constantly moist because gases need water for their diffusion
- being thin to ensure a short diffusion distance
- having a concentration gradient across the surface
- having respiratory surfaces very close to a rich network of blood capillaries that either carry gases away from or bring gases to the respiratory surface.

In mammals, the respiratory surface is kept moist and protected from drying out by being folded inside the body surface — a bit like pockets within the body.

Human respiratory system

Figure 4.47 shows the human respiratory system with the lungs that are key organs in gas exchange. Lungs are the respiratory organs, not only in people, but also in other terrestrial vertebrates.

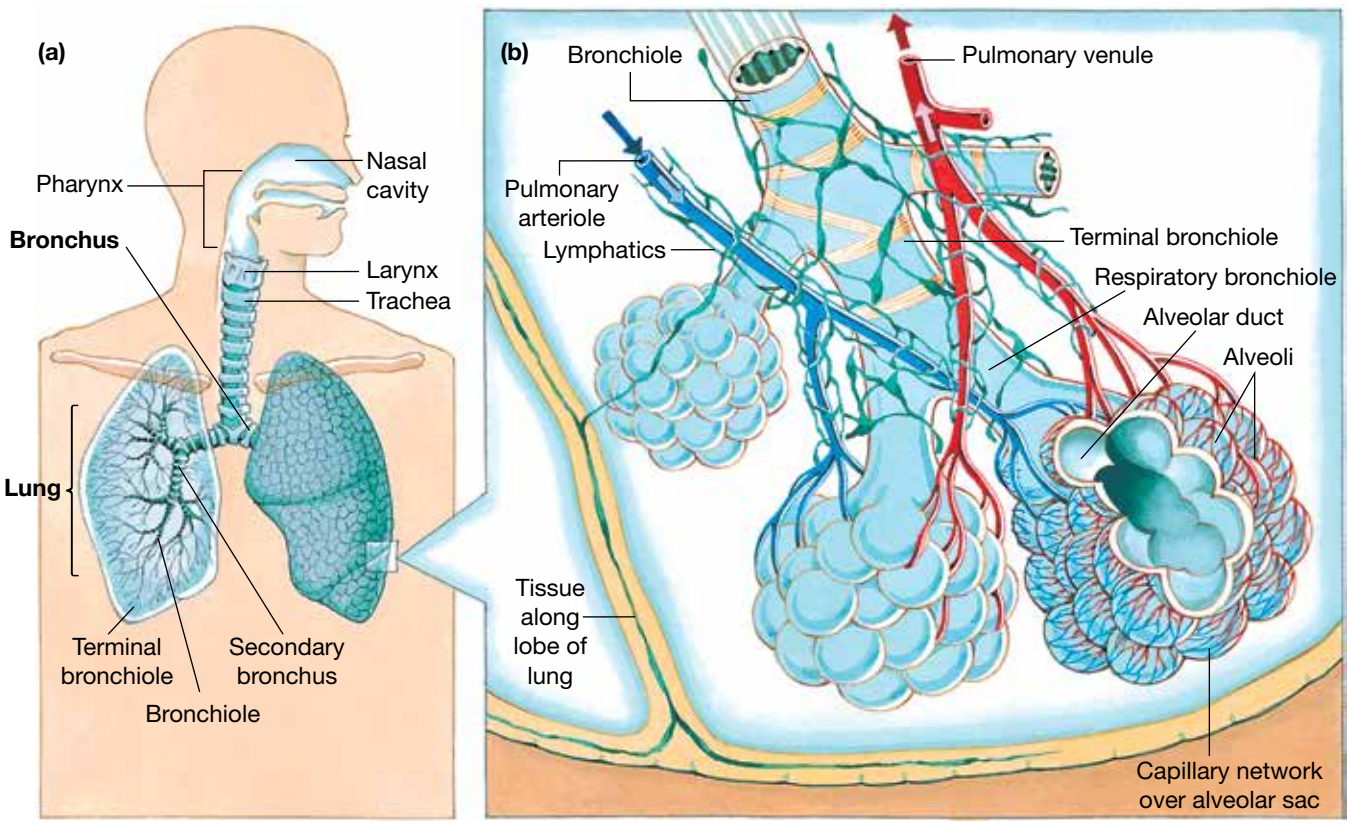

FIGURE 4.47 **(a)** Organs of the human respiratory system. The major organs for gas exchange are the lungs. **(b)** A portion of the lung expanded to show some detail. Note in particular the clusters of alveoli at the ends of the terminal bronchioles. A cluster of alveoli forms an alveolar sac. Alveoli provide the respiratory surfaces where gas exchange occurs. As expected, they are closely associated with a network of capillaries.

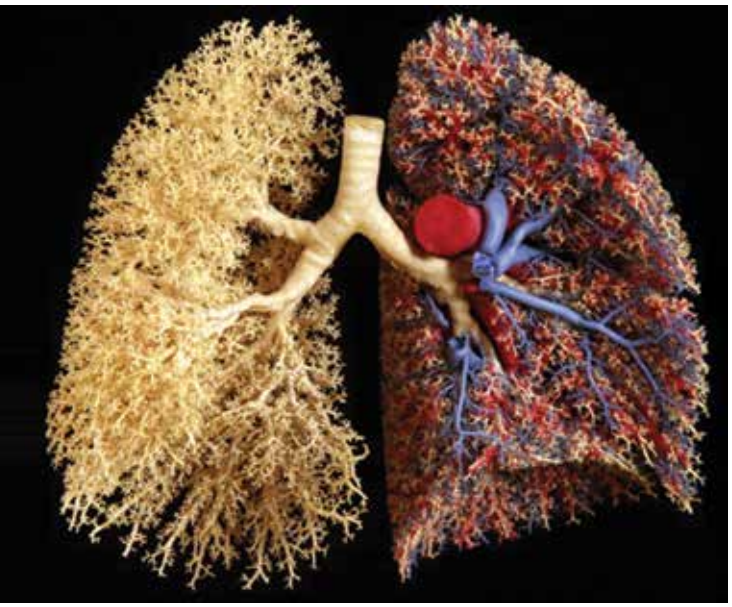

FIGURE 4.48 Latex cast of the airways (white), the arterial blood vessels (red) and the veins (blue) of the mammalian lung (Image courtesy of the Institute of Anatomy, University of Bern, Prof Ewald R Weibel)

The lungs are paired, lobed organs lying in the thoracic cavity (the chest). Air reaches the lungs via an airway that starts at the nasal cavity and continues as the trachea (windpipe), that is, the main airway in the chest. The trachea divides into two bronchi (singular: bronchus) that enter the lungs. Within the lungs, each bronchus divides into tubes of smaller and smaller diameter, called bronchioles. Figure 4.1 (p. 133) indicated the extensive branching of the airways. At the ends of the smallest bronchioles are alveolar sacs composed of many alveoli.

The lung has a rich supply of blood vessels. Blood vessels deliver blood loaded with carbon dioxide from body cells to the capillary beds that surround the alveoli. Here, carbon dioxide is unloaded into the alveoli and oxygen is picked up from the alveoli for delivery to all body cells. Figure 4.48 shows the complex of blood vessels (arteries and veins) and the airways in a mammalian lung.

The interior of the lung is not smooth like an inflated balloon. Rather, the interior of the lung contains many tiny air-filled, moist compartments — these are the alveoli (see figure 4.49). These alveoli create a large internal surface area that forms the respiratory surface. This is where exchange of gases occurs between the air in the alveoli and the blood in the capillary networks that surround the alveoli. The junction between the alveoli and the capillaries is called the blood–air barrier or the alveolar–capillary barrier. It is essential that gases can diffuse across this barrier. But it is also essential that air bubbles cannot get into the blood from the lungs and that blood cannot get into the lungs.

ODD FACT

The right lung is larger than the left lung. The right lung consists of three lobes of lung tissue while the left lung has just two lobes.

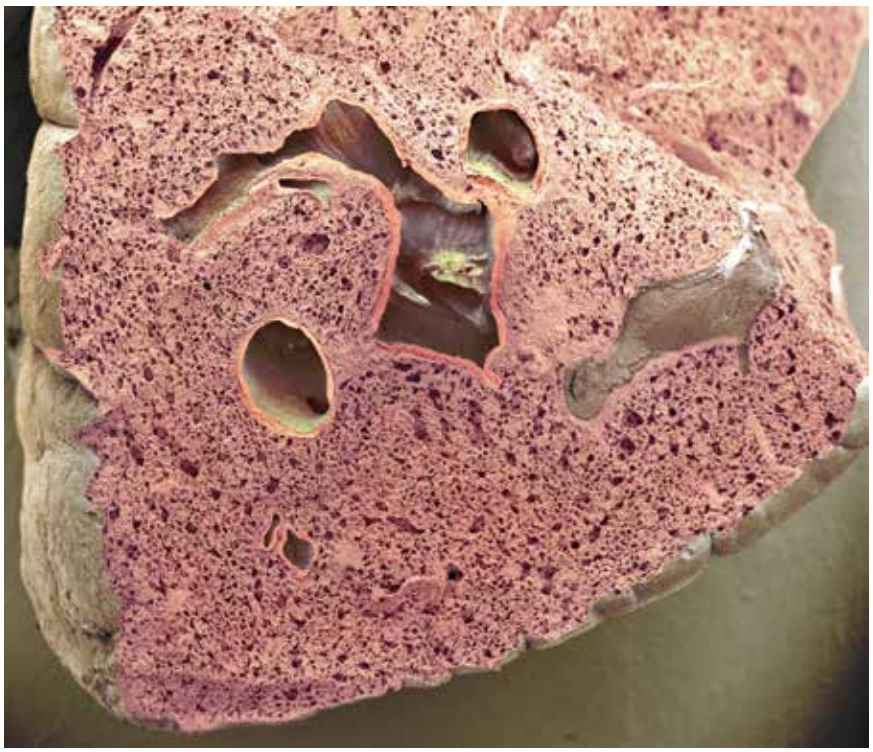

FIGURE 4.49 Healthy lung tissue is moist, soft and spongy because of the many air-filled alveoli present in the lung tissue. The pink colour comes from rich blood supply to the lungs, including the blood in the many capillaries that surround the alveoli. The larger holes visible in this image are bronchioles.

ODD FACT

On average, the human lung is estimated to contain more than 400 million alveoli, with a surface area of about 130 m^2.

Figure 4.50 shows a section through the alveoli in the deepest sections of the lungs. The spaces are the air sacs of the alveoli and they are closely associated with capillaries. You can identify the capillaries because they are filled with red blood cells. The junction between the alveoli and the capillaries are the sites of gas exchange.

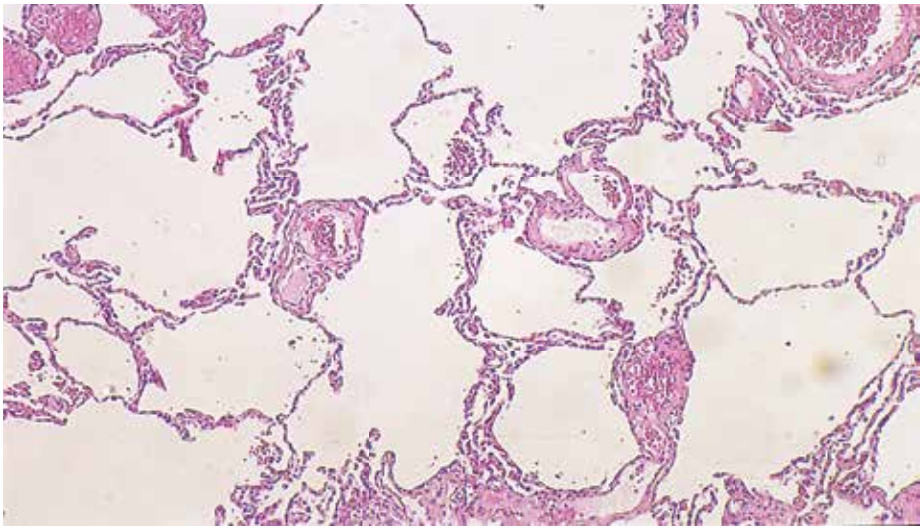

FIGURE 4.50 Photomicrograph showing a section through alveolar tissue of the lung. Note the thin boundaries between the alveoli that, in association with the capillary walls, form the blood–air barrier.

This branching of tubes, which ends in about 300 million alveoli, **provides an extremely large surface area across which gases are exchanged.** It has been estimated that the surface area of the alveoli is about 130 m^2. Compare this with the surface area of the skin of an average adult — about 2 m^2!

The alveolar–capillary membrane is very thin (only about 0.004 mm thick). Oxygen diffuses from the air in the alveoli across the alveolar–capillary membrane into the blood where it combines with haemoglobin in the red blood cells. At the same time, carbon dioxide diffuses from the blood, mainly from the plasma, into the alveoli (see figure 4.51).

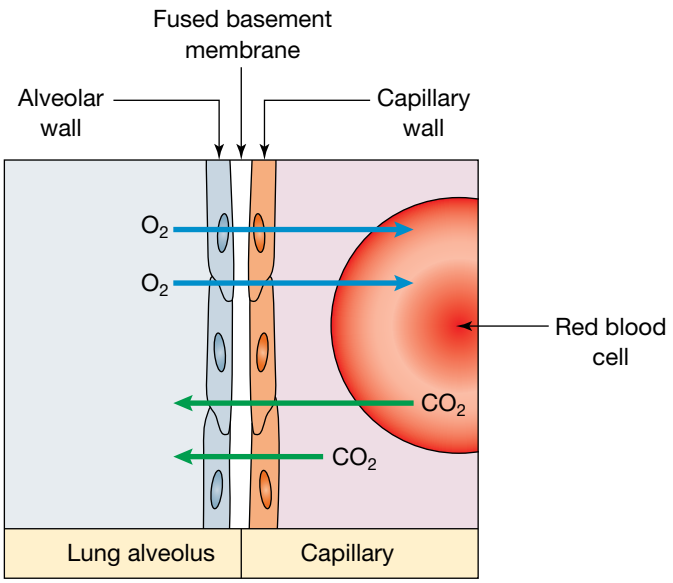

FIGURE 4.51 Alveoli provide the respiratory surfaces of the lungs for gas exchange. This diagram shows part of the alveolar respiratory surface. Note the thin border of the respiratory surface (left) that is just one cell thick. It is very close to a capillary (right) that also has a border just one cell thick. Gas exchange can readily occur with oxygen moving by diffusion from alveoli to blood and waste carbon dioxide moving by diffusion from the blood into the alveoli.

Although most carbon dioxide is carried in the blood in the form of bicarbonate ions (70 per cent) in plasma, about 23 per cent combines with haemoglobin and the balance is dissolved in plasma.

When a person breathes in and out, air moves in and out of the lungs. Air going into the lungs contains more oxygen than air leaving the lungs, and air leaving the lungs contains more carbon dioxide than air entering the lungs. Steep concentration gradients enable oxygen to diffuse from the alveoli into the capillary blood, and carbon dioxide to diffuse from the capillary blood into the alveoli. The concentration gradient for oxygen is constantly maintained because the continuous blood flow brings oxygen-poor blood to the capillaries surrounding the alveoli, while regular breathing brings oxygen-rich air into the alveoli. Likewise, the concentration gradient for carbon dioxide is constantly maintained because blood brings carbon dioxide–rich blood to the capillaries surrounding the alveoli, while breathing brings air that is poor in carbon dioxide into the alveoli. There is never a complete changeover of air in the lungs. When we breathe out, there is always some air left in the lungs. This mixes with air that enters the lungs. We can reduce the amount of air that is left in the lungs by breathing more deeply; however, there is always a mixture of new and used air in the lungs.

When you breathe in the diameter of each alveolus expands to about 0.1 mm, and when you exhale its diameter shrinks to about 0.05 mm.

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Unit 1 AOS 1 Topic 4 Concept 8
Organ and system failure: respiratory disease
Concept summary and practice questions

What can go wrong?

The alveoli of the human lungs provide the respiratory surface that enables gas exchange to occur. **Emphysema** is a respiratory disease in which the alveoli progressively become more and more damaged. The walls of the alveoli become weak, overstretched and can rupture, and they lose their elasticity. Breathing out becomes more and more difficult, but not breathing in. Figure 4.52 shows an example of normal alveoli alongside alveoli with the typical damage of emphysema.

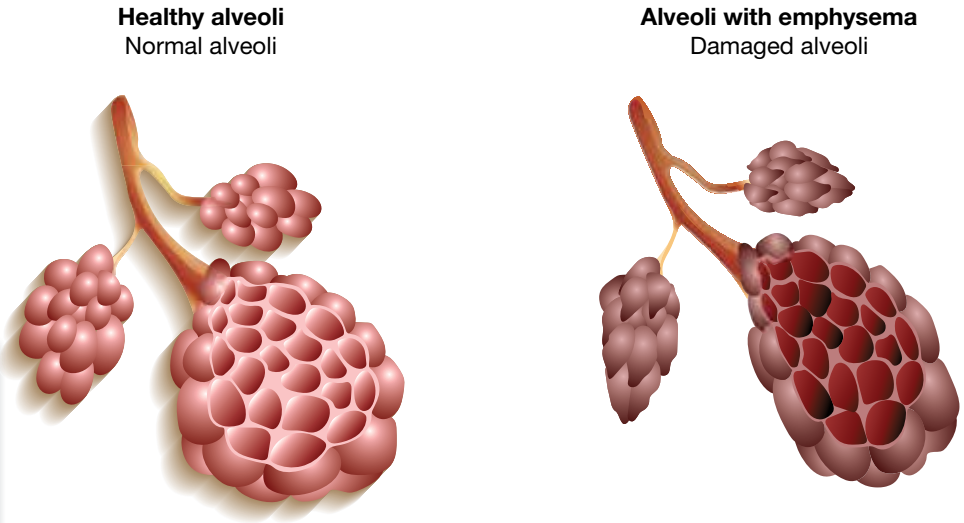


FIGURE 4.52 Diagram showing normal alveoli of human lung (left) and alveoli showing the typical damage of emphysema (right)

The damage to the alveoli results in the creation of fewer large air spaces in place of the normal numerous small spaces within the alveolar sacs. This significantly reduces the respiratory surface area of the lungs for gas exchange. A further complication is that the loss of elasticity of the alveoli means that persons with emphysema becomes less and less able to empty their lungs when they exhale. Overall, their ability to take up oxygen and remove carbon dioxide is severely restricted. Persons with emphysema feel permanently short of breath and cannot sustain physical exercise.

The leading cause of emphysema is smoking, with the risk increasing as the amount of tobacco smoked and the number of years of smoking increase. Emphysema can also result from long-term exposure to air pollution or dust, or occupational exposure to certain chemicals or industrial fumes.

Some people may develop an inherited form of emphysema. This form of emphysema is very rare and is due to an inherited deficiency of a protein, known as alpha antitrypsin, that protects the elastic structures of the lungs.

Unfortunately, once alveoli are damaged, this damage cannot be reversed. However, medical treatment may assist in relieving the symptoms of emphysema and slow its progression. Among possible treatments are the use of bronchodilator medication or corticosteroid aerosols to reduce breathlessness, participation in rehabilitation programs involving breathing exercises and the use of supplemental oxygen to raise the blood oxygen levels when oxygen saturation levels become low, as may occur in the later stages of this disease.

KEY IDEAS

- Animals exchange gases with their external environment through special surfaces in their respiratory systems.
- Respiratory surfaces have a large surface area, are moist, have thin cellular boundaries and are closely linked to a transport system.
- Gas exchange typically involves oxygen needed for aerobic respiration and carbon dioxide, a waste product of that same reaction.
- Mammals exchange gases with their external environment via respiratory surfaces in the alveoli of their lungs.
- Alveoli walls are closely bound to capillary walls, forming an air–blood barrier.
- Gas exchange occurs across the air–blood barrier by diffusion of oxygen from alveoli into blood and by diffusion of carbon dioxide from the blood into the alveoli across this air–blood barrier.
- Emphysema is a respiratory disease in which the alveoli become progressively and permanently damaged.

QUICK CHECK

20 Identify whether each of the following statements is true or false.

a Oxygen passes from alveoli to capillaries by diffusion.

b The largest branches of the airway passages leading into the lungs are called bronchioles.

c Two-way gas exchange is a means of removing N-wastes in animals.

d In lungs, movement in gases across the respiratory surface is by active transport.

e Respiratory surfaces must be moist.

f The damage to alveoli in emphysema cannot be reversed.

Tissues and organs in vascular plants

Vascular plants, also termed higher plants, are a group of plants that have woody (lignified) tissue, termed **xylem**, for the transport of water. These plants also have living tissue, termed **phloem**, for the transport of organic compounds (sugars) produced by photosynthesis. The plants with which you are most familiar, such as flowering plants, shrubs and trees, conifers or pines, and ferns, are all vascular plants.

Three primary organs are present in vascular plants:

- leaves
- stems
- roots.

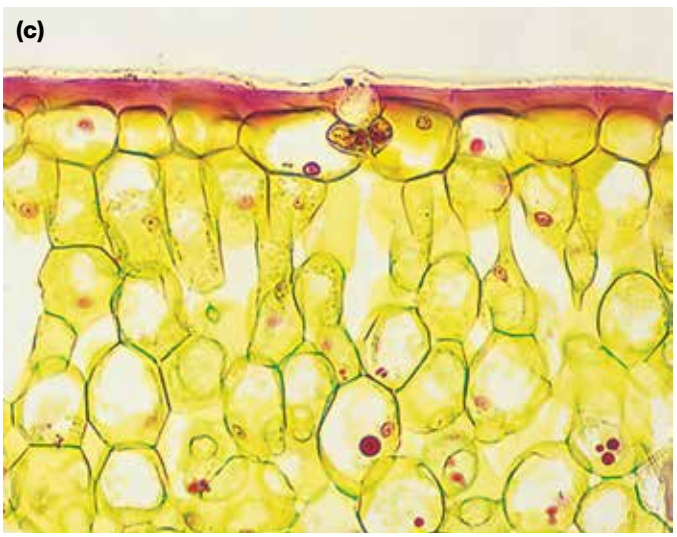
ODD FACT

Grasses have no meristematic tissue at the tips of their shoots. Instead, they have meristematic tissue (known as intercalary meristem) at the base of their leaves where they join the root. This means that grass can grow after it has been mowed but not so a daisy.

These organs are made up of various tissues. Just as in animals, tissues in plants are groups of similar cells working as a functional unit.

In higher plants, tissues can be differentiated into two groups on the basis of their ability(or lack of ability) to undergo cell division:

- **Meristematic tissues** are made of cells that can undergo cell division and can continue to divide for the life of the plant. Meristematic tissue is found in the tips of roots and of shoots and is responsible for an increase in the length of the plant stems and roots. Meristematic tissue is also present along the length of stems and roots and is responsible for the increase in girth of a plant.
- **Permanent tissues** are made of cells that can no longer divide. Permanent tissues include several tissue types that differ in their functions.
  - **Ground tissues** provide support and storage areas for plants and are the site in leaves where photosynthesis occurs, for example, the parenchyma tissue that is composed of thin-walled cells (see figure 4.53a).
  - **Vascular tissues** are involved in the transport of water and nutrients, for example, xylem tissue that transports water and dissolved minerals from the roots to the rest of a plant, and phloem tissue that transports sugars throughout a plant (see figure 4.53b).
  - **Dermal tissues** protect plants and minimise water loss, for example, the epidermis that forms the outer cell layers of leaves and stems. Typically the leaf epidermis tissue is made of flattened cells covered by a water-proof non-cellular waxy cuticle (see figure 4.53c).



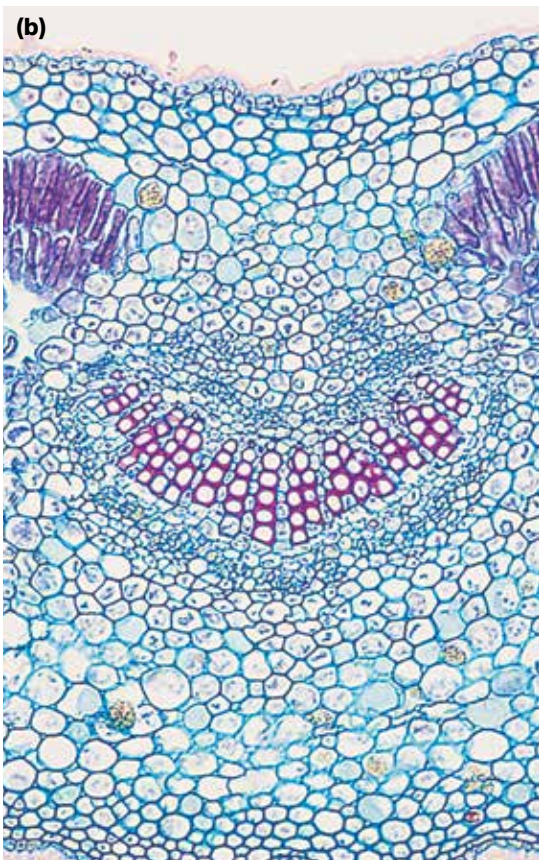


FIGURE 4.53 Light micrographs showing examples of plant tissues: **(a)** parenchyma, a ground tissue **(b)** vascular tissue **(c)** epidermis, a dermal tissue, that is overlaid by a non-cellular waxy cuticle (pink)

Figure 4.54 shows a simple classification of the various tissues in vascular plants.

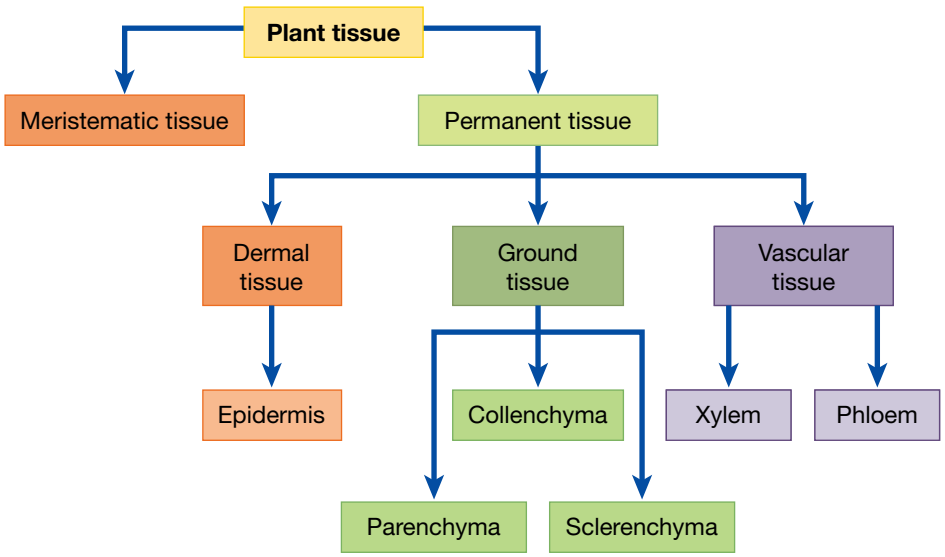


FIGURE 4.54 A classification scheme of the major tissues in vascular plants

Figure 4.55 shows the typical locations of these various tissue types in vascular plants.

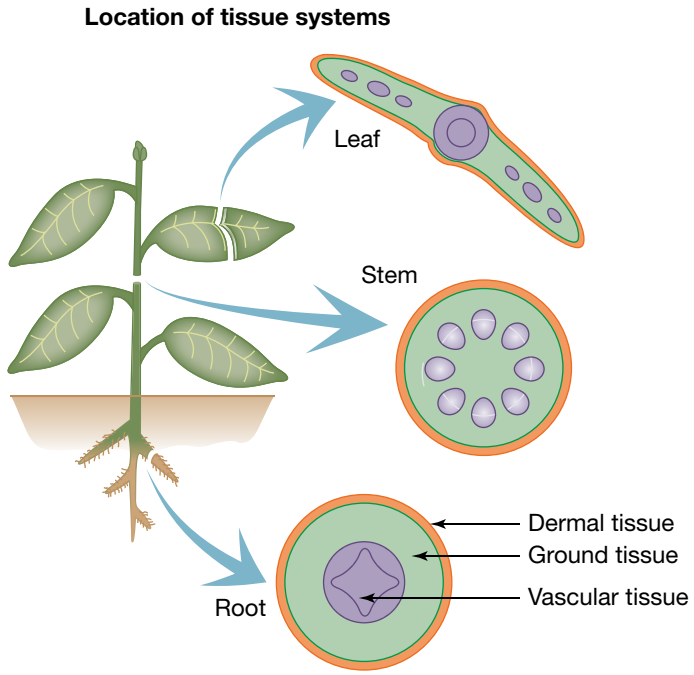


FIGURE 4.55 Location of various tissue types in parts of a vascular plant. The different types of tissue are denoted by various colours.

Transport in plants

Water is essential for the survival of plants and for their growth. This is no problem for aquatic plants and algae as they are surrounded by water. How do terrestrial plants obtain the water that they need?

- The source of water for intake by higher terrestrial plants is water in the soil.
- Water input at the roots must be supplied to the cells in all parts of the plant, both sub-aerial and aerial.
- The transport system for water in these plants is xylem tissue.
- Water loss in plants occurs via the open stomata of leaves in a process known as **transpiration**.

study on
Unit 1
AOS 1
Topic 4
Concept 4
Autotrophs: water intake and water loss
Concept summary and practice questions

In higher plants, water and dissolved minerals are transported from roots to shoots through the xylem tissue. Some minerals, the macronutrients, are required in relatively large amounts for normal growth. Others, the micronutrients (also called trace elements), are needed in relatively small amounts. The xylem is one component of the vascular tissue of a plant; the other is the phloem, which transports organic nutrients, such as sucrose, from the leaves to all other parts of the plant, as well as hormones and any other organic material made by the plant. Such a system is necessary because only cells containing chloroplasts can photosynthesise and all other living cells in a plant rely on photosynthetic cells for their organic nutrients.

The xylem and the phloem form an extensive network of ducts that reach from roots to leaves. The structure of these two tissues is outlined in figure 4.56.

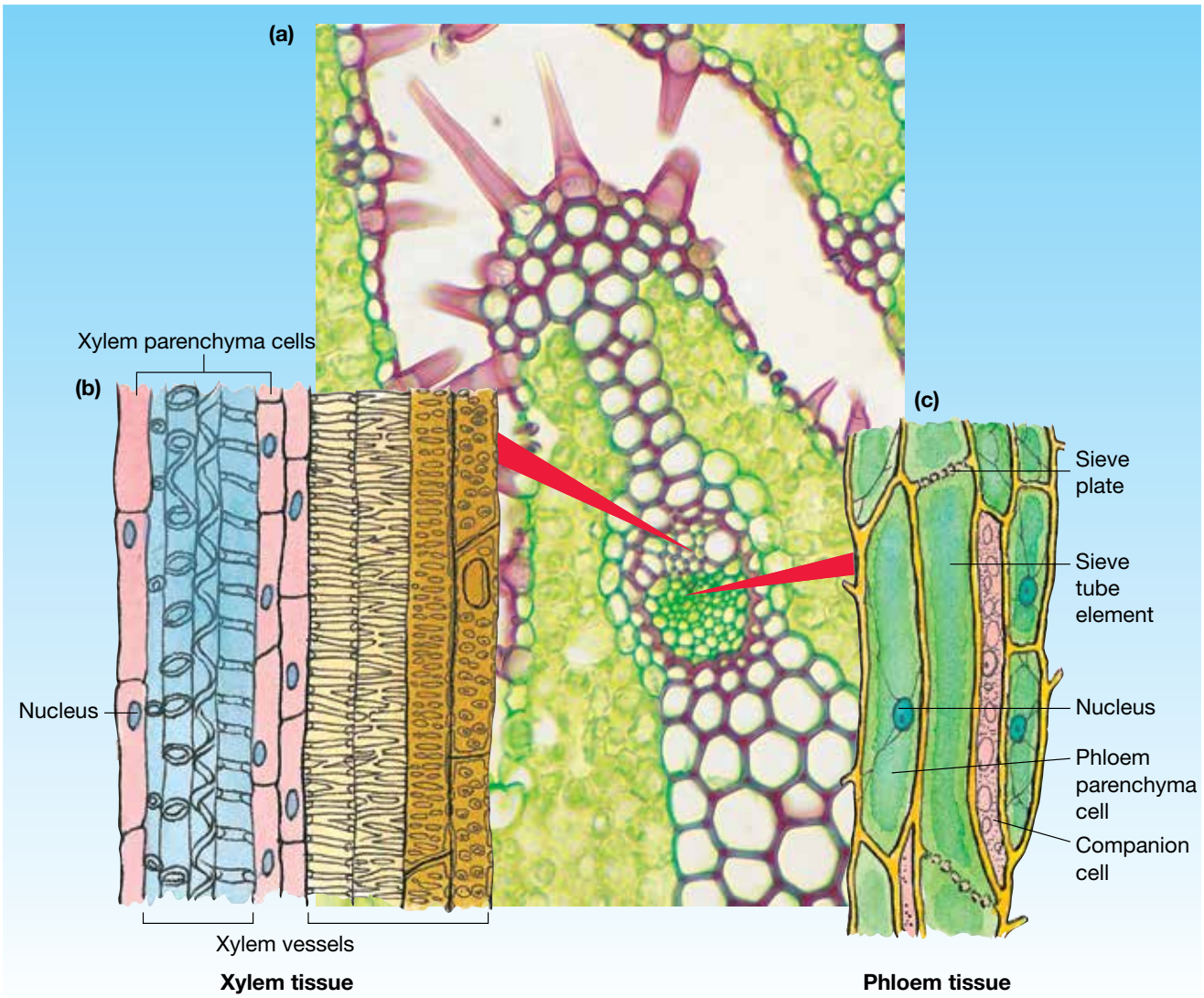


FIGURE 4.56 **(a)** Transverse section through a portion of marram grass, *Ammophila arenaria*, showing a vascular bundle **(b)** Longitudinal section through xylem tissue. Note the xylem parenchyma cells and xylem vessels with their different kinds of lignified thickening. **(c)** Longitudinal section through phloem tissue. Note the phloem parenchyma, companion cells and the lack of nuclei in sieve tube elements.

FIGURE 4.57 Water moves to great heights in trees, from roots to the highest leaves.

ODD FACT

About 95 per cent of the water that is taken in by plants is used for transpiration and the remainder is used as a reactant in photosynthesis.

As you know, materials such as glucose and oxygen are transported through your blood circulatory system. Blood is driven around your body through the action of a pump, your heart. The maximum height that your pumping heart must raise your blood is from your toes to your scalp, perhaps 183 cm for a tall person. Plants do not have hearts, but they can move water from their deep underground roots to their highest leaves, certainly a lot more than 183 cm (see figure 4.57). How does this happen? Let's follow the path of water as it moves from intake at roots to leaves.

How material moves in vascular tissue

Movement of water through xylem

Water is absorbed by root hairs, moves through the cortex into the xylem in the vascular tissue and is transported throughout a plant, often to great heights. If a plant relied on air pressure alone to force water in the soil into the roots and up the stem, the maximum height of any plant would be about 10 m. Some trees are up to 100 m tall and so there must be some special features that make it possible for water to get to the top of such trees. Energy provided by the sun plays a major role in the process.

You will know from your study of photosynthesis that gases enter and leave the leaf through the stomata. Most of the water lost by the plant moves out through stomata in the form of water vapour. The loss of water vapour from a plant via the stomata of its leaves is termed transpiration. The chain of events in transpiration is as follows.

The walls of the mesophyll cells are moist and the air spaces around them contain water vapour. As the sun shines, stomata open and gases are able to diffuse in and out of the leaf. Water vapour moves through the stomata into the air surrounding the leaf. Water evaporates from the wall of the mesophyll cells to replace that lost from the air spaces. As water evaporates from the surface of the mesophyll cells, water moves out of the cells to ensure that the walls are kept moist. In turn, water moves from the small xylem vessels into the mesophyll cells.

When water moves out of the xylem in the leaf, it is replaced by water that is sucked in from the xylem leading into the leaf. In effect, water vapour moving out through the stomata sets up a chain reaction in which water in the xylem is moved through the vessels by the pulling or sucking movement of water ahead of it. Because of the pulling action, **water in xylem vessels is under tension that is transmitted along the whole water column** (see figure 4.58).

What keeps water molecules together as they are pulled through a plant? Why does the column not break? Water has a tensile strength because of the **cohesion** of the molecules. They tend to stick together and the smaller the diameter of the tube the molecules are in, the greater the tensile strength. Water molecules stick to the walls of xylem vessels (see figure 4.59). The cohesive property of water molecules prevents their pulling apart or pulling away from the walls of the xylem vessels as they are sucked up through the xylem (see figure 4.60).

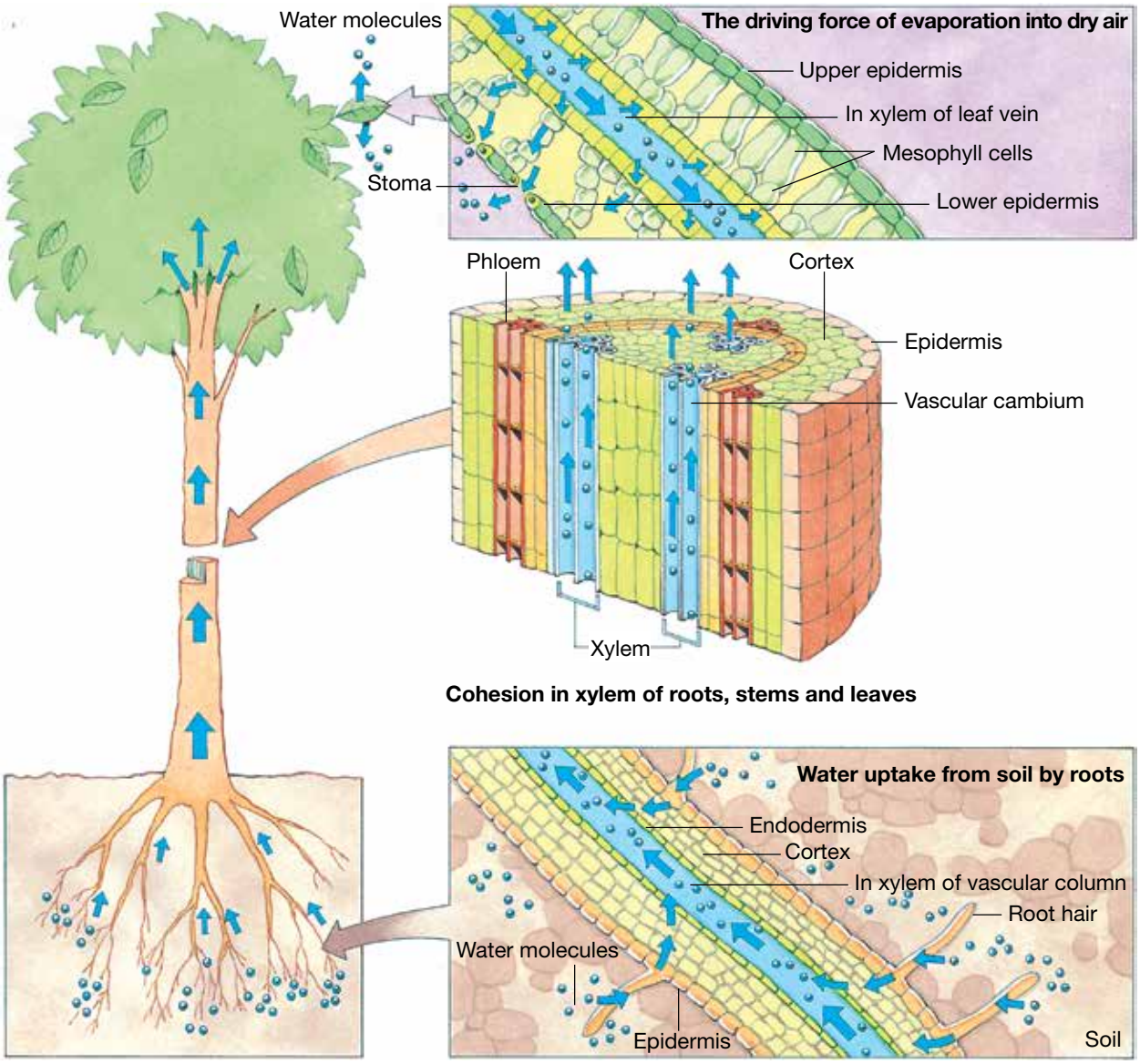


FIGURE 4.58 Water is absorbed from the soil by roots and passes into xylem tissue, which carries it to all parts of the plant. Some of the water is used by cells but much passes through stomatal pores in leaves and is lost by transpiration.

Glucose is produced during photosynthesis. It is either stored locally as starch or transported by phloem in the form of the disaccharide sucrose to other parts of the plant.

Movement of organic substances through phloem

Soluble organic substances are transported by phloem tissue (see figure 4.60). These substances travel from the leaves, where they are synthesised, to other parts of the plant where they are used or stored. Phloem also transports organic substances from storage sites to other regions of the plant for use. The transport of organic material through a plant is called **translocation**.

Sucrose: from leaves to phloem

Photosynthesising leaves produce sugars and so are the source of organic matter for all parts of the plant. **Sugars are actively transported, mainly as a sucrose, from leaves to other parts of the plant via sieve tubes.** The energy required for the active transport is provided by companion cells. As the concentration of sugar in phloem increases, water moves from the xylem by osmosis into the sieve tubes in that region. This increased volume of water increases the pressure in sieve tubes (see figure 4.60). Note the sieve tube elements in figure 4.61.

FIGURE 4.59 Longitudinal section of xylem tissue from the dicotyledon *Acacia* sp. Note the elongated xylem vessels, one with spiral thickening.

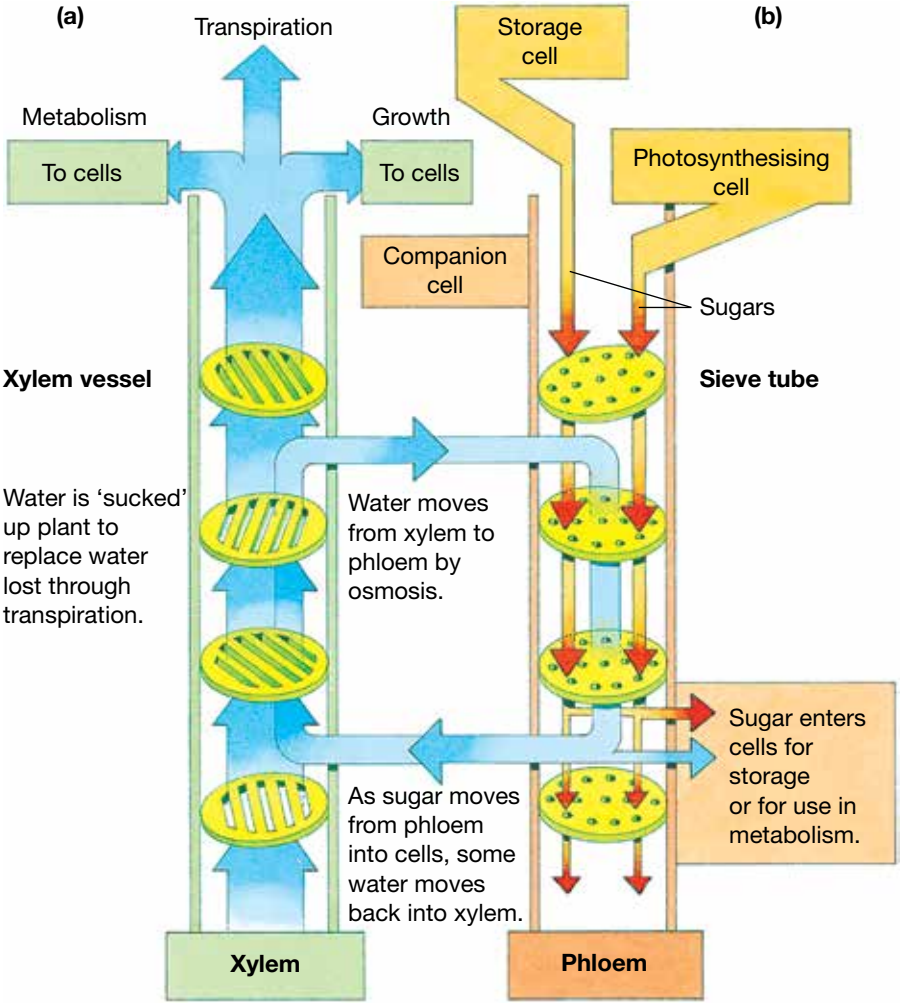


FIGURE 4.60 **(a)** Loss of water from xylem through transpiration and use in metabolism pulls water through xylem vessels. **(b)** Sugars are pushed down the phloem. Sugar moves from a region of high pressure near its site of production to regions of lower pressure where sugars are used.

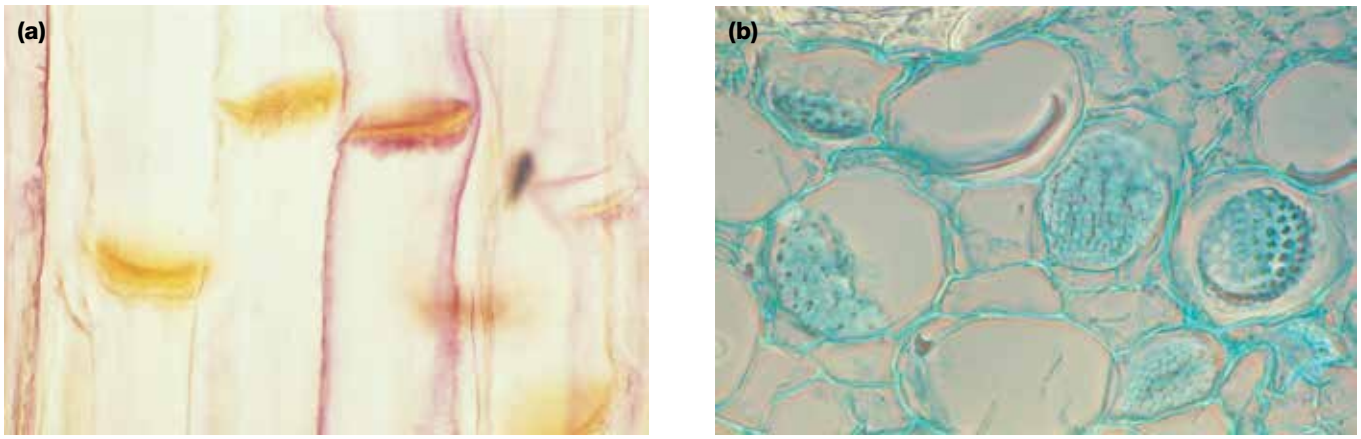


FIGURE 4.61 Sections of the phloem of the dicotyledon *Cucurbita* sp. **(a)** Longitudinal section showing sieve tubes in the stem. Note the transverse sieve plates. **(b)** Transverse section showing sieve plates with sieve pores

Sucrose exits the phloem

Sucrose is actively transported from the phloem into cells (see figure 4.60) where it is either stored as starch or broken down into the monosaccharides used in metabolism. Parts of a plant that use organic material made elsewhere in the plant are called sinks; examples include storage tissues, such as potatoes and actively growing tissues, such as buds.

When sugar leaves the phloem to enter a sink, the effect is to increase the concentration of water in the sieve tube in that region. Water moves out of the sieve tube. The loss of water from the sieve tube close to the sinks results in a decreased pressure in the sieve tubes in that region.

In summary, a region of higher pressure exists in sieve tubes near the sugar source and a region of low pressure exists near the sugar sink. This difference in pressure pushes sugar-rich sap through sieve tube columns from the sources (leaves) to the sinks (e.g. roots). When the sugar arrives at sinks, it is used in different ways:

- It is stored as starch.
- It is used as subunits for building structural components of cells.
- It is used as an energy source in cellular respiration.

ODD FACT

The sap of *Sarcostemma australe* is one of many Aboriginal traditional medicines and is used on small skin lesions.

KEY IDEAS

- Vascular tissue in plants comprises the xylem and phloem.
- Water and mineral ions enter a plant through the roots and are transported throughout a plant in the xylem.
- Sugars are made by chloroplasts in chlorophyll-containing tissues and are conducted to other parts of the plant through the phloem.

QUICK CHECK

21 Why are root hairs so important to the water transport system of a vascular plant?

22 Comment on the validity of the following statement: Xylem tissue and phloem tissue each contain different kinds of cells.

23 By what mechanism does water reach the tops of tall trees?

24 In which part of the vascular tissue would you expect to find a higher concentration of:

a water
b sucrose
c plant hormone
d mineral ions?

BIOCHALLENGE

1 In the 1940s during the Nazi occupation of Holland, a young Dutch doctor, Willem Kolff (1911–2009) set out to build a machine to replace the key functions of the human kidney. In 1943, Kolff succeeded in constructing the first practical kidney dialysis machine. It was a crude construction built from available bits and pieces, including sausage skins and a washing machine. With continued refinements, by 1945, Kolff's kidney dialysis machine saved the life of a person who was close to death from acute kidney failure.

- **a** What possible function might the sausage skins have served?
- **b** What role might the washing machine have played?

Figure 4.62 shows one of Kolff's early kidney dialysis machines — quite a contrast to the modern dialysis machine shown in figure 4.3b on page 136.

2 Figure 4.63 shows some detail about the transport of oxygen from blood capillaries into cells and the removal of carbon dioxide from cells into blood capillaries.

Examine figure 4.63 and answer the following questions.

- **a** List the various forms in which each of the dissolved gases are transported in the blood:
  i oxygen ii carbon dioxide.
- **b** Why does the exchange of gases between the tissues and the blood take place in the capillaries of tissues rather than in their arteries or veins?
- **c** What are the relative percentages of carbon dioxide and oxygen carried in the blood:
  i in combination with haemobglobin
  ii dissolved in the plasma?
- **d** By what process do oxygen and carbon dioxide cross the plasma membranes into and out of cells?
- **e** Is this an energy-requiring process?
- **f** Briefly outline the fate of the carbon dioxide that moves from tissues into red blood cells.

FIGURE 4.62 One of Kolff's early kidney dialysis machines on display at the Museum Boerhaave in Leiden, The Netherlands. This dialyser used 30 to 40 m of cellophane tubing wound on a drum made of wooden slats that revolved in a large drum filled with 70 L of a saline rinsing fluid. (Given this further information, review your answers to 1a and b.)

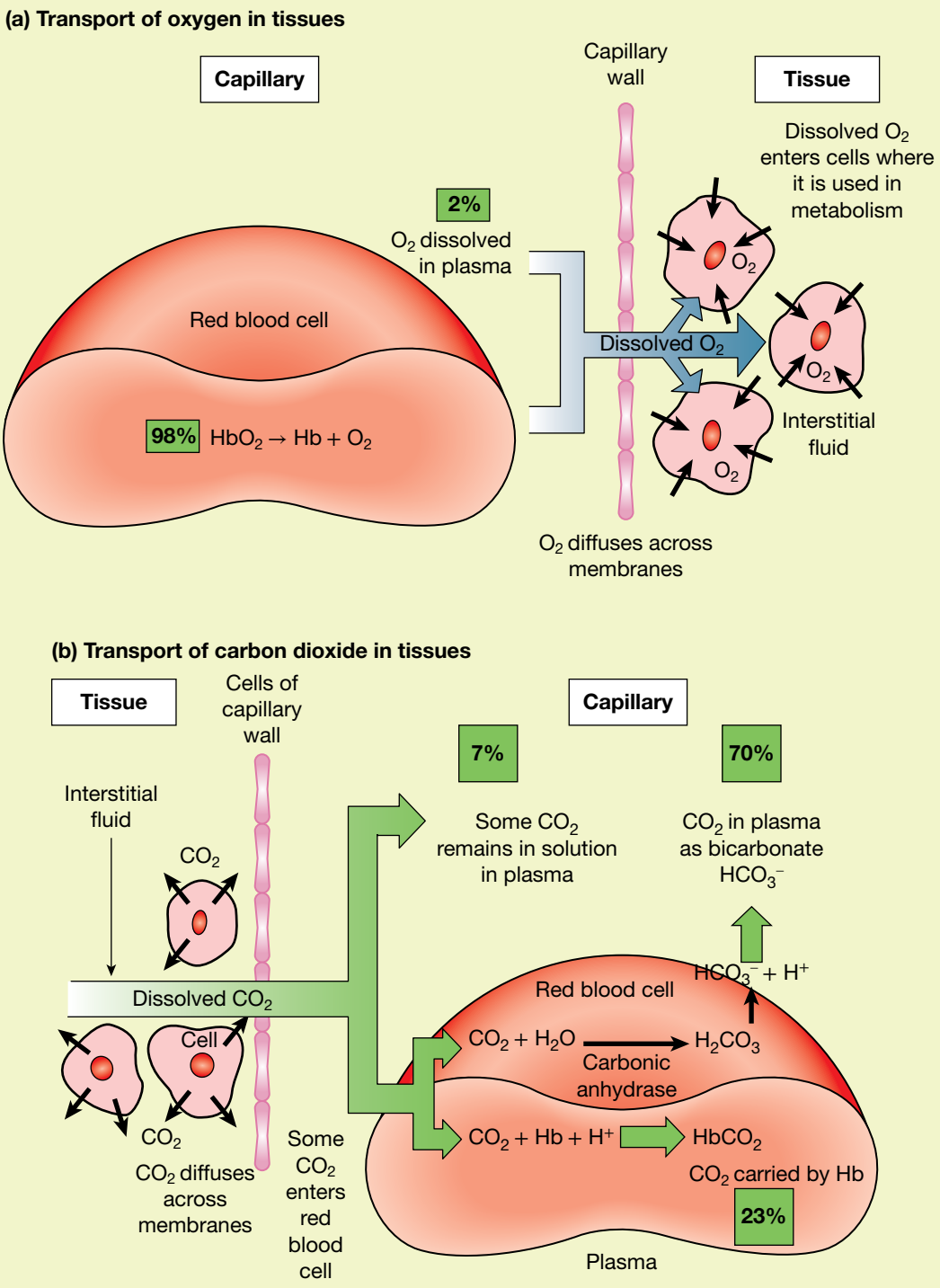


FIGURE 4.63 The blood circulatory system plays an essential role in the supply of oxygen to and the removal of carbon dioxide from cells of body tissues. Haemoglobin (Hb) is involved in the transport of both dissolved gases. **(a)** Movement of oxygen from blood in capillary into cells **(b)** Movement of carbon dioxide from cells into blood in capillary

Chapter review

studyon
Unit 1
AOS 1
Topic 4
Functioning systems
Sit topic test

Key words

aorta
aortic aneurysm
atherosclerosis
atrium
blood circulatory system
Bowman's capsule
calcitriol
chronic kidney disease
cohesion
connective tissues
coronary angioplasty
coronary bypass graft surgery
deamination
dermal tissue
emphysema
end stage kidney disease
epithelial tissue
erythrocytes
erythropoietin
excretion
filtration
glomerulus
ground tissue
haemodialysis
hypertonic
hypertrophic cardiomyopathy (HCM)
hypotonic
leucocytes
loop of Henle
meristematic tissues
muscle tissue
nephron
nervous tissue
organ
peritubular capillaries
permanent tissue
phloem
pulmonary artery
pulmonary vein
secretion
stem cell
system
translocation
transpiration
vascular tissue
ventricle
xylem

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map. You may add other words in drawing your map.

2 **Applying your understanding to a new concept** ➜ Student A stated 'Freshwater fish do not drink water.' Student B commented 'That can't be right. Water is essential for life.'
Consider the comments from these students.
- **a** Indicate whether you agree with each student, and give a brief reason for your choice.
- **b** What soundly based biological comments might you might add to this conversation?

3 Comment on or briefly explain the following observations.
- **a** The epidermis of a root lacks the waterproof cuticle found on the epidermis of most leaves.
- **b** Movement of oxygen from lung alveoli into capillaries of the lungs does not require energy.

4 Figure 4.64 shows the circulatory system of a fish. A and V indicate the auricle and ventricle of the heart. The arrows show the direction of flow of blood in the system. Consider the regions M, N, O, P and Q.
- **a** Which of the regions would you classify as artery and which as vein?
- **b** How would the concentration of oxygen in the blood in region P compare with that in regions M and Q? Explain.
- **c** How would the blood pressure in regions P, Q and M compare with each other? Explain.

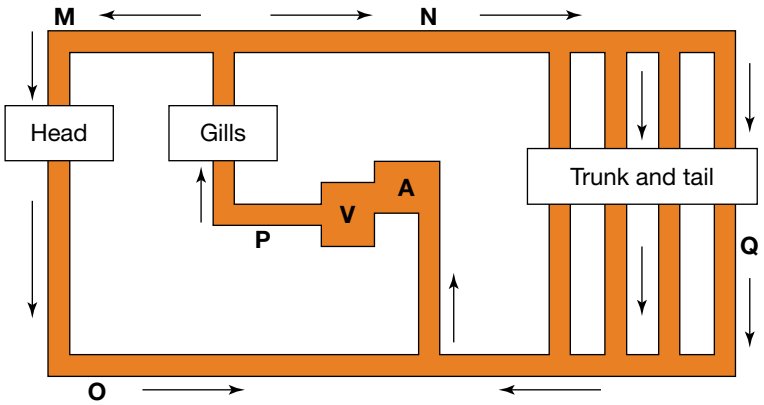


FIGURE 4.64

5 **Applying biological understanding** ➜ Explain the following statements.
- **a** Increasing your rate of exercise increases your rate of breathing.
- **b** After sleeping with blocked nasal passages, you wake with a dry mouth.
- **c** In humans, the surface area of lung alveoli is far greater than the surface area of the skin.
- **d** Carbon dioxide is sometimes used in fumigation for an insect infestation in a confined space.

6 **Interpreting and applying biological principles** ➜ A bird has a series of air sacs as well as two lungs. The air sacs are elastic and expand and contract rather like bellows. Gases do not diffuse through the internal surfaces of the sacs (see figure 4.65; the arrows show the direction of air flow).

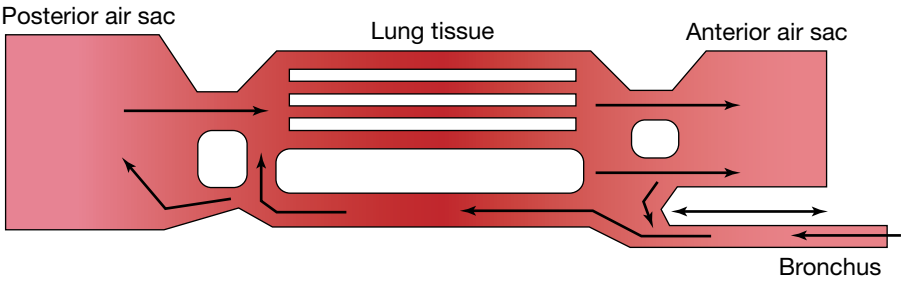


FIGURE 4.65

When a bird breathes in, air is drawn into the posterior air sacs, which expand. Some air already in the sacs is pushed toward the lungs; this causes a push on air in the lungs. When the bird breathes out, air is forced out of the anterior air sacs, into the bronchus and then out of the body. Air is drawn from the lungs into the anterior air sacs; this drawing effect results in air in the posterior sacs being drawn into the lungs. Birds have a unique ventilating system in that air is continually pushed and drawn across the lung tissue.

a Explain how such a system increases the efficiency of the lung as an excretory organ.

b Suggest the likely advantage of such a system for birds.

c Explain how the movement of air in relation to lung tissue in a bird differs from that in humans.

7 Applying understanding → When a plant is transplanted, root hairs are often damaged. Before transplanting, a gardener often removes many of the leaves. Explain how these two events are related.

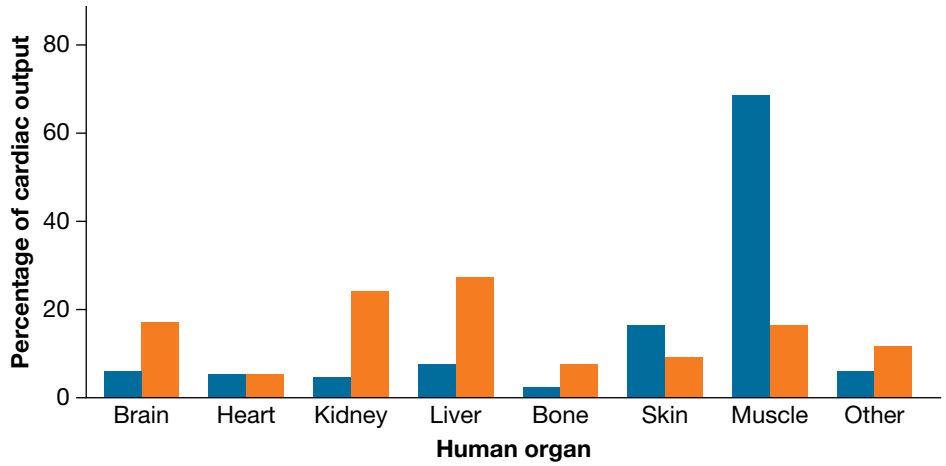
8 Interpreting graphs → During strenuous exercise, the output of blood from the heart (cardiac output) increases relative to its output when at rest. This means that although some organs receive a smaller percentage of the cardiac output, their total blood supply remains unchanged. Other organs receive a much greater blood supply. Figure 4.66 shows the percentage of cardiac output distributed to various organs of a healthy person (i) at rest and (ii) during strenuous exercise.

Examine this figure and answer the following questions:

a Which colour (orange or blue) represents the distribution of the cardiac output in the person at rest?

b At rest, which two organs receive the greatest share of the cardiac output?

c Which two organs receive the greatest share of the cardiac output during strenuous exercise?



Source: http://btc.montana.edu/olympics/physiology/pb01.html

FIGURE 4.66 Distribution of cardiac output at rest and during exercise

9 Demonstrating knowledge and understanding ➜
Consider a tiny living organism, known as a hydra — just visible to the unaided eye — that lives in a freshwater pond. Figure 4.67 shows a diagram of its body plan: it has a two-cell thick body wall separated by a non-cellular gel-like material. Several different cell types are present in this organism including cells with flagella that line the gut cavity and several kinds of stinging cells (cnidocytes) with a mini-harpoon that fires, penetrating and paralysing the prey on which this organism feeds.

a What kind of organism is a hydra?
b On what information did you base your decision?
c Does a hydra show evidence of cell specialisation?
d Would you predict that organs are present in a hydra? Explain.
e What level of organisation does a hydra show (cellular, tissue, organ or system)?

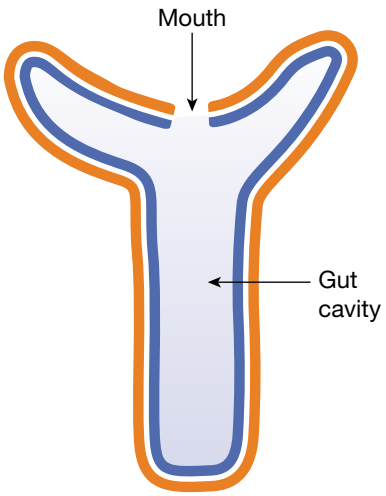


FIGURE 4.67 Simplified diagram of body plan of a hydra with its two main cell layers: an outer ectoderm and an inner endoderm

10 Demonstrating knowledge and understanding ➜
Complete the table below by inserting the animal which has the level of organisation in the first column from the following animals: jellyfish, flatworms, earthworms, sponges.

Level of organisation	Animal
cell	
tissue	
organ	
system	

11 Demonstrating knowledge and understanding ➜

a Identify the body system and the organ within that system that is affected by the following disorders.
  i Emphysema
  ii Aneurysm
  iii Hypertrophic cardiomyopathy
  iv Atherosclerosis
b Briefly describe how emphysema affects the functioning of the respiratory system.
c What risk factors are associated with the occurrence of emphysema?

12 Demonstrating knowledge and understanding ➜
What is the difference between the members of the following pairs?

a Haemodialysis and peritoneal dialysis
b Epithelial tissue and connective tissues in animals
c Meristematic and connective tissues in higher plants
d Ammonia and uric acid
e Xylem and phloem

CHAPTER

5 Adaptations for survival

FIGURE 5.1 The spinifex hopping mouse (*Notomys alexis*), also known as the tarrkawarra, is a marsupial mammal that lives in sandy desert regions in parts of Australia. They display many adaptations that equip them to survive in a hot and arid environment. In this chapter we will explore some of the many structural, physiological and behavioural adaptations that enable plants and animals to survive in deserts and in other extreme environments.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- recognise how structural, physiological and behavioural features can contribute to the survival of organisms
- recognise that a feature is adaptive in a specific set of environmental conditions
- gain knowledge of particular adaptations that equip organisms for survival in various environmental conditions in Australia
- understand that each organism has a tolerance range for every environmental factor and that beyond that range survival is at risk.

The *Rule of Threes*

The *Rule of Threes* provides a reasonable guideline for priority-setting for anyone lost in a harsh environment. The rule states:

- You can live for about 3 minutes without air. (Exceed that and a person is at risk of death from asphyxiation.)
- You can live for about 3 hours without shelter (in a harsh environment). (Exceed that and a person is at risk of death from exposure.)
- You can live for about 3 days without water (if you have shelter). (Exceed that and a person is at risk of death from dehydration.)
- You can live for about 3 weeks without food (if you have shelter and water). (Exceed that and a person is at risk of death from starvation.)

Leaving aside the immediate requirement for air (in fact, the oxygen in air), these times are guidelines only and will vary according to the severity of the conditions, as well as a person's body weight, genetic factors and whether or not the person is already dehydrated.

The *Rule of Threes* is a useful rule-of-thumb for human survival in the harsh cold conditions of the high latitudes of the northern hemisphere. Teachers of basic skills for survival in a freezing wilderness may refer to the *Rule of Threes* because it stresses the priorities for survival. First priority — direct your focus and your energy into securing shelter; second priority — water; third priority — then, only after shelter and water are secured, worry about food. In the freezing cold of a northern hemisphere snowstorm, one challenge is to find shelter in order to avoid a drop in body temperature (**hypothermia**). In contrast, in the desert heat of the Australian outback in summer, the challenge is to find protection against the heat and avoid heat stroke (**hyperthermia**). Regardless of whether people are challenged by the freezing tundra of Canada or the desert heat of outback Australia, another essential for their short-term survival is water: prolonged dehydration can kill.

Food is a requirement for survival of heterotrophs (animals and fungi) but, in contrast to water, food is not necessary for short-term survival. In 1981, a number of political prisoners in Northern Ireland staged hunger strikes in protest against the presence of British military personnel in the region. Ten protesters, who did take water, died after periods without food of between 46 and 73 days. The period of survival without food is influenced by a person's health and stored energy reserves.

Bushfires are a serious threat to survival in fire-prone areas of Australia, especially the south-east sector of the country. The box on pages 233–4 relates to a tragic event during a bushfire in Victoria in 1998. Sadly, some firefighters died when a fierce bushfire suddenly changed direction.

In this chapter, we will look at a range of **adaptations** that contribute to the survival of animals and plants in a variety of environments. **An adaptation is a genetically controlled structural, behavioural or physiological feature that enhances the survival of an organism in particular environmental conditions.** It is important to note that the value of a feature as an adaptation exists in relation to a specific way of life and in a particular set of environmental conditions. In another set of environmental conditions and a different way of life, the same feature may be maladaptive. For example, freshwater fish extract dissolved oxygen from the water in which they live using their gills, the organ for gas exchange (see figure 5.2). Gills provide an efficient structure for extracting oxygen from water. However, if removed from the water, the fish gills are maladaptive. Without the buoyancy of water to support them, the feathery gill filaments collapse, and with no water flowing over them the fish cannot obtain oxygen and suffocates. Likewise, mammalian lungs are adapted for gas exchange with the air, but they are useless for extracting dissolved oxygen from water.

FIGURE 5.2 Rows of gill filaments of a fish. Note that each filament has many small projections (lamellae) on it. These greatly increase the surface area available for the life-supporting process of gas exchange. Normally, water enters the mouth of the fish, passes to the pharynx and is forced over the gill surfaces and exits. Would you predict that a rich blood supply would be present in the gill lamellae?

Adaptive features of an organism are innate, that is, built into its genetic make-up.

Some adaptations reflect the *Rule of Threes*. For animals, survival depends on their structural, physiological and behavioural features that enable them to exploit the available resources of shelter, water and food in a particular environment. For plants, survival also depends on their structural, physiological and behavioural features that contribute to their success in accessing water and sunlight in their environments.

ODD FACT

Some bacteria have a very high temperature tolerance. The bacterial species known as *Sulfolobus acidocaldarius* survives temperatures in boiling hot sulfur springs. This species of bacterium dies from cold at temperatures below 55 °C.

Tolerance range

The particular environmental conditions in which a particular species can successfully live and reproduce define its **tolerance range**. **Every organism has a tolerance range for environmental factors** such as temperature, desiccation, oxygen concentration, light intensity and ultraviolet exposure. A tolerance range identifies the variation within which organisms can survive. Figure 5.3 shows the tolerance range for a fish species in terms of water temperature. The extremes of this range are the **tolerance limits** for that environmental factor.

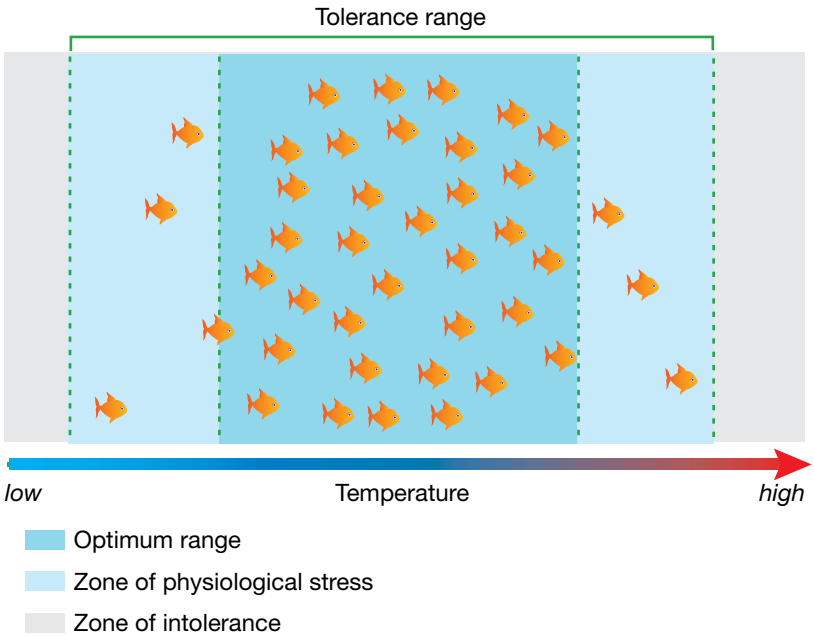


FIGURE 5.3 Tolerance range in terms of temperature for a fish species. Notice that, as water temperature moves closer to the tolerance limits, fewer fish are found. This is the so-called zone of physiological stress. What happens beyond the tolerance limits?

ODD FACT

Reef-building coral polyps live in warm, clear shallow seas, but if the temperature of the water falls below 18 °C the polyps die. What is the lower end of the temperature tolerance range for coral polyps?

If an environmental factor has a value above or below the range of tolerance of an organism, that organism will not survive unless it can escape from, or somehow compensate for, the change. In some species migration is one such escape behaviour, while others retreat underground. Tolerance ranges differ between species and are influenced by structural, physiological and behavioural features of organisms. For example, the cold tolerance of various mammals is influenced by structural features such as fur density, shape of the body (see figure 5.4) and extent of insulating fat deposits, and by their behaviours, such as hibernating ('coping-with-it' strategy). In figure 5.4, can you identify which fox species is the Arctic fox (*Vulpes lagopus*) and which is the Simien Fox (*Canis simensis*)?

FIGURE 5.4 Apart from the difference in their fur thickness, these two fox species differ in their ear sizes. Smaller ears have a lower surface-area-to-volume ratio than larger ears. Which fox would be better able to conserve its body heat and tolerate lower temperatures? Why? (Surface-area-to-volume ratio is discussed in chapter 1, pp. 12–14.)

Any condition that approaches or exceeds the limits of tolerance for an organism is said to be a limiting factor for that organism. Terrestrial and aquatic environments can differ in their limiting factors. Table 5.1 shows environmental factors that influence which kinds of organism can survive in various habitats.

TABLE 5.1 Examples of limiting factors in various habitats. Only one example of a limiting factor is given for each environment. Can you identify another limiting factor for one of these habitats? Those species that can survive under certain environmental conditions have tolerance ranges that accommodate those conditions.

Habitat	Limiting factor	Comment
floor of tropical rainforest	light intensity	Low light intensity limits the kinds of plants that can survive.
desert	water availability	Limited water supply means that only plants able to tolerate desiccation can survive.
littoral zone	desiccation	Exposure to air and sun limits the types of organism that survive.
polar region	temperature	Low temperatures limit the types of organism that are found.
stagnant pond	dissolved oxygen levels	Low dissolved oxygen levels limit the types of organism that can live there.

The structure and the physiology of plants and animals determine their tolerance range. For each organism, the limits of its tolerance range for various environmental factors are fixed, except for the occurrence of an enabling mutation.

The human species is the only organism that makes extensive use of technology to extend the limits of its natural tolerance range. As air-breathing mammals, we are not prevented from entering the watery world of the fish; technology such as scuba tanks enable us to do this. Technology enables people to survive in hostile environments on and beyond Earth, where conditions are outside the tolerance range of an unaided person. Equipment and hi-tech clothing enable a mountaineer to survive an ascent to the peak of one of the highest mountains on Earth (see figure 5.5a). An extremely sophisticated spacesuit enables an astronaut to leave the International Space Station, which is orbiting about 250 km above Earth, and install cables (see figure 5.5b).

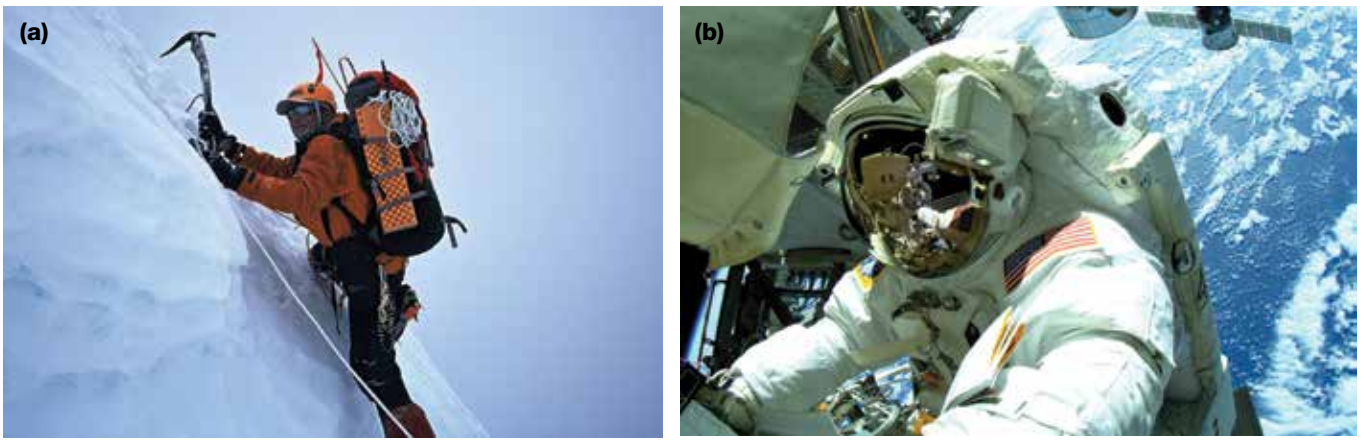


FIGURE 5.5 **(a)** Andrew Lock is Australia's most accomplished high-altitude mountaineer and the only member of the British Commonwealth to have climbed all 14 of the world's 8000-metre-plus mountains. Here he is ascending to the peak of Mt Annapurna, 8091 m above sea level, one of the world's most dangerous climbs. You can find more information about Andrew's ascents of the 14 peaks at http://andrew-lock.com/the-fourteen-8000ers. **(b)** Commander Barry Wilmore, a US astronaut, on a space walk from the International Space Station on 1 March 2015

KEY IDEAS

- Adaptations are structural, physiological or behavioural features that enable an organism to survive and reproduce in particular environmental conditions.
- The tolerance range of an organism defines the range of environmental conditions in which a particular species can successfully live and reproduce.
- The human species uses technology to extend the limits of its natural tolerance range.

QUICK CHECK

1 What is meant when a structural feature of an organism is said to be 'maladaptive'?
2 Give an example of a physical feature that could be labelled as 'maladaptive' and the conditions in which that label could be given.
3 Identify whether each of the following statements is true or false.
   a Excluding technological support, survival is not possible beyond the extremes of an organism's tolerance range.
   b Adaptations are features that equip organisms to survive in all conditions.
   c The extreme ends of a temperature tolerance range mark the tolerance limits of an organism for temperature.
   d A behaviour that is learned is an example of an adaptation.

The desert environment

Australia is the driest inhabited continent on Earth and has been arid for millions of years. As vast areas of the continent dried out, ancestral species evolved over many generations. As a result of mutations, individuals of some species developed features that enhanced their survival in arid conditions and it was their offspring that had a greater chance of survival. Their descendants are the native plants and animals that live successfully in the vast desert regions and semi-arid areas of outback Australia. Today, much of inland Australia is covered by deserts, mainly sandy deserts with some stony deserts (see figure 5.6). Seventy per cent of Australia's land surface is either arid (average annual rainfall of 250 mm or less) or semi-arid (average annual rainfall of 250 to 350 mm).

FIGURE 5.6 **(a)** Much of inland Australia is hot and arid and covered by deserts. This figure shows our 10 major deserts, ranging from the largest, the Great Victoria Desert, more than 400 000 km^2, to the smallest, the Pedirka, just over 1000 km^2. **(b)** Most of these deserts are sandy deserts, such as the Simpson Desert, a large area of sand plains and dunes in central Australia. **(c)** Some areas are stony deserts, such as Sturt Stony Desert, a rock-covered desolate area.

ODD FACT

Sturt Stony Desert was reached by an expedition led by Charles Sturt in August 1844. A member of his expedition exclaimed: 'Good heavens! Did ever man see such country'.

The environmental factors that dominate desert environments are temperature and aridity (absence of surface water).

The temperatures in Australian deserts in summer are very high. For example, the *average* daily maximum temperature for the month of February 2015 across much of inland Australia was in the range of 36 to 42 °C. For coastal Victoria, the figure was 24 to 27 °C (see figure 5.7a). The rainfall in central Australia in the same month was low, with most inland regions receiving rainfall of 0 to 25 mm. In contrast, in the same month a few coastal regions of eastern Australia received 600 to 800 mm of rain (see figure 5.7b). Because of the high temperatures of the desert areas, any small amounts of summer rain quickly evaporate and do not exist as **free-standing water**. In spite of the high temperatures and aridity of deserts, some plants and animals live successfully in these areas because they have adaptations that equip them for life in this environment.

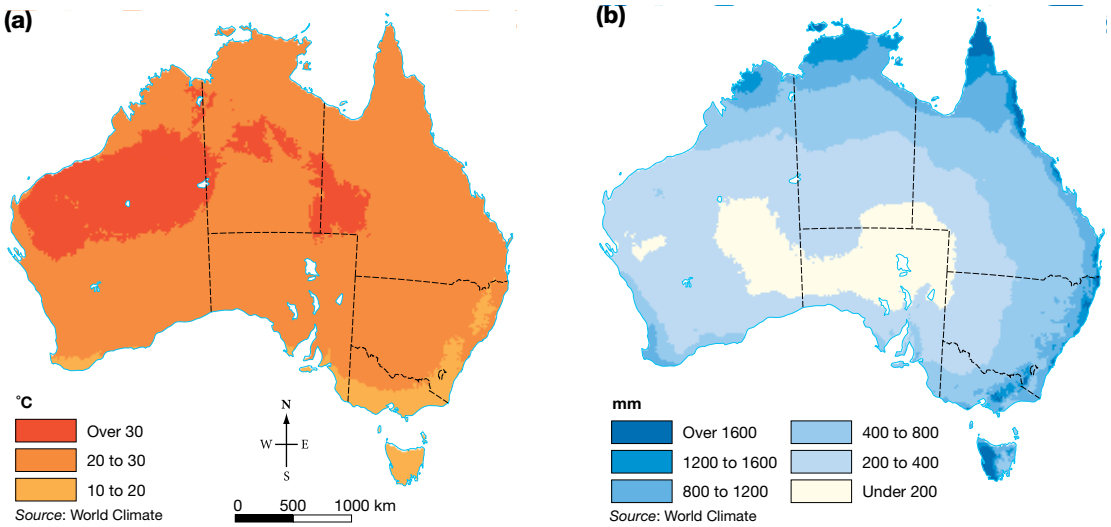


FIGURE 5.7 Much of inland Australia consists of large areas of arid, hot deserts. **(a)** Map showing the mean maximum temperature across Australia in February 2015 (The mean maximum temperature is the average daily maximum air temperature for the month.) **(b)** Map showing the rainfall in millimetres for the month of February 2015

Water is essential for life

One of the key threats to survival in the arid Australian outback is dehydration. Water loss by an animal is normally compensated for by water gain so that, overall, over a period of time, **water balance** exists. That is:

water-in = water-out

OR

water gain – water loss = 0

In chapter 6 we will examine water balance and its regulation.

In desert conditions, the water content of the body can become unbalanced if water loss exceeds water gain over an extended period, producing a state of dehydration. The more severe the dehydration and the faster it occurs, the more deadly the potential consequences.

Water is a remarkable substance with properties that are critical for living organisms (see the following box).

WATER: A SPECIAL MOLECULE

Water has several special properties that enable it to play important roles in biological settings.

Water molecules tend to stick together

The tendency of water molecules (H_2O) to stick together can be expressed more scientifically as molecules having high cohesion. The cohesiveness is due to the fact that the oxygen end of a water molecule has a slight negative charge, while the hydrogen ends have a slight positive charge (see figure 5.8).

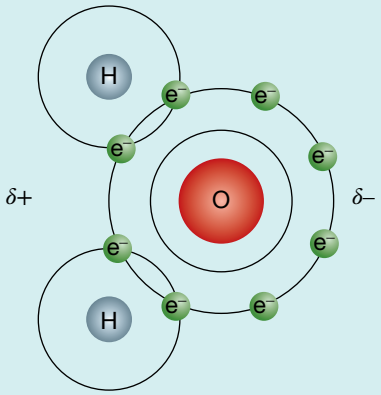


FIGURE 5.8 A water molecule showing its arrangement of electrons (e-), two in the inner shell and six electrons in the outer shell. Each of the two hydrogen atoms shares its single electron with the oxygen atom. Oxygen is a larger atom than hydrogen and because of this the electrons are pulled toward oxygen and away from the hydrogen, resulting in a net negative charge for the oxygen end of a water molecule and a net positive charge for the hydrogen end.

Because of these slight positive and negative charges, water molecules are attracted to each other and stick together (in groups of up to 4 water molecules). This attractive force is known as **hydrogen bonding** (see figure 5.9). The cohesive nature of water is what makes it a versatile solvent for polar molecules (see next paragraph). The cohesive nature of water is one key factor that enables water columns in the xylem tissue of vascular plants to move at the top of trees.

Water is a versatile solvent

Water is the predominant solvent in living organisms. The chemical reactions that occur in cells involve the synthesis of complex molecules from simple ones and the breakdown of complex molecules. These chemical reactions occur in solution so that water, as a solvent, is necessary. Likewise, nutrients can be absorbed from the alimentary canal into the bloodstream only if they are in solution. How does water act as a solvent for hydrophilic or polar compounds? Let's look at how water dissolves a hydrophilic solid, such as a crystal of common salt.

The top of figure 5.10 shows a crystal of common salt (NaCl) when it is first placed in water. At this stage, the salt crystal has not dissolved. However, after the salt comes into contact with the water, the salt dissociates (separates) into sodium ions (Na^+) and chloride ions (Cl^-) (see bottom of figure 5.10). Note that, in solution, the sodium ion (Na^+) is surrounded by water molecules arranged with their oxygen atoms closest to the sodium ion. Check out the arrangement of water molecules that surround the chloride ion (Cl^-). Which end of the water molecule is closer to this ion?

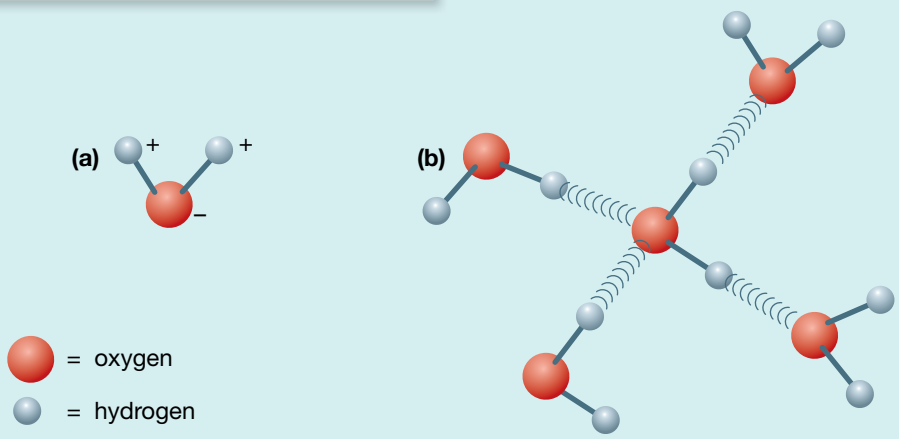


FIGURE 5.9 **(a)** Each water molecule consists of one oxygen atom (O) joined to two hydrogen atoms (H) by a strong covalent bond. **(b)** Water molecules are attracted to each other because of the slight negative charge on the oxygen atom and the slight positive charge on each hydrogen atom. The attractive forces that hold water molecules together are called **hydrogen bonds**, shown here as short curved lines.

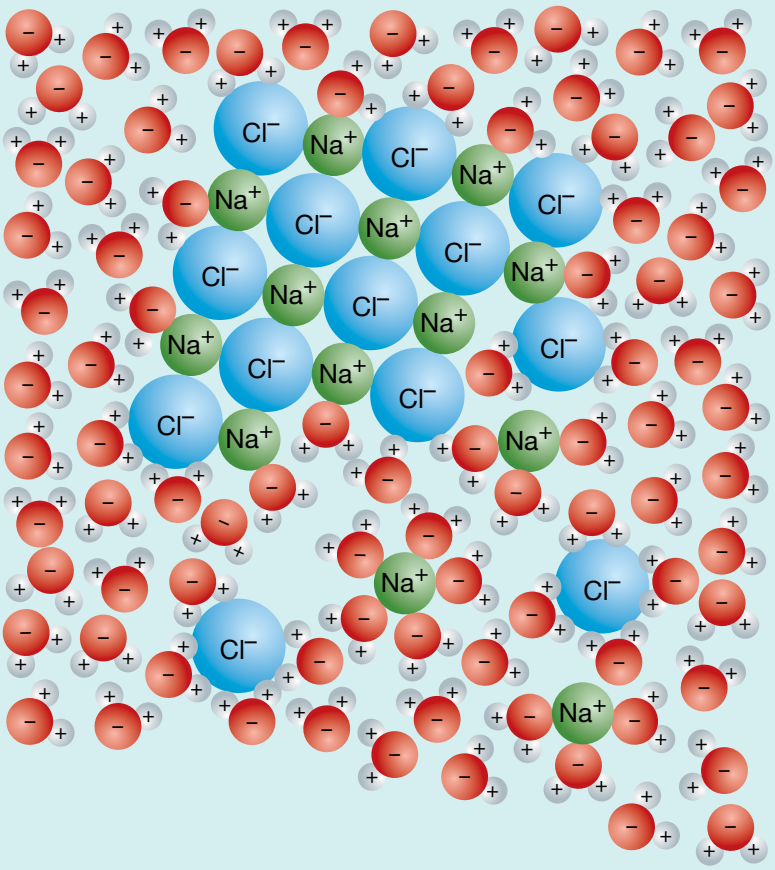


FIGURE 5.10 A salt crystal (top) in water will dissociate into its constituent sodium ions (Na^+) and chloride ions (Cl^-) (bottom). These ions are attracted to different parts of the water molecules and become surrounded by them. Which part of a water molecule has a slight positive charge?

Each sodium ion and each chloride ion becomes surrounded by a shell of water molecules; this is possible because of the cohesive nature of water molecules. For the chloride ions, it is the positively charged side of the water molecules that surround them. In contrast, for the sodium ions, it is the negatively charged portion of the water molecules that surrounds them. These shells of water molecules separate the sodium ions from the chloride ions and, by removing the attraction between these ions, keep the salt in solution.

Water resists temperature changes

Resistance to temperature changes means that, relative to other compounds, more heat energy must be added to or removed from water to produce a given change in its temperature. This relatively greater resistance is because of the many hydrogen bonds that exist between water molecules in solution. (Remember, water molecules are cohesive!)

Water has a relatively high specific heat capacity

Specific heat capacity refers to the heat energy required to raise the temperature of a given mass of a substance by one degree. For example, the specific heat of liquid water is 4186 joules per kg per degree Celsius, while that of air is 1046 J. So, given the same input of heat energy, the temperature of a body of water changes far less than the temperature of the surrounding atmosphere.

Biologically, this means that large bodies of water provide relatively more stable thermal living conditions for the organisms that live in those environments in comparison with terrestrial organisms.

Water has a high heat of vaporisation

The heat of vaporisation refers to the input of heat energy required to convert a liquid to vapour (gas). For water, the heat of vaporisation of liquid water is 2260 kJ/kg; for comparison, that of petrol is about 600. The high heat of vaporisation of water is an important factor in cooling mammals exposed to heat stress.

The major mechanism for cooling in humans and other primates is the evaporation of sweat that is produced when the body starts to overheat. Not all mammalian species produce sweat in order to lose heat. Some species, such as dogs, use panting to cool themselves. Yet other species, such as kangaroos and wallabies, lick the fur and skin of their forearms and paws (see figure 5.11). Cooling in all these cases — sweating, panting and saliva spreading — is due to the evaporation of water from the sweat or the saliva on the skin or fur surface. The heat energy needed to evaporate the water is taken from warm blood in vessels close to the skin surface, cooling the blood. This blood then returns to the body core, cooling it.

Both the high heat of vaporisation and the high specific heat capacity of water were factors in preventing the deaths of the firefighters caught in a bushfire discussed in the box on pages 233–4.

(continued)

FIGURE 5.11 Evaporation of saliva from the kangaroo's forearms and paws requires heat energy. The heat energy needed to change the state of water from liquid to vapour comes from the kangaroo's body, cooling it.

Water has a high heat of fusion

This refers to the heat that must be removed from liquid water to convert it to a solid (ice). For example, the heat of fusion of liquid water is 333 kJ/kg, while that of ethanol, another liquid, is 104 kJ/kg.

Solid water is less dense than liquid water

Density is a measure of the mass of a substance per unit volume (mass/volume). Most substances are more dense in their solid state than their liquid state. This is not the case for water; liquid water is more dense than solid water (ice) and, as a result, ice floats on water. An important consequence of this is that when small bodies of water such as ponds and lakes freeze in very cold climates ice forms at the surface. This ice acts as an insulating layer that assists in keeping the underlying water liquid. If ice were more dense than liquid water bodies of water would freeze in very cold weather from the bottom up, with deadly consequences for aquatic life (see figure 5.12).

FIGURE 5.12 Water in two of its physical states, as liquid water and as ice. Ice floats on water because it has a lower density.

Some density values are:

- liquid water = 1.00 g/cm^3
- sea water = 1.02 g/cm^3
- solid water (ice) = 0.93 g/cm^3
- coconut oil = 0.93 g/cm^3.

Refer to figure 5.10 and see if you can explain why sea water is more dense than pure water. (Answer: Adding Na^+ ions and Cl^- ions to the water increases the volume of the water. However, because the mass of the ions (Na^+ = 23, Cl^- = 35) is greater than the mass of the water molecules (18), adding these ions to the water increases its mass by a greater factor, thus increasing its density).

To appreciate both the importance of water in living organisms and to understand how some animals can thrive in desert conditions, let us first look briefly at the water content of healthy adult people and their sources of water gain and water loss.

Water in the human body

Like all living organisms, the human body consists mainly of water. An average adult male consists of about 60 to 65 per cent water by weight, equivalent to about 45 litres. For an average adult female, the figure is about 50 to 55 per cent, corresponding to about 30 litres (see figure 5.13a). The values can vary according to a person's age, state of health and weight. People with obesity, for example, have a lower percentage of water than those who are lean. The water content of the different tissues and organs of the human body varies from more than 80 per cent in the blood to about 10 per cent in adipose tissue (see figure 5.13b).

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Unit 1
AOS 2
Topic 1
Concept 9
Humans: water balance
Concept summary and practice questions

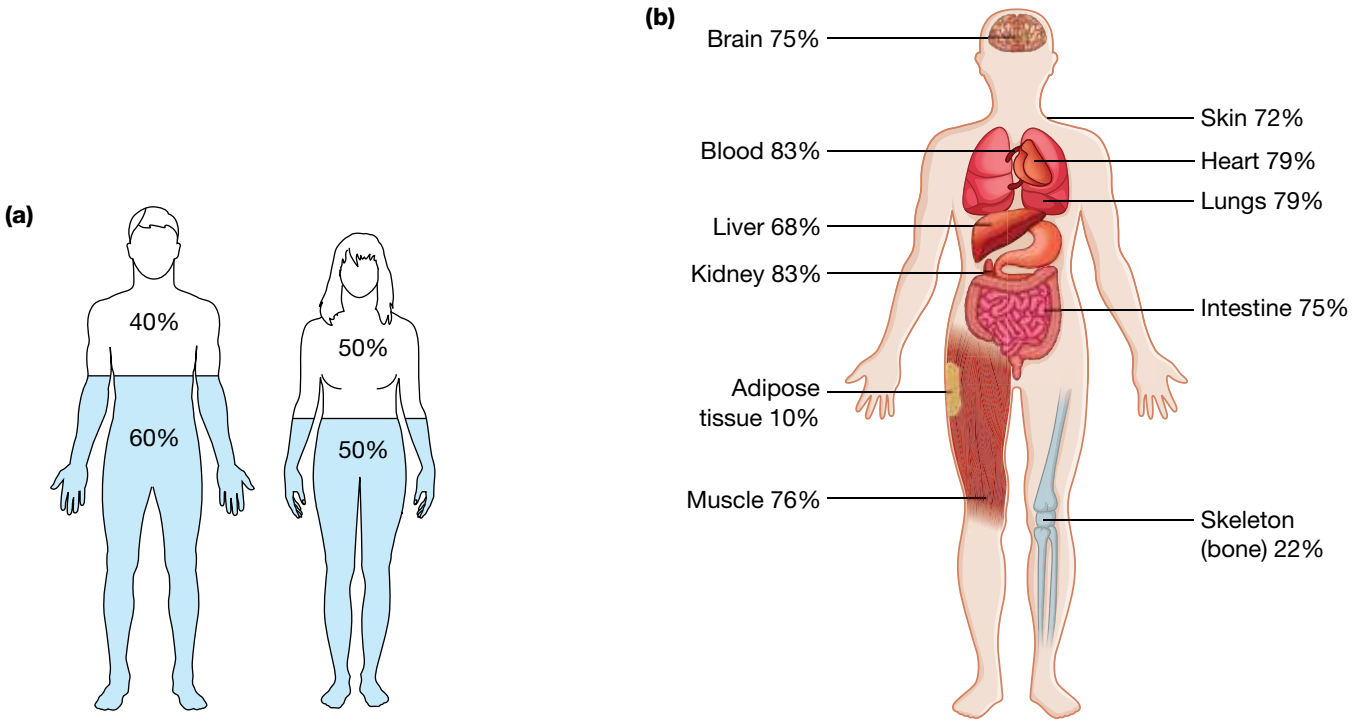


FIGURE 5.13 **(a)** Average percentage of body water in adult humans. Note the sex difference in the average percentage of total body weight that is composed of water. The average figure is lower for females because they have a higher percentage of fat. **(b)** Percentage water content of various human tissues and organs. Which tissues have the lowest water content? Do these data explain the difference between the average water content of adult males and females shown in part (a)?

Of the total water content of the body, most is contained within **intracellular fluid** (about two-thirds). This is the fluid *inside* the body cells, mainly the aqueous fluid of the cytosol. The remaining one-third of water is present as **extracellular fluid**; this is composed of **interstitial fluid**, which fills the spaces between cells and bathes their plasma membranes (about 26%), and **plasma**, the liquid portion of the blood (about 7%) (see figure 5.14a). The water content of the body is of course not just water: it contains dissolved solutes including proteins, sugars and minerals ions, such as sodium, potassium and chloride.

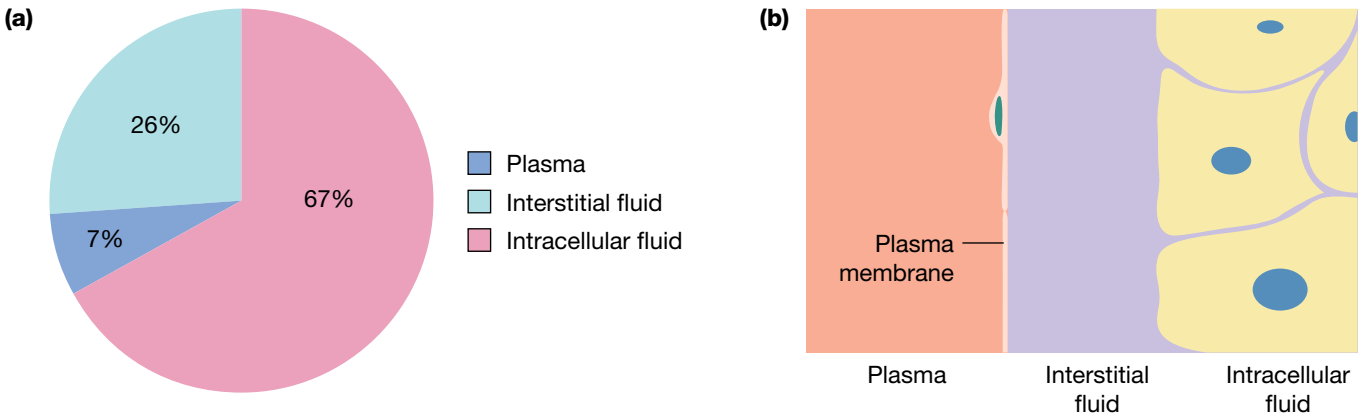


FIGURE 5.14 **(a)** Average distribution of the total water content of the body across the three 'compartments' in an adult human. In an average adult male weighing 70 kg, the total water of about 42 L is distributed as about 28 L of intracellular fluid within cells, about 11 L of interstitial fluid surrounding cells and about 3 L circulating in the blood plasma. **(b)** The body water compartments are separated but water can move between them. The cellular wall of the capillaries separates the plasma from the interstitial fluid. Plasma membranes of cells separate the interstitial fluid from the intracellular fluid.

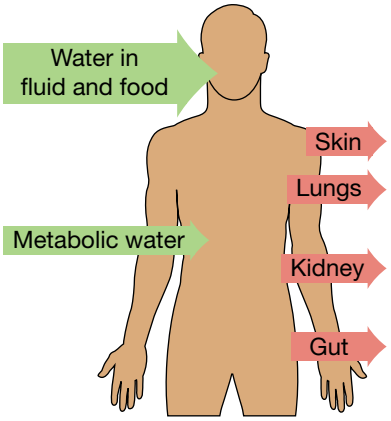


FIGURE 5.15 Water is both gained by and lost from the human body. Water losses (shown in pink) occur from the skin, lungs, gut and kidneys. Water gain (shown in green) occurs by absorption of water from fluid and food taken into the gut. Water gain also comes from metabolic water produced by aerobic cellular respiration.

Figure 5.15 shows the routes by which water is lost from and gained by the human body.

Water loss

In people, as in other mammals, water is lost through several avenues. A healthy adult human loses water from:

- the kidneys in the urine
- the lungs in exhaled breath. When we breathe out, we lose water vapour from the lungs and their passages. Typically we do not notice this loss, so this loss is said to be **insensible water loss**. We can, however, see this water loss on a cold day when the warm water vapour in exhaled breath condenses into tiny water droplets on contact with the cold air outside (see figure 5.16).
- the gut in egested faeces
- the skin, in water lost via pores in the skin and as sweat secreted by sweat glands. The loss of water via pores in the skin is an example of insensible (not noticed) water loss, and is the loss of pure water. In contrast, sweat contains dissolved solutes. Note that sweating does *not* occur until the body is subjected to heat stress, but the insensible loss of water from the pores of the skin occurs all the time.

The total daily loss of water in a person in a temperate climate and in a non-exercising state is on average 2.5 L. Table 5.2 shows the proportion of this loss through the different avenues of water loss.

FIGURE 5.16 Small amounts of water vapour are lost from the lungs in every exhaled breath. Normally, we are unaware of this loss. On a cold day, however, when the warm water vapour hits the cold air, it condenses into tiny droplets of water that are visible.

TABLE 5.2 Average minimum daily water loss by a non-exercising adult in a temperate climate

Organ	Volume lost (L/day)
kidneys	1.5
lungs	0.4
skin (via pores)	0.4
skin (from sweat glands)	0.0*
gut (via faeces)	0.2

*Sweating can be a major source of water loss, but sweating occurs only under conditions of heat stress.

Under changed conditions, water loss by a person can increase markedly, for example:

- Water loss from the skin is greatly increased when sweating occurs in response to an increase in core body temperature, such as during periods of vigorous exercise or during periods of exposure to high environmental temperatures. Sweating is initiated by the region of the hypothalamus of the brain in response to an increase in core body temperature. One study found that water loss from sweating can exceed 1.5 L per hour in persons working in very hot environmental conditions.
- Water loss from the gut is greatly increased when a person has severe diarrhoea or bouts of vomiting. In the case of diarrhoea caused by a cholera infection water loss can be fatal if medical treatment is not received (refer to chapter 1, p. 37). This highlights the dangers of severe dehydration.

Water gain

Water is gained from two sources: one external and one internal (see below).

The external sources of water gained by the human body are the aqueous fluids we drink and the water content of foods that we ingest (see table 5.3).

TABLE 5.3 Water content of some fresh fruits and vegetables

Food item	Percentage water
apple	84
banana	74
carrot	87
lettuce	96
orange	87
peas	79
watermelon	92
zucchini	95

Source: Adapted from www2.ca.uky.edu/enri/pubs/enri129.pdf.

Water enters the gut from where it is rapidly absorbed into the blood circulatory system — within 5 minutes of drinking the fluid. Absorption of water occurs mainly in the small intestine and, to a lesser extent, in the colon of the large intestine. Water is then distributed via the bloodstream throughout the body to the interstitial fluid and then to cells. (Passage of water into cells across the plasma membrane may occur either by osmosis or by facilitated diffusion through channel proteins known as aquaporins (refer to chapter 1, p. 33).

The internal source of water is produced during aerobic cellular respiration. Recall the summary equation for aerobic respiration (refer to chapter 3, p. 113):

$$\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water}$$

Note that water is a product of aerobic respiration, and this water is called **metabolic water**. This water is produced in one of the last steps in aerobic respiration:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

The volume of metabolic water produced each day is about 0.4 L. This amount is not sufficient for human survival, and must be supplemented by an intake of external water. One study identified that, on average, humans gain the water they need from fluids they drink (about 60%), from food they ingest (about 30%) and from metabolic water (about 10%).

KEY IDEAS

- Most of inland Australia is arid or semi-arid and is covered by sandy deserts.
- Water is essential for life and is a major component of the human body.
- In the human body, water is present in three 'compartments': plasma, interstitial fluid and intracellular fluid.
- For survival, water loss must be balanced by water gain.
- Water loss from the human body occurs through several channels, the main one being via the kidneys.
- Water gain by people is either external, from food and drink, or internal, from metabolic water.

QUICK CHECK

4 Which human tissue has:
   a the highest water content
   b the lowest water content?
5 Where would you find:
   a intracellular fluid
   b plasma
   c interstitial fluid?
6 In a healthy human adult, where is most water located?
7 List the routes for water loss by a person.
8 What is the origin of metabolic water?
9 True or false? A person continually loses water in sweat.

Adaptations for survival: desert animals

In this section, we will look at some examples of adaptations that enable animals to survive and reproduce in a desert environment. The key environmental challenges of desert life are avoiding excessive water loss that can result in dehydration and avoiding overheating that can result in hyperthermia, both conditions being potentially deadly.

In the previous section we saw that people, like most mammals, replace most of the water that they lose by drinking liquid water. This is easy when access to clean piped water is available. In the desert, however, free-standing water is neither predictably nor reliably available. After an occasional heavy rain or storm, temporary creeks, transient lakes and small pools of water exist in the desert. For most of the time, however, creek beds are dry, lakes are dry saltpans, and pools and puddles of water do not exist. This lack of free-standing water in the desert can persist for years, even decades. How is survival possible for animals and plants under these conditions?

Survival without drinking: the mulgara

Some mammals have features that equip them to survive in hot desert environments, including the ability to survive without drinking liquid water. Among them is the crest-tailed **mulgara** (*Dasycercus cristicauda*), a small native marsupial mammal that lives in sandy desert regions of central Australia (see figure 5.17). Mulgaras are carnivorous marsupials and their prey includes insects, scorpions and spiders. Like all mammals, mulgaras need water to egest their faeces, to excrete their wastes in urine and to cover evaporative loss of water vapour from their airways. How can they survive without drinking water? The mulgara achieves this by minimising its water loss to such an extent that it can meet all its water needs from the water content of its food and from metabolic water alone.

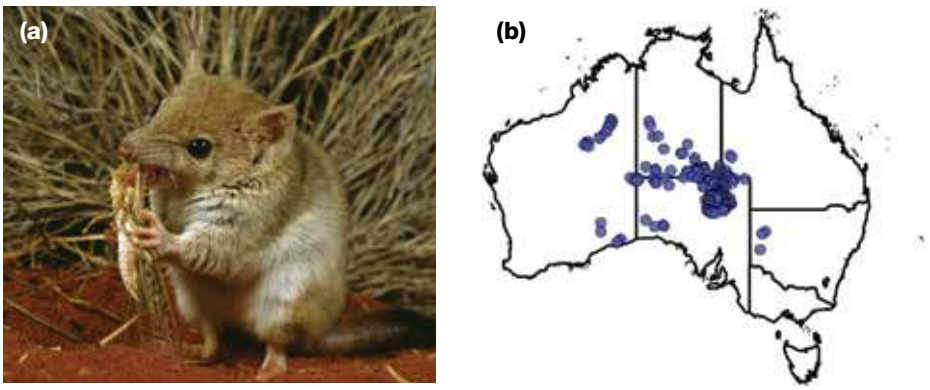


FIGURE 5.17 **(a)** The crest-tailed mulgara survives in the hot and arid desert environments of central Australia. Here the mulgara is eating a locust that provides it with both nutrients and water. The mulgara can survive without an intake of liquid water. In addition to its food, what is the other important source of water gain for the mulgara? **(b)** Distribution of the crest-tailed mulgara

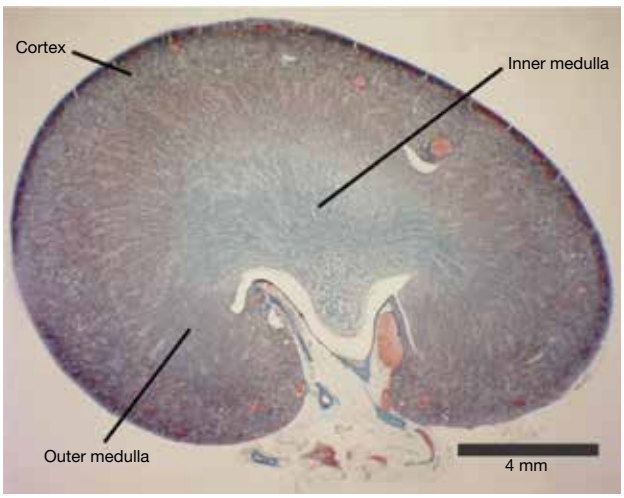
Water-conserving features present in mulgaras include structural, physiological and behavioural adaptations. One structural and physiological adaptation is that mulgaras minimise water loss by producing very concentrated urine (nearly 4000 mOsm/L) compared to humans (1200 mOsm/L). This means that a mulgara can rid its body of nitrogenous wastes, in the form of urea, using far less water than a person. This is achieved by two measures relating to the function and structure of the nephrons of the kidney (refer to figure 4.43, p. 170). These two measures are:

1. a reduction in glomerular filtration, meaning that less fluid leaves the blood and enters the kidney tubules
2. an increase in tubular reabsorption, meaning that more fluid is reabsorbed from the tubules and returned to the blood, particularly in the **loop of Henle**.

The units of concentration milliosmoles per litre (mOsm/L) refers to the osmotic strength of a solution.

Studies have shown that a strong correlation exists between the structure of a kidney and its ability to concentrate urine. In particular, the efficiency of the kidney is associated with a thicker medulla such that kidneys with a thicker medulla can produce urine that is more concentrated than kidneys with a thinner medulla. A thicker medulla allows for longer kidney tubules, in particular for longer loops of Henle. These U-shaped loops are where the greatest concentration of the kidney filtrate occurs. Figure 5.18a shows a longitudinal section of a kidney with a relatively thick medulla.

(a)



(b)

FIGURE 5.18 **(a)** Longitudinal section of the kidney of the numbat (*Myrmecobius fasciatus*), a marsupial mammal. (Image courtesy of CE Cooper and PC Withers) Termites form the exclusive diet of the numbat. Note the medulla (inner and outer) where the loops of Henle of its kidney tubules are situated. **(b)** The numbat, an Australian marsupial mammal

The relative **medullary thickness** of a mammalian kidney (that is, the thickness of medulla divided by kidney size) is positively correlated with the capacity of the kidney to concentrate the urine and so reduce water loss. The higher the relative medullary thickness, the higher the maximum concentration of the urine. In addition, the relative medullary thickness is greater in desert-dwelling mammals than in non-desert dwellers. Who do you think has kidneys with a thicker medulla: mulgaras or people?

Other structural and physiological adaptations include:

- Mulgaras produce very dry faeces and this means that they lose less water via their gut than animals that produce moist faeces.
- Mulgaras reduce insensible water loss from their airways by exhaling breath that is a few degrees cooler than the air they inhale. Warmer air holds more water than cooler air. The nasal passages allow outgoing breath to lose heat through the blood in the vessels in their nasal tissues, so that the air is cooled before it is breathed out. This conserves some water that would otherwise be lost as vapour if the exhaled breath were warmer.
- Mulgaras have few sweat glands so that the loss of water by sweating is minimised.

In summary, mulgaras minimise water loss through various structural and physiological adaptations. Because of this, mulgaras can obtain sufficient water for their needs from the water content of their food *and* from the metabolic water produced in aerobic respiration. If necessary, mulgaras can survive in the desert environment without drinking liquid water. Overall, mulgaras succeed in balancing their water loss and water gain, so that water-in equals water-out.

In addition, mulgaras exhibit adaptive behaviours that assist them to avoid overheating, for example:

- Mulgaras avoid the desert heat, particularly in summer, by sheltering during the day in their burrows and being active at night when conditions are cooler. This behaviour also assists in water conservation because sheltering in a humid burrow reduces the loss of water vapour from breathing and by diffusion from the skin. (For a person, the average daily loss from these channels is about 800 mL.)
- Mulgaras have their fat stores concentrated in their tail. Desert animals tend to store their body fat in a single location rather than having fat deposits spread under their skin and across the entire body surface. (The camel's fat store is concentrated in its hump). A possible explanation is that body fat acts as an insulator and slows heat loss from the body.

Survival without drinking: the tarrkawarra

Let's meet another water saver. The tarrkawarra, or spinifex hopping mouse (*Notomys alexis*), is a placental mammal that lives in sandy deserts in Australia (see figures 5.1 and 5.19). Because it can survive without drinking liquid water, the tarrkawarra can endure long periods of drought. Its kidney tubules reabsorb almost all the water from the kidney filtrate so that it produces highly concentrated and almost solid urine. In fact, tarrkawarras produce the most concentrated urine of any mammal. Their kidneys can produce urine with a concentration of 9370 mOsm/L.

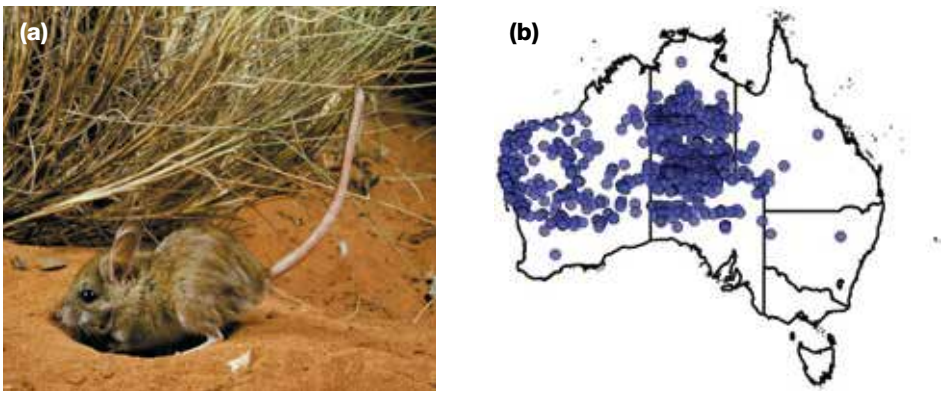


FIGURE 5.19 **(a)** The tarrkawarra, or spinifex hopping mouse, has the distinction of producing the most concentrated urine of any mammal. **(b)** The tarrkawarra lives in arid and semi-arid regions of Australia.

Table 5.4 shows a comparison of the maximum concentrating abilities of the kidneys of various mammals. This table also shows the urine-to-plasma (U/P) ratio, that is, the concentration of electrolytes, such as sodium, potassium and chloride ions, in the plasma relative to that in the urine.

TABLE 5.4 Comparison of maximum concentration of urine in several mammals (max. mOsm/L) and maximum ratio of electrolyte concentrations in the urine versus in the blood plasma (max. U/P). What does a ratio of 4 mean?

Species	Max. mOsm/L	Max U/P
human	1200	4
dog	2500	7
camel	2800	8
rat	2900	9
sheep	3500	11
tarrkawarra	9000	25

The sources of water gain and water loss for the tarrkawarra are outlined in the following section, as well as the adaptations that enable it to minimise its water loss so that water-in equals water-out. Achieving this water balance is essential for survival.

Water balance in the tarrkawarra

Water sources for the tarrkawarra are food, metabolic water and free-standing water. Water loss by the tarrkawarra can occur via the skin, faeces, exhaled air, urine and, in females only, milk.

Water gained through food

The main food for the tarrkawarra is dry seeds. The amount of water these contain depends on the **humidity** of the air in which the seeds are found. The relative humidity at night is greater than that during the day. The nocturnal habits of the tarrkawarra result in the animal collecting seeds at a time when the water content is likely to be at its highest. In addition, seed is stored in the burrows in which the tarrkawarra lives. The burrows are more than a metre deep, well insulated and have a relatively high humidity because animals huddle together there during the day (refer to figure 5.1). Seeds stored in burrows also have a greater water content than seeds collected from a plant. The tarrkawarra also eats green leafy shoots and insects when they are available but can gain weight on a diet containing dry seed only.

Metabolic water

When carbohydrate and fatty foods are oxidised in an animal's body, the main end products are carbon dioxide and water. This oxidation water, or metabolic water, is used by the tarrkawarra. The tarrkawarra does drink free-standing water if it is available but can survive without it. Free-standing water sources may include dew that can appear after a cold night and rainwater (although rare). A summary of the sources of water for the tarrkawarra is shown in figure 5.20.

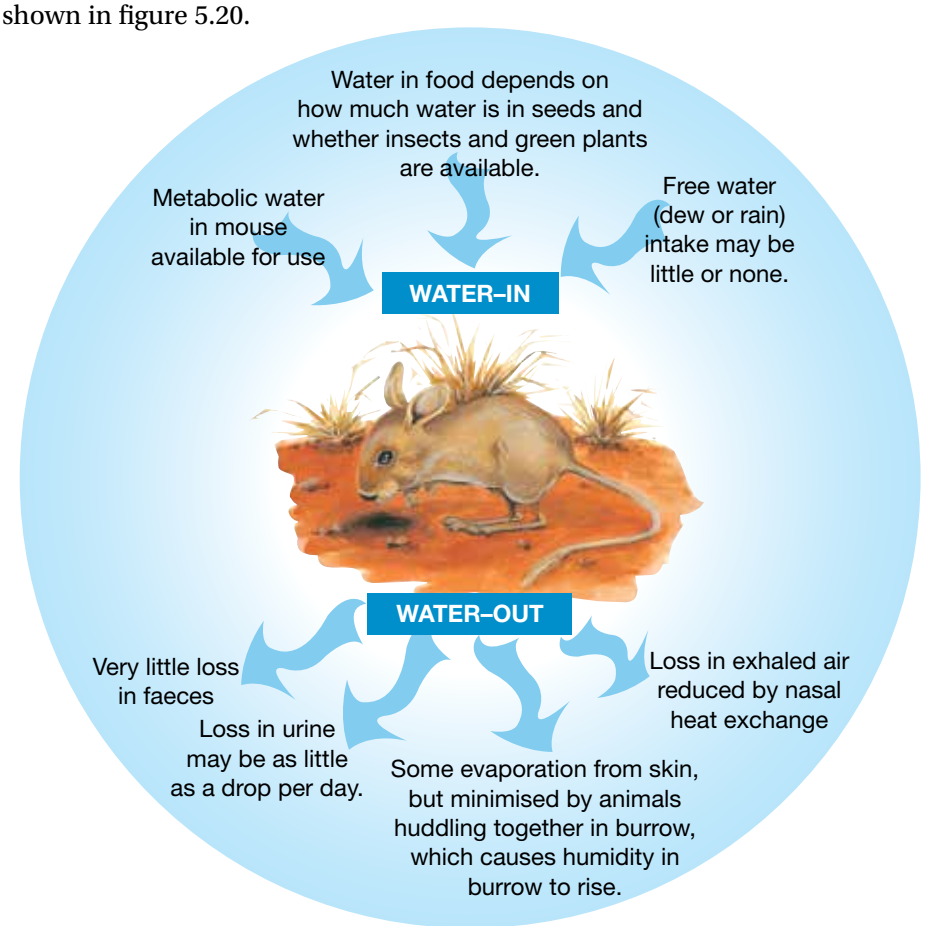


FIGURE 5.20 An outline of how the tarrkawarra achieves water balance. For survival, water-in must balance water-out.

Water loss from the skin

Although a tarrkawarra has no sweat glands, some water is lost by diffusion through the skin. Evaporation from the skin occurs but this is minimised. During hot days, animals stay in their burrows huddled together. Air surrounding the group increases in humidity and has the effect of reducing water loss from the skin.

Water loss in faeces

Tarrkawarra faeces are very dry and little water is lost in this way.

Water loss in exhaled air

Air that moves from the lungs to the surrounding atmosphere is saturated with water vapour. This could result in significant water loss. In the tarrkawarra, a special heat exchange system in the nasal passages reduces that loss. The temperature of air entering the body is lower than body temperature and so nasal passages are cooled as air enters. Warm air exhaled from the lungs passes over these cooled areas and is also cooled. Exhaled air is at a lower temperature than body temperature. As the air is cooled, some of the water vapour from the lungs recondenses on the walls of the nasal passages. Hence, not all the water vapour that leaves the lungs leaves the body.

Water loss in urine

Mammals must produce urine to be able to excrete their nitrogenous waste: urea (see chapter 4, p. 165). Oxidation of proteins results in urea that must be excreted. Tarrkawarras produce the most concentrated urine recorded for any mammal. Although some water loss occurs through the kidneys, it is clear that the kidneys are a significant site of water conservation in tarrkawarras.

Water loss in milk for the young

Female tarrkawarras, like all mammals, feed their young with milk. The loss of water through having to feed young is balanced to some extent by a mother drinking the urine her young produce. The water in urine is recycled. It has been estimated that a female who is feeding her young requires only one millilitre of water per day. This water for lactation is obtained from fresh green food, rainwater or dew. Although tarrkawarras live in very dry areas with little free-standing water, their structural, behavioural and physiological characteristics enable them to survive in harsh desert environments.

Surviving by dormancy

Frogs in the outback? Surely not!

Some frog species live in arid inland Australia. Frogs typically live in moist surroundings and need a body of water in which to reproduce. How do they survive long periods of drought in the inland? Some frog species that live near and breed in ephemeral waterholes respond in an amazing manner when the waterholes begin to dry out. The frogs burrow deeply into the soft mud at the bottom of their waterholes. Once underground at depths of up to 30 cm, the burrowing frogs, such as the trilling frog (*Neobatrachus centralis*) (see figure 5.21), make a chamber that they seal with a mucous secretion. The frogs then go into an inactive state known as **dormancy** in which breathing rates and heart rates are minimal and energy needs are greatly reduced. Their low energy requirements are met from their fat reserves. Read the account written by two explorers about burrowing frogs:

> One day during the dry season we came to a small clay-pan bordered with withered shrubs . . . It looked about the most unlikely spot imaginable to search for frogs, as there was not a drop of surface water or anything moist within many miles . . .

The ground was as hard as a rock and we had to cut it away with a hatchet, but, sure enough, about a foot [30 cm] below the surface, we came upon a little spherical chamber, about three inches [76 mm] in diameter, in which lay a dirty yellow frog. Its body was shaped like an orange . . . with its head and legs drawn up so as to occupy as little room as possible. The walls of its burrow were moist and slimy . . . Since then we have found plenty of these frogs, all safely buried in hard ground.

Source: WB Spencer and FJ Gillen, *Across Australia*, Macmillan and Co., London, 1912.

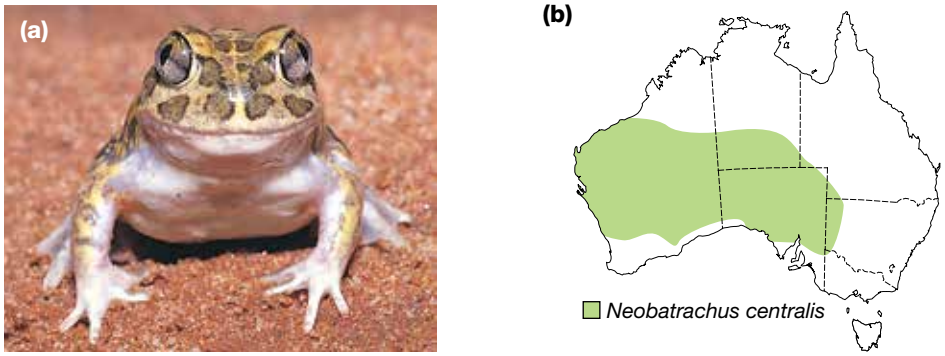


FIGURE 5.21 **(a)** The trilling frog (*Neobatrachus centralis*) is so called because of its high-pitched trill. **(b)** Distribution map of the trilling frog in Australia

The frogs remain buried and are protected from desiccation until the next rains come — this may be a wait of 1 or 2 years. The frogs come out of their dormant state only when soaking rains fall and soil moisture rises. Once activated, the frogs return to the surface to feed and breed in temporary pools. The completion of the life cycle is very fast. Within days of being laid, eggs undergo embryonic development, hatch and the resulting tadpoles metamorphose to produce small frogs. These new populations of frogs feed on larvae of crustaceans and insects that have also hatched from dormant eggs.

Other animal species survive extended periods of drought by sealing themselves off from the drying conditions. For example, the univalve (one-shell) freshwater mollusc (*Coxiella striata*) seals itself inside its shell by closing the shell opening with a hard lid (**operculum**). These inland molluscs must stay sealed tightly in their shells for months or years.

Surviving by moving around

Some species cope with drought by moving from affected areas to areas where conditions are more favourable. For example, banded stilts (*Cladorhynchus leucocephalus*) live near salt lakes in inland Australia and rely on these lakes for brine shrimps, which are their main food source (see figure 5.22). When one salt lake dries up, these birds simply fly to another salt lake.

FIGURE 5.22 A group of banded stilts. What strategy do they use when their salt lake habitat dries up?

FIGURE 5.23 The Australian budgerigar lives in large flocks in the arid inland of Australia. By taking flight, they can move away from areas when conditions deteriorate and seek more favourable conditions elsewhere.

Another species that moves widely throughout desert areas is the budgerigar (*Melopsittacus undulatus*). Flocks of these birds move to more favourable areas in search of food and water (see figure 5.23). In order to avoid the desert heat, they travel in the cooler periods of the day.

The strategy of moving quickly over large distances to seek out transient free-standing water in the arid outback of Australia is largely restricted to birds that are capable of flight. Many animal species and all plant species, however, cannot use a 'get-up-and-go' strategy in periods of drought.

Surviving through offspring

Survival can be viewed in terms of the successful survival of an individual organism that lives to reproduce on many occasions. Survival can also be considered from the point of view of survival of a species. Members of some species found in waterholes in the arid outback cannot survive long periods of drought. When the waterhole dries up, all the organisms die. Yet, these species are successful residents of the arid outback. How is this achieved?

Some species are unable to survive long dry periods and all members of the species die. In this case, **the species survives through its offspring.** This occurs in the case of crustacean species, such as fairy shrimps and shield shrimps. How?

When water is present in abundance, female shrimps produce eggs that are not drought resistant. As waterholes begin to dry out, fairy shrimps and shield shrimps (see figure 5.24) produce drought-resistant fertilised 'eggs'. These eggs are in fact cysts and each contains a fully developed embryo encased in a hard protective shell. By the time the water has gone, all the adult shrimps are dead but the cysts they have left behind can withstand desiccation for long periods. These cysts are in a state of dormancy and can lie in the dust of dry waterholes for more than 20 years.

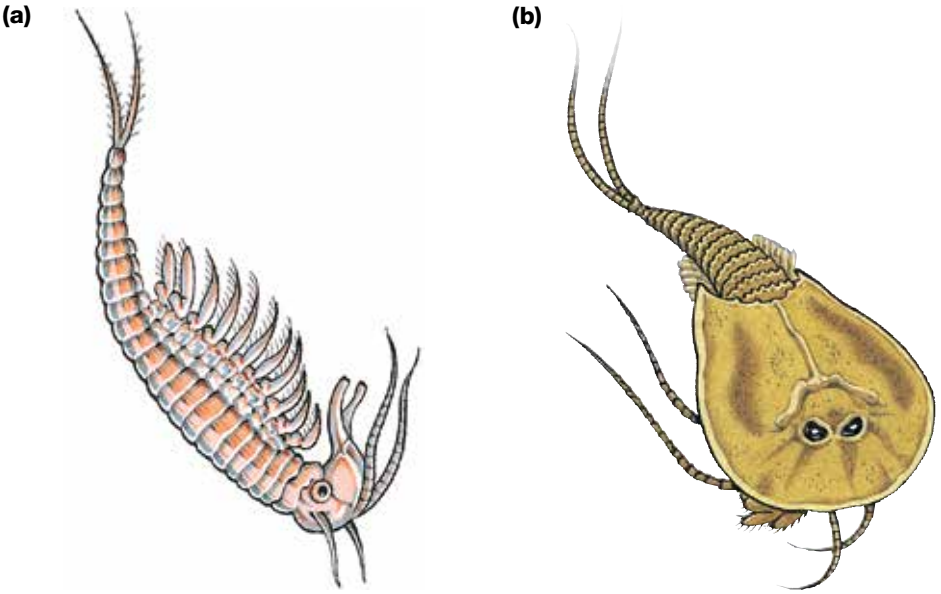


FIGURE 5.24 **(a)** A fairy shrimp (*Branchinella* sp.) about 3 to 4 cm in length. Fairy shrimps swim with their legs uppermost. **(b)** A shield shrimp (*Triops australiensis*) about 1.5 cm in length. How does this species survive drought?

When the drought breaks and the waterholes temporarily refill, the cysts hatch. Within just a few days, the newly hatched shrimps mature and reproduce. This is necessary because the waterholes and puddles in which they live will soon dry out. Male shrimps die after mating. Females carry large numbers of tiny drought-resistant cysts in a brood sac on their underbodies. Before the pools and waterholes turn to mud and then to dust, the female shrimps release their cysts and then die. These dried-out dormant cysts will lie in the dust or be blown by the desert wind, and the next generation of shrimp will emerge only when the rains come, perhaps years later, and short-lived waterholes and pools reappear.

What about the camel?

Camels, both the dromedary (*Camelus dromedarius*) and the Bactrian camel (*C. bactrianus*) are known as 'the ships of the desert'. Camels are large placental mammals. They are not native to Australia but large feral herds of camels, mainly dromedaries, live in arid areas of Australia, being descendants of camels imported in the 1800s. What adaptations do camels possess that enable them to survive in a desert environment?

FIGURE 5.25 The long eyelashes and slit-shaped nostrils of the camel enable it to survive in the arid inland of Australia.

Structural features that enable camels to survive in desert conditions include:

- a double row of long eyelashes and slit-shaped nostrils that can be closed — both features protecting the camel from wind-borne sand particles (see figure 5.25)
- bony structures in their nasal passages that enable the water vapour in their outgoing breath to be absorbed; it is then exhaled as dry air
- oval shaped red blood cells; the oval shape enables them to continue circulating even when the viscosity (thickness) of the blood increases due to the camel becoming dehydrated and losing body water
- the inbuilt fat store in the hump, which can be metabolised for energy production if food is not available. The oxidation reaction involved is also a source of metabolic water for the camel.

Physiological adaptations that minimise water loss in camels include:

- the ability to produce concentrated urine because of efficient kidneys; the urine they do produce is released and runs down their legs and its evaporation cools them
- the ability to produce very dry faeces because of a long colon in their gut
- the ability to allow their body temperature to vary over a wide range, from 34 to 42 °C, depending on the external temperature (unlike other mammals that maintain their internal body temperature within a narrow range). When it is hot during the day, the camel's body temperature rises. Sweating comes into play only when the camel's body temperature reaches 42 °C. (This is an important water conservation measure because sweating involves significant water loss.) At night, when it is cooler, this body heat is lost and the camel's body temperature falls.

Camels can lose up to 40 per cent of their body water, whereas an adult person can lose only 15 per cent. When water does become available, camels are able to drink large volumes — more than 100 litres in a day. This large intake of water, however, does not cause osmotic complications; for example, a camel's red blood cells can swell to more than double their volume before they burst, while the red blood cells of other large mammals would burst before this.

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KEY IDEAS

- Native mammals of the Australian deserts show many structural, physiological and behavioural adaptations that equip them for living in arid Australia.
- A range of adaptations may be seen in desert-dwelling marsupials that enable them to minimise water loss and, if necessary, survive without drinking water.
- Other survival strategies seen in various animal species include becoming dormant, moving around and producing drought-resistant offspring.

QUICK CHECK

10 List three water-conserving adaptations that may be seen in the mulgara.
11 Which organism can produce the more concentrated urine: a person or a mulgara?
12 Identify two features relating to kidney function that enable desert-dwelling marsupials to produce very concentrated urine.
13 Give an example of an animal that survives the long periods of drought in the desert:
- **a** by becoming dormant
- **b** by moving around
- **c** by producing drought-resistant offspring.

Vegetation types of arid Australia

Figure 5.26 shows the distribution of the major vegetation types in Australia.

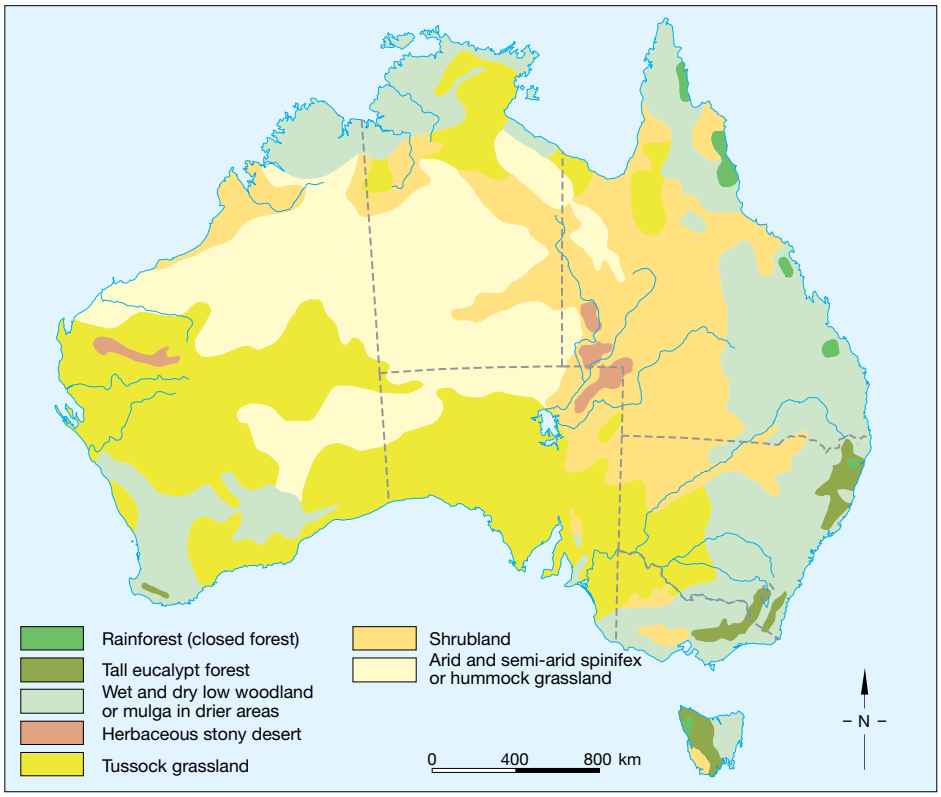


FIGURE 5.26 Major vegetation types in Australia

In terms of area, the dominant vegetation type in Australia is **hummock grassland**, which covers almost a quarter of the Australian land surface, including the sandy plains and dunes of the major deserts. Hummock grasslands are dominated by species of spinifex grasses (*Triodia* spp.) (see figure 5.27). Do not think about these grasslands in terms of the green grass of a front lawn or a suburban park. Spinifex grasses, such as buck spinifex (*Triodia basedowii*) are stiff, drought-resistant grasses.

FIGURE 5.27 Hummock grasslands are dominated by spinifex (*Triodia* spp.). These hummock grasslands cover much of the Australian sandy deserts. Note the typical hummock shape of the spinifex plant that gives these grasslands their name.

In terms of area covered, the next largest vegetation type is shrubland. Different kinds of shrubland exist. The kind of shrubland that is present in an area depends on rainfall and soil type, with each kind having a different dominant plant species. **Acacia shrublands** occur across the arid and semi-arid areas of Australia and are dominated by mulga (*Acacia aneura*) (see figure 5.28a). **Chenopod shrublands** occur in arid regions with salty soils and are dominated by saltbushes (*Atriplex* spp.) and bluebushes (*Maireana* spp.) (see figure 5.28b).

FIGURE 5.28 Australian shrublands cover much of the continent. Included among them are: **(a)** acacia shrublands, dominated by mulga and **(b)** chenopod shrublands, dominated by saltbushes and bluebushes.

Table 5.5 shows the pattern of distribution of the major vegetation types in Australia as determined by environmental physical factors of rainfall, temperature, evaporation rate, and mineral-nutrient levels (rich or poor) and salt levels of the soil (salinity).

TABLE 5.5 Patterns in the distribution of various types of vegetation in Australia

Vegetation type	Climate
• hummock grasslands	arid: lowest and erratic rainfall, high evaporation rates, high temperature
• acacia shrublands	arid: low rainfall, high temperature
• chenopod shrublands	arid and semi-arid: low rainfall, high temperature, salty or alkaline soils
• tussock grasslands dominated by *Astrebla* spp.	semi-arid: annual rainfall between 200 and 500 mm, clay soils
• tropical grasslands dominated by *Sorghum* spp.	tropical: summer monsoons and winter drought
• mallee woodlands	temperate: intermediate rainfall, poor soil
• eucalypt forests	temperate: high rainfall, poor soil
• rainforests	tropical or temperate: high and reliable rainfall, rich soil

ODD FACT

The difference between woodlands and forests is the area of sky blocked by the upper canopy of leaves, as seen by a person looking up to the sky from below. For forests, the foliage coverage is from 30 to 100 per cent of the sky, while for woodlands, the coverage is less than 30 per cent.

Adaptations in desert plants

Let's look at how plants of the arid inland of Australia survive through structural and physiological adaptations that equip them to:

- maximise water uptake
- minimise water loss
- produce drought-resistant seeds.

Maximising water uptake

The part of a plant that takes up water is the root system. In arid areas of Australia, some trees growing along dry creek beds produce long, unbranched roots that penetrate to moist soil at or near the watertable. Once moisture is reached, the major root branches and forms lateral roots. **Plants that produce these deep roots are called water tappers** and their major root can grow to depths of 30 m. The part of the root that is located in the upper dry soil is covered by a corky waterproof layer of cells that prevents water loss.

Other plants growing in arid regions develop extensive root systems that spread out horizontally, far beyond the tree canopy but just below the soil surface. In this case, the plant takes up water from an extensive area around it.

Minimising water loss

Transpiration is the loss of water vapour by evaporation from moist surfaces inside the plant (see figure 5.29). This loss of water vapour occurs through pores, known as **stomata** (singular: stoma), which are typically present on the lower surface of plant leaves (see figure 5.30). The higher the wind speed and the higher the temperature of the leaf, the greater the rate of water loss.

For a plant to reduce its water loss, the principal strategy is to reduce the loss of water vapour by transpiration through the stomata on its leaves. Transpiration cannot be stopped permanently because it is essential for the process of moving columns of water through xylem tissue, from where water is supplied to all cells of a plant (refer to chapter 4, p. 181). Stomata are also the pores through which the carbon dioxide required for photosynthesis enters leaves and they must open to allow carbon dioxide to diffuse into the leaves.

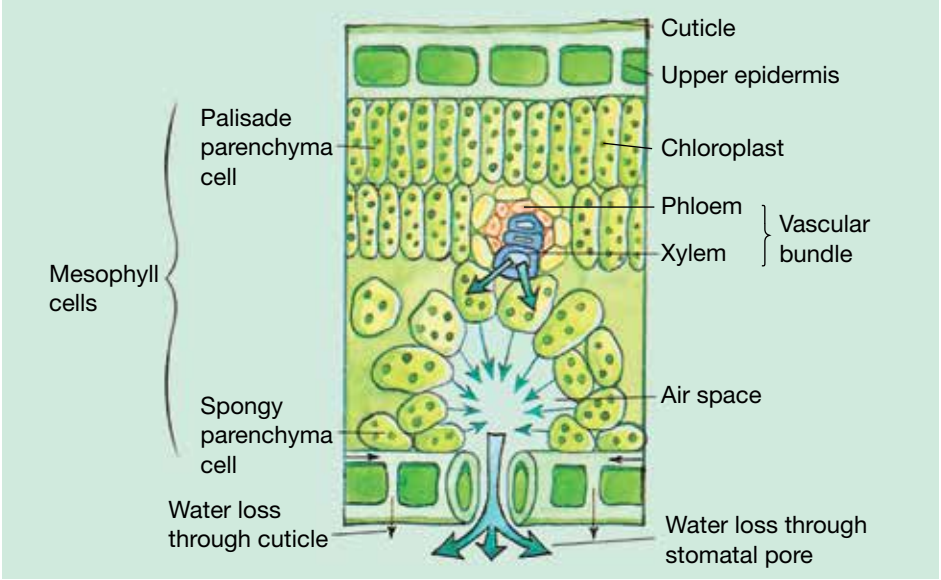


FIGURE 5.29 In a leaf, water moves from xylem into surrounding mesophyll cells. As water vapour moves out of the leaf through stomata, water evaporates from the moist surfaces of the mesophyll cells. Most water is lost from a leaf through stomata, but a little evaporates from the cuticle.

Let's explore how various adaptations of leaves, mainly structural, can reduce the water loss in plants.

Presence of a thick cuticle

Most water loss from plants occurs via their stomata, but some water is also lost directly across the surfaces of cells exposed to the external environment. This latter water loss is minimised by the presence of a waxy **cuticle** on the exposed upper surface of leaves (see figure 5.31). The cuticle is composed of a waterproof material called cutin. Plants that live in arid environments typically have leaves with thicker cuticles than those in non-arid regions.

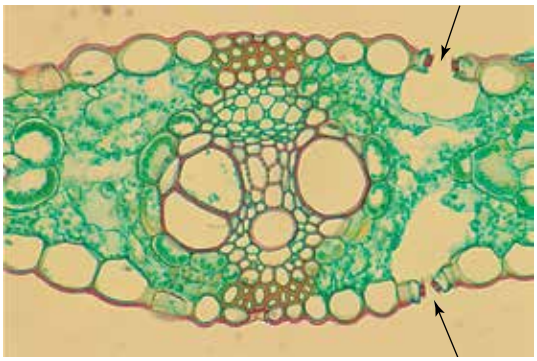
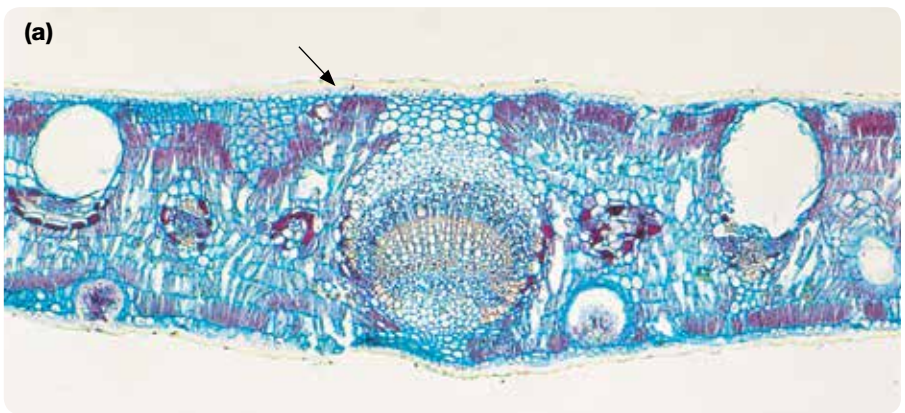


FIGURE 5.30 Transverse section (200X) through a monocotyledon leaf. Note the stomata (arrowed) on each surface, and the large vascular bundle comprising large thick-walled cells of the xylem tissue and thin-walled cells of phloem. This plant has stomata on both its upper and lower leaf surfaces. More commonly, stomata are restricted to the lower surface only.



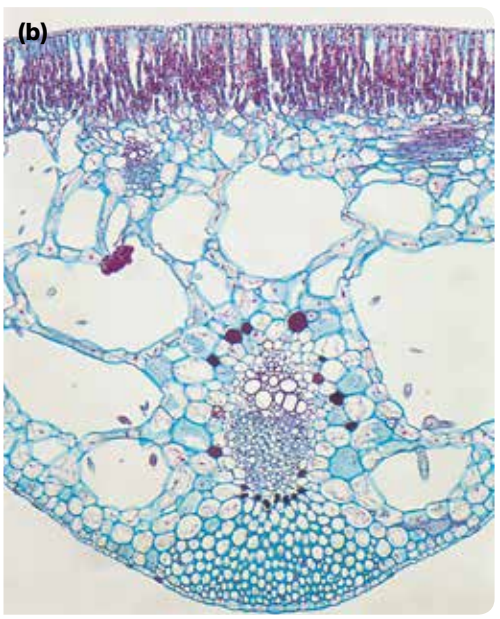


FIGURE 5.31 Transverse sections through leaves from two different species of plant: **(a)** *Eucalyptus globulus* and **(b)** waterlily (*Nymphaea* sp.). The two leaves are at the same magnification. Note the thick cuticle (arrowed) of the Eucalyptus leaf and apparent lack of cuticle on the waterlily leaf. The thicker the cuticle, the less transpiration occurs.

Reduced number of stomata per unit of surface area

Fewer stomata per unit area of leaves means that water loss by transpiration is reduced.

Presence of sunken stomata

The rate of water loss of a leaf from its stomata is affected by several factors including the humidity of the air surrounding the stomata. Water vapour is lost from leaves via their stomata more rapidly when they are immediately surrounded by dry air than when they are surrounded by humid air. Why? The concentration gradient of water vapour from inside the leaf to outside is steeper in drier conditions relative to more humid conditions.

Another related factor that affects water loss by transpiration is wind speed. On a windless day, the loss of water by transpiration is low because the stomata are surrounded by a boundary of still air with a level of humidity similar to that inside the leaves. In contrast, on a windy day, the water vapour that transpires from leaves is immediately blown away so that more water vapour diffuses from the leaves. The windier the day, the higher the rate of transpiration.

Unlike 'typical' stomata that are situated at the leaf surface, **sunken stomata** are located in pits below the leaf surface. This position below the leaf surfaces creates a region of relatively higher humidity in the air space immediately surrounding the sunken stomata as compared with stomata at the leaf surface. The presence of sunken stomata reduces water loss by transpiration (see figure 5.32). Likewise, the presence of hairs on the upper surfaces of leaves and around the stomata would be expected to reduce the speed of airflow over leaves and contribute to a reduction in water loss.

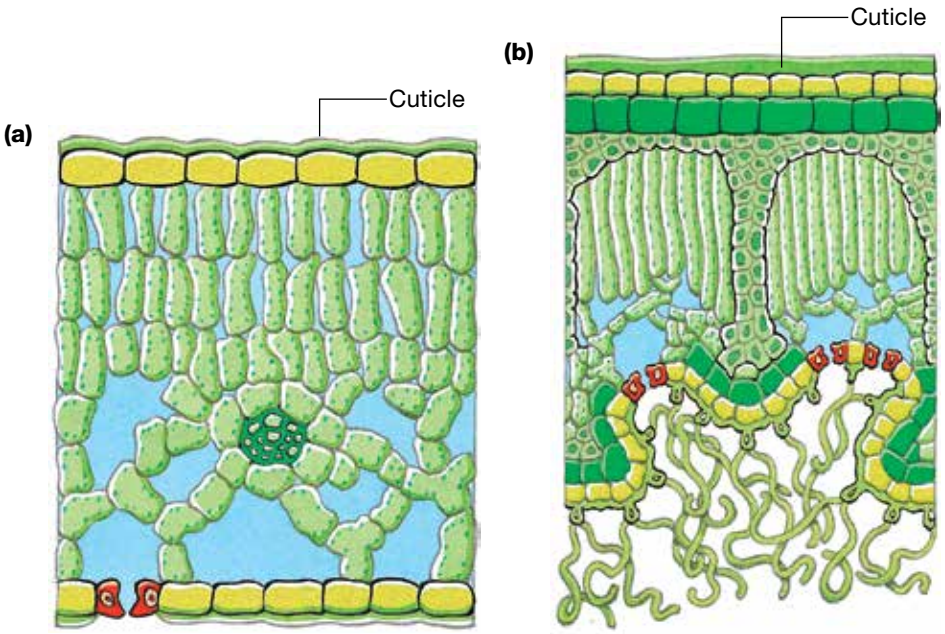


FIGURE 5.32 **(a)** Transverse section of a 'typical' leaf with stomatal openings flush with the lower leaf surface. Guard cells surrounding the stoma are shaded red. **(b)** Transverse section of a leaf from a plant with its stomata sunk below the leaf surface. Note also the hairs on the lower leaf surface and the thick cuticle on the upper surface.

Leaf colour, size and margins

Temperature is another factor that affects the rate of water loss by transpiration; lower temperatures mean less transpiration. Leaves of some shapes gather less heat from exposure to the sun than other shapes and so reduce water loss. Leaves with a small surface area reduce the area from which transpiration occurs.

- *Leaf colour*. Silver or glossy leaves reflect relatively more sunlight producing lower leaf temperatures.
- *Leaf shape*. Small, narrow or cylindrical leaves have a small surface area. When exposed to the sun, these leaves gather less heat than larger flat leaves and so stay cooler, minimising water loss (see figure 5.33).

FIGURE 5.33 Some leaf shapes expose a smaller surface area to the sun and so stay cooler, such as: **(a)** small leaves and **(b)** cylindrical leaves.

Plants of the Australian genus *Hakea* show a variety of adaptations that enable the plants to minimise water loss. As well as cylindrical leaves, *Hakea* plants also have a thick cuticle on their leaf epidermal cells and have sunken stomata. Look at figure 5.34a. Note the cylindrical cross-section shape of the *Hakea* leaf and the position of some stomata (arrowed). Figure 5.34b shows the detail of a sunken stoma in a *Hakea* leaf.

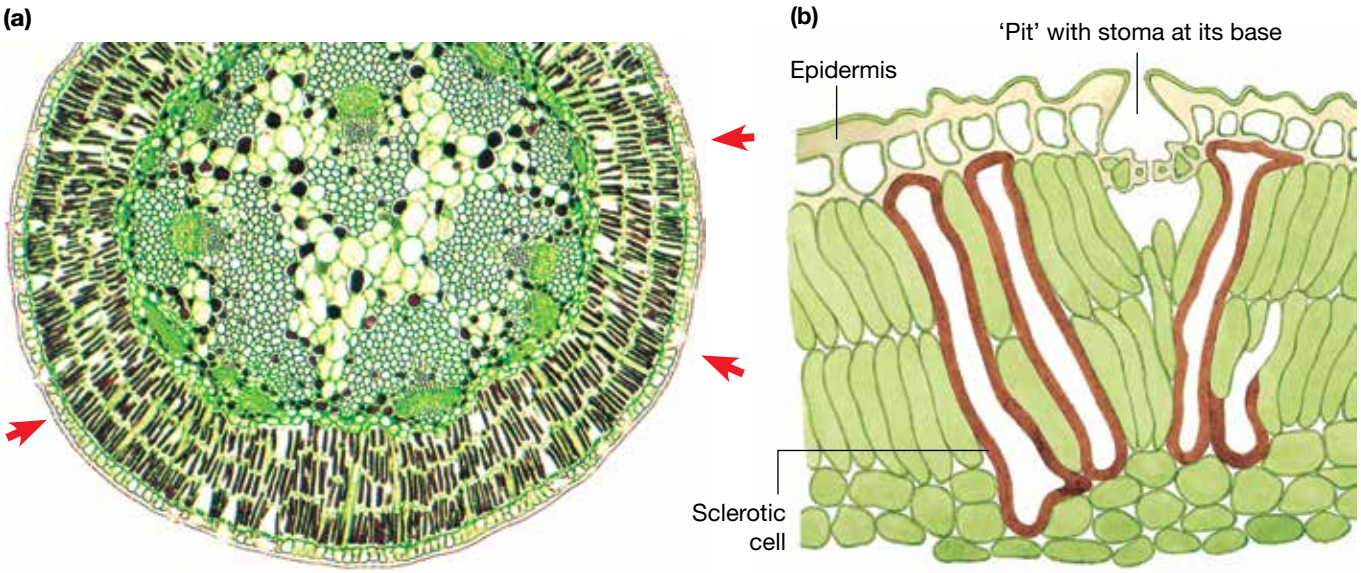


FIGURE 5.34 **(a)** A transverse section through a *Hakea* leaf with indications (arrows) of positions of some of its stomata **(b)** Details of a sunken stoma of *Hakea*. Note the position of the stoma below the surface of the leaf and the 'pit' above the stomal opening.

- *Leaf margin*. Leaves are thinnest where their upper and lower surfaces meet, that is, at their margins. Plants lose more heat from thinner regions than from thicker regions. The larger the ratio of edge length to surface area of a leaf, the faster a leaf will be cooled. Cooler leaves have lower transpiration rates. Leaves with incised margins have a larger edge-length-to-surface-area ratio than leaves with entire margins. These leaves are thus cooler and so have a lower transpiration rate (see figure 5.35a).
- *Leaf orientation*. The orientation of leaves can influence leaf temperature (see figure 5.35b). Leaves with a vertical orientation have less exposure to sunshine and so gain less heat and are cooler. Cooler means less water loss.

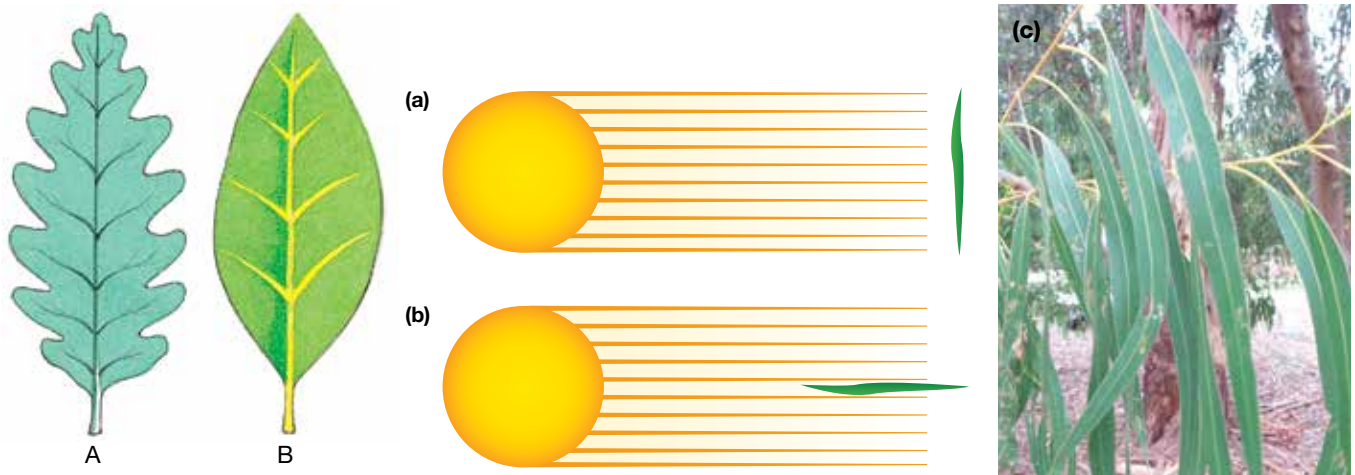


FIGURE 5.35 **(a)** At left is a leaf with an indented margin and at right is a leaf with an entire margin. Which leaf will cool more quickly? **(b)** Diagram showing how the orientation of leaves can affect the amount of heat gained when exposed to the sun. Which leaf orientation would be expected to gain more heat: vertical or horizontal? **(c)** Vertically oriented leaves are common in *Eucalyptus* species.

Rolled-up leaves

Figure 5.36 shows a **rolled-up leaf** of marram grass (*Ammophila arenaria*). Although this is not an Australian species, some related species in Australia have the same characteristics. These leaves have a number of features to restrict water loss, including:

- hinge cells that lose turgor if water is lost and cause the leaf to curl inwards, creating a humid chamber for the stomata
- stomata on only one side of the leaf so that when the leaf curls, no stomata are directly exposed to the environment
- stomata located in 'folds' of the leaf so that they are shielded from air currents even when the leaf is unrolled
- a thickened cuticle on the surface that is exposed when the leaf curls. Note the hairs on the upper epidermis of the leaf in figure 5.36b.

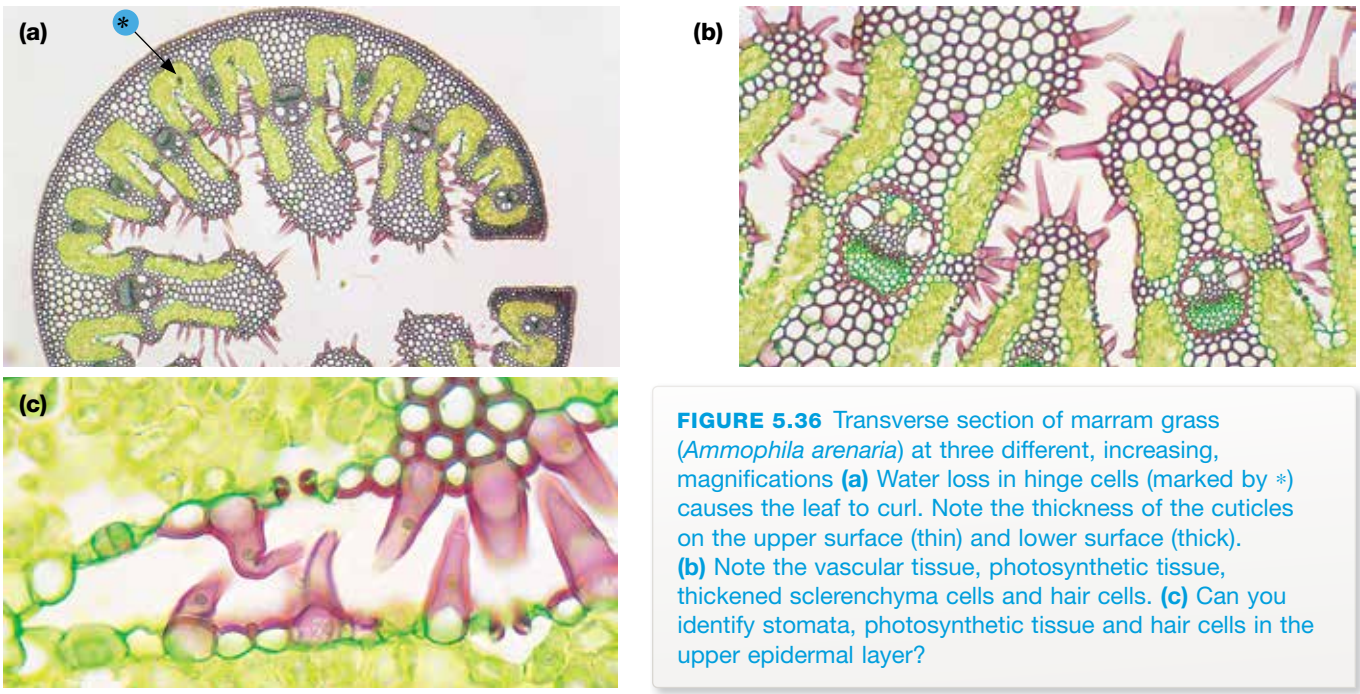


FIGURE 5.36 Transverse section of marram grass (*Ammophila arenaria*) at three different, increasing, magnifications **(a)** Water loss in hinge cells (marked by *) causes the leaf to curl. Note the thickness of the cuticles on the upper surface (thin) and lower surface (thick). **(b)** Note the vascular tissue, photosynthetic tissue, thickened sclerenchyma cells and hair cells. **(c)** Can you identify stomata, photosynthetic tissue and hair cells in the upper epidermal layer?

FIGURE 5.37 Cacti have succulent stems, few or no leaves and extensive shallow roots. Note the succulent stems of prickly pear cactus, *Opunta stricta*, which can store large quantities of nutrients and water. Also note the berries. These contain seeds that can be distributed over large areas by birds and other animals.

No visible leaves

Various plants that survive in drought conditions have no visible leaves, for example, cacti, succulent plants that are members of the *Cactaceae* family and native to the Americas (see figure 5.37). Their leaves are reduced to spines and their stems are swollen with cells that contain water stores in their vacuoles. These plants have extensive shallow roots, thick cuticles on their surfaces and few stomata.

Leaves that aren't leaves

Members of the genus *Acacia*, commonly called wattles, are widespread in Australian environments, including arid and semi-arid regions. Mulgas (*Acacia aneura*) are the dominant species in the acacia scrublands. As many *Acacia* species mature, their feathery leaves are replaced by their flattened leaf stalks. These flattened leaf stalks are known as **phyllodes**. Figure 5.38a shows a transitional state in which the feathery true leaves of an *Acacia* plant are starting to be replaced by leaf stalks that are gradually thickening. Phyllodes enable plants to survive in arid conditions because they provide a store of water in large parenchyma cells at their centre. In addition, phyllodes have fewer stomata than true leaves and so lose less water by transpiration.

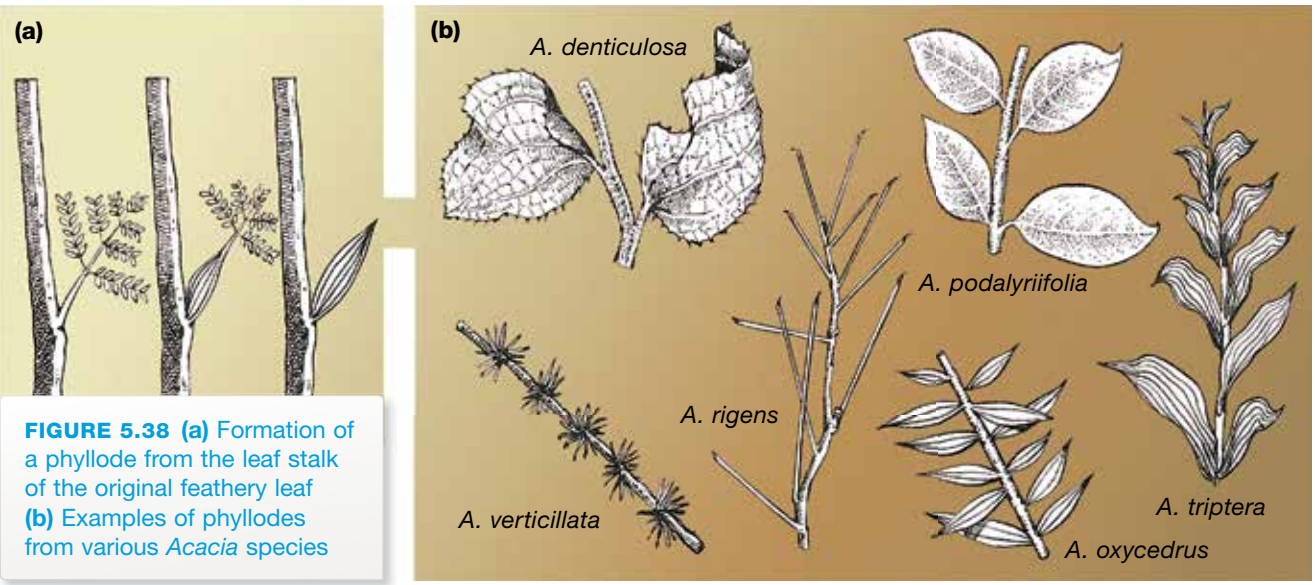


FIGURE 5.38 **(a)** Formation of a phyllode from the leaf stalk of the original feathery leaf **(b)** Examples of phyllodes from various *Acacia* species

Plants of the genus *Casuarina* and *Allocasuarina* show a different adaptation. These plants have what appear to be fine needle-like leaves, but in fact they are modified branches that function as leaves and are known as **cladodes**. The leaves are reduced to tiny scales that encircle each joint of the cladode (see figure 5.39). Cladodes have fewer stomata than true leaves and so lose less water by transpiration.

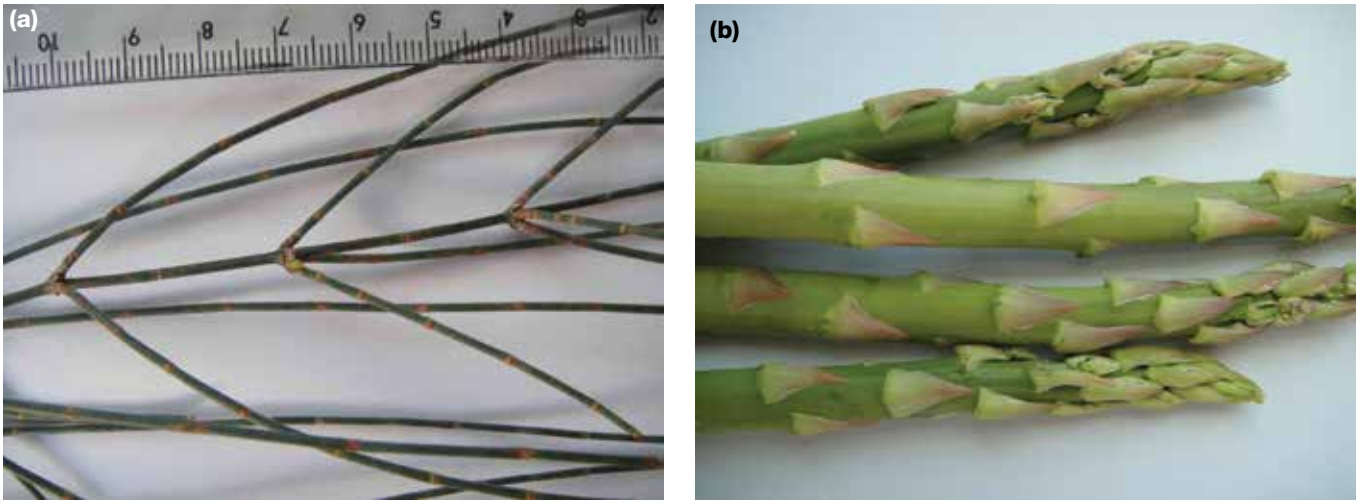


FIGURE 5.39 **(a)** Cladodes from a plant belonging to the Australian genus, *Casuarina*. Note the rings of tiny scales that are all that remain of the true leaves. **(b)** Asparagus is another example of a cladode.

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Shedding leaves

To minimise water loss, when plants become stressed in drought conditions, they may conserve water by dropping their leaves. This is a strategy that is seen in the bladder saltbush (*Atriplex vesicularia*). In conditions of severe drought this saltbush closes its stomata, drops its leaves and sheds its fine roots.

Producing drought-resistant seeds

Populations of some herbaceous flowering plants can survive in arid regions of Australia. **These plants germinate from seeds, then flower and produce new seeds in a very short period.** Plants that complete their life cycles in just two to three weeks are said to be **ephemeral**. Because they produce **drought-resistant seeds**, populations of ephemeral plants can survive in arid regions. The outer coats of the seeds of these plants contain a water-soluble chemical that inhibits seed germination. So, dry conditions = no germination. When heavy rains fall, this chemical is dissolved and the seeds germinate to produce seedlings. Shortly after, the new plants produce flowers in a synchronised display (see figure 5.40). The plants soon die, but not before they have produced seeds that will lie dormant until the next heavy rains.

As was seen in figure 5.40, local rainfall over a region of desert can transform areas of the red centre of Australia to a green centre.

Some years, very heavy rains that fall hundreds of kilometres from the desert can reach the desert months later. This can occur with the monsoon rains that fall in Queensland and flow through rivers of the Channel Country, with the water spilling out over extensive floodplains (see figure 5.41). When this happens vast regions of the desert are transformed into watery habitats where fish and waterbirds breed.

FIGURE 5.40 A magnificent display of flowers of ephemeral plants in the Australian desert. What event caused this blooming of the desert? Populations of these plant species exist most of the time as seeds, not plants!

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Rain brings Red Centre's desert landscape to life

FIGURE 5.41 A flooded river plain in the Simpson Desert. This water originated from torrential rainfall in western Queensland that eventually flowed into dry riverbeds in the desert, transforming the sandy plains to shallow lakes. (Image courtesy of Stan Sheldon)

On rare occasions, the water may reach as far south as Lake Eyre in South Australia. Normally, Lake Eyre is a dry saltpan but it sometimes becomes a giant lake and breeding ground for birds, including pelicans (see figure 5.42).

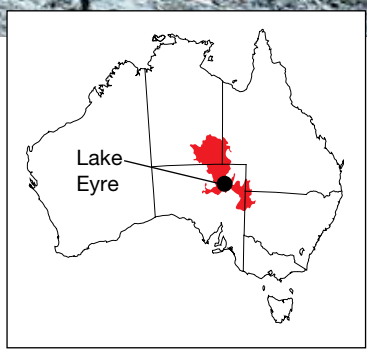

FIGURE 5.42 **(a)** Torrential rains in Queensland early in 2011 resulted in water flowing into Lake Eyre, transforming much of it into a shallow lake by August. This view of Lake Eyre (taken on 5 December 2011 from the International Space Station) shows water still present in some sections, including Belt Bay and Madigan Gulf. The green and pink colours are due to high densities of archaea that thrive in these highly salty aquatic conditions. The bright white surface of Lake Eyre South (at lower right hand corner) shows that the water has already evaporated from there, returning it to its dry saltpan state. **(b)** Pelicans in large numbers breed on the shores and on mounds in Lake Eyre when it fills with water.

KEY IDEAS

- The arid and semi-arid areas of inland Australia are dominated by hummock grasslands, acacia shrublands and chenopod shrublands.
- Desert plants show a variety of adaptations to maximise water uptake and to reduce water loss.
- The major loss of water in plants occurs as water vapour lost by transpiration from the leaf stomata.
- Many adaptations exist in desert plants for reducing water loss from their leaves.
- Ephemeral plant species of desert regions produce drought-resistant seeds that germinate only after rain or flooding.

QUICK CHECK

14 What is the major avenue of water loss by plants?
15 Identify one example of an adaptation that enables a plant to conserve water by:
- **a** reducing water loss from cells at the leaf surface
- **b** reducing water loss from the leaf stomata
- **c** reducing the absorption of heat, thus staying cooler and reducing the rate of transpiration.

16 What is a phyllode?
17 How do phyllodes enable a plant to conserve water?
18 What feature prevents drought-resistant seeds from germinating before rain falls?

The dominant plants

Let us now have a closer look at three plants that are dominant species in the arid and semi-arid areas of Australia: the mulgas of the acacia shrublands, the saltbushes of the chenopod shrublands and the spinifexes of the hummock grasslands found in the major deserts.

Mulgas: tree of the arid inland

Acacia shrublands of arid inland Australia are dominated by mulga (*Acacia aneura*), which can exist either as trees or small shrubs (refer to figure 5.28a, p. 215). Mulga trees have many features or adaptations that equip them for survival in arid conditions (see figure 5.43).

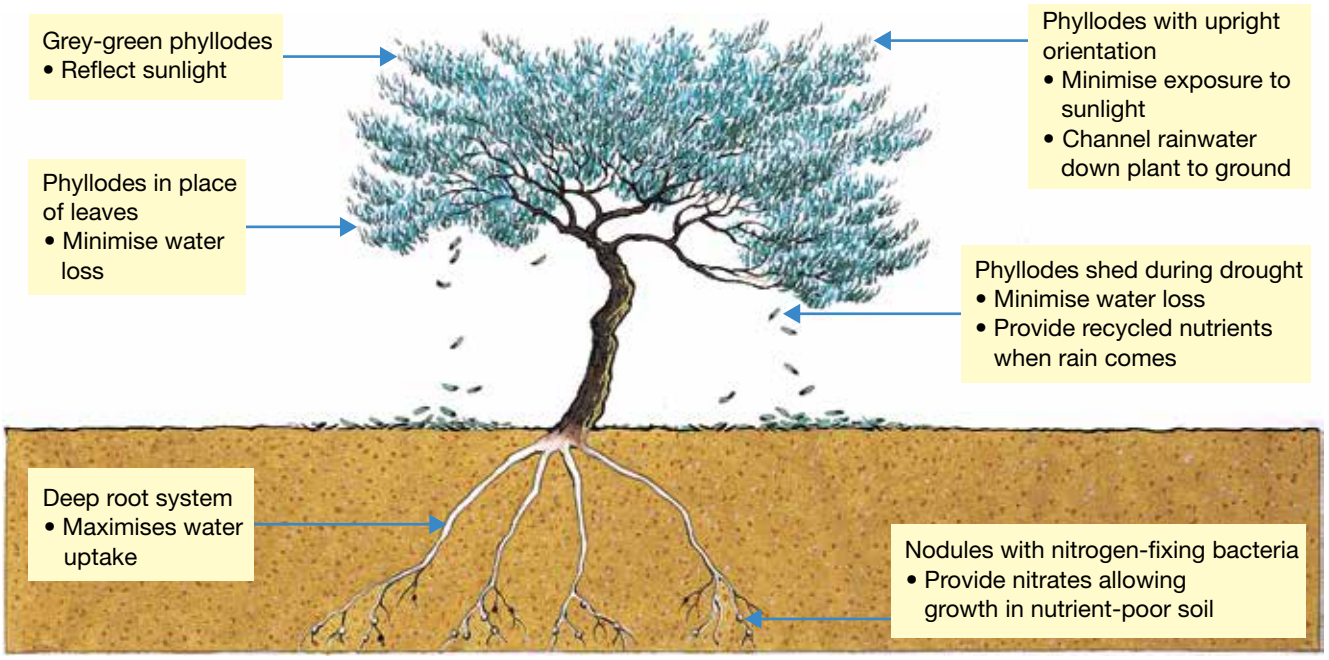

FIGURE 5.43 Some of the adaptations of the mulga tree. The vertical orientation of sparse foliage of mulga trees ensures that the little rain that falls is directed to the roots of the plant.

The root system of a mulga tree is concentrated around the base of the tree. When rain falls, it is caught by the upward-pointing leaves of this tree and funnelled down the branches to the centre of the tree. From there, the water falls to the ground around the trunk where the root system is most concentrated.

Mulga trees grow in regions where the rainfall is low and unreliable because they are drought resistant and can survive a year or more without water. In dry years, a mulga tree does not produce any flowers. If, however, heavy rains fall in the summer, a mulga produces flowers and, if rains occur in the following winter, seeds are formed. The seeds germinate to produce seedlings the following summer and require rain to survive. Notice that a pattern of rainfall over three seasons (summer-winter-summer) is required for a new generation of mulgas to be produced. This pattern of rainfall occurs during a La Niña event.

Saltbushes (chenopods)

Soils of some areas of the hot, arid inland contain high concentrations of salt. Many species of salt-tolerant plants live in this environment, such as species of saltbush (*Atriplex* spp.) (see figure 5.44) and bluebush (*Maireana* spp.). These plants are also drought resistant.

FIGURE 5.44 The saltbush (*Atriplex cinerea*) is salt tolerant and drought resistant.

Saltbushes grow in soils that are too salty for many other plant species. They can survive because they excrete the dissolved salt that is taken up by their roots from cells in their leaves. As a result, the leaves of saltbushes are covered in fine salt crystals. As well as being an excretory product, these salt crystals reflect the sun's heat and contribute to keeping the plants from overheating.

Saltbushes have structural adaptations to conserve water. Their leaves:

- have sunken stomata
- are covered in hairs
- are oriented so that they expose a minimal surface to the sun's rays.

Saltbushes produce seeds that have high concentrations of salt in their outer coats and this salt prevents germination. Saltbush seeds germinate only after the salt has been washed out after heavy rainfall. As soon as the salt inhibition is removed, the seeds germinate and new seedlings quickly become established. The salt inhibition of germination means the next generation of saltbush plants appears in times of good rainfall when their chance of survival is maximised.

Spinifexes of the hummock grasslands

The leaves of spinifex plants contain high levels of silica grains, which makes them rigid and sharp-pointed (see figure 5.45). Spinifex hummocks provide shelter for desert animals: mammals such as the tarrkawarra and reptiles such as many species of lizard and snake. The only animals that use spinifex as a food source are termites that feed on the litter from dead plants.

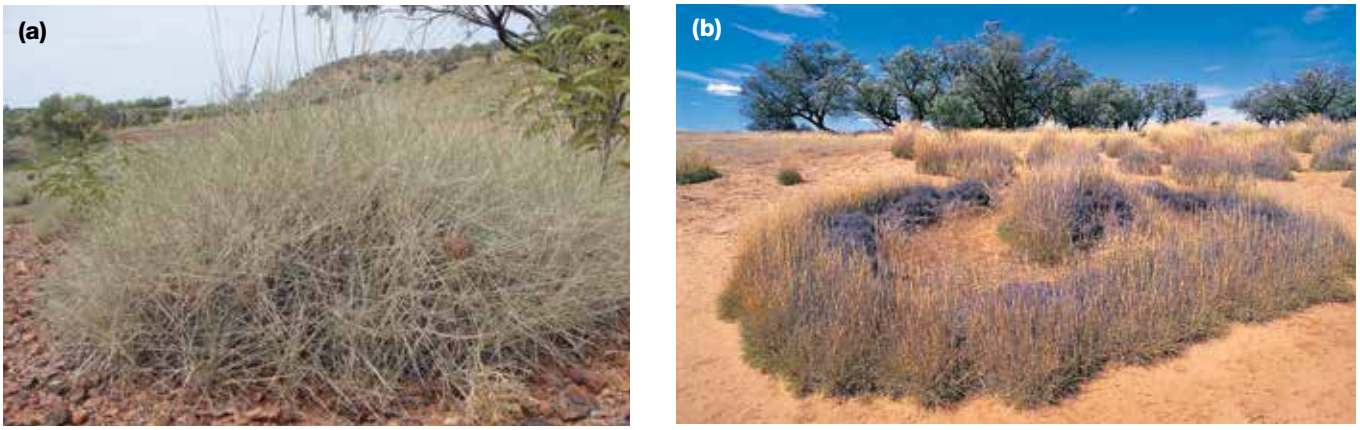

FIGURE 5.45 **(a)** Close up of a spinifex plant showing its hard spiky leaves **(b)** Spinifex grasses grow in circular clumps that, over time, extend outwards forming larger circles. The oldest part of the plant is at the inside of the circle. These shoots will be the first to age and die, while new growth forms on the outside of the ring.

Spinifex grasses show physical adaptations to desert conditions including:

- a deep root system that extends 3 m or more into the soil, maximising water uptake
- rolled-up leaves that
  - position the stomata inside the curved leaves, reducing their exposure to the wind, reducing the amount of water vapour lost by transpiration via the stomata
  - reduce the leaf area exposed to the sun, reducing the amount of heat absorbed and water loss
- roots that grow from the same nodes as the stems, meaning that each stem has its own supply of water and dissolved minerals
- seedlings that, under adverse conditions, can enter a dormant state, meaning that, rather than dying, the seedlings survive until favourable conditions return.

KEY IDEAS

- Mulgas, the dominant plant of the acacia shrublands of arid regions, show various adaptations to minimise water loss and maximise water uptake.
- Saltbushes of the chenopod shrublands show adaptations for minimising water loss and also for surviving in very salty soils.
- The spinifexes of the hummock grasslands of the deserts show adaptations to maximise water uptake and minimise water loss.

QUICK CHECK

19 Identify an adaptation that enables:
- **a** mulga shrubs to maximise water uptake
- **b** saltbushes to minimise heat absorbed
- **c** spinifexes to reduce water loss.

20 What feature enables saltbushes to survive in very salty soils?

Survival in the cold

To this point, the focus of this chapter has been on adaptations that enable the survival of Australian animals and plants in the arid and semi-arid regions of this country. Plants and animals also show adaptations that equip them for life in cold conditions on land and in water. Let us look briefly at a few examples.

Adaptations: animals in the cold

Ice can damage or kill

Processes that are essential for life include chemical reactions that take place between substances that are dissolved in liquid water, that is, in solution. These processes cannot take place in solid water (ice). If all the liquid water in a living organism were replaced by solid water, life would be destroyed. When ice forms, the solid water expands. If cells freeze, the expanding ice crystals rupture the cell membranes and kill the cells.

Many living things can exist on land in Antarctica or the Arctic. During winter, the air temperatures fall well below the freezing point of pure water. How do living things survive in these low temperatures? **Organisms have special features or behaviours that enable them to survive extremely low temperatures.**

Pure water freezes at 0 °C, but water with dissolved material in it has a lower freezing point than this. For example, a very concentrated salt solution (280 g/L, or 4.8 M) starts to freeze only when the temperature falls to about –18 °C. One strategy used by some living things to assist their survival in very low temperatures is to produce **antifreeze** substances. For example, some insects, fishes, frogs and turtles can survive in regions that have low temperatures during winter. These animals make antifreeze substances such as glycerol, amino acids and sugars, or mixtures of substances, at the start of the freezing season. These antifreeze substances are released into their body fluids. The presence of these dissolved substances lowers the freezing point of their body fluids to well below that of the surrounding water temperatures. This means that the body fluids of these organisms stay liquid.

Some frogs and toads burrow underground to avoid freezing temperatures.

Birds and mammals living in Antarctica or the Arctic use another strategy to protect themselves from the damaging effects of low temperatures. Birds and mammals convert chemical energy present in their food into heat energy. This internal supply of heat keeps the body temperatures of these birds and mammals well above the freezing point of pure water. This heat is retained by excellent insulation; mammals have **insulating layers** of fat under the skin and thick fur, and birds have layers of feathers (see figure 5.46). Would you expect that these Antarctic animals would need to eat more or less than animals of comparable size living in temperate conditions?

ODD FACT

What is frostbite? At temperatures below freezing, body parts such as hands, feet, nose, chin and ears are at risk of damage from the cold. Sometimes just the skin freezes. In more severe cases, the skin and underlying tissues become frozen. If ice crystals form, the affected part of the body can be permanently damaged. Gangrene may result from damage to the blood supply. In this case, amputation of the frostbitten part may be necessary.

FIGURE 5.46 Emperor penguins (*Aptenodytes forsteri*) are the largest of the penguin species, with adult birds more than 1 m tall and weighing 40 kg. One of their survival mechanisms is to huddle in large groups. What is a possible advantage of this behaviour?

Burramys has a long sleep

The mountain pygmy possum, *Burramys parvus*, is the only Australian mammal that lives permanently in alpine regions. Its distribution is limited to two small areas (see figure 5.47), one in Kosciuszko National Park of New South Wales and the other near Mount Hotham in Victoria. *Burramys* has both behavioural and physiological features that enable it to survive the low winter temperatures of its alpine environment. It collects and hides seeds and fruits for use during winter. Unlike other pygmy possums, *Burramys* has no storage of fat in its tail. At low temperatures during winter, *Burramys* goes into a torpor that is equivalent to hibernation. When mammals hibernate, their heartbeat slows down considerably and their breathing rate drops. Body metabolism is significantly reduced and their body temperature drops. In captivity, *Burramys* can hibernate at about 6 °C and remains in that state for three to seven days at a time. Normal body temperature is around 36.1 °C and during hibernation drops to that of the environment. The body metabolism of *Burramys* in hibernation ranges between 0.6 per cent and 3.9 per cent of the normal metabolic rate of an active *Burramys* at 6 °C. Hibernation and the reduced metabolic rate for periods means that the amount of food required by an animal, overall, to survive in winter is reduced.

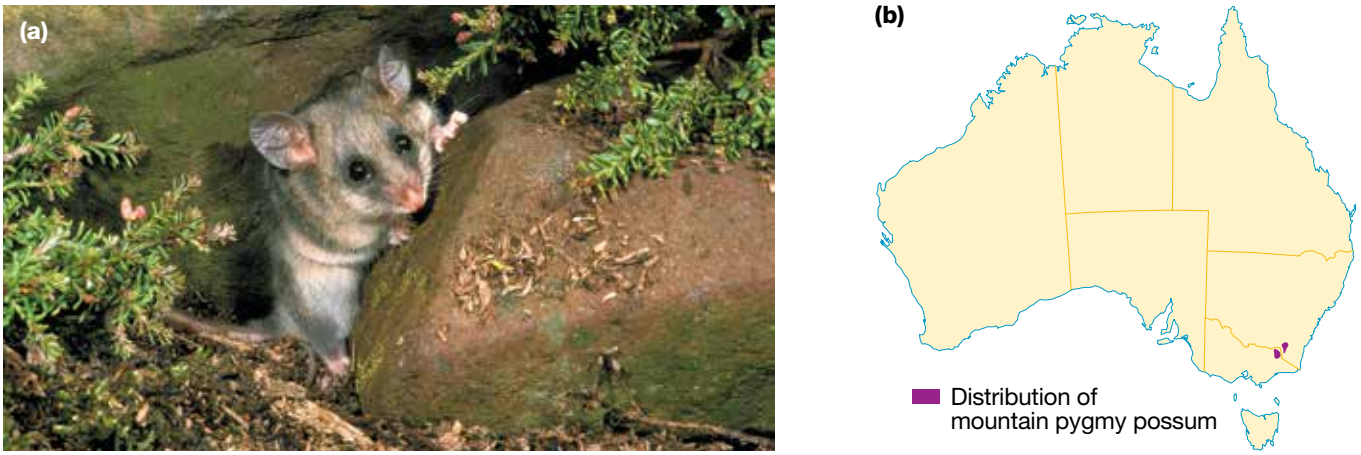

FIGURE 5.47 **(a)** Mountain pygmy possum, *Burramys parvus* **(b)** Its distribution is limited to two small areas.

Adaptations: mammals in water

The time marine mammals can stay under water is determined by the amount of oxygen they are able to carry in their lungs or store in other body tissues. Mammals, such as elephant seals (*Mirounga leonina*) and sperm whales (*Physeter macrocephalus*), that dive to great depths are able to do so because they have special characteristics which increase their oxygen-carrying capacity. For example, they have a much higher concentration of red blood cells than many other mammals.

Whales and dolphins (order Cetacea) are mammals that spend their entire lives in water. Like all mammals, they are endothermic and they breathe air so must come to the surface every so often. The females give birth to young that they suckle on milk secreted by mammary glands.

Most land mammals have an insulating fur coat that assists in the regulation of the body temperature. Whales and dolphins rely on an insulating layer of fat or blubber below the skin. This layer may be up to 50 cm thick and can vary with the different seasons. Cetaceans maintain a stable body temperature of 36 to 37 °C in an environment that is usually less than 25 °C and may be as low as 10 °C. In addition to blubber under the skin, fat may also be deposited around organs and tissues such as the liver and muscles, and in bone in the form of oil. These deposits can make up to half of the body weight of an animal.

Countercurrent systems to warm blood

Whales and dolphins also maintain their body temperature by using a countercurrent exchange system (see figure 5.48). There is a fine network of vascular tissue within the fins, tail flukes and other appendages. An outgoing artery is paired with an incoming vein. Blood coming from the body core to the skin is warm. Blood flowing from the skin back to the body core has been cooled. In this countercurrent exchange system heat in the blood coming from the core flows to the blood returning from the skin. This warms the blood flowing in from the skin and so prevents the venous blood from cooling the internal organs and muscles. At the same time, the blood moving out to the skin is cooled and so the loss of heat across the skin is reduced. This countercurrent system is also present in the feet, wings and bills of penguins.

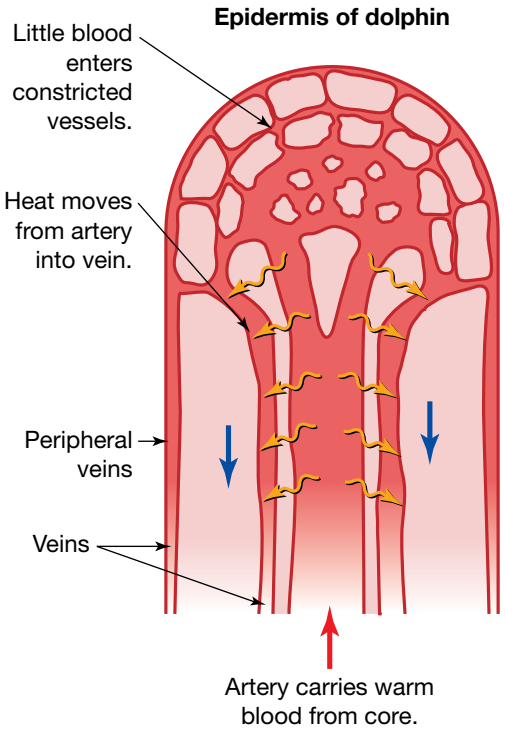

FIGURE 5.48 A countercurrent exchange system in the skin of dolphins. When the animal needs to conserve heat, the outermost blood vessels contract, little blood flows and heat loss from these vessels is reduced. In addition, heat flows from the warm blood coming from the core of the body into the cooler blood that is returning to the body from the skin. Yellow arrows show direction of heat flow; direction of blood flow is shown in artery (red arrow) and in veins (blue arrows).

Heat is readily lost from appendages such as hands and feet. Whales and dolphins have few protruding parts (fins and tail flukes). This means that they have a relatively small surface-area-to-volume ratio and heat loss across the skin is further minimised. These features enable large whales to live in the cold waters of the Antarctic Ocean.

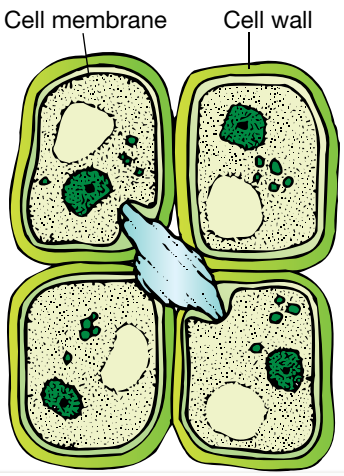

FIGURE 5.49 Ice formation in living plant tissue. Water leaves cells and adds to ice crystals growing in the spaces between the cells. Although the ice punctures cell walls, the cell membranes are merely pushed inward and the cells remain intact.

Adaptations: plants in the cold

Many plants survive in subzero temperatures without being damaged by these extremely low temperatures. Unlike animals, plants do not produce an 'antifreeze'. They gradually become resistant to the potential danger of ice forming in their tissues as the temperature falls below 0 °C. How does this occur?

Remember that water is transported through plants in very fine xylem vessels and is subjected to a number of forces. These forces affect the way in which water behaves in plants in freezing temperatures. As the temperature surrounding the plant drops below freezing, ice forms suddenly in the spaces outside the living cells of the plant. The inside of the cells doesn't freeze because the concentration of ions in the cytosol is greater than the concentration outside the cell. The cytosol has a lower freezing point.

Because ice has formed, the concentration of water inside the living cells is higher than the concentration outside and so water moves out of the cells. The ice crystals outside the cells grow (see figure 5.49). The movement of water out of the cells increases the ion concentration inside the cells and so lowers their freezing point even further. The living cells are then able to withstand further drops in the external temperature because the more concentrated cytosol acts as an antifreeze. The ice crystals grow between the cells and do not damage the cell membranes, which are pliable and bend under pressure of the ice.

The temperature falls as the elevation above sea level increases; the higher the elevation, the lower the temperature.

Many species of trees are able to withstand extremely low temperatures before they are killed (see table 5.6). The temperatures at which the living tissue in a tree is killed influences the latitudes at which it can grow. Which tree in table 5.6 is most likely to be found in the northern latitudes of Canada? Note that as one travels further north (or south) from the equator at sea level, the average temperature falls. The higher the latitude, the lower the temperature.

TABLE 5.6 Lethal temperatures for some trees

Species	Temperature (°C) at which killed
redwood (*Sequoia sempervirens*)	–15
southern magnolia (*Magnolia grandiflora*)	–15 to –20
swamp chestnut oak (*Quercus michauxi*)	–20
American beech (*Fagus grandifolia*)	–41
sugar maple (*Acer saccharum*)	–42 to –43
black cottonwood (*Populus trichocarpa*)	–60
balsam fir (*Abies balsamea*)	–80

Ultimately, if there is an excessive drop in the surrounding temperature, ice crystals form inside the cells, which die and so the tree may die. It has been suggested that an excessive drop in temperature damages the protein molecules that form part of the cell membranes so that ions can leak out of the cell. Australia does not experience the sustained extremes of low temperatures found in many other countries and low temperature is rarely a limiting factor for plant growth. Growth of native plants in Australia is determined by whether a plant has the adaptations to survive the various altitude zones and their associated temperatures. Some plants, particularly exotic garden plants, may be killed or damaged by an unusually severe frost.

KEY IDEAS

- Adaptations of animals living in cold environments include the presence of insulating layers, the production of antifreeze compounds and the use of countercurrent exchange systems.
- Plants use different strategies to survive in subzero environments.

QUICK CHECK

21 What is the action of antifreeze substances?
22 When does ice crystal formation become lethal for plant cells?
23 In a countercurrent exchange system, in which direction does heat flow: from artery to veins or from veins to artery?

studyon
Unit 1 AOS 2 Topic 1 Concept 3
Biomimicry
Concept summary and practice questions

Biomimicry

Biomimicry (*bios* = life; *mimesis* = to imitate) is the practice of learning from and being inspired by nature's best ideas to achieve technological advances, expressed in new designs, products and processes. The inspiration may be an observation of an energy-efficient action or structure in a plant or an animal, microscopic or macroscopic. It's a case of watch and wonder.

A leader in the field has written about biomimicry in the following terms:

> The core idea is that nature, imaginative by necessity, has already solved many of the problems we are grappling with . . . The conscious emulation of life's genius is a survival strategy for the human race, a path to a sustainable future. The more our world looks and functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.
>
> *Source:* Interview with Janine Benyus, author of *Biomimicry Innovation from the World of Nature* from http://futurepositive.synearth.net/2003/12/19.

Biomimicry is based on the premise that biological evolution has been occurring for more than 3.6 billion years; in that time many biological designs and structures have evolved and been trialled in the living world, and the world around us is filled with survivors that exemplify successful biological designs and strategies. Biomimicry uses a 'biology-to-design' approach that starts with the study of a natural phenomenon, developing an understanding of how it works, and then applying that understanding to a human design challenge or problem.

Burrs and Velcro

A well-known example of biomimicry came not from the laboratory, but from a dog that walked through thick vegetation. In the early 1940s, a Swiss engineer went through the tedious process of removing burrs from the hair of his dog. He wondered why the burrs were so difficult to remove. Upon examination, he found that the projections on the burrs had tiny hooks at their ends. The inspiration was to recognise that this annoying feature of burrs could be applied to hold items other than burrs to dog hair together. This was the beginning of Velcro® (see figure 5.50).

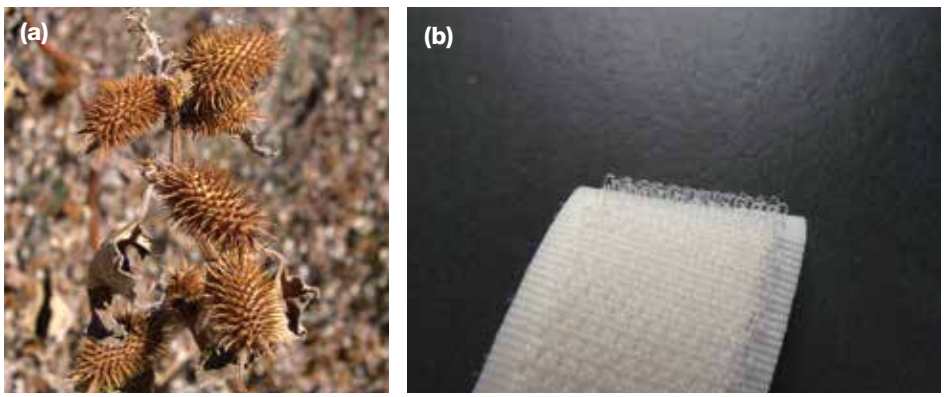

FIGURE 5.50 The concept of Velcro was inspired by burr seeds caught in the hairs of an engineer's dog. **(a)** Burrs are a kind of seed. Several plants produce burr seeds, such as Noogoora burr, also known as the cocklebur (*Xanthium strumarium*). **(b)** Like burrs, Velcro has projections with tiny hooks at their ends.

Lotus leaves and paint

In the 1990s, German researchers used a scanning electron microscope to study the leaves of the lotus plant (*Nelumbo nucifera*). They found that the leaf surface was covered with microscopically tiny bumps and that water droplets fell off the leaves taking with them any dirt particles. The lotus leaf is in fact a self-cleaning structure. The concept of self-cleaning was patented and its first commercial application was a paint, marketed under the brand name Lotusan®, that mimics the rough lotus leaf (see figure 5.51). Other applications inspired by the self-cleaning and dirt-repellent properties of lotus leaves have been in camera lens coating and wallpapers.

FIGURE 5.51 **(a)** The sacred lotus (*Nelumbo nucifera*), also known as the Indian lotus, with its leaves. Lotus leaves are clean even when the waterlily is growing in muddy water. This is due to their rough surface structure, apparent only on scanning electron microscope examination. **(b)** The self-cleaning Lotusan paint, inspired by the leaves of the lotus is marketed as having 'Lotus-Effect® Technology'. Like lotus leaves, exterior surfaces treated with this paint have less dirt particles adhering to them and are self-cleaning when exposed to rain.

Sharks and ships

Sharks are ocean predators that can move at speed in pursuit of their prey. Their skin appears smooth, however, the outer surface of a shark is covered by overlapping scales called **denticles**. These denticles have grooves running down their length (see figure 5.52). As the shark moves through water, the water is channelled by these grooves and moves across the shark's skin surface more efficiently, with less drag than if the surface were smooth.

FIGURE 5.52 A close-up image of the overlapping scales of shark skin. Note the longitudinal grooves.

Marine designers and engineers are using shark-skin technology in the design of ships' hulls to produce ships that move with less friction and drag that slow boats down. One claim is that the drag on boats with this technology is reduced by 67 per cent. In addition, the shark-skin technology makes it more difficult for marine organisms, such as barnacles and algae, to stick to the hulls of boats. This would mean that toxic cleaning chemicals would not need to be used to remove these organisms. What economic advantage might a reduction in drag produce for a commercial cargo ship? The use of shark-skin technology is also being explored in the aircraft industry. Tests are being carried out on the use of paints that have an imitation sharkskin pattern embossed into their surface.

A US company used shark-skin technology to design more efficient blades for wind turbines. They have produced blades that spin through the air more smoothly and with less drag.

ODD FACT

Shark-skin technology was used for swimsuits that were custom-fitted to world-class swimmers. After many world records were broken in a very short period by swimmers wearing these suits, the suits were banned from use in competitive swimming in 2009.

Beetles and water bottles

A South Korean designer has produced a 'Dew Bank Bottle', inspired by the Namibian Beetle (*Stenocara gracilipes*) that collects moisture from ocean fog that drifts into the Namib desert each morning. The protective outer forewings (elytra) of the beetle are covered in tiny bumps that have hydrophilic (water-loving) tips and hydrophobic (water-repelling) sides. The beetle faces away from the incoming fog, arches its back, and tiny water droplets condense and run down grooves to the beetle's mouth. The Dew Bank Bottle imitates the water collection technique of the beetle. Water vapour condenses on the rounded metal surface of the water bottle and is collected in the bottle.

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Weblink
Biomimicry

The discipline of biomimicry is expanding as people, including designers, engineers, architects and scientists, look to the natural world for inspiration. Biomimicry is opening new fields for the development of new synthetic materials as people 'think outside the box'. The gecko that can walk up walls and across ceilings raises possibilities for new materials for adhesion. The slippery glass-like inner surface of a pitcher plant raises possibilities for new materials for anti-adhesion. The structure of the compound eye of an insect raises possibilities for miniature motion detectors. The study of photosynthesis in plants raises possibilities for new ways of harnessing the energy of sunlight. The structure of mollusc shells raises possibilities for the design of new ceramics. The list goes on.

KEY IDEAS

- Biomimicry is the practice of learning from and being inspired by nature's best ideas to achieve technological advances, expressed in new designs, products and processes.
- Many examples of biomimicry exist.
- Biomimicry is a developing discipline that is increasingly affecting human life through the development of new designs and products.

QUICK CHECK

24 What was the biological structure that inspired the development of Velcro?
25 What is a denticle?
26 What performance improvements have flowed from shark-skin technology?
27 What is Lotus-Effect® Technology?

DEATH IN A BUSHFIRE

The photograph in figure 5.53 appeared on the front page of *The Age* on Friday 4 September 1998. The caption read: 'Twelve metres between life and death: two identical fire tankers — one burnt out, another unscathed — in the blackened bush near Linton'. Five men survived in the tanker on the left of the photo, while five men died in the truck on the right.

FIGURE 5.53 One fire truck was burnt out and the other was unscathed in a serious bushfire in 1998.

Distance was not the important factor for the firefighters and trucks shown in the photograph. The truck containing the firefighters that survived had a reserve of water. Two of the crew huddled under a fire blanket in the cabin. The remaining three firefighters in the back of the unburnt truck turned small water hoses on themselves and then pointed them skywards so that water rained over the whole of their truck. Note the unburnt vegetation near the unburnt truck. This vegetation was also protected by the veil of water sprayed over the truck.

The men who perished in the fire were in a truck with no water. The change in fire direction happened so quickly there was no time for the men to get to the other truck. The fierceness of the fire, which is indicated by the complete absence of living vegetation near the burnt truck, meant that radiant heat would have been extreme and death inevitable for the unprotected. Water in the front truck was insufficient to protect the second truck. A key issue identified was that low-water-level warning devices should be installed in all Country Fire Authority tankers.

(continued)

Surviving a bushfire

Bushfires are an integral part of the Australian bush. The Black Saturday fires of 7 February 2009 caused the deaths of 173 Victorians. How can your chance of survival be increased if you are in such danger? Remember that, apart from the flames themselves, it is the level of radiant heat that kills.

Make sure you are well clothed and take cover. Wear protective clothing to reduce your exposure to radiant heat. Wear long pants and a long sleeved shirt or light pullover. Natural fibres such as light wool or close-weave cotton are best. Wear solid footwear, preferably leather, and cover your head with an appropriate hat. Remember: **cover up to survive** (see figure 5.54).

FIGURE 5.54 Radiant heat can kill. Remember, as soon as you become aware of a fire, cover up to survive.

Take cover inside your house. You will be protected from the radiant heat. Shut windows and doors. This ensures your supply of oxygen and prevents embers from blowing into the house.

You run the risk of becoming dehydrated in a bushfire. Drink water often even if you don't feel thirsty. Avoid alcohol and fizzy drinks.

If caught on the road in a car DO NOT get out and run. Stay in the car until the fire passes. Park the car with lights on and the engine running in a clear area away from vegetation, especially any that is dry. Close the windows and vents and get as low as you can within the car and cover yourself with a woollen blanket (see figure 5.55).

FIGURE 5.55 In the country and other fire-prone areas always carry woollen blankets in your car. They will help protect you from radiant heat.

Radiant heat can be the killer. It can lead to heat exhaustion, heart failure and dehydration. Some people have died from asphyxiation (lack of oxygen) during a bushfire. Why do you think this occurs? Find out more information by going to the Country Fire Authority website, www.cfa.uic.gov.au.

BIOCHALLENGE

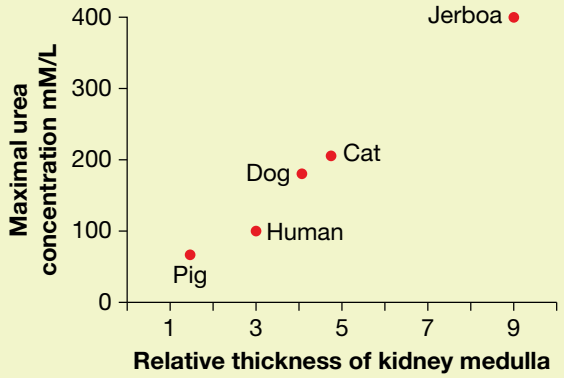

FIGURE 5.56 Relationship between thickness of medulla and maximal urea concentration

Examine figure 5.56 and answer the following questions:

1 What relationship is illustrated in this graph?

2 a The medulla of the kidney contains a particular part of the kidney nephron. What part of the nephron is this?
  b As the medulla becomes thicker, what can happen to the loop of Henle?
  c Which mammal would be expected to have longer loops of Henle in its kidney nephrons: pig or cat?
  d True or false? A longer loop of Henle is an adaptation that enables greater reabsorption of water from the filtrate in the kidney nephrons.

3 a You will be familiar with mammals such as pigs, dogs and cats, but you are unlikely to know much about jerboas (*Allactaga* spp.). However, based on the data in figure 5.56, what predictions might you make about:
    i the environment in which jerboas survive
    ii two structural adaptations that might be present in a jerboa?
  b Do an online search for information about jerboas. Were your answers to part (a) correct?

4 Fish, like other vertebrates, have kidneys. Consider a freshwater fish and a saltwater fish. One of these fishes has kidney nephrons with long loops of Henle, while the nephrons in the other fish have almost no loops of Henle. Which fish has the long loops of Henle and which virtually lacks them? Briefly justify your decision.

5 Figure 5.57 that shows an early (1790) illustration of an Australian plant. The description that accompanied this illustration reads as follows: '. . . the leaves which first appear on the seedling plant being pinnated, as is represented in the small figure on the plate, while those which afterwards come forth grow in whorls'.
  a Note the small figure at the right side of the image. What does this illustrate?
  b The illustration on the left side shows the foliage of the mature plant.
    i What change has occurred in the foliage as the plant ages?
    ii In the text quoted above, Curtis refers to structures that 'grow in whorls'. What is the correct biological term for these structures?
    iii How are the structures in part (ii) formed?
  c This species of acacia grow in dry forests and sandy soils. What advantages might this feature confer on this plant?

FIGURE 5.57 Early illustration of *Acacia oxycedrus*, an Australian native plant, that appeared as Plate 110 in volume 4 of Curtis's *Botanical Magazine*, published in London in 1790. Curtis called this plant the whorled-leaved mimosa, but it now has the common name of spike wattle.

Chapter review

Key words

acacia shrubland
adaptation
antifreeze
biomimicry
chenopod shrubland
cladode
countercurrent exchange system
cuticle
denticle
dormancy
drought-resistant seeds
ephemeral
extracellular fluid
free-standing water
humidity
hummock grassland
hydrogen bond
hydrogen bonding
hyperthermia
hypothermia
insensible water loss
insulating layer
intracellular fluid
interstitial fluid
limiting factor
loop of Henle
medullary thickness
metabolic water
mulgara
operculum
phyllode
plasma
rolled-up leaves
stomata
sunken stomata
transpiration
tolerance limit
tolerance range
water balance
water tapper

Questions

1 **Making connections** ➜ Use at least eight of the key words in this chapter and draw a concept map. You may use other words in drawing your map.

2 **Applying and communicating your understanding** ➜ Explain how each of the following features assists a plant to survive in a very hot environment.
- **a** Desert plants generally have deeply penetrating root systems.
- **b** Succulent plants (that store water) have stomata that open only at night.
- **c** Some plants have special cells, called hinge cells, on the surface of their leaves that also have stomata. When hinge cells lose water, the leaf rolls up with the hinge cells on the inside of the rolled leaf.

3 **Applying your understanding** ➜ Look at figure 5.48 on page 229. Assume a dolphin needed to lose heat. What changes would occur in the countercurrent exchange system to facilitate that loss?

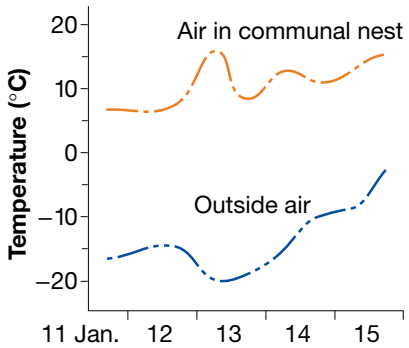

FIGURE 5.58 Temperature inside a communal nest of beavers compared with the outside air temperature

4 **Interpreting data and communicating ideas** ➜ Many small animals that are solitary over summer tend to become social during winter and often construct nests under the snow. The temperature inside a communal nest of beavers was compared with the temperature of the outside air. The results are shown in figure 5.58.
- **a** What is the maximum difference between the temperature of the beaver nest and the temperature of the outside air?
- **b** Suggest what causes this difference in temperature.

5 **Applying your understanding** ➜ Identify a physiological characteristic that assists each of the following to maintain water balance.
- **a** Humans (on a hot day)
- **b** Sea birds
- **c** The tarrkawarra (*Notomys alexis*)

6 **Applying your understanding in new contexts** ➜ Air in the Antarctic is relatively dry. Antarctic explorers can become dehydrated relatively quickly. Explain the relationship between these statements. How can Antarctic explorers reduce the chance of dehydration?

7 **Applying your understanding** ➜
- **a** Explain why most stems and leaves on plants have a waterproof cuticle and yet roots do not.
- **b** When cuttings of plants are first potted, they have no roots and may wilt. Wilting is prevented if the pot is enclosed in a plastic bag and shaded from sunlight. Explain why this treatment prevents wilting.

8 You have been given the task of selecting plants for growth in a hot dry environment in a glasshouse.
- **a** Identify five key features you would look for in the plants that you select.

b Briefly explain your choices.

c Would all of these features be expected to serve as adaptations if these same plants were to be grown in a low-light tropical rainforest?

9 Using skills of analysis ➜ Two closely related mammalian species differ in their range. One species, A, lives in a sandy desert, while the other, B, lives in a cool temperate grassland. Devise four relevant questions about structural, physiological or behavioural features of these mammals that will show which species lives in which habitat, and give the answers to each question.

Show your questions and your answers by constructing a table along the following lines:

Question	Species A	Species B
1. What is the comparative ear length of each species?	longer	shorter
2.		
3.		
4.		
5.		

10 Applying knowledge and understanding ➜ Suggest an explanation for, or comment on, each of the following observations.

a The young of tiny bats such as the bent-wing bat, *Miniopterus australis,* huddle very tightly together in large groups on the walls of caves where they live, rather than being widely separated.

b One plant species grows equally well in soils with a high salt content but a second plant species dies if the salt concentration in the soil exceeds a low value.

c Brown trout, *Salmo trutta,* are found in cold, fast-flowing mountain streams, but are absent from warm, sluggish waters.

d If placed in sea water, goldfish, *Carassius auratus*, will die.

e Desert mammals are typically active at night.

f A person who suffers from obesity has a lower body water content than a lean person.

CHAPTER

6 Survival through regulation

FIGURE 6.1 The Simpson Desert includes parallel sand dunes that stretch over hundreds of kilometres. In this image we see the edge of a dune and, on the left, the hummock grasslands that separate this dune from the next one. In a desert, people face the dual challenges of maintaining their body temperatures and their water (fluid) levels within a narrow range. In this chapter, we will explore the homeostatic mechanisms that regulate these and other factors, keeping physiological values within tolerance limits.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- gain an understanding of the concept of homeostasis and the operation of homeostatic mechanisms to maintain conditions in the internal environment of the human body within a narrow range
- list examples of biological variables that are subject to homeostatic regulation
- identify the components of a stimulus-response model in homeostasis and feedback loops
- gain knowledge of malfunctions in homeostatic mechanisms and their outcomes.

Death in the outback

In the corner of the Simpson Desert in south-west Queensland lies Ethabuka Station, a remote 200 000 hectare property. It was once a cattle station but is now a wildlife reserve, acquired in 2004 by Bush Heritage Australia. Ethabuka is located in a harsh region of Australia that includes large areas crossed by a series of long parallel sand dunes that have little to no shade, no free-standing water and are subject to searing daytime temperatures that can reach up to 50 °C.

FIGURE 6.2 The Simpson Desert with its red sandy plains and dunes covers an area of 176 500 km^2. Its beauty conceals the threat to survival faced by people who enter this environment without careful planning, a suitable vehicle and adequate water, fuel and protection from the heat.

In November 2012, two workers, Mauritz Pieterse and Josh Hayes, left the Ethabuka homestead in a four-wheel drive (4WD) to carry out routine maintenance on water bores, a task that would normally take a few hours. Unfortunately, about 16 km from the homestead, their 4WD became bogged in a sand dune. After trying unsuccessfully to free the vehicle, the two workers made the fateful decision to leave the car and walk back to the homestead. In dry and very hot conditions a good supply of water is essential for survival but, tragically, the pair did not have enough water with them.

A message was sent by two-way radio at 12 noon to the two workers but no response was received from them. This suggests that they had left their bogged vehicle by that time. When there was still no response at 5 pm, the alarm was raised. Aware of the radio silence, Greg Woods, the manager of another station located more than 200 km away, set out on a 6-hour drive in his 4WD to search for the two workers. Just before midnight, Woods found Mauritz lying dead in the desert sands about 6 km from the bogged 4WD. He had collapsed within a few hours of starting to walk back to the homestead but had told his friend to continue walking. The expert view expressed at the time was that his death was the result of severe **dehydration** and **heat stroke**. Woods then began an urgent search for Josh Hayes and found him 2 km away, close to death. Because of the prompt actions of Greg Woods, Josh survived.

The vast arid inland of Australia has been described as 'unforgiving and hostile territory' that, sadly, has claimed many other lives. With summer temperatures reaching up to 50 °C, survival time in this environment without adequate water and shelter is limited.

The Gibson Desert in Western Australia was the scene of another tragedy. In April 2005, the bodies of Bradley Richards, 40 years old, and his nephew, Mac Bevan Cody, 21, and their dog were found on the remote Talawana track beside their broken down 4WD (see figure 6.3a). In late March, the two men left the outback town of Newman in Western Australia, intending to travel north to find work. Unfortunately, their vehicle broke down. Lacking detailed maps of the area, the two men walked several kilometres to the east, back along the track that they had travelled, searching for water. Unable to find water, they returned to their vehicle. Had they walked in the opposite direction, they would have reached Georgia Bore and its supply of water (see figure 6.3b). With no one aware of their travel plans and with the Talawana track closed at that time of year, sadly, the two men perished.

FIGURE 6.3 The Talawana track runs for several hundred kilometres through the Gibson Desert. **(a)** The vehicle of Bradley Richards and Mac Cody, now moved off the track, marks the place where their tragic deaths occurred. **(b)** Georgia Bore, a source of fresh water, is located just 9 km to the west of where the truck in which Bradley Richards and Mac Cody were travelling broke down. (Images courtesy of Libby Sakker)

The Great Sandy Desert in Western Australia came into public awareness in April 1987 when the remains of 16-year-old James Annetts and 17-year-old Simon Amos were found after having been missing for months.

The two boys had responded to an advertisement for jackaroos to work on a cattle station in the Kimberley region of Western Australia. After just 7 weeks working on the main station, each was sent to be the sole caretaker at properties 150 km apart. Their only contact with the station manager was by radio.

In early December 1986, for an unknown reason, the boys left together in a utility and drove along an isolated track into the Great Sandy Desert (see figure 6.4). The utility became bogged. Unable to free the vehicle, the boys walked 18 km and made a camp. It was at this camp in April 1987 that the remains of Simon were found, a rifle nearby, a gunshot wound to his skull. The remains of James were found 1 km away from the campsite. In regard to Simon's death, the coroner concluded that 'after his supply of water and food was exhausted, he [Simon] became distressed so much that he turned his rifle upon himself'. In regard to James's death, it was concluded that 'he too succumbed to the harsh environment . . . it is reasonable to assume that the medical cause of death was dehydration and exhaustion in association with hyperthermia'.

FIGURE 6.4 Map showing remote location in the Great Sandy Desert of the bogged utility abandoned by James Annetts and Simon Amos. Note the Gibson Desert, further south, which is the location of the Talawana track where the broken down vehicle of Bradley Richards and Mac Cody was found.

These deaths are a tragic reminder of the need to take appropriate precautions when travelling in the remote arid outback of Australia, and an example of the extreme dangers of **hyperthermia** (*hyper* = above; *therme* = heat) and dehydration (loss of body water). These conditions can lead to **heat exhaustion** and, in extreme cases, fatal heat stroke. Later in this chapter (see pages 258–9), we will examine how the combination of hyperthermia and dehydration can result in death.

Sources of heat gain and heat loss

In the following sections, we will explore the various means by which heat is gained by or lost from the human body. Heat gain and heat loss may occur by:

- physical processes
- physiological processes
- behavioural activities.

Physical processes of heat gain and heat loss

Heat can be gained by the human body from the external environment through **radiation**, **conduction** and **convection**. This heat gain occurs when the external (ambient) temperature is higher than the body temperature.

Heat can be lost from the human body to the external environment through the processes of radiation, conduction and convection when the body temperature is higher than the external (ambient) temperature. In addition, another process — **evaporation** — can be a major source of heat loss from the human body.

Let's look at how these physical processes of radiation, convection, conduction and evaporation can cause the body to either gain heat from or lose heat to the environment.

- *Radiation* requires no physical contact between objects for the transfer of heat, principally as infra-red radiation, to occur. Heat is transferred by radiation from a warmer object to a cooler object. If you stand in the sun on a very hot day in summer, the exposed parts of your body will gain heat by radiation. On a cold day, you radiate body heat to the environment and so lose heat. However, if you move indoors and stand *in front of* a heater on a cold day, you will gain some of its radiant heat. At rest, most of the heat that you lose is by radiation to the environment.
- *Convection* is the process of heat transfer resulting from the mass movement of air (or water) past exposed areas of the body when each is at a different temperature. The greater the rate of movement of the air or the water past the body, the greater the rate of transfer of heat. The movement of air from a fan across your exposed skin surfaces on a hot day moves warm air away, replacing it with cooler air, so that you lose heat. Likewise, a cold wind will remove heat from exposed surfaces of your body, and the higher the wind speed, the greater the heat loss. However, if you move indoors and place your hands *above* a heater, you gain heat from the upward convective flow of warm air from the heater. In a similar manner, the movement of hot wind on a summer's day will cause you to gain heat from the environment.
- *Conduction* involves heat transfer by immediate physical contact with another object at a different temperature. The direction of heat transfer is from the warmer to the cooler object. You lose heat by conduction when you put your hand on a cold metal railing; you gain heat by conduction when you hold a hot object in your hands. Heat loss by conduction is typically small and is limited to parts of the body that come into immediate contact with external objects that are good conductors of heat.

Figure 6.5 illustrates heat gain from the external environment by a person through the processes of radiation, convection and conduction.

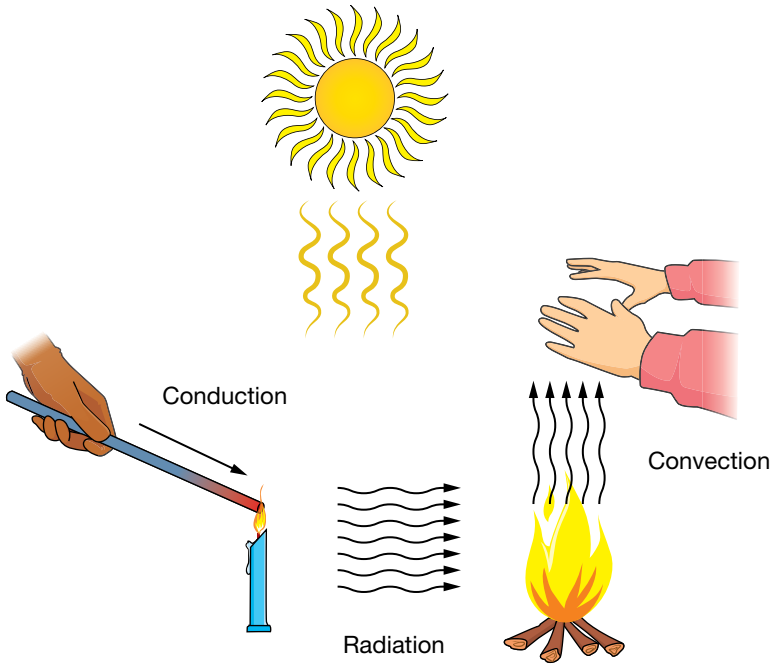

FIGURE 6.5 Diagram showing the differences between radiation, convection and conduction. Which of these processes requires direct physical contact for the transfer of heat? Which process involves the transfer of heat by moving air?

Heat loss by convection and conduction is a major concern if a person is immersed in cold water for an extended period. Such a person is at risk of extreme loss of body heat (**hypothermia**). Why? Heat loss by convection is high because water is generally moving and, as it moves, cold water removes heat from the body. A given volume of moving water can transfer much more heat than the same volume of air because water has a heat capacity about 1000 times that of air. The loss of body heat by conduction in cold water is also high because heat is conducted away from the body about 25 times faster in water than in air at the same temperature.

Heat gain by convection and conduction is also an issue for people who soak in hot tubs in water at high temperature for extended periods. This practice may place some people at risk of hyperthermia with an uncontrolled rise in body temperature. In Australia, the maximum temperature allowed for hot tubs is 40 °C, and the recommended setting is 37 °C. In the United States, deaths have occurred as a result of people using hot tubs with excessively hot water (43 °C).

- *Evaporation* is the conversion of liquid water to vapour, a process that requires an input of heat energy. As a result, evaporation is a source of heat loss from the body (but never heat gain). The source of the water that evaporates may be external, as for example, with the evaporation of water droplets from the skin of a person who has been swimming, or evaporation from wet clothing that a person is wearing. Both of these can be significant sources of heat loss from the body.

  In addition, the water that evaporates may come from internal sources. These sources are:
  - the insensible water that is lost as vapour from the body via the skin pores, from the internal moist surface of the lungs and airways, and from the moist membranes of the mouth and nose
  - the sweat from the sweat glands of the skin.

ODD FACT

Major mechanisms for heat loss by a person in cold air are radiation and evaporation; conduction and convection are the major means of heat loss for a person immersed in water.

However, sweating comes into operation only when a person is exposed to external temperatures of about 37 °C or higher, or when a person retains excessive internal heat generated through metabolism, such as may occur during strenuous exercise or manual labour.

The evaporation of water is most effective when the air is dry and, even better, when there is a wind to assist cooling. As the surrounding air becomes more humid — with higher levels of water vapour — and as the air movement slows, evaporation is less effective as a cooling mechanism because the humid air cannot remove as much water as dry air. For example, at 100 per cent humidity in still air, sweat does not evaporate from a person, but simply drops from the body as liquid water, a situation often described as 'futile' or 'useless' sweat. Sweat that drops from the body as liquid is useless because it cannot contribute to the cooling of the body and, even worse, it involves a loss of fluid from the body that can contribute to dehydration.

Figure 6.6 shows the various channels of heat loss from a boy on a still day when the external air temperature is lower than the person's **core body temperature**. Under these conditions, the boy on the diving board loses heat to the environment mainly through the physical processes of radiation and evaporation, with less loss by convection and conduction. What change, if any, will happen after the boy dives into the pool, assuming that the water temperature is 25 °C?

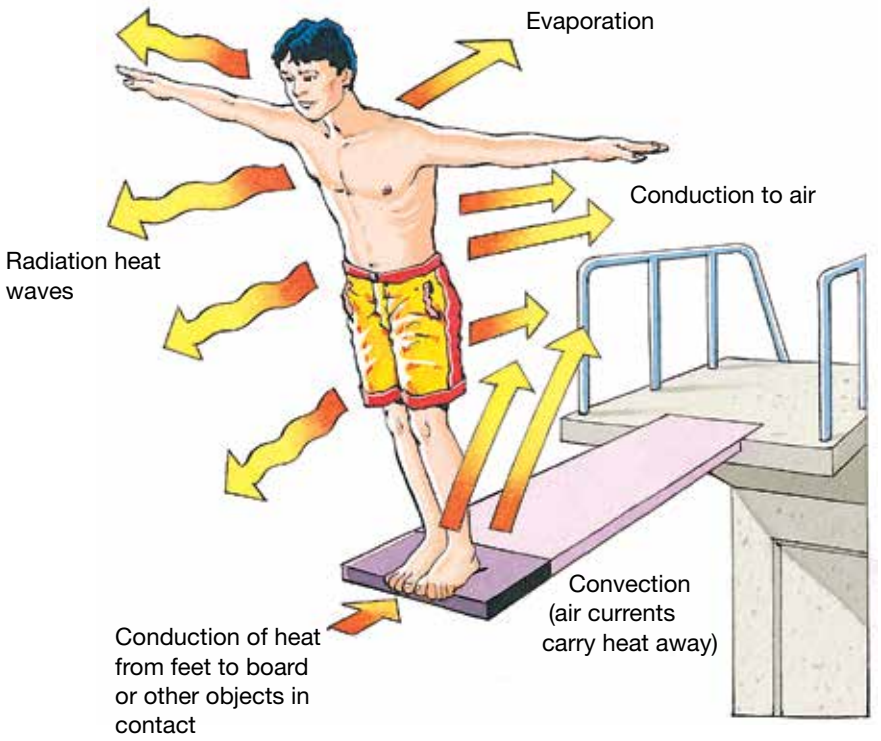

FIGURE 6.6 The boy's core body temperature is higher than the external temperature. He loses heat to the external environment by radiation, evaporation and convection, and a small amount to conduction where his bare feet are in contact with the diving board.

Physiological processes for heat gain and heat loss

Physiological processes are not under a person's conscious control but occur automatically — you do not have to think about starting them. These processes are initiated by centres in the **hypothalamus** of the brain. For example, the hypothalamus has a centre with a temperature set point against which changes in body temperature are monitored. In a normal healthy person this set point is about 37 °C.

If the body temperature falls below the set point, these physiological processes increase heat production within the body and reduce heat loss. As a result, the body temperature rises. (This is a bit like switching the heater on in a room and closing the windows.) If, however, the body temperature rises, these physiological processes produce an increase in heat loss from the body so that the body temperature falls. (This is a bit like opening the windows in a hot room to let cooler air in.)

Heat produced by shivering

Shivering is the alternate contraction and relaxation of small muscle groups and is an involuntary action. The hypothalamus contains a centre that controls shivering. This centre activates nerves that control muscles in the upper limbs and body trunk. When muscles shiver, almost all of the energy of contraction is converted into heat energy.

Although maximum shivering can produce significant amounts of additional heat for a body — up to five times what is normally required — it cannot be sustained for long because it drains the energy reserves of the muscle tissue.

Heat produced by metabolism

Metabolic processes in the body produce heat. The minimum amount of heat generated internally is the so-called **basal metabolic rate**. This is the level of metabolism needed to maintain the living state in a person at rest, fasting, and in a thermo-neutral (temperate) environment. However, if the core body temperature falls, the level of metabolism rises above the basal rate, producing more internal heat.

The increase in metabolic rate is initiated by a centre in the hypothalamus. The hypothalamus releases a hormone that causes the release of other hormones — first by the **pituitary gland** and then by the **thyroid gland**. The hormone **thyroxine**, which is released by the thyroid gland, produces an increase in metabolic rate by body cells. The hypothalamus, the pituitary gland, and the thyroid gland are part of the **endocrine system** of the human body (see figure 6.7).

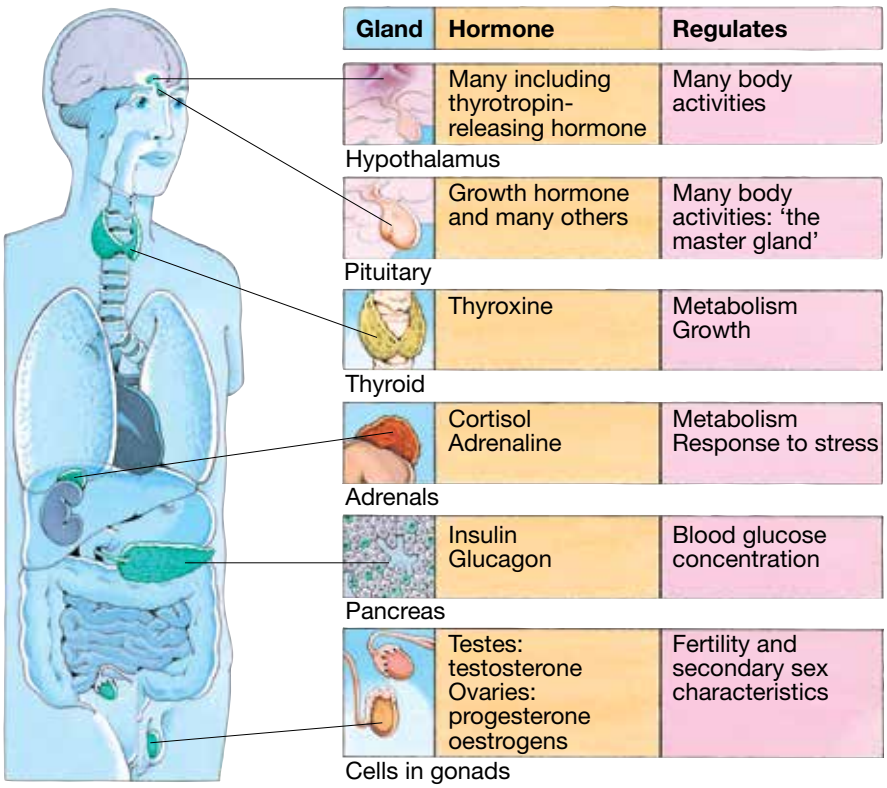

FIGURE 6.7 The endocrine system: its main glands, the hormones they produce and their actions. The endocrine system helps regulate functions of the human body by releasing hormones (chemical messengers) into the bloodstream that travel to and act on target cells. Hormones play important roles in the homeostatic regulation of physiological variables, including core body temperature.

Motor nerves from the hypothalamus also cause the adrenal glands to secrete the hormones adrenaline and noradrenaline (refer to figure 6.7). These hormones increase the basal metabolic rate, particularly in skeletal muscles and also in **brown fat**, a special kind of fat of particular importance in young babies (refer to the box in chapter 3, pp. 118–19). Brown fat is also present in human adults, but in very small amounts in the neck and the upper chest. Because of brown fat metabolism, babies produce about five times as much heat (per unit of body weight) from metabolic pathways as adults.

Varying blood flow to the skin surface

When cold is detected by cold receptors in the skin (see figure 6.9), the hypothalamus sends nerve impulses that cause **vasoconstriction** of arterioles that lead to capillary beds close to the skin. These impulses cause a ring of muscle around the arterioles to constrict, or become narrower. When this happens, the blood flow to the capillaries under the skin is greatly reduced. Instead, almost all the blood flows through **shunt vessels** that directly connect arteries and veins (see figure 6.8). As a result of the restricted blood flow to the skin, heat loss from the skin is reduced and heat is retained within the body, increasing the body temperature.

In contrast, in hot conditions, the hypothalamus sends nerve impulses that cause **vasodilation**. These impulses cause the ring of muscle around arterioles to relax. This allows blood to flow close to the skin surface. As a result, heat loss from the body increases, causing a drop in body temperature.

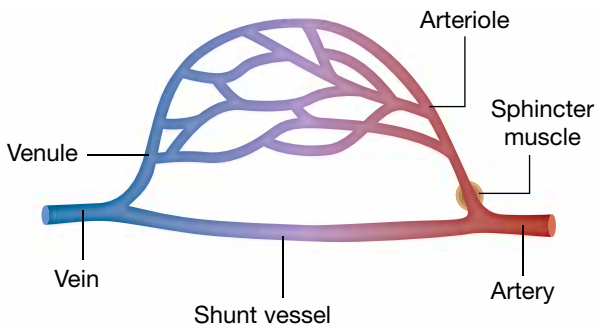

FIGURE 6.8 Shunt vessels form a direct connection between arteries and veins. Nerve impulses from the hypothalamus control the band of muscle around the arteriole. The contraction or the relaxation of this muscle band determines whether or not blood will flow to capillaries just below the skin surface. What happens if this band of muscle contracts and closes the arteriole?

Hair 'on end' conserves heat

Piloerection means 'hair standing on end'. Although it is not important for conservation of heat in humans, the ability to raise hair is important for mammals that have a covering of hair over most of their body surface. A layer of air becomes trapped in the erect hair above the skin and acts as an insulation layer between the skin of the animal and the external environment. Nerve impulses from the hypothalamus travel to a muscle at the base of each hair, causing the muscle to contract and the hair to rise. Fluffed up feathers play a similar insulating role in birds.

Figure 6.9 shows a longitudinal section through the human skin. Note the various features of the skin that are involved in homeostatic control of body temperature:

i arrector pili muscles that contract in response to nerve stimuli from the hypothalamus and raise the hair
ii hot and cold temperature receptors (see insert) that register skin temperature and transmit that information via nerves to the hypothalamus
iii sweat glands that produce sweat for evaporative cooling
iv capillaries that supply blood to the skin with their blood flow controlled by the hypothalmus which can either constrict or relax a band of muscle around the arterioles that supply these capillaries.

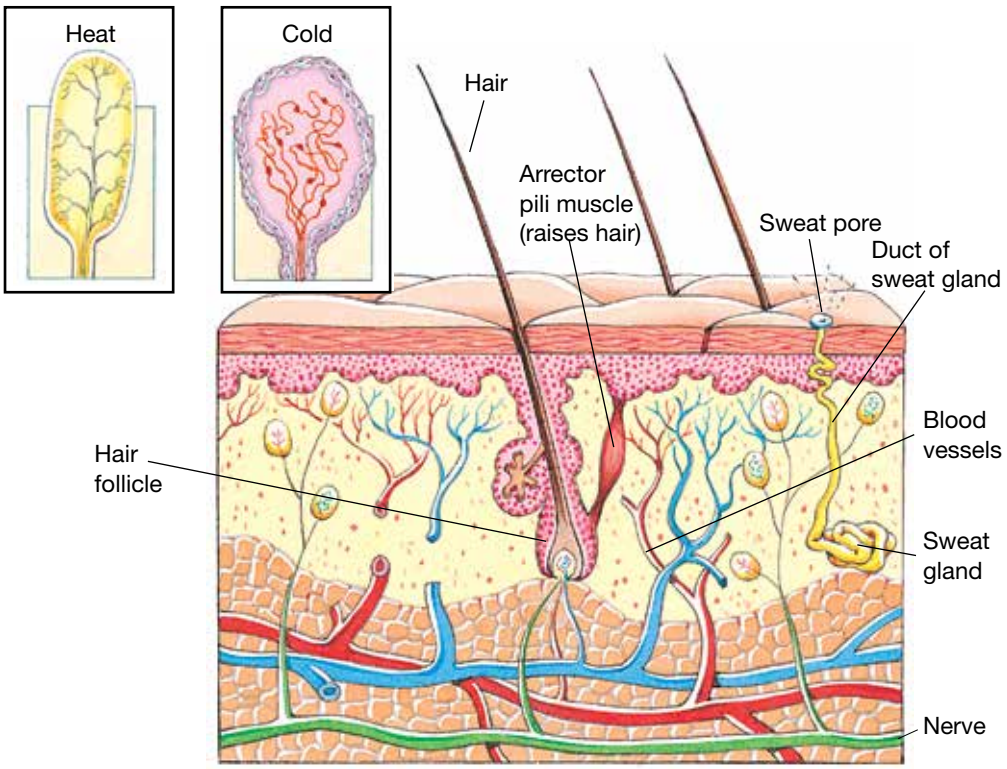

FIGURE 6.9 Longitudinal section through human skin showing some of the features that are involved in homeostasis

Cooling by evaporation

Another physiological process involved in heat loss is sweating. Like the other processes mentioned above, sweating is controlled by a centre in the hypothalamus. Nerve impulses from the hypothalamus activate sweat glands (see figure 6.9). Liquid sweat on the skin evaporates forming a vapour. The evaporation of sweat requires heat energy and this is taken from blood vessels close to the skin and so the body is cooled. When liquid water evaporates, energy is needed to change its state from liquid to gas. The evaporation of one millilitre of liquid sweat from a person requires about 2500 joules of energy. This is more than the amount of heat energy produced by burning a match. Cooling achieved in this way is called **evaporative cooling** (see figure 6.10). You can observe the effect of evaporative cooling by placing your hand in front of a fan and comparing the cooling effect when your hand is dry with the effect when your hand is wet.

FIGURE 6.10 Evaporation of sweat is a major means of heat loss from the human body. Sweating begins only when the ambient temperature is about 38 °C or when the body temperature is higher than normal because of intense exercise over a prolonged period.

Figure 6.11 shows a summary of the major physiological processes involved in producing and conserving heat or in losing heat. Note that conserving heat means preventing heat loss; this is different from generating heat.

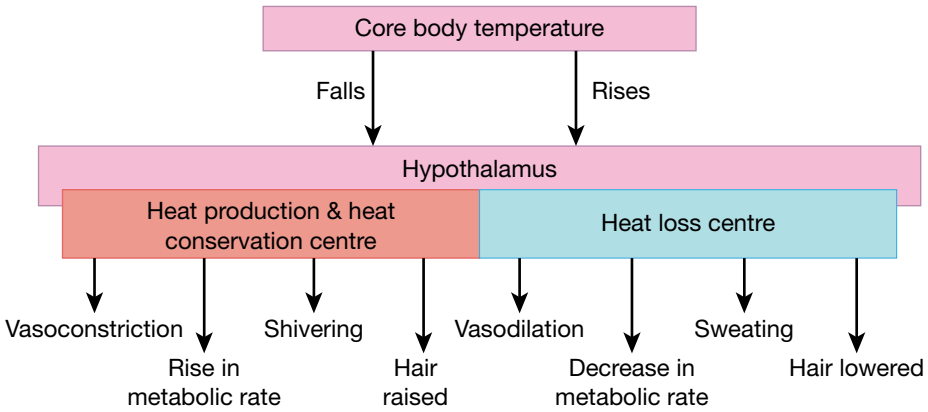

FIGURE 6.11 Diagram showing **heat-generating** and **heat-conserving** physiological mechanisms of the human body (left) and **heat loss** or cooling off processes (right). All these processes are initiated in the hypothalamus of the brain, with signals from the hypothalamus to other organs being transmitted by nerve impulses or by hormones.

Behavioural activities for heat gain and heat loss

Behavioural activities are actions that are under a person's conscious control. Some examples of conscious behavioural activities that people might undertake to gain, conserve or lose heat are shown in table 6.1.

Physical exercise is a major voluntary behaviour by which body heat can be generated. As physical exercise becomes more vigorous, the rate of heat production increases. In fact, as we will see later in this chapter (see p. 258), prolonged vigorous exercise can produce heat exhaustion, and if no relief is given, this can develop into heat stroke with possibly fatal consequences.

ODD FACT

Humans have sweat glands over almost all their body surface. In contrast, members of the dog and the cat families have sweat glands on only a few small areas that are not fur-covered, such as noses and paw pads. The primary means of heat loss to the environment by these mammals is by **panting**, which removes body heat through evaporation from the tongue and moist surfaces of the mouth (see figure 6.12).

FIGURE 6.12 Because dogs have very few sweat glands, their main means of losing body heat after they have been exercising is through panting. Where are the sweat glands in dogs? How does a dog lose heat when it pants?

TABLE 6.1 Examples of behavioural activities that may be undertaken by a person to gain, conserve or lose body heat. Can you think of other behaviours that might contribute to heat gain, heat conservation or heat loss?

Behaviours for gaining and conserving heat	Behaviours for losing heat
vigorously exercising	removing a layer of clothing
putting on another layer of clothing	having a cold shower
soaking in a hot bath	resting in the shade
having a hot drink	using an ice pack
rubbing your hands together	removing your hat and gloves
reducing body surface area by wrapping your arms around you	sitting in front of a fan
wearing a hat and gloves	maximising the body surface area exposed to a cooling wind
standing in front of a heater	soaking your feet in cold water

Normally, during extended periods of vigorous exercise the body compensates for excessive metabolic body heat from muscle activity in two ways:

1. by beginning to sweat
2. by an increase in the blood flow to the surface areas of the body from where excessive heat can be lost through radiation from the skin. In fact, during vigorous exercise, peripheral blood flow can increase up to ten times — which explains why a person's face reddens under such conditions.

Changing our clothing is one behaviour in which we commonly engage to regulate body heat — either adding clothes to conserve body heat or removing clothes to lose heat. Wearing clothing causes a significant reduction in the loss of body heat from a person. A naked person radiates body heat to the environment to varying degrees over their entire body surface. This may be seen in the heat signature of a naked person (see figure 6.13a). Areas of greatest heat loss are the upper trunk, neck and head. Heat loss from the hands and feet is relatively less. (Can you suggest why?) When the person adds grade 3 thermal clothing (see figure 6.13b), heat losses from the trunk and the arms that are covered by the clothing are greatly reduced. If grade 5 thermal clothing is worn (see figure 6.13c), there is a further reduction in heat loss from the trunk. In addition, because the trunk is warmer, the heat loss from the legs is also reduced.

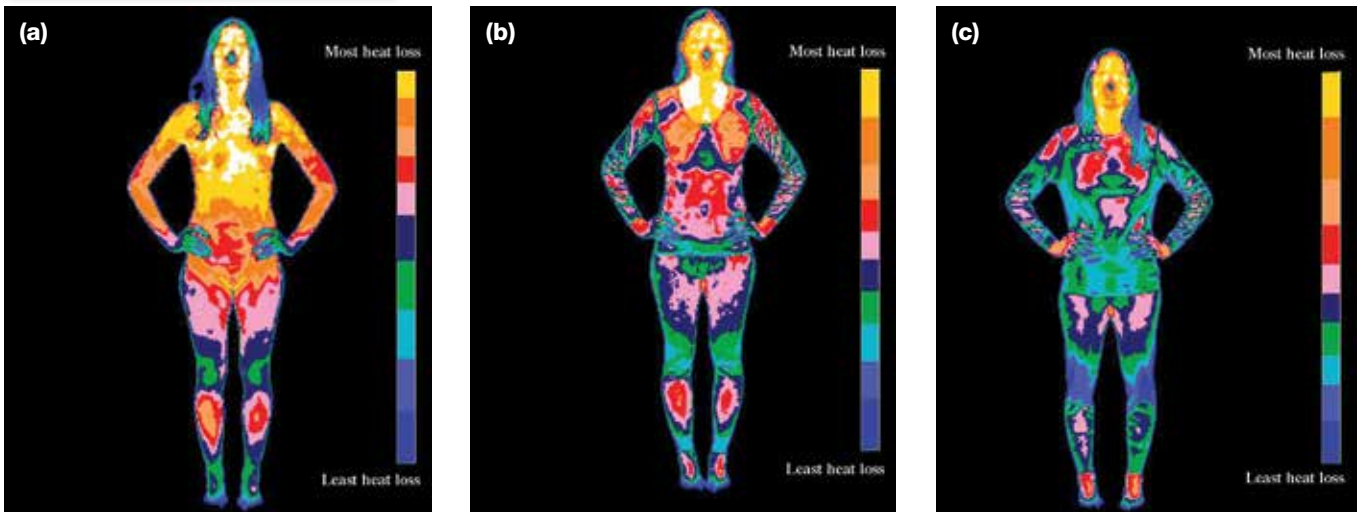

FIGURE 6.13 Infra-red images of a female subject showing the heat loss under various conditions **(a)** Naked subject **(b)** Subject wearing grade 3 thermal clothing **(c)** Subject wearing grade 5 thermal clothing. In the naked subject, where are the areas of greatest heat loss? What is the impact of clothing on heat loss from the body?

FIGURE 6.14 An *Arctic Heat* cooling vest. The grey compartments contain a gel that can hold a particular temperature for long periods. (Image with kind permission of Arctic Heat Pty Ltd)

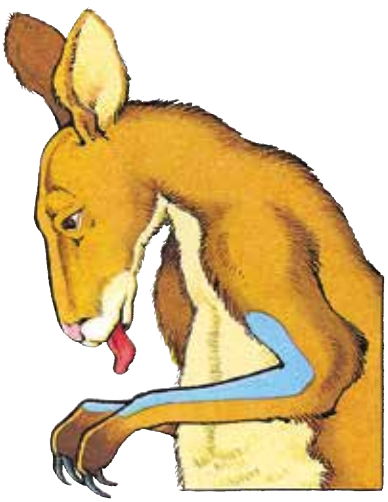

FIGURE 6.15 A red kangaroo (*Macropus rufus*) showing the 'saliva spreading' behaviour, a cooling mechanism. How does licking this area cool the kangaroo?

As well as preventing heat loss, specialised clothing has also been designed to assist in cooling the body. Body cooling vests have been developed to prevent over-heating or to assist in reducing the heat load of a body after exercise. The *Arctic Heat* Body Cooling Vest is an Australian-made lightweight garment designed specifically for body cooling. The vest is two-layered, with an internal layer of merino wool and an outer micromesh layer made of so-called 'wicking' material. This is a fabric that is woven in a particular way in order to draw moisture from the skin to the exterior from where it can evaporate, so that the skin is kept dry and cool.

The key feature of this garment is the presence of the crystals in the grey compartments of the vest (see figure 6.14). One exposure to water activates these crystals, converting them to a gel that can hold a particular temperature for long periods. Once activated, the vest can be placed in water at a required temperature for two to three minutes and dried. If lower temperatures or longer periods of cooling are required, the vest can be placed in a refrigerator or freezer for a short period. Examples of people who make use of this cooling vest are members of professional sporting teams and people engaged in heavy manual labour, who may be at risk of over-heating.

As seen in chapter 5 (pp. 201–2), other mammals have unique behaviours for losing body heat. One such example is the practice of **saliva spreading** that is seen in some wallabies and kangaroos. On a hot day, these marsupials can be seen licking an area on their forelimbs (see figure 6.15). These areas (shown in blue) have a thin covering of fur and a rich supply of blood vessels. The saliva spread over these areas evaporates and the heat energy required for this process is taken from the body. Thus, this is an example of evaporative cooling. (Another example of evaporative cooling identified in chapter 5 (p. 213) was that of camels being cooled by letting their urine track down their back legs.)

KEY IDEAS

- Deserts are environments in which dehydration and hyperthermia can threaten human survival.
- Heat may be gained by or lost from the human body by radiation, convection and conduction.
- Heat loss can occur by evaporation from the body, both insensible water and sweat.
- Metabolic activity is one source of heat gain for the human body.
- Heat gain or heat loss is influenced by many factors.

QUICK CHECK

1 Identify a key difference between:
   - **a** radiation and conduction
   - **b** ambient and core body temperature
   - **c** insensible water and sweat
   - **d** the major source of evaporative cooling in a dog and in a person.

2 Give an example of each of the following.
   - **a** A behavioural factor that can increase heat loss
   - **b** A physiological factor that results in heat gain
   - **c** An environmental factor that affects the rate of heat loss from the body
   - **d** A physical means by which heat is gained

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Homeostasis
Concept summary and practice questions

Homeostasis: staying within limits

Homeostasis is the outcome of processes that maintain a steady state or constancy within the body for certain physiological variables and the chemical compositions of body fluids. Homeostasis involves monitoring levels of variables and correcting changes in these levels, typically by negative feedback. **Homeostatic mechanisms** produce a relatively stable internal environment by maintaining key variables within narrow limits.

One variable under homeostatic control is core body temperature. The temperature of the external environment can vary — hot one day, cold the next. Regardless of the variation in the external temperature, the core body temperature of the human body at rest is *about* 37 °C, with a typical narrow range from about 36–39 °C (see figure 6.16).

ODD FACT

The core body temperature of most mammals is in the range of 36–39 °C, and that of most birds is in the range of 39–42 °C.

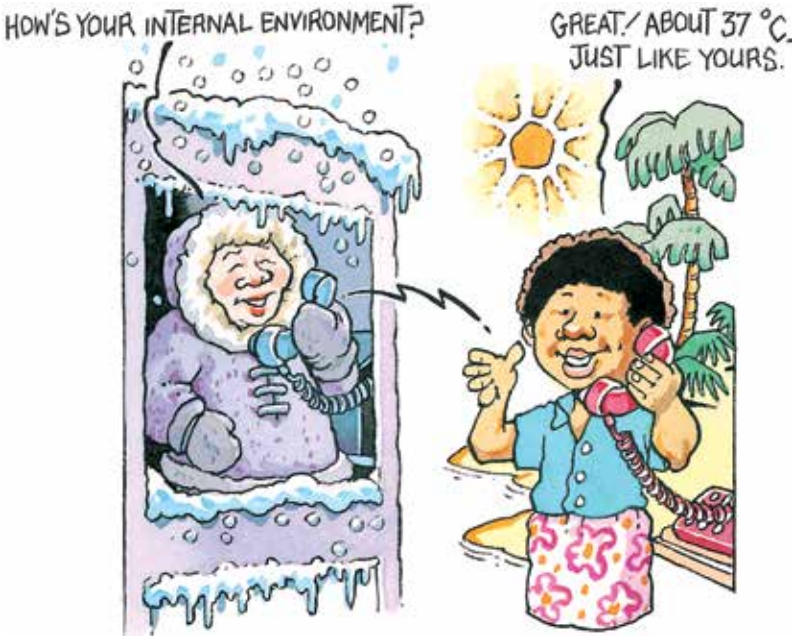

FIGURE 6.16 The temperatures in the external environment may be different, but the internal environment stays the same.

Core body temperature is just one example of the operation of homeostasis. The major variables within the human body that are maintained within narrow limits by homeostatic mechanisms are shown in table 6.2.

TABLE 6.2 Summary of major variables that are subject to homeostasis in humans

Variable	Normal tolerance range	Comments
temperature	36.1–39 °C	Temperature of internal cells of the body is called the core temperature.
blood glucose	3.6–6.8 mmol per L	Blood glucose is typically maintained within narrow limits regardless of diet.
water	Daily intake must balance daily loss.	Body tissues vary in their water content. Bone contains about 20% water and blood about 80% water. In prolonged dehydration, fluid moves from cells and tissue fluid into the body.
ions, e.g. plasma Ca^{2+}	2.3–2.4 mmol per L	Specific ions are required by some tissues.
pH of arterial blood	7.4	pH regulation is necessary for enzyme action and nerve cells.
blood pressure — arterial diastolic (relaxed) systolic (contracted)	13.3 kPa (1000 mmHg) 5.33 kPa (40 mmHg)	Transport of blood depends on maintenance of an adequate blood volume and pressure.
urea (nitrogenous wastes) in plasma	< 7 mmol per L	Waste products of cellular processes must be removed by kidneys to prevent toxic effects on cells.

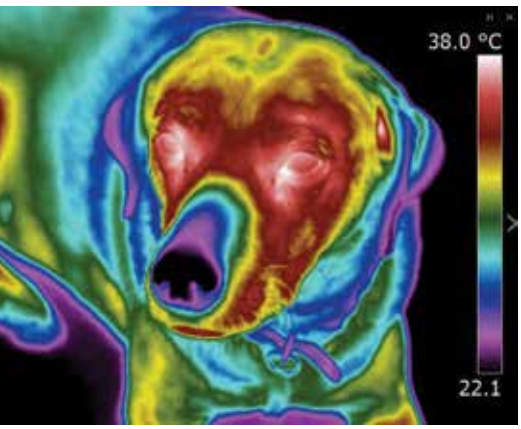

FIGURE 6.17 Heat signature of Lettie, a Labrador dog, obtained with an infra-red camera that detects surface temperatures. The black colour indicates that her nose is the coldest surface area. Why is this the case? Her warmest areas are those that overlie areas with a rich supply of warm blood.

Looking at body temperature

Core body temperature relates to the temperature in organs and deep tissues within the core of the body. Core temperature must be distinguished from **peripheral surface temperatures** that can be many degrees cooler. For example, when the ambient temperature is 23 °C, the core temperature in the deep body tissue of a person is about 37 °C, but the temperature of that person's hands will be less, perhaps only 30 °C, and the temperature of the feet even cooler, perhaps 25 °C. It is the core temperature that is important and the core body temperature of a person can be measured at several sites, including the mouth (oral measurement), the rectum (rectal measurement), and the ear, where the temperature of the ear's tympanic membrane or eardrum indicates the temperature of the brain stem and the hypothalamus in the brain.

The difference between the core temperature of a mammal and its peripheral surface temperature can be revealed using an infra-red camera that produces an image called a **thermograph**. A thermograph shows the surface temperatures or heat signature of an object. Figure 6.17 shows the heat signature of Lettie, a Labrador dog. The bar at the right shows colour-coded temperatures in order. The coolest areas are black and then purple; the warmest areas are red (warmest) then yellow. The black of Lettie's nose pad is her coolest area. Other body areas are covered by fur that conserves heat, keeping those areas warmer to various degrees. In spite of all this variation in her surface temperatures, Lettie's core body temperature is maintained within the narrow doggy range of 37.7 °C to 39.2 °C.

Body temperature: constant or changing?

The core body temperature of a healthy person averages about 37 °C, and varies only within a narrow range, from 36–39 °C, depending on factors such as air temperature, level of physical activity, and food intake. For example, during vigorous exercise, the core temperature may temporarily rise to 40 °C. If the body temperature rises, mechanisms come into action to lower the temperature and return it to within the narrow range. If the body temperature falls, other mechanisms come into action to raise the temperature and return it to within the narrow range. All other mammals and birds are also able to regulate their body temperature and maintain it within specific limits.

Many animals *cannot* regulate their body temperatures within narrow limits. Figure 6.18 shows the changes in the body temperature of a red-bellied black snake (*Pseudechis porphyriacus*) over one 24-hour period. Because the snake's temperature does not stay within a narrow range, it is apparent that it cannot regulate its body temperature. At the beginning of the day when the snake emerges from a hollow in a log, its body temperature is about 15 °C, but as it moves above ground and exposes its body to the sun's heat, its temperature increases to about 30 °C. Snakes exert some control over their body temperature, but only during the day, by behaviours such as shuttling back and forth between sunny and shady areas. When snakes get too hot, they move out of the sun and into the shade. Then, as they start to cool down, they move from the shade back into the sun. For snakes, their heat source is external to the body.

FIGURE 6.18 **(a)** A red-bellied black snake **(b)** Variation in the body temperature of a black snake over a 24-hour period. Note the regular fluctuations in body temperature during the day as the snake moves between sun and shade.

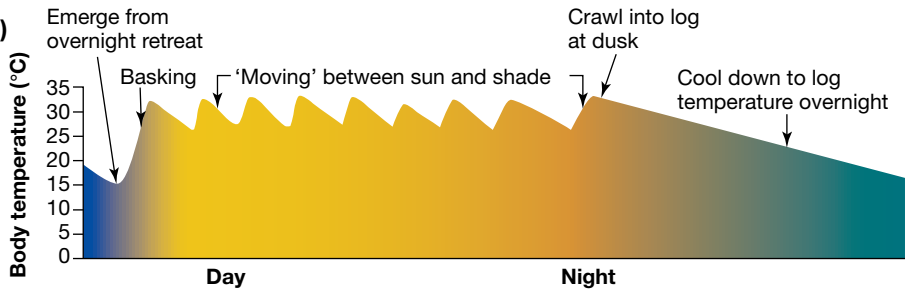

FIGURE 6.19 Reptiles rely on the external heat of the sun for their body heat, while mammals rely on internal heat from their own metabolism.

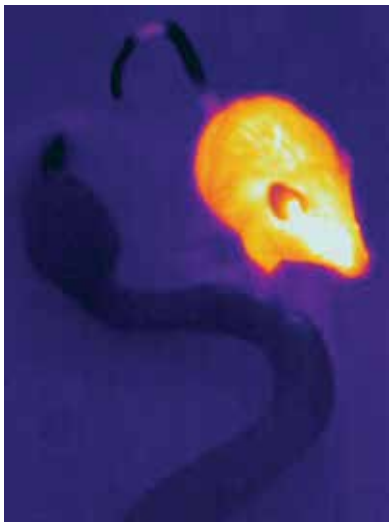

FIGURE 6.20 A false coloured thermographic image taken with an infra-red camera. This image shows the heat energy (infra-red radiation) emitted from a mammal (rat) and from a reptile (snake). Note the very different heat signatures of the rat and the snake. How would the image change, if at all, if the snake had basked in the sun before the image was taken?

Source of body heat

The source of body heat for mammals and birds is the heat produced by their own internal metabolic processes. People, along with other mammals and birds, whose body temperature comes from internal metabolic heat, are said to be **endothermic** (*endo* = within; *thermos* = heat). In contrast, the body heat of reptiles comes from an external source, the sun. Animals that rely on an external source of heat are said to be **ectothermic** (*ecto* = outside; *thermos* = heat) (see figure 6.19).

For mammals, a proportion of the chemical energy from their food is used to warm their bodies. Because reptiles do not need energy from their food intake for staying warm, their energy requirements are less than that of mammals, and reptiles need to eat far less often than mammals. The energy requirement of a reptile is just ten per cent of that of a mammal with the same body mass.

The striking difference that can exist between the body temperatures of a mammal and a reptile is shown in figure 6.20. The heat signatures of the two different kinds of animal are very apparent.

Regulating body temperature

The core temperature of the human body is highly regulated, that is, kept within a narrow range by various homeostatic mechanisms. The regulation of body temperature is called **thermoregulation** and it ensures a balance between heat gain and heat loss so that body temperature is kept relatively constant. Thermoregulation is one example of homeostatic regulation. Other examples include the maintenance of relatively constant blood glucose concentration, water balance in the body, blood pressure and blood pH.

Homeostasis as a stimulus-response model

Homeostatic regulation involves the monitoring of the value of a variable, such as body temperature, detecting if it starts to move outside the normal range and making adjustments to correct the situation. This process can be represented by a **stimulus-response model** with feedback (see figure 6.21). The model starts with a stimulus and ends with a response that feeds back to and, typically, counteracts the original stimulus. Stimulus-response feedback models can be used to show how homeostatic mechanisms act in the body and maintain a fairly constant state.

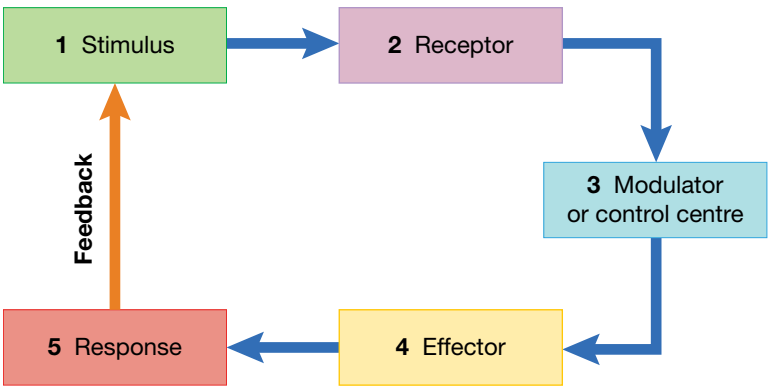

FIGURE 6.21 Diagram of a stimulus-response model with feedback

As per figure 6.21, the components of a stimulus-response model are as follows:

1. *Stimulus*. A stimulus is a change, either an increase or a decrease, in the level of an internal variable.
2. *Receptor*. A receptor is the structure that detects the change and sends information to the control centre.

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3. *Modulator or control centre.* The control centre evaluates the change against the set point for that variable and sends signals to the effector about the correction needed. If a variable has increased above its set point, the correction will be to decrease the level of the variable. If the variable has decreased below its set point, the correction needed will be an increase in the level of the variable.

   In the human body, the control centre is typically the hypothalamus of the brain.
4. *Effector*. The effector adjusts its output to make the required correction.
5. *Response*. The response is the corrective action taken.

When the response feeds back to and counteracts the change in the variable, it is called **negative feedback**.

A negative feedback system is a process in which the body senses a change in a variable and activates mechanisms to reverse the change so that internal conditions within the body are maintained within narrow limits. A key feature of a negative feedback system is that the response is opposite in direction to that of the original stimulus. So, if the stimulus is an increase in a variable, such as an increase in body temperature, then the response is a decrease in the same variable. Negative feedback is an important control mechanism in almost all processes of homeostatic regulation.

Figure 6.22 shows a highly simplified negative feedback system. A stimulus such as a fall in body temperature produces a shivering response that produces metabolic heat that raises the body temperature. This response counteracts the original stimulus, returning the body temperature to within the normal range. As a result, shivering stops. (You would not want to continue shivering and producing more heat once your body temperature was back to normal, otherwise you would run the risk of overheating.)

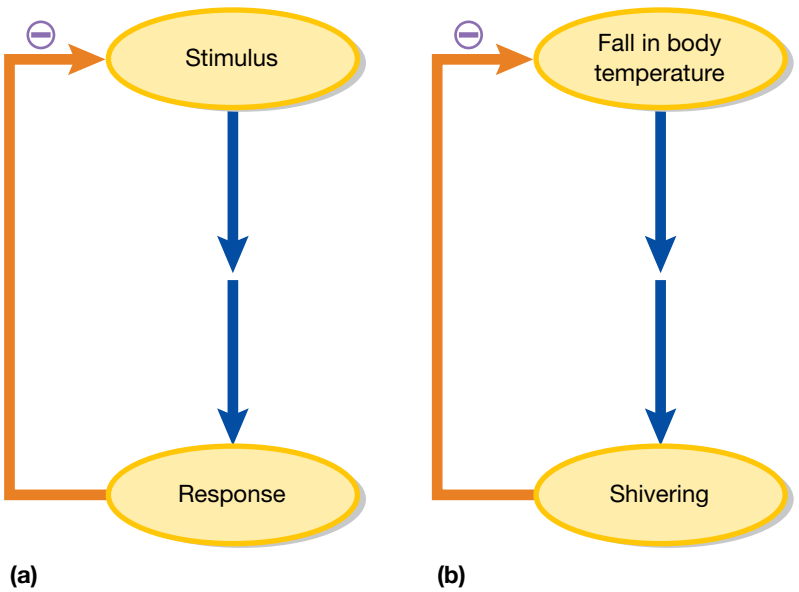

FIGURE 6.22 Negative feedback loop **(a)** Diagram showing a highly simplified generalised negative feedback system in which a change in a variable acts as a stimulus that produces a response to counteract the original change and return the variable to normal levels **(b)** Diagram showing the shivering response to the stimulus of a drop in body temperature. The shivering response generates body heat and so counteracts and removes the stimulus. (The negative sign denotes the lessening or reversing of the original change.)

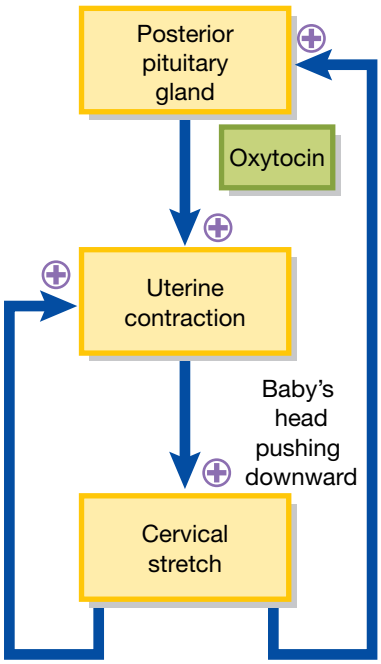

FIGURE 6.23 Positive feedback system in which oxytocin produced by the posterior pituitary gland stimulates contraction of the uterus and also stimulates the pituitary gland to produce even more of the hormone. Note the positive feedback nature of the inputs.

In most cases, the feedback is negative and counteracts the stimulus. However, feedback can also be positive. A feedback system is a cycle of continuing change in which an original change is increasingly amplified. As a result, **positive feedback** increases the deviation from an ideal normal value. Unlike negative feedback, which maintains the levels of variables within narrow ranges, positive feedback is rarely used to maintain homeostasis.

Positive feedback is involved in the process of childbirth. During labour, as a baby starts its journey from its mother's uterus, the hormone **oxytocin** is produced. The action of oxytocin is to increase the contractions of the wall of the uterus. The cervix at the exit of the uterus has pressure receptors that are stimulated by pressure from the baby's head. The pressure receptors send signals to the brain to produce oxytocin. The oxytocin travels via the bloodsteam to the uterus, stimulating even stronger contractions of the wall of the uterus. The increased rate of contractions causes the release of more oxytocin, creating a positive feedback cycle that leads to even greater contractions (see figure 6.23). This cycle continues, producing more and stronger contractions that continue until the baby is born.

Temperature: too cold

As discussed above, the normal core temperature of the human body at rest is about 37 °C but it can vary within a range from 36–39 °C, and keeping the body temperature within this normal range involves a process called thermoregulation. When heat gain by the body and heat loss from the body are in balance, the body temperature will be maintained within its normal limits. This occurs when:

heat gain = heat loss or heat gain – heat loss = 0

Thermoregulation is important because each species has a preferred temperature range for the optimal functioning of the enzymes involved in its metabolism.

If the human body temperature falls below 35 °C, a state of hypothermia begins. Normally, if the core body temperature of a person falls below its narrow range, homeostatic mechanisms come into operation to correct the situation and restore the temperature to within its range. If a person is in a cold environment with light clothing only, heat gain and heat loss are out of balance, with heat loss being in excess of heat gain. As a result, the core body temperature falls. In these circumstances, the drop in core temperature is detected and acts as a stimulus that produces a response to reverse the change in body temperature in a process that involves negative feedback.

Figure 6.24 shows an outline of events that occur when the core body temperature falls. A fall in body temperature is the stimulus that is detected and processed by the hypothalamus through its temperature set point. When the temperature falls below this set point, the hypothalamus signals a range of automatic 'heating-up' instructions for effectors. These effectors are the thyroid gland, arterioles in the skin and skeletal muscles. Some responses by the effectors reduce heat loss from the body, for example, the vasoconstriction that diverts blood through shunt vessels away from the skin surface. Other responses increase metabolic heat production, for example, the production of the hormone thyroxine by the thyroid gland, which boosts the metabolic rate of body cells. What is the role of the shivering response in raising the body temperature? These responses are part of a homeostatic mechanism that acts to raise the core temperature back to within its normal limits.

We can summarise the homeostatic mechanisms that correct a fall in body temperature as a stimulus-response with negative feedback (see figure 6.25 p. 257). The response reverses the stimulus and so acts as negative feedback.

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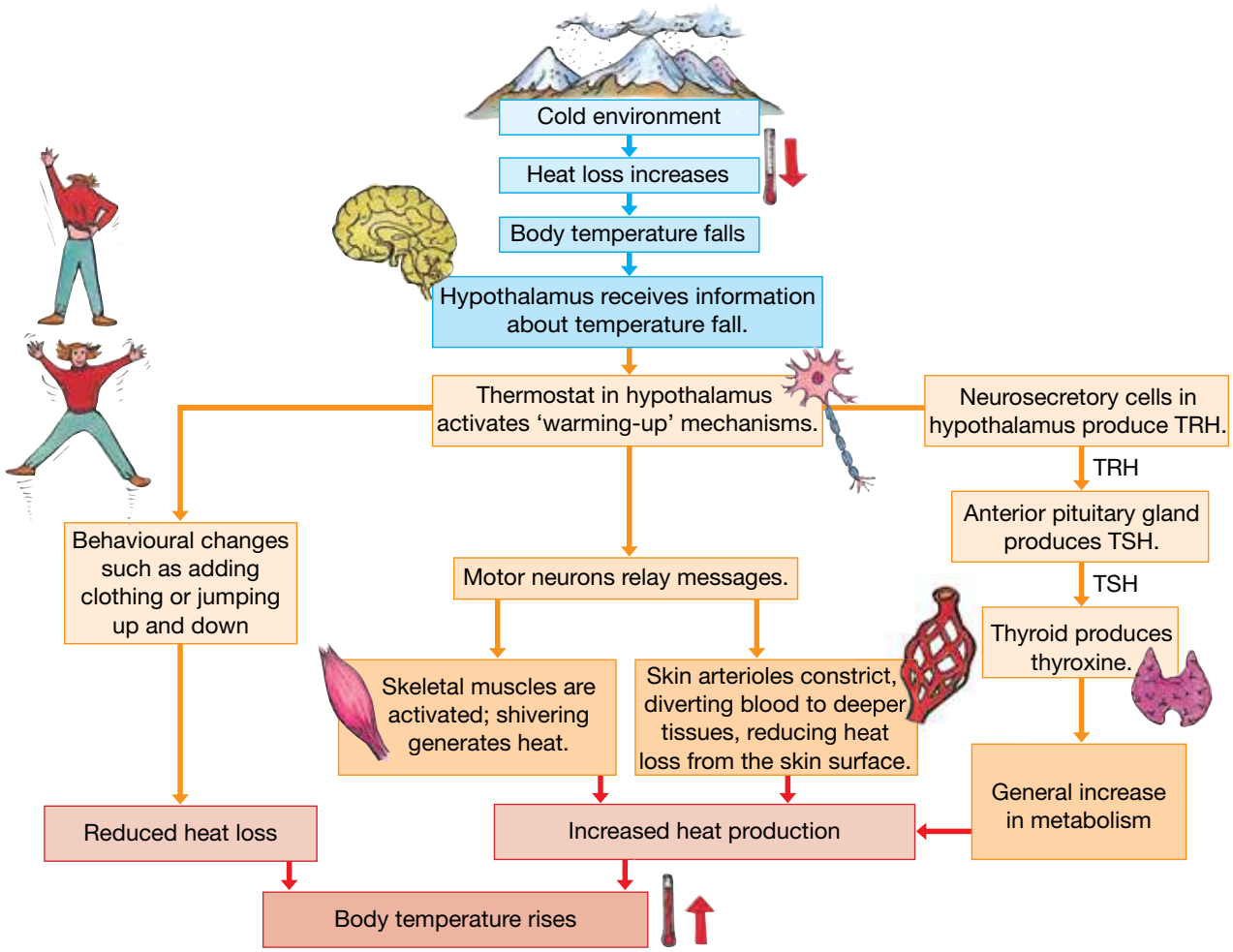

FIGURE 6.24 Responses to the stimulus of a fall in body temperature. Hormones involved are thyroid-releasing hormone (TRH) from the hypothalamus, thyroid-stimulating hormone (TSH) from the pituitary gland and thyroxine from the thyroid gland.

Temperature: too hot

The core body temperature of a person can increase outside the normal range. If the core body temperature rises above 39 °C, a state of hyperthermia has started. Core temperature may rise above the normal narrow range, for example, when a person is exposed to a hot environment for an extended period or when a person engages in strenuous physical activity for a lengthy period. These situations involve an imbalance between heat gain and heat loss, with heat gain being in excess of heat loss. As a result, heat builds up in the deep body tissues, raising the core body temperature.

In these circumstances, the increase in core body temperature is the stimulus that starts the homeostatic mechanisms that will lower the temperature to within the normal narrow range. The stimulus is detected by heat receptors in the skin and various organs and is processed by the hypothalamus. Because the stimulus is a rise in temperature above its set point, the hypothalamus signals a range of automatic 'cooling down' instructions for effectors. These effectors include arterioles of blood vessels close to the skin surface and sweat glands in the skin. The result is vasodilation, which increases blood flow to the skin, and sweating, which is a source of evaporative cooling. Figure 6.26 shows a stimulus-response model for an increase in core body temperature.

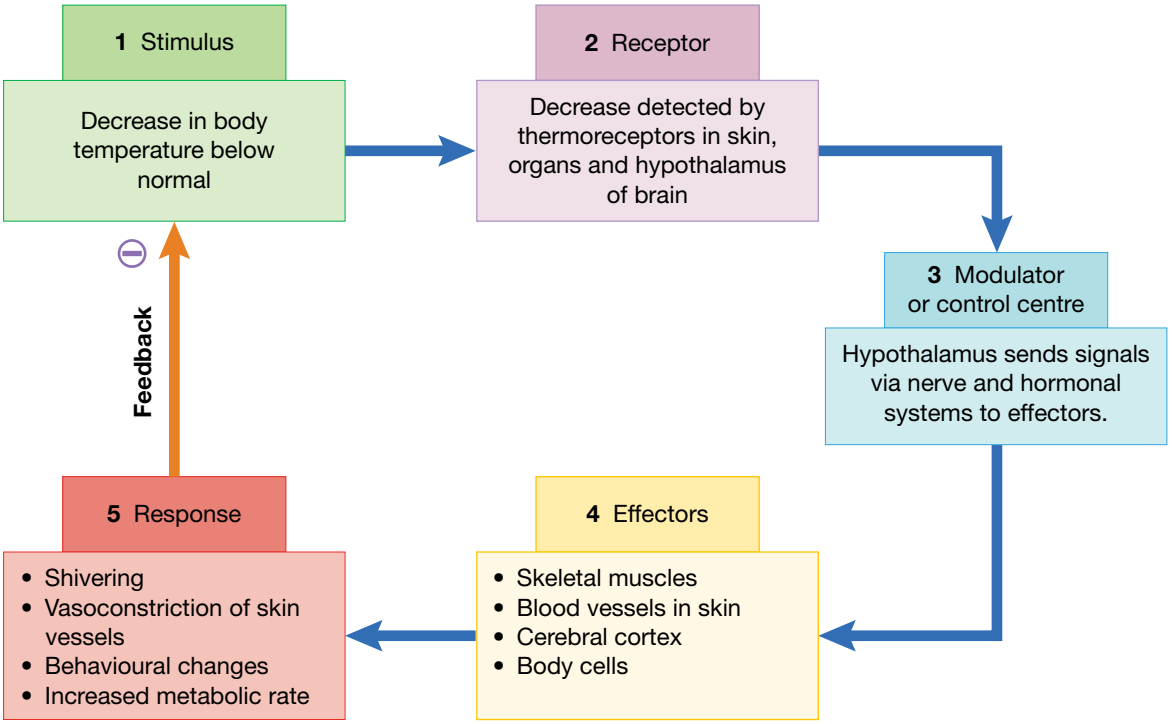

FIGURE 6.25 Diagram showing a stimulus-response model for a drop in core body temperature. The fall in temperature stimulates various responses that act to restore the core body temperature to within its narrow range.

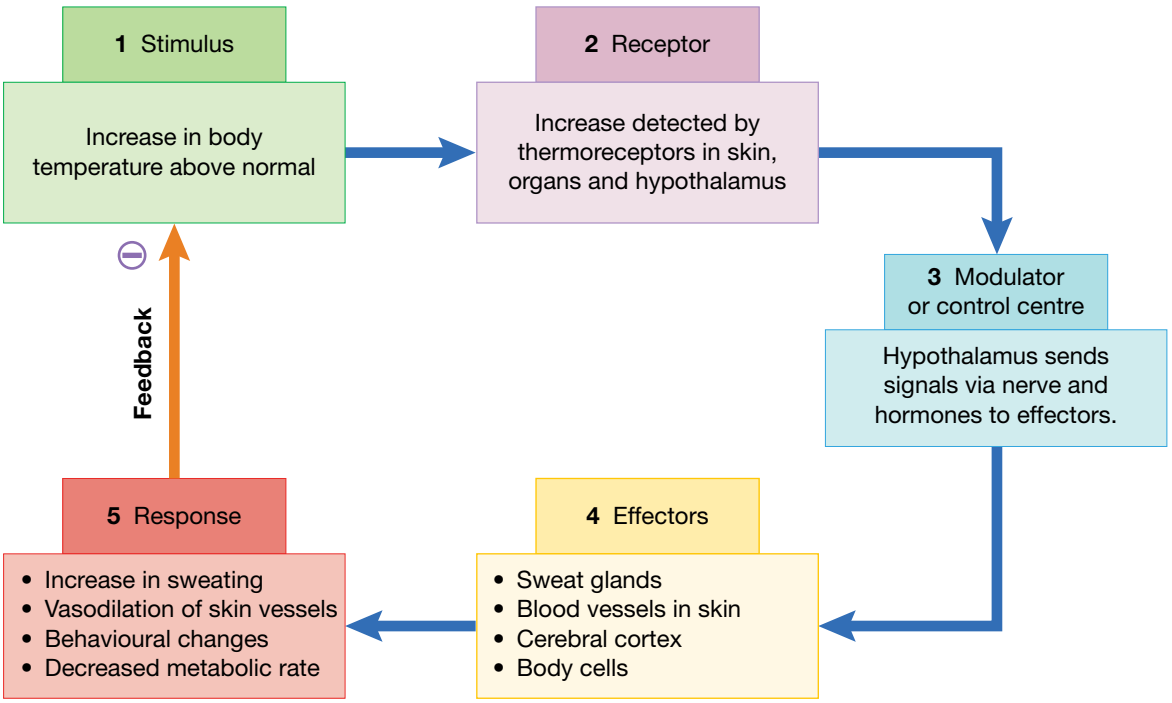

FIGURE 6.26 Diagram showing a stimulus-response model for an increase in core body temperature. The increase in core temperature stimulates various heat loss or cooling responses that act to restore the core temperature to within its narrow range.

When homeostasis fails: heat stroke

The core body temperature of a person may increase outside the normal range under abnormal conditions, for example, extended exposure to unusually hot environmental conditions or excessive physical activity over a prolonged period. Under these conditions, the homeostatic mechanisms of the body can fail, resulting in an uncontrolled increase in core body temperature. As this starts, heat cramps are experienced, then heat exhaustion and, if the heat gain continues, the critical and potentially deadly situation of heat stroke may occur.

What can happen in the desert?

In the peak daytime temperatures of a desert (45 °C plus), the ambient temperature is higher than the normal human body temperature (36–39 °C). In this situation, the body gains heat by:

- conduction from the hot air and ground in direct contact with a person
- heat radiated from the air, the ground and any other objects in the person's environment
- convection, if hot winds are blowing.

In addition, any physical activity produces metabolic heat that adds to the person's heat gain. These various sources of heat gain cause a person's core body temperature to increase.

If the core body temperature rises, homeostatic mechanisms normally operate to lower the body temperature and return it to within the normal range. The major mechanism involved is evaporative cooling. To achieve cooling, the blood flow to vessels close to the skin is increased and sweat is produced by the sweat glands. Evaporative cooling removes heat from the warm blood in vessels close to the skin surface. This warm blood has come from the body core and, after being cooled, it returns to the body core, thus cooling the body.

However, in the searing heat of a desert during daytime, evaporative cooling, even at its maximum, may not be sufficient to reduce the body temperature. In trying to cool the body in the desert heat, the blood flow to the skin is very greatly increased. This means that the blood flow to vital organs is greatly decreased and, as a result:

- the decreased blood flow to the brain can cause dizziness and confusion
- the decreased blood flow to the gut can cause nausea and vomiting.

As evaporative cooling becomes less effective, the heat store in the body core continues to build because heat gain is greater than heat loss. As a result, the core body temperature rises and a condition termed hyperthermia results.

In an attempt to reverse the hyperthermia and return the core body temperature to normal, the sweat glands produce even more sweat. Sweating causes fluid loss that, in hot conditions, can occur at the rate of several litres per hour. If this fluid loss continues without being replaced, dehydration results. Excess sweating causes not only water loss but also the loss of salts. When a person is dehydrated, the water content of the blood is decreased. This decrease reduces the volume of blood in the circulatory system and this, in turn, causes a drop in blood pressure.

The combined effects of hyperthermia and dehydration initially produce the condition of heat exhaustion. The symptoms of heat exhaustion include extreme fatigue, profuse sweating, weakness, muscle cramps, an abnormally rapid heart rate, dizziness, headache, nausea and a drop in blood pressure.

The drop in blood pressure worsens the situation. When blood pressure falls, a homeostatic mechanism is normally activated to raise it to normal levels. This mechanism acts by stopping the blood flow to the skin and re-directing the blood to the major circulation in the body core. However, evaporation can cool the blood only in vessels close to the skin. Stopping the blood flow to the skin stops the movement of warm blood from the core to the skin so that it cannot be cooled. In a person suffering from heat exhaustion, this reflex mechanism causes a further rise in core body temperature. Evaporative cooling at this stage can affect only the body surface, not the core temperature.

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ODD FACT

Sweat is composed of water and several electrolytes, in particular sodium. Excessive sweating, without fluid replacement, leads to dehydration and to an imbalance in the ions (electrolytes) in the blood, such as sodium (Na^+) and chloride (Cl^-). This electrolyte imbalance can cause muscle cramps, irregular heartbeat, dizziness and mental confusion.

The situation of the person with heat exhaustion can get even worse! As dehydration becomes more severe, the body can no longer produce sweat. At this stage, the major cooling mechanisms of the body have completely stopped. The homeostatic mechanisms that normally control body temperature have been overwhelmed and have ceased. Heat loss now equals zero. However, heat gain through metabolic heat and gain of environmental heat continues. Consequently, the core body temperature continues to increase in an uncontrolled manner. The situation of heat exhaustion has now developed into heat stroke, a critical and life-threatening condition. Symptoms of heat stroke include high core body temperature in excess of 41 °C, slurred speech, hallucinations, and multiple organ damage. Unless corrected, death is inevitable.

Death from heat stroke occurs in desert environments where people walk long distances in the heat of the day, without water, but generating metabolic heat and gaining environmental heat. This type of situation may have occurred in the unfortunate death of Mauritz Pieterse in the Gibson Desert in 2012 and the near-death of his companion, Josh Hayes. Deaths in the desert inevitably involve hyperthermia with associated dehydration at levels that lead to the failure of the normal processes of homeostatic regulation.

Homeostasis can also fail in other situations in which excessive internal heat is produced so that heat gain is greater than heat loss and where measures to prevent dehydration are not in place. These situations include endurance events, such as triathlons and fun runs, and occupations in which strenuous physical labour is involved.

In mass participation runs in Australia, care is taken to ensure that participants do not risk heat exhaustion, and expert medical supervision is on hand. These events include the *City2Sea* run in Melbourne and the *City2Surf* road running event over 14 km in Sydney.

Read what one participant in the Sydney City2Surf run does to avoid heat exhaustion:

> When I run, I wear a painter's cap in which I place a bag of ice cubes, and I continually soak the cap with water. I never pass a water station without stopping to drink two full glasses and pour one over my head. Wherever there is a hose, I run through the spray, and I carry a cup in the hope that I can fill it with water. And I purposely run 15 to 30 seconds per mile slower than my usual time.

ODD FACT

Heat stroke is the second most common cause of death among athletes in the United States.

When homeostasis fails: hypothermia

Extreme cold can kill. Homeostasis can fail when people are exposed to very cold temperatures. When the core body temperature falls below the normal range and when the homeostatic mechanisms designed to maintain core body temperature fail, a person can be at risk of death from hypothermia (*hypo* = below; *thermos* = heat).

Several forms of hypothermia are recognised:

- **Acute hypothermia** occurs when a person is suddenly exposed to extreme cold, such as immersion in cold water. This was the situation for hundreds of passengers on board the ill-fated *RMS Titanic* that sank in the North Atlantic Ocean in April 1912. The water temperature on that evening is thought to have been just above −2 °C. Those passengers who could not get into life boats and were immersed in the ocean died quickly from hypothermia. (Ocean water freezes at a lower temperature than fresh water.) Other people at risk of acute hypothermia are those who are caught suddenly unprepared and exposed to cold conditions.
- **Exhaustion hypothermia** occurs when a person is exposed to a cold environment, is exhausted, and does not have sufficient food. As a result, such persons cannot generate sufficient metabolic heat to compensate for their loss of heat and their core body temperature falls. Antarctic explorers and mountaineers climbing for days at high altitude on Earth's highest mountains are at risk of exhaustion hypothermia.

ODD FACT

The human body is more tolerant of a drop in body temperature below the normal range than a rise in temperature. However, once the body temperature falls below 21 °C, death will inevitably result.

The first signs of hypothermia are shivering, numbness in the hands and feet, and loss of manual dexterity. As the core body temperature continues to fall, shivering becomes more violent, muscle coordination decreases, and thinking becomes confused and even irrational. When hypothermia approaches an extreme level, the metabolic rate is so low that it cannot fuel muscle contraction so that shivering stops, the heart rate and the breathing rate slow to very low levels, and the person loses consciousness. Finally when the core body temperature drops to less than 21 °C, the heart stops and death occurs.

Some military campaigns have been lost not by defeat in battle, but by hypothermia. In June 1812, an army of more than 680 000 men under the control of French Emperor Napoleon invaded Russia. They reached Moscow in September of that year. Finding a deserted city, lacking supplies and faced with the oncoming winter, Napoleon and his now starving troops had no option but to retreat so they left the city in October 1812. The retreat was chaotic (see figure 6.27) with hundreds of thousands of French soldiers dying from attacks by Russian troops, from the cold and from hunger.

FIGURE 6.27 Cold and starving stragglers of the French Army in the disastrous retreat from Moscow during October to December 1812

The following is a description written by a French doctor on the effects of the cold on the retreating French soldiers:

> . . . some, pale and depressed by inanition [exhaustion from lack of food] swooned away and died, stretched on the snow. Others . . . were seized by shivering to which quickly succeeded languor and propensity to sleep. They were seen walking insensible and ignorant where they went: scarcely could you succeed in making them understand a few words . . . In a word, when no longer able to continue walking, having neither power nor will, they fell on their knees. The muscles of the trunk were the last to lose the power of contraction. Many of those unfortunates remained some time in that posture contending against death. Once fallen, it was impossible for them with their utmost efforts to rise again . . . Their pulse was small and imperceptible; respiration, infrequent and scarcely perceptible in some, was attended in others by complaints and groans. Sometimes the eye was open, fixed, dull, wild, and the brain was seized by quiet delirium. . .
>
> *Source:* Pierre Jean Moricheau-Beaupré, *A treatise on the Effects and Properties of Cold, with a Sketch, Historical and Medical, of the Russian Campaign*, tr. by J Clendinning, Oxford University, 1826.

ODD FACT

In some medical situations, a patient may be deliberately placed in a hypothermic state, for example, after a heart attack or during open heart surgery when the blood is diverted and bypasses the body.

Failure of homeostasis: thyroid disorders

The thyroid gland produces the hormone thyroxine in response to the release of thyroid-stimulating hormone (TSH) from the pituitary gland. Thyroxine directly affects the metabolic rate and the cardiovascular function of a person. If thyroxine levels in the blood are too high, the metabolic rate

FIGURE 6.28 Which person is suffering from hyperthyroidism?

increases, but if too low, the metabolic rate falls. Severe metabolic disorders arise when the thyroid gland is overactive, producing excessive amounts of thyroxine or when it is underactive, producing insufficient amounts of the hormone.

An overactive thyroid gland results in an increase in the basal metabolic rate of an affected person — a condition known as **hyperthyroidism**. A person with hyperthyroidism will show many symptoms including an increase in the resting heat rate, an elevated body temperature, an increase in appetite, unexplained weight loss, sensitivity to and sweating in warm conditions and relative insensitivity to cold conditions (see figure 6.28). This condition may be the result of the growth of nodules on the thyroid or local inflammation; genetic factors can also predispose a person to hyperthyroidism.

Management of hyperthyroidism may involve surgical removal of part of the thyroid gland or the administration of anti-thyroid medication that interferes with the ability of the thyroid gland to take up iodine from the blood. Iodine is an essential component of thyroxine (see figure 6.29). Carbimazole is one such anti-thyroid medication. Carbimazole is converted to an active form in the body and it prevents the precursor of thyroxine from binding the iodine atoms that are needed to produce active thyroxine.

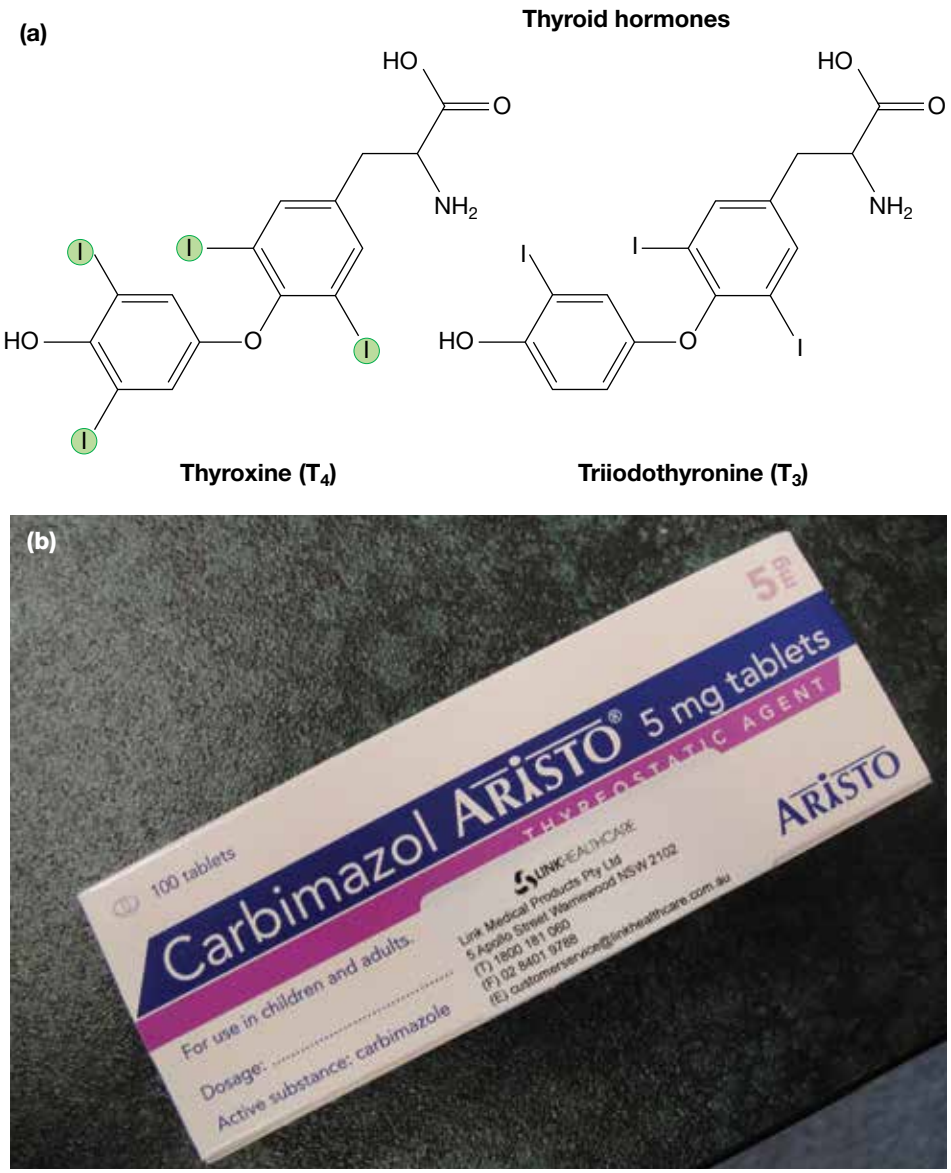

FIGURE 6.29 **(a)** Molecular structure of the hormone, thyroxine. Note the four iodine atoms that form part of its structure. **(b)** Carbimazole, an anti-thyroid medicine

In contrast, the thyroid gland can become underactive, producing a condition known as **hypothyroidism**. In hypothyroidism, the metabolic rate of the body falls below normal. Symptoms of hypothyroidism include sensitivity to the cold, lethargy, and unexpected weight gain. Hormone replacement by administration of thyroxine tablets is used in the treatment of hypothyroidism.

Hypothyroidism can occur in people when their long-term diet is chronically deficient in iodine. In the past, this could occur in a person living well away from the sea and whose diet lacked iodine-rich foods, in particular, seafood. These people often showed extreme swelling of the thyroid gland, a condition known as **goitre** (see figure 6.30).

FIGURE 6.30 This image shows a severe case of goitre in a woman. The goitre most probably resulted from an iodine-deficient diet over the course of the woman's life.

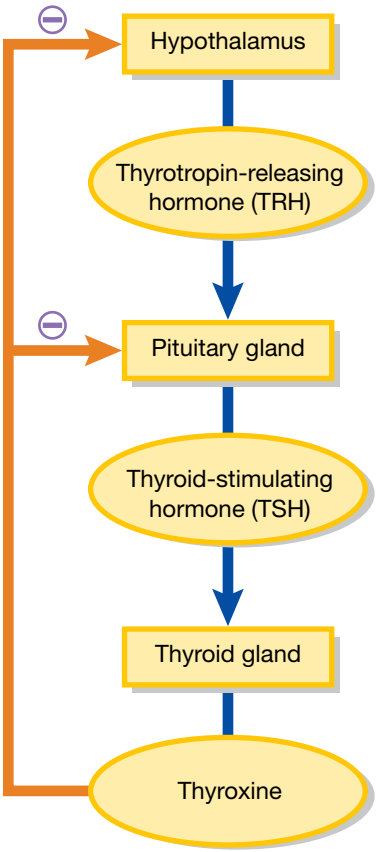

FIGURE 6.31 Negative feedback from the thyroxine hormone produced by the thyroid gland stops the release of thyroid-stimuating hormone by the pituitary gland. In hypothyroidism, the levels of thyroxine are not sufficient to provide this negative feedback, so the release of TSH continues. The result is an enlargement of the thyroid.

The enlargement of the thyroid gland in goitre is an attempt to respond to the signal to produce more thyroxine that comes from the thyroid-stimulating hormone (TSH) released by the pituitary gland. Normally, when thyroxine is produced in adequate amounts, this acts as a negative feedback mechanism on the pituitary gland and stops the production of TSH (see figure 6.31). However, in untreated hypothyroidism, this negative feedback cannot occur and so the pituitary gland continues to release TSH.

Since October 2009, Australian bread manufacturers have been required to use iodised salt in place of non-iodised salt, making bread iodine-fortified. This regulation was made by Food Standards Australia New Zealand (FSANZ) in response to the finding that large numbers of adults and children do not have the recommended intake of iodine. Iodised salt can also be used in the manufacturing of other foods and, when this occurs, it is noted in the ingredient list of the food label.

If thyroid deficiency is present during fetal development and from birth, this condition is termed **congenital hypothyroidism**. If untreated, the affected child shows severe defects in both mental development and physical growth. This condition may arise as a result of hypothyroidism in the mother. Successful treatment of congenital hypothyroisdism depends on early diagnosis and treatment with thyroxine.

KEY IDEAS

- Homeostasis is the maintenance within a narrow range of conditions in the internal environment.
- Body temperature is a highly regulated variable in mammals.
- When the core body temperature rises above normal, homeostatic mechanisms operate to increase heat loss and decrease heat gain.
- When the core body temperature drops below normal, homeostatic mechanisms operate to increase heat gain and decrease heat loss.
- Homeostatic mechanisms can be overwhelmed in extremely hot and extremely cold conditions.
- The thyroid hormone thyroxine plays a role in homeostatic regulation through its action on metabolic rate.

QUICK CHECK

3 Identify whether each of the following statements is true or false.
- **a** Core body temperature is a highly regulated variable in all animals.
- **b** The main source of body heat in reptiles is external, while that of mammals is internal.
- **c** Warming mechanisms that come into action when the core body temperature falls include shivering and an increase in metabolic rate.
- **d** A major cooling mechanism for the human body is evaporative cooling.
- **e** In heat stroke, sweating stops.

4 Give an example of one symptom associated with each of the following conditions and briefly explain why this symptom appears.
- **a** Hyperthermia
- **b** Hypothyroidism

Regulating body fluids

Water is the most common compound present in all living organisms, including the human body. This water is present mainly as the intracellular fluid of the cytosol. The remaining water is found in the interstitial fluid that bathes cells, and in the plasma of the blood. These fluids are not pure water but contain many solutes, that is, compounds in solution.

In the human body, the metabolic reactions essential for living occur in the aqueous medium of cells. In addition, water is essential for many functions:

- The absorption of nutrients from the alimentary canal depends on their being water-soluble.
- The watery plasma of the bloodstream transports digested nutrients to cells and also circulates the red blood cells that carry oxygen to cells.
- Wastes are excreted from the body via the kidney in solution in aqueous urine.
- Sweating helps cool the body during periods of exercise and in hot environments.
- Water acts as a cushioning fluid around the brain (cerebrospinal fluid) and in joints (synovial fluid).
- Water acts as a lubricant for the mucous membranes that line the airways and the passages of the alimentary canal.

In chapter 4, the sources of water gain and water loss were identified:

- Water is gained externally from the fluids we drink and the fluid content of foods we ingest. A second source of water is gained internally from metabolic water.
- Water is lost from the lungs, skin (via pores and from sweat), gut (from faeces) and mainly from the kidneys, with the average daily loss being about 2.5 litres.

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ODD FACT

A psychiatric disorder that causes people to drink excessive amounts of water is called psychogenic polydipsia. This disorder can lead to low sodium levels in the blood.

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Unit 1 AOS 2 Topic 1 Concept 9

Water balance
Concept summary and practice questions

Because the human body does not store water, any water loss must be compensated by water gain to ensure balance. Normally, a balance exists between water intake and water loss, which may be shown as follows:

water intake + metabolic water – water loss = 0

For a healthy person, this translates as the formula shown in figure 6.32.

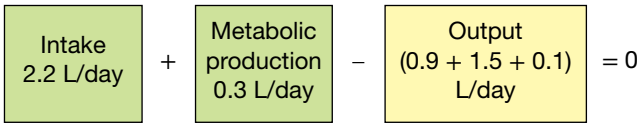

FIGURE 6.32 Water gain/loss balance in a healthy person

The water content of the human body can become unbalanced. The level of water may become too low because of an excessive loss of water (such as may occur due to excessive sweating in hot conditions), because of having an inadequate intake of fluids, or because of an abnormal loss of body fluids (such as may occur with the uncontrolled diarrhoea that accompanies cholera). Likewise, the water levels in the body can become too high because of impaired kidney function that produces insufficient urine or because of drinking excessive amounts of water.

Water balance is closely associated with the concentration of mineral salts (electrolytes), such as sodium and potassium in the blood. When water levels in the body are unbalanced, electrolyte levels are also unbalanced.

This is because the body water is not just water, but is a complex solution of dissolved solutes. When the level of body water falls, the concentration of these solutes increases. When the water level in the body is high, the concentration of these dissolved solutes becomes lower (see figure 6.33).

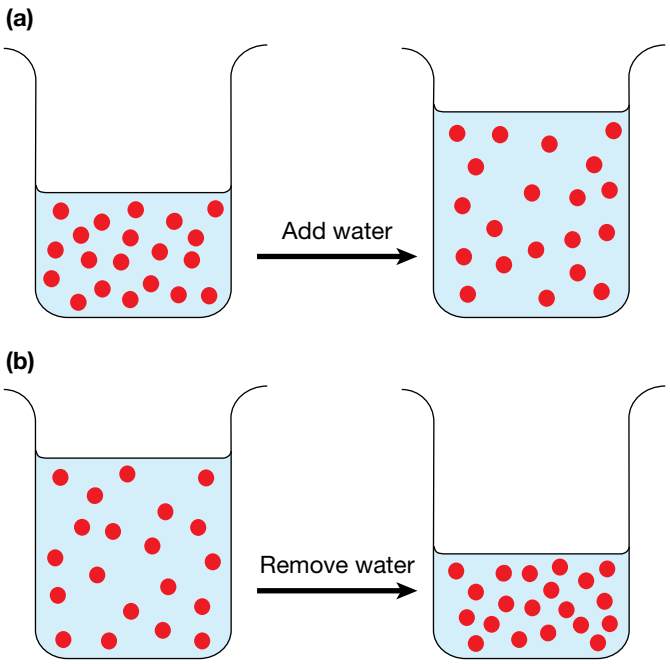

FIGURE 6.33 **(a)** When water is added to a solution, it dilutes the solution, making it less concentrated. **(b)** When the water content in a solution is lowered, this makes the solution more concentrated.

The concentration of fluids in the human body is regulated, that is, kept within a narrow range, by homeostatic mechanisms. The regulation of body fluids is called **osmoregulation**. Osmoregulation is the process of controlling the water content of the human body and its solute concentration.

An important function of osmoregulation is to ensure that the water content of the body is in balance, so that the body fluids do not become too concentrated or too diluted. If, for example, the interstitial fluid that bathes cells becomes too diluted, this will cause water loss from the cells because water will move by osmosis from inside the cells to the interstitial fluid.

Let's now look at one component of osmoregulation, that is, the regulation of water levels in the human body.

Water levels: too low

When water levels in the body fall below the normal level, the concentration of dissolved compounds

(solutes) in body fluids rises. In order to restore the balance, homeostatic mechanisms are activated.

Figure 6.34 shows an outline of events that occur when the water levels in the body are too low. This causes the concentration of dissolved solutes in body fluids, including the blood, to rise. The drop in water level and rise in solute concentration in the blood is the stimulus that is detected by osmoregulator cells in the hypothalamus as blood circulates through the brain. These cells monitor the osmolarity, or concentration of solutes, in the blood plasma against a set point. In this case, the water levels are low, so the concentration of dissolved solutes is too high and is above the set point.

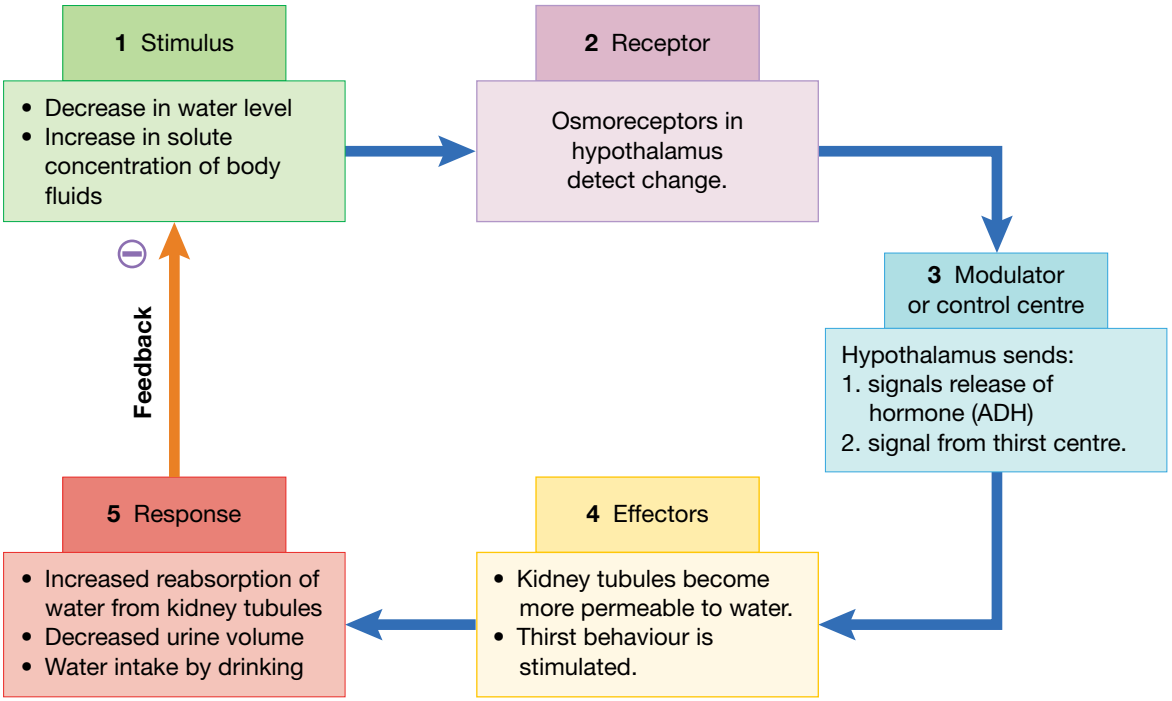

FIGURE 6.34 Diagram showing a stimulus-response model for a drop in body water levels that causes the concentration of dissolved solutes in the body fluid to increase. The change stimulates responses that act to restore the water level to within its narrow range, and so restore the normal concentration of body fluids.

The hypothalamus identifies the corrective actions required and sends signals to effectors that take action as follows:

1. The hypothalamus sends a signal to the pituitary gland to release **antidiuretic hormone** (ADH).

   The antidiuretic hormone travels though the bloodstream to the kidney where it acts on cells lining the collecting ducts of the kidney and makes them more permeable to water. This means that the reabsorption of water back into the blood is increased. As a result, the volume of urine produced falls. When a person is extremely dehydrated, the urine produced by that person is low in volume and dark yellow in colour.
2. The thirst centre of the hypothalamus sends a signal that stimulates the sensation of thirst, which motivates a person to drink fluids. The urge to drink becomes stronger as the body's need for water increases.

Under normal conditions, these responses counteract the drop in water level and restore the normal balance of water level (and concentration of dissolved solutes in the body fluids).

Water levels: too high

When water levels in the body increase above normal, the concentration of dissolved compounds (solutes) in body fluids drops. In order to restore the balance, homeostatic mechanisms are activated.

Figure 6.35 shows an outline of events that occur when the water levels in the body are too high. Water levels that are too high dilute the body fluids, causing the concentration of dissolved solutes in body fluids to drop. The rise in water level and the drop in solute concentration becomes the stimulus that will initiate homeostatic mechanisms to correct this situation and restore the normal balance.

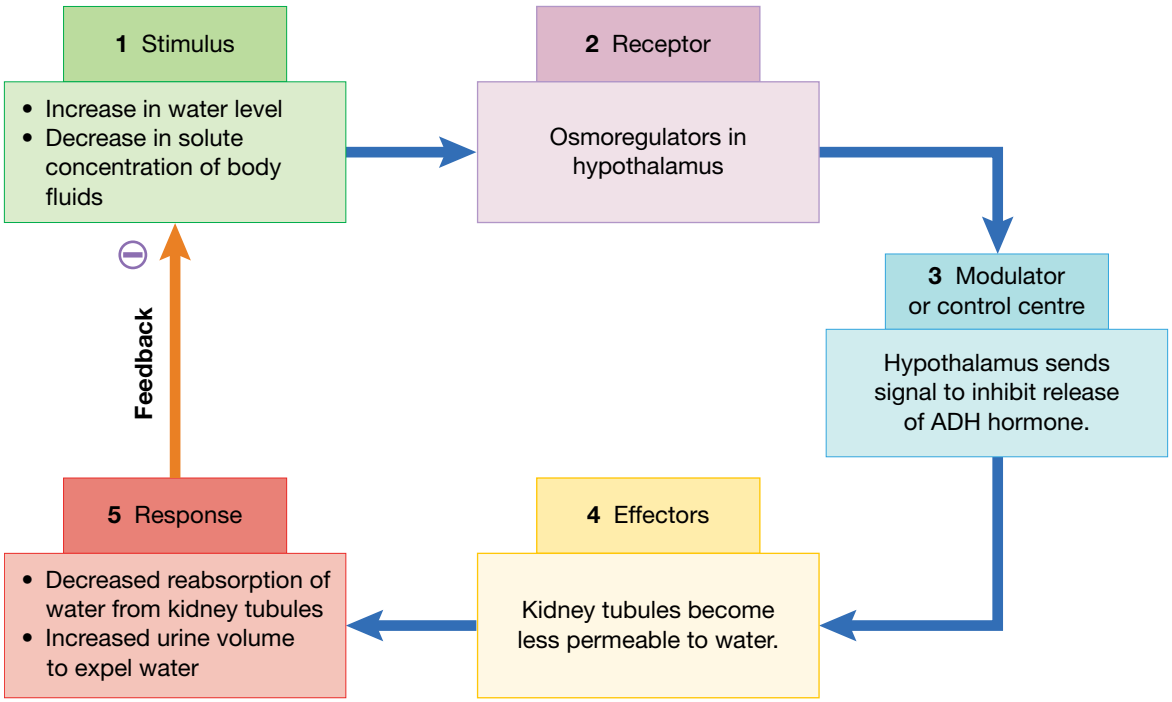

FIGURE 6.35 Diagram showing a stimulus-response model for an increase in body water levels that dilutes the body fluids and causes the concentration of dissolved solutes in the body fluid to fall. The change stimulates responses that act to restore the water level to within its narrow range and so restore the normal concentration of body fluids.

This stimulus is detected by osmoregulator cells in the hypothalamus as blood circulates through the brain.

The hypothalamus identifies that corrective actions are required, namely that water levels in the body must increase, and signals this to effectors. A signal from the hypothalamus to the pituitary gland results in the inhibition of the release of ADH. When ADH is not present, the collecting ducts of the kidneys become impermeable to water so that water reabsorption from the kidneys back into the blood is reduced, and greater volumes of urine are produced. In addition, the sensation of thirst from the thirst centre in the hypothalamus is suppressed. (Although people may still drink fluids in this case, it is not due to feeling thirsty, but rather because of habit or social practices such as having an afternoon coffee with friends.)

These responses counteract the increase in water level in the body and restore both the water levels and the concentration of dissolved solutes in the body fluids back to within narrow limits.

KEY IDEAS

- Water levels and solute concentrations of body fluids in the human body are under homeostatic regulation.
- When water levels fall, the solute concentrations of body fluids increase.
- The kidney is a key organ in maintaining water levels within the body at appropriate settings.

QUICK CHECK

5 Identify a homeostatic mechanism that will result in:
   a preventing water loss from the body
   b decreasing the concentration of solutes in body fluids
   c increasing water gain by the body.
6 Where does the thirst stimulus originate?
7 What is the site of action of antidiuretic hormone (ADH)?

Regulating blood glucose levels

FIGURE 6.36 A digital glucometer can be used to measure the blood glucose level using a tiny drop of blood from a finger prick.

Glucose is the fuel that provides energy for the functioning of cells. Through the process of cellular respiration, glucose is broken down to carbon dioxide and water and its chemical energy is transferred to ATP (refer to chapter 3, page 91). Glucose is obtained in the food that we eat and it is distributed to cells in solution in the plasma of the blood. The level of glucose in the blood is highly regulated, with homeostatic mechanisms keeping blood glucose levels within narrow limits.

The blood glucose level in a healthy person who is fasting is typically between 3.9 and 5.5 millimoles per litre (mmol/L). Regardless of what a person eats, blood glucose levels are normally back under 5.5 mmol/L within about two hours of eating a meal. Blood glucose levels can be monitored using a digital mini-glucometer (see figure 6.36).

Two hormones are important in the homeostatic regulation of blood glucose levels: **insulin** and **glucagon**. Both hormones are produced in the **pancreas** by special cells called the islets of Langerhans. Insulin is produced by the beta cells and glucagon is produced by the alpha cells in these islets.

Figure 6.37a shows a section through pancreatic tissue that includes an islet of Langerhans. Examine figure 6.37b, which shows details of one islet of Langerhans. The islet is surrounded by a ring of red-stained cells that produce the pancreatic digestive enzymes. Within the islet can be seen many beta cells (yellow with a red nucleus) that secrete insulin, and a small number of alpha cells (red with a red nucleus) that secrete glucagon.

Insulin facilitates the transport of glucose into some body cells, especially fat cells, muscle cells and red blood cells. Glucagon has an opposite effect by acting on liver cells, causing them to mobilise their glycogen store and release glucose. Glucagon also stimulates the production of glucose by the liver cells, using building blocks obtained from other nutrients found in the body, for example, protein.

Blood glucose levels: too low

If the blood glucose level falls below normal, this stimulus is detected by the pancreas and the following responses occur:

1. The alpha cells of the pancreas (see figure 6.38) increase their production of the hormone glucagon. Glucagon acts on liver cells, stimulating the conversion of the storage polysaccharide, glycogen, to glucose that is released into the bloodstream. Glucagon also stimulates the synthesis of new glucose from other compounds in cells, such as amino acids.
2. The beta cells of the pancreas decrease their production of insulin so that the uptake of glucose from the blood into body cells is reduced.

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Unit 1 AOS 2 Topic 1 Concept 8

Blood glucose regulation
Concept summary and practice questions

ODD FACT

The structure of insulin was identified by Dorothy Crowfoot Hodgkin (1910–94) who was awarded the Nobel Prize in Chemistry in 1964.

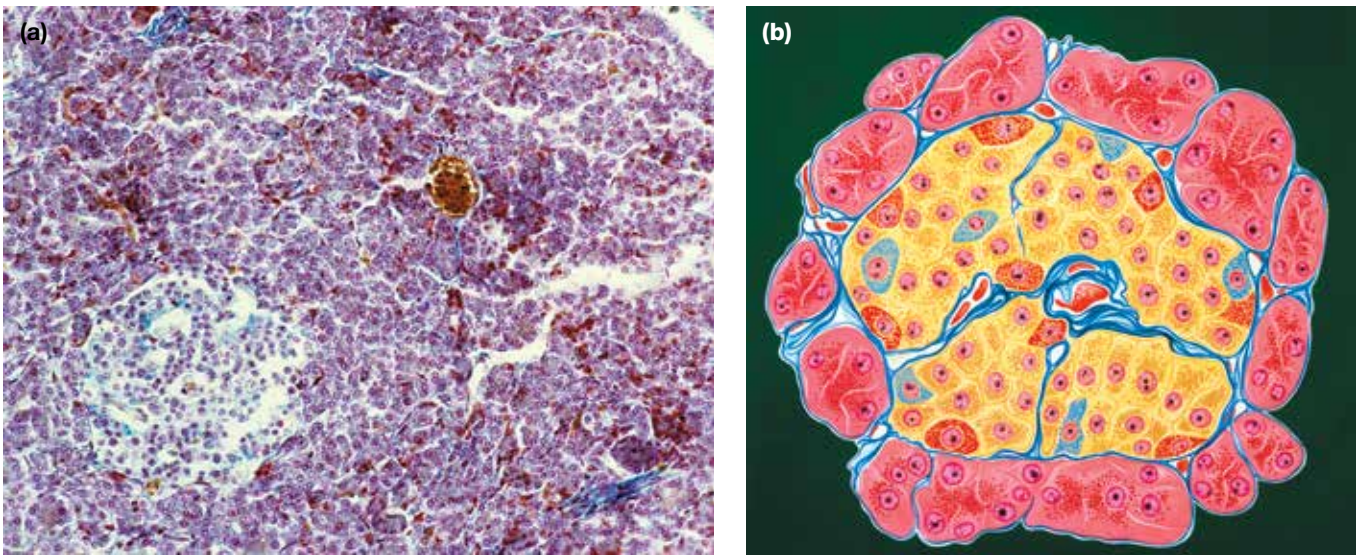


FIGURE 6.37 (a) Section through pancreas tissue showing one islet of Langerhans (the pale circle, lower left). The islets are clumps of secretory cells that form part of the hormone system. The islets also contain nerve cells that influence insulin and glucagon secretion. **(b)** Groups of cells in the islet of Langerhans (yellow) surrounded by acini cells (pink). Note the large numbers of beta cells (yellow), which secrete insulin, alpha cells (red), which secrete glucagon, and delta cells (blue), which secrete somatostatin and gastrin. The circle of acini cells (pink) produces the pancreatic digestive enzymes.

The combined effect of these two responses is an increase in the blood glucose level. The increase in glucose levels acts as a negative feedback mechanism counteracting the initial stimulus and stopping the response of the alpha cells.

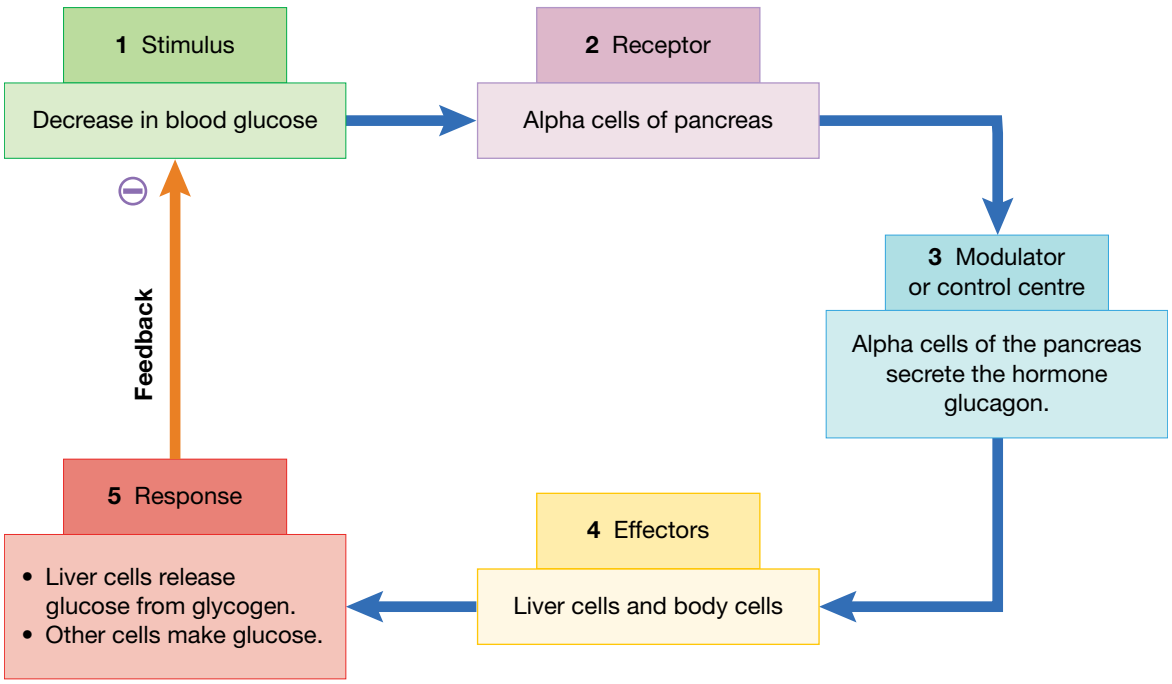


FIGURE 6.38 Diagram showing a stimulus-response model for a decrease in blood glucose levels. The decrease stimulates responses that act to increase the glucose level to within its narrow range.

ODD FACT

If the blood glucose level falls to 2.2 mmol/L or lower, unconsciousness and brain damage can occur.

Blood glucose levels: too high

If glucose levels in the blood increase above the normal range, glucose must be shifted from the blood into the liver and muscle where it is stored as the polysaccharide, glycogen.

When blood glucose levels rise above normal limits, the beta cells of the pancreas detect this increase and initiate a response in which insulin production is increased and glucagon production is decreased (see figure 6.39). The increase in the circulating hormone, insulin, acts on body cells, facilitating their uptake of glucose from the blood into body cells, especially muscle and fat cells.

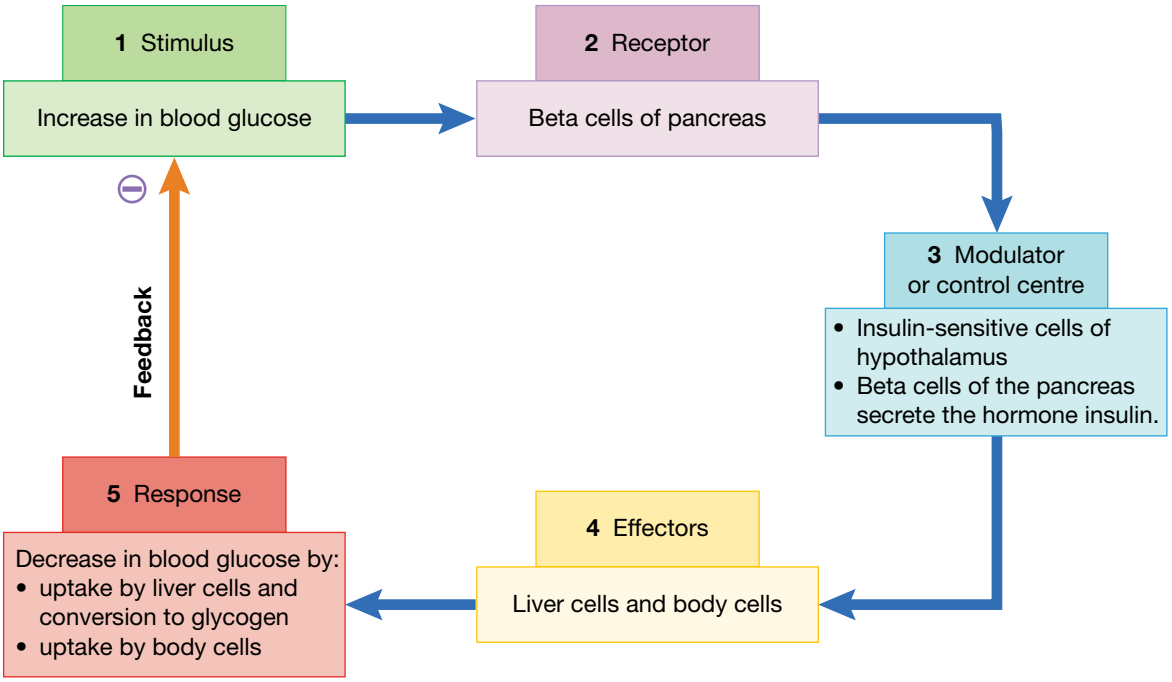


FIGURE 6.39 Diagram showing a stimulus-response model for an increase in blood glucose levels. The increase stimulates responses that act to restore the glucose level to within its narrow range.

Insulin molecules bind to receptors on the plasma membrane of cells. The binding produces a signal that causes glucose transport proteins enclosed in vesicles within the cytosol to move to the plasma membrane. Once there, the transport proteins form trans-membrane carriers that enable glucose to move into cells by facilitated diffusion.

The control centre involved when blood glucose levels increase is generally thought to be the beta cells of the pancreas. However, more recent evidence indicates that the hypothalamus may also play a coordinating role. Researchers have found evidence for glucose-sensing cells within the hypothalamus that regulate insulin secretion to maintain glucose homeostasis. (*Source:* O Chan and RS Sherwin, 'Hypothalamic regulation of glucose-stimulated insulin secretion', *Diabetes* vol. 61, p. 564, 2012.)

In reality, the homeostatic mechanisms that increase and decrease blood glucose levels are acting all the time, making the necessary adjustments to these levels as they rise and fall (see figure 6.40). As a result of negative feedback mechanisms involving both insulin and glucagon, a steady state is achieved, with small fluctuations, in blood glucose levels.

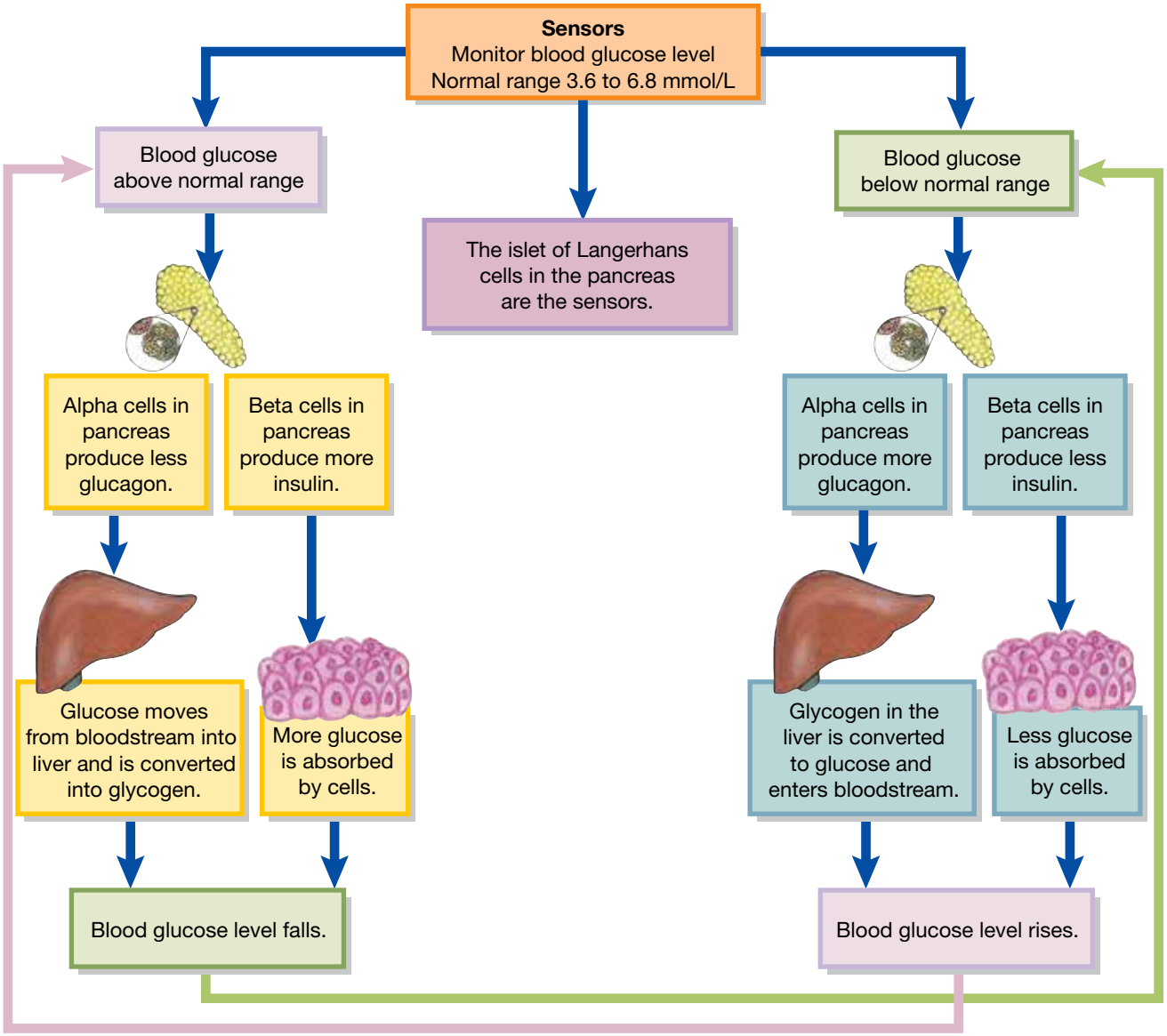


FIGURE 6.40 Summary of events that maintain a steady state in the level of blood glucose in a non-diabetic person. This system involves negative feedback from the actions of both insulin and glucagon.

Diabetes

In the previous section, we saw that the blood glucose level is normally regulated by homeostatic mechanisms that maintain glucose levels within a narrow range. The beta cells of the pancreas are responsible for the production of the hormone insulin. This hormone plays a key role in stopping blood glucose from increasing above the normal level by facilitating the uptake of glucose by body cells.

Glucose levels out of control

The homeostatic mechanisms that regulate blood glucose levels can fail when insulin production fails. This results in a condition known as **type 1 diabetes**, which is characterised by a blood glucose level that is higher than normal. Why? Glucose is the main source of energy for body cells, but glucose is too large to diffuse across the plasma membrane and must be actively transported

into cells. Insulin facilitates this transportation. Because insulin production is defective in type 1 diabetes, the body cells of a person affected by this condition cannot take up glucose from the bloodstream. As a result, the glucose levels in the blood rise above normal, a condition termed **hyperglycaemia** (*hyper* = above; *glykys* = sweet; *haima* = blood).

Glucose is also present in the urine of an affected person. Normally, any glucose that enters the kidney tubules from the bloodstream is reabsorbed back into the blood through a process of active transport. However, the carrier proteins involved in returning glucose from the fluid in the kidney tubules back into the bloodstream are not able to deal with the high level of glucose filtered from the blood of a person with diabetes.

Type 1 diabetes is a chronic disorder in which the beta cells of the pancreas produce little or no insulin.

This condition most commonly appears in childhood, but may also appear later in life. The cause of this condition is not certain, but one view is that type 1 diabetes is an autoimmune disorder in which the immune system specifically turns against the body's own beta cells in the pancreas, attacking them as if they were foreign cells.

Risk factors for type 1 diabetes include a family history of the disorder and the presence of certain genes in a person's genetic make-up.

The homeostatic mechanisms that regulate blood glucose levels can also fail when insulin is produced but the body cells of a person do not respond to it. In this case, insulin is present, but the cells are said to be **insulin resistant**. This is known as **type 2 diabetes**. Since the insulin cannot carry out its normal function, the glucose levels of a person with type 2 diabetes build up in the blood.

Risk factors for type 2 diabetes include being overweight, especially with excess weight around the waist, and a lifestyle characterised by low levels of physical activity and a diet heavy in fat and low in fibre. In addition, a family history of diabetes increases the risk of developing type 2 diabetes.

ODD FACT

In ancient times, the Chinese recognised people as having diabetes by the fact that their urine attracted ants.

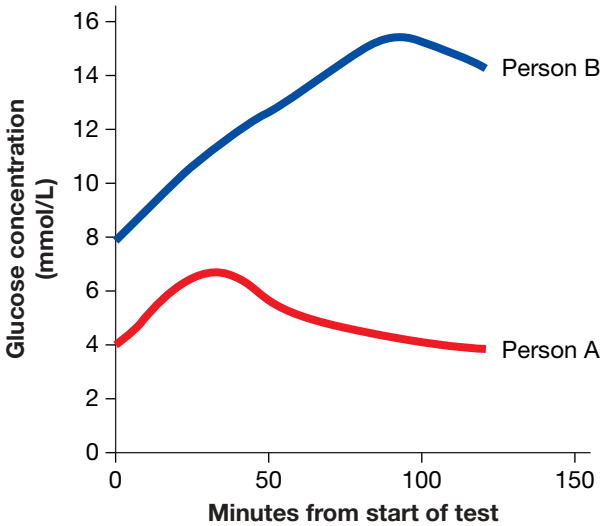


FIGURE 6.41 Blood glucose levels after ingestion of a standard quantity of glucose, administered in solution. Person A is not affected by diabetes, while person B has diabetes. Note that the blood glucose levels of person A are back within the normal range by about one hour after ingesting glucose. In contrast, the glucose level in person B is still very high two hours after ingesting glucose.

Diabetes is typically recognised by a distinctive set of symptoms (see below) and is confirmed by blood tests:

- One test is the fasting plasma glucose test. This test is done after a person has fasted overnight. The blood glucose levels in a healthy person typically fall in the range of 3.9–5.5 mmol/L. If this value exceeds 7.0 mmol/L, a diagnosis of diabetes is identified.
- Another test that can identify diabetes is the oral glucose tolerance test (OGTT). In this test, a subject who has not eaten for 12 hours is given a standard dose of 75 mg of glucose in solution. Blood samples are taken from the person immediately before drinking the glucose solution, and then at 30-minute intervals up to 120 minutes.

Figure 6.41 shows the OGTT results for two people. Person A is healthy and unaffected by diabetes; person B has diabetes. Note that person B, with diabetes, shows a rapid rise in blood glucose after drinking the glucose solution and that this level remains high even after 120 minutes. This result signals that person B is *either* not producing insulin and has type1 diabetes *or* is resistant to the action of insulin and has type 2 diabetes. In contrast, the blood glucose level of person A, who is unaffected by diabetes, at first rises in response to the ingested glucose, but then rapidly returns to the normal range in response to the homeostatic mechanisms that regulate blood glucose levels.

Symptoms of diabetes

Table 6.3 outlines the symptoms that people with diabetes may experience.

TABLE 6.3 Symptoms of diabetes

Symptom	Details
increased thirst frequent urination	These symptoms arise in response to the higher than normal levels of glucose in their blood. The body increases its output of urine in an attempt to remove the excess glucose from the blood. The large volume of urine excreted means that the loss of water from the body via this route is excessive and this, in turn, stimulates thirst.
low energy levels fatigue extreme hunger possible weight loss	These symptoms arise in diabetes sufferers because the body cells are starved of glucose and hence, are starved of energy. Without an adequate supply of glucose in body cells, they cannot generate sufficient ATP through cellular respiration to meet their needs. In addition, the loss of glucose from the body in urine represents a loss of calories that can lead to weight loss.
blurred vision	Untreated elevated glucose blood levels can, over time, cause damage to the capillaries in various organs and tissues, including the eyes, kidneys and nerves. For example, blurred vision is a consequence of damage to capillaries in the retina of the eye.
diabetic ketoacidosis	This symptom arises in type 1 diabetes because the body cells cannot use their normal fuel, glucose, for energy production. Instead, the body cells metabolise fat for energy production. The breakdown products of fat metabolism include acids called **ketones**. If ketones reach high concentrations in the blood, as may happen with persons whose diabetes is not under control, the blood becomes more acidic, producing a serious condition known as ketoacidosis. One of the symptoms of diabetic ketoacidosis is a strong fruity smell to the breath.

Treatment of diabetes

People with diabetes that is the result of a deficiency of insulin due to damaged beta cells of the pancreas are treated with insulin replacement. This typically occurs by injection or through an insulin pump (see figure 6.42). However, the amount of insulin injected must be carefully controlled. If a person inadvertently injects too much insulin, a dangerous condition of too little glucose in the blood occurs, termed **hypoglycaemia** (*hypo* = under or below; *glykys* = sweet; *haima* = blood) can occur. Hypoglycaemia may lead to fainting or even coma. It is treated by giving the affected person a source of glucose, such as glucose tablets, honey or a sweet.

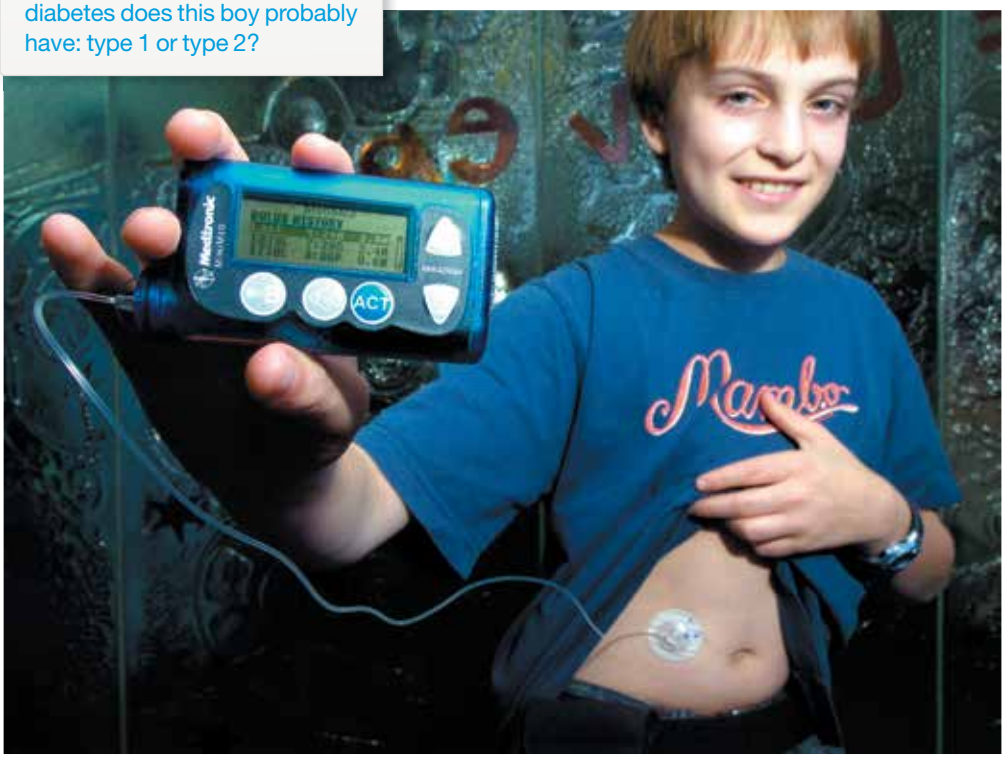


FIGURE 6.42 A portable insulin pump being used by a young boy with diabetes injects insulin slowly and continuously into the bloodstream. Which type of diabetes does this boy probably have: type 1 or type 2?

In contrast, treatment for persons with type 2 diabetes typically involves lifestyle changes, such as changes to diet that put a focus on healthy eating (high fibre and low fat) and on regular exercise. Many people can control type 2 diabetes through these lifestyle changes but in some cases diabetic medicine may be needed.

KEY IDEAS

- Blood glucose levels are normally highly regulated.
- Insulin and glucagon are two hormones involved in the homeostatic regulation of blood glucose levels.
- In diabetes, blood glucose levels are above the normal range.
- Diabetes can result from either a deficiency in insulin production or from a condition of insulin resistance.

QUICK CHECK

8 Identfy whether each of the following statements is true or false.
- **a** Insulin acts to increase blood glucose levels.
- **b** The hormone glucagon causes the breakdown of glycogen to its glucose subunits.
- **c** Treatment of type 1 diabetes uses hormone replacement.
- **d** Blood glucose levels are under homeostatic regulation.

9 What is the difference between hyperglycaemia and hypoglycaemia?

10 Why might persons with diabetes keep a sweet in their pocket?

BIOCHALLENGE

Normally, a person's core body temperature is tightly regulated to keep it within a narrow range. However, general anaesthetics can disrupt the normal thermoregulation so that homeostatic mechanisms cannot maintain the body temperature within the normal limits. For this reason, the core temperature of a person under general anaesthetic in an operating theatre is closely monitored (see figure 6.43).

FIGURE 6.43 After receiving a general anaesthetic, this patient will be closely monitored in terms of core body temperature, blood pressure, heart rate and breathing rate.

Two different types of disruption to thermoregulation are possible, as follows:

- In very rare cases, certain general anaesthetics cause a rise in body temperature, a life-threatening condition known as malignant hyperthermia. This is a rare inherited condition that is due to the **RYR1** gene.
- In most people, a general anaesthetic causes a drop in the core body temperature, a situation termed anaesthesia-induced hypothermia, but this is not a life-threatening condition.

1 In a person with inherited malignant hyperthermia, exposure to certain general anaesthetics produces a rapid rise in core body temperature to 40 °C or higher. When this condition occurs, the following symptoms appear:

- elevated heart rate
- increased rate of breathing
- greatly increased metabolic rate
- muscle rigidity (cramping)
- muscle tissue breakdown
- increased lactic acid content.

a Considering these symptoms, what is the probable source of the excess heat produced? Briefly explain.

b If an episode of malignant hyperthermia occurs after a general anaesthetic has been given to a patient, a specific drug is administered. Suggest another possible measure that might be used to reduce the person's high temperature.

c It is very difficult to identify the true incidence of persons with malignant hyperthermia in a population. Suggest a likely reason for this.

2 Consider a patient who shows anaesthesia-induced hypothermia after receiving a general anaesthetic.

a Identify four symptoms that would be expected to appear in a person showing a fall in core body temperature.

b From the following list, identify which process (if any) might be an underlying cause of the net loss of heat in a person with anaesthesia-induced hypothermia:

i opening of shunt vessels with a redistribution of blood from core to peripheral blood vessels
ii increased sweating from exposed areas of the body
iii shivering
iv decreased evaporation of fluid from the lungs and moist surfaces of the mouth and throat.

Briefly explain your choice.

3 Bony fish (all fish, excluding sharks and rays) use homeostatic mechanisms to maintain their water balance. Water balance also involves maintaining a balance of the salts in body fluids. Fish that live in fresh water and fish that live in sea water face different challenges in achieving a water balance.

Here are some facts:

- The scale-covered skin of most fish is relatively impermeable to water and salts.
- However, both freshwater and seawater (marine) fish must have permeable surfaces across which oxygen can be taken into the body and carbon dioxide can be excreted from the body – these permeable surfaces are their gill surfaces.
- The gill surfaces of both kinds of fish allow not only the passage of oxygen and carbon dioxide, but also the movement of water and salts.
- The body fluids of freshwater fish have a higher solute concentration than fresh water and so are hypertonic to the water in which freshwater fish live.
- In freshwater fish, water tends to move into the body across the gill surfaces and salts tend to be lost from the body via the same surfaces.
- The body fluids of marine fish have a lower solute concentration than sea water and so are hypotonic to the water in which marine fish live.
- In marine fish, water tends to be lost from the body across the gill surfaces and salts tend to be gained by the body via the same surfaces.

Complete table 6.4 by placing the following entries into the correct cells. Your final result should show some of the homeostatic mechanisms involved in maintaining water and salt balance in these fish.

- Does not drink.
- Produces large volumes of urine.
- Drinks large amounts of water.
- Takes in salts across gills.
- Produces very small volumes of urine.
- Secrete salts out across gills.

TABLE 6.4

Variable	Freshwater fish	Saltwater fish
volume of urine produced		
volume of water drunk		
salt movement across gills		

Chapter review

Key words

acute hypothermia
antidiuretic hormone
basal metabolic rate
behavioural activities
brown fat
conduction
congenital hypothyroidism
convection
core body temperature
dehydration
ectothermic
endocrine system
endothermic
evaporation
evaporative cooling
exhaustion hypothermia
glucagon
goitre
heat conservation
heat exhaustion
heat generation
heat loss
heat stroke
homeostasis
homeostatic mechanism
hyperglycaemia
hyperthermia
hyperthyroidism
hypoglycaemia
hypothalamus
hypothermia
hypothyroidism
insulin
insulin resistant
ketones
negative feedback
osmoregulation
oxytocin
pancreas
panting
peripheral surface temperature
piloerection
pituitary gland
positive feedback
radiation
saliva spreading
shivering
shunt vessel
stimulus-response model
thermograph
thermoregulation
thyroid gland
thyroxine
type 1 diabetes
type 2 diabetes
vasoconstriction
vasodilation

Questions

1 **Making connections** ➜ Use at least eight of the key words in this chapter and draw a concept map. You may use other words in drawing your map.

2 **Applying your understanding in a new context** ➜ Some homes have central heating. When the air reaches a certain temperature, a thermostat turns the heat off. When the temperature drops below a certain level, a thermostat turns the heater on. Explain whether you think this is similar to, or different from, the control of internal body temperature.

3 **Applying your understanding** ➜ Suggest an explanation for each of the following observations.
- **a** The smallest penguins, the fairy penguin (*Eudyptula minor*), are found in temperate climates in southern Australian states. The largest penguins, the emperor penguin (*Aptenodytes forsteri*), live in Antarctica.
- **b** Cougars or mountain lions (*Puma concolor*) in the northern regions of North America are, on average, larger than those in the southern regions.

  Of what advantage might this size difference be?

4 **Communicating understanding** ➜ Give an explanation in biological terms for the following observations.
- **a** High temperatures in a humid climate are more uncomfortable than the same temperatures in a dry climate.
- **b** More heat is lost from the human body when the air surrounding the body is cool and moving than when the air at the same temperature is still.
- **c** The cooling effect of sweat is less when the surrounding air is humid than when it is dry.
- **d** Immersion in cold water can produce greater and faster heat loss than exposure to the air at the same temperature.
- **e** The skin of a person suffering from heat stroke is pale and dry.
- **f** The Reptile House at a zoo is typically air conditioned and warm.

5 **Applying your knowledge and understanding** ➜ Consider each of the following comments and indicate, giving a brief explanation, whether it is biologically valid.
- **a** 'My dog must be very sick. The surface temperature of its nose is only 21 °C.'
- **b** 'After working out strenuously in the gym, I towel myself down so as to avoid getting a chill.'
- **c** 'I don't need to feed my pet lizard as often as my pet budgerigar.'

6 **Applying your knowledge and understanding** ➜ An athlete entered a triathlon competition on a very hot day (43 °C, 45% humidity). She completed the swim and the bike ride but started experiencing problems during the run. After about 1.6 km, she had diarrhoea and muscle cramps, and by the 10 km mark she had headaches and had stopped sweating. The athlete managed to finish the race but became delirious and was admitted to hospital. In hospital, the athlete deteriorated further with

several serious symptoms, including seizures, and muscle breakdown. She was placed on artificial life support and, fortunately, survived.

a Identify the condition that developed in this athlete that resulted in her admission to hospital.

b Consider the various problems/symptoms experienced by the athlete during and after the race. Choose two of these and suggest an explanation for their occurrence.

7 **Applying your understanding** ➜ Refer to figure 6.17, the thermograph of Lettie, the Labrador dog.

a Explain why Lettie's nose pad is the coolest area of her body.

b Lettie's ears are colder than the adjacent areas of her head. Suggest a possible reason for this difference.

c Suggest what the ambient temperature might have been at the time this thermograph was produced.

8 **Applying your knowledge** ➜ When the walls of a small blood vessel are damaged, platelets in the blood cling to the damaged site and start clot formation. These platelets release chemicals that attract more platelets to the site of the damage, and this process continues until a blood clot is formed.

What type of feedback system is this? Briefly explain your decision.

9 **Applying your understanding in a new context** ➜ A cat sleeps on two different days. Figure 6.44a shows her on day 1, while figure 6.44b shows her on day 2.

Suggest, giving reasons, how the temperature on the two days might have differed.

FIGURE 6.44 Images of a sleeping cat on two different occasions **(a)** day 1 and **(b)** day 2

10 **Applying your understanding in a new context** ➜ A person has fallen into the cold, still water of a lake and will not be rescued immediately. In these circumstances, what might the person do to avoid loss of body heat while waiting for rescue? (The person is not in danger of drowning as he is wearing a life jacket.)

Student A suggested that the person should keep active by continually swimming around.

Student B suggested that the person should stay as still as possible and keep legs close together and arms close to the body.

Carefully consider the two alternatives and decide, giving reasons, which is likely to be the better strategy for minimising heat loss.

11 **Organising and presenting data** ➜ Components of the total heat loss by a patient in an operating theatre have been estimated as follows:

- radiation (about 60%)
- conduction and convection combined (about 15%)
- evaporation (about 22%)
- other (about 3%).

Show these data in a pie chart or bar graph.

12 **Communicating understanding** ➜ The body fluid of some animals, such as octopus and squid, and sharks and rays has the same osmotic pressure as the sea water (see figure 6.45). Identify a possible advantage of this situation in terms of water balance.

FIGURE 6.45 This image shows a ray. The body fluid of rays and their close relatives, sharks, has an osmotic concentration that is equal to the sea water in which they live.

13 **Applying your knowledge and understanding** ➜ Dehydrating or drying is a long-established means of preserving food. Explain briefly why dehydration is a highly effective food preservative.

14 **Communicating understanding** ➜ Briefly explain the difference between the members of the following pairs.

a Ectotherm and endotherm

b Vasoconstriction and vasodilation

c Thermoregulation and osmoregulation

d Core temperature and peripheral temperature

15 Analysing and interpreting information ➜ An experiment was carried out on mice to determine whether the pituitary gland controlled growth. Ninety mice were divided into three equal groups. Treatments and results are shown in the following table.

Treatment	Group A Pituitary gland removed	Group B Pituitary gland removed and daily injections of pituitary gland hormone given	Group C No treatment
average mass at start	218 g	221 g	214 g
average mass after one month	200 g	530 g	527 g

a Explain which you consider to be the control group in this experiment.
b What hypothesis does the data support? Explain your answer.

16 Applying your understanding in a new context ➜ Examine the thermographs in Figure 6.46 of Oscar, the spaniel, taken on different occasions. Explain, in biological terms, the difference between parts (a) and (b). Note that the crossbars identify the temperature at a particular point.

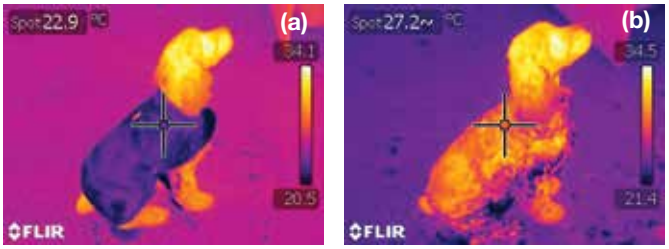


FIGURE 6.46 Thermographs of Oscar, the spaniel

CHAPTER

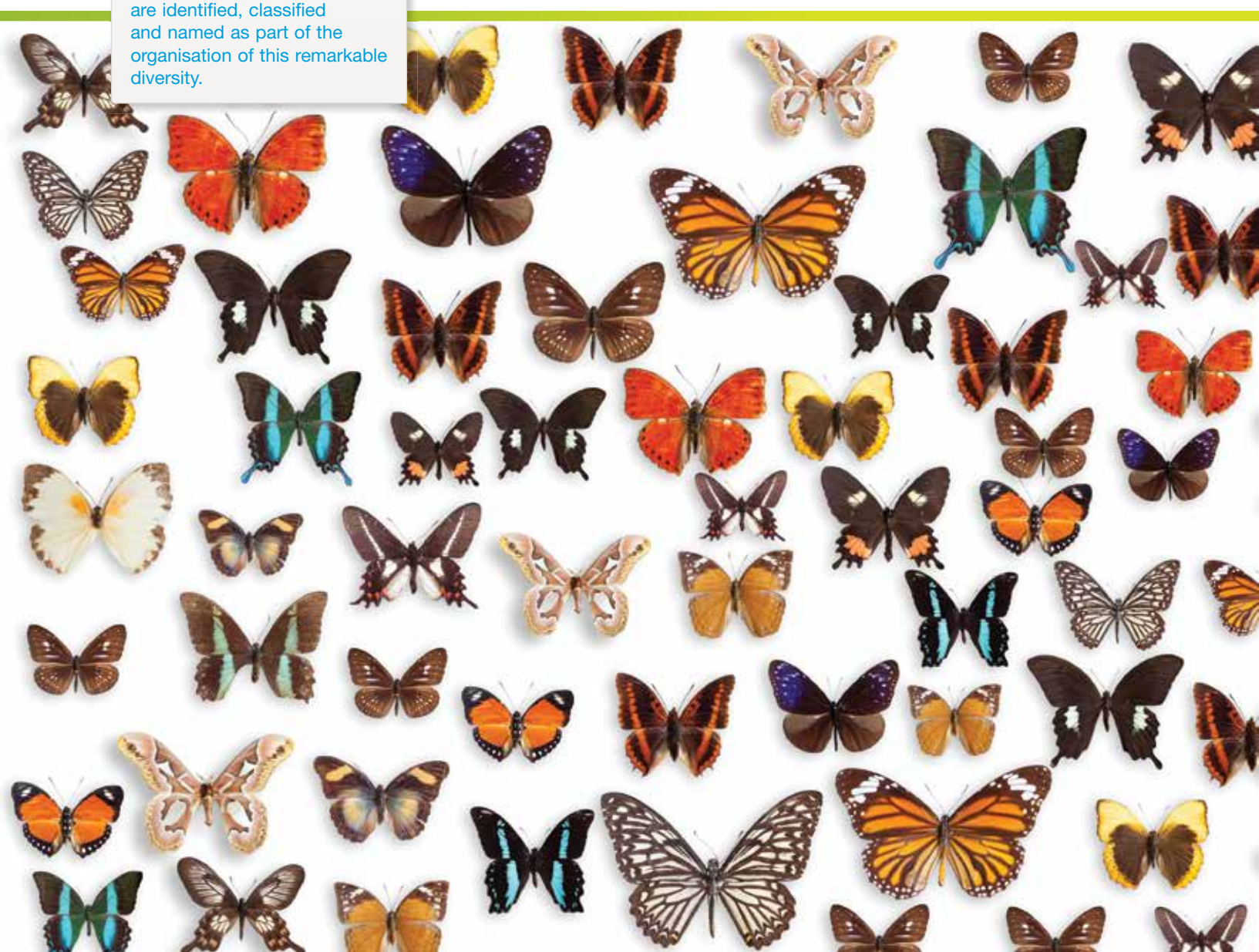
7 Biodiversity and its organisation

FIGURE 7.1 The living world of planet Earth contains millions of different kinds of organisms, microscopic and macroscopic. For example, for butterflies alone, there are about 17 500 different kinds or species. The science of taxonomy is concerned with the organisation of this biodiversity. In this chapter, we will explore how organisms are identified, classified and named as part of the organisation of this remarkable diversity.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- become aware of biodiversity on Earth and the use of computer technology to record it
- recognise the value of identification and scientific naming of organisms
- develop knowledge of the principles of classification and the hierarchy of levels up to phylum
- gain understanding of how classification of all living organisms into kingdoms and then into domains occurred.



What's in the tree tops?

If you could sample the various insects and spiders that live in a particular kind of eucalyptus tree, how many different kinds might you expect to find? Maybe ten? Possibly fifty? Perhaps, even one hundred?

Perth biologists Harry Recher and Jonathan Majer set out to answer that question by collecting and identifying the different kinds of invertebrates, mainly insects and spiders, that live on the leaves of specific kinds of eucalypt. They spent 2 years collecting insects and spiders from four selected kinds of tree — grey box (*Eucalytpus mollucana*) and narrow-leaved ironbark (*E. crebra*) growing at a site in New South Wales, and jarrah (*E. marginata*) and marri (*E. calophylla*) growing at a study site in Western Australia. Figure 7.2 shows how, over a 1-year period, biologists made the collections at each site. Using this procedure, the biologists collected large numbers of insects and spiders, but how many different kinds were there? How diverse are the populations of insects and spiders that live in these different kinds of eucalypt?

FIGURE 7.2 Sampling life in the treetops. After setting up the collecting traps, the biologists sprayed the tree with an insecticide of short-term effect. Would you expect this technique to be used to sample insects that lived under the bark?

We need to distinguish between the concepts of 'number' and 'diversity'. 'Number' refers to the total count of objects regardless of any differences between them. 'Diversity' refers to the number of different kinds of object. So, consider two parking lots: lot A has 100 parking places, occupied by 50 Fords and 50 Holdens; lot B has 50 parking places occupied by 12 Fords, 10 Daihatsus, 10 Mazdas, 8 Holdens, 7 Hondas and 3 Hyundais. In terms of cars, which lot has the greater number of cars? Lot A. The greater diversity of cars? Lot B.

The two biologists classified and identified the insects and spiders they had collected. What they found greatly surprised them. From the upper leafy canopies of just four different kinds of eucalypt growing in two areas, the biologists collected about 1600 different kinds of insect and spider — a remarkable diversity of living things. For the New South Wales trees, about half of the different kinds of insect and spider were found on both the grey box and the narrow-leaved ironbark and half were found on one or the other kind of tree only. A similar pattern was found with the Western Australian trees. All four kinds of tree showed a seasonal variation in the kinds of insect and spider present. Figure 7.3 shows the total number of different kinds of insect and spider found on the upper leaves of two kinds of eucalypt.

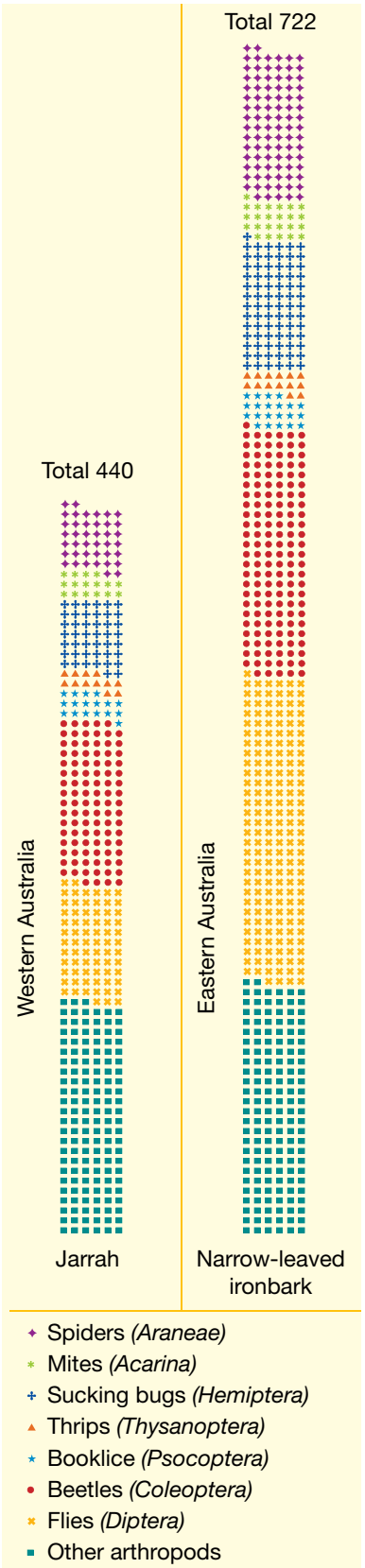


FIGURE 7.3 Different kinds of invertebrate found on two kinds of eucalypt. The invertebrates are organised into eight broad groups: spiders, mites, bugs, thrips, booklice, beetles, flies and others.

This study showed that eucalypt trees support a very diverse population of invertebrates, greater than was previously recognised. This biological diversity is even greater when it is realised that the collecting technique caught only insects and spiders that lived on the upper leafy canopy of the trees. Some invertebrates would not have featured in the sampling, such as those living on and under the bark, on lower branches, in leaves and in the roots. Knowing that their collection was incomplete, the biologists estimated that the east coast eucalypts may be home to a total of at least 1000 different kinds of insect and spider and that the west coast eucalypts supported about 750 different kinds.

From their study of just two kinds of eucalypt, the biologists were able to estimate the number of different kinds of spider and insect that might live on the 700 different kinds of eucalypt in Australia. Their estimate is that eucalypt forests Australia-wide may be home to perhaps 250 000 different kinds of insect and spider. This study highlighted one aspect of the biological diversity of Australia — the invertebrates of Australia's eucalypt forests.

Biodiversity: the variety of life

Biodiversity is the variety of all living organisms on planet Earth — it includes the different animals, plants, fungi, protists and microbes (bacteria and archaea), the genetic information that they contain, and the ecosystems of which they form a part. This biodiversity is essentially linked to the physical settings in which organisms live and with which they interact.

Biodiversity may be identified at three levels: species diversity, genetic diversity and ecosystem diversity (see figure 7.4).

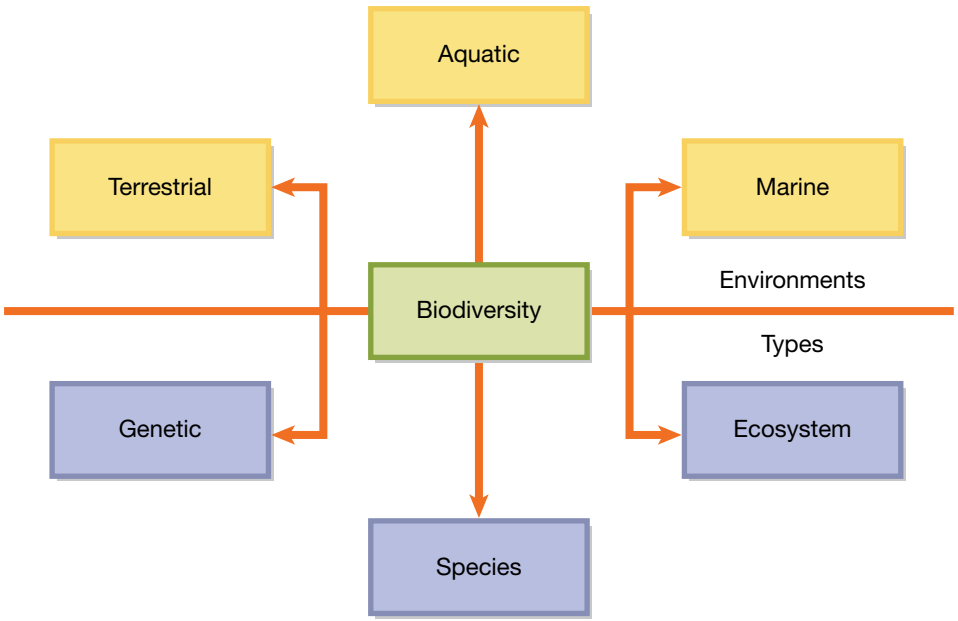


FIGURE 7.4 Diagram showing the elements of biodiversity

1. **Species diversity** refers to the variety of different kinds of organism living in a particular habitat or region. For example, the biologists from Perth looked at the species diversity of invertebrates in Australia's eucalypt forests. Other examples would be the diversity of plant species of the Gibson Desert, or the species diversity of Australian marsupial mammals. Figure 7.5 shows a tiny sample of the Earth's biodiversity. Most commonly when people talk about 'biodiversity' they are thinking about biodiversity in the context of species diversity.

FIGURE 7.5 A tiny fraction of the species biodiversity on Earth today. How many different kinds of organism can you count?

2. **Genetic diversity** refers to the variety of genes or the number of different inherited characteristics present in a species. Different populations of the same species may have different levels of genetic diversity. Populations with a high level of genetic diversity are more likely to have some individuals that can survive and reproduce when environmental conditions change.
3. **Ecosystem diversity** refers to the variety of physical environments in which organisms live and with which they interact. The ecosystems of this planet range from biologically rich ecosystems, such as coral reefs and rainforests, to biologically sparse ecosystems, such as the Antarctic landmass and rocky deserts, and they vary in geographic location from the hydrothermal vents of the ocean depths, to the Movile Caves of Romania, to the alpine grasslands on high mountains.

A definition of biodiversity from the International Convention on Biological Diversity is:

> The variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems
>
> *Source:* www.cbd.int/convention/articles/default.shtml?a=cbd-02.

Biodiversity: changes over time

The various kinds of organism living on Earth today are just a sample of the biodiversity that has existed on Earth over time. Consider an area of Australia that today is covered in grasses, dotted with eucalyptus trees and flowering shrubs, and populated by animals and birds such as kangaroos, wombats and parrots. 150 million years ago that area was occupied by different kinds of organism. At that time, there were no grasses, no eucalypts, no flowering shrubs, no kangaroos, wombats or parrots. Instead, plant-eating and carnivorous dinosaurs, strange flying reptiles and plants, mostly unfamiliar to us, may have lived there.

Over geological time, there have been remarkable changes in Earth's biodiversity. The seas of 450 million years ago had no fish and were dominated by nautiloids, trilobites and crinoids (see figure 7.6a), but today fish dominate the seas (see figure 7.6b).

FIGURE 7.6 Changes in biodiversity over time **(a)** 450 million years ago, the seas had no fish but were dominated by animals, such as nautiloids, crinids and trilobites. **(b)** Dominant animals of present day seas are fishes.

Identifying the diversity of life

What is it? It looks like a chestnut. Chestnuts are the glossy brown edible nuts of trees of the genus *Castanea*, and they are commonly roasted and eaten in Europe. Mis-identification can result in problems.

It is August 1770 and some British sailors pass the time on the banks of the Endeavour River in northern Queensland. They are part of the crew of the *Endeavour* voyage of James Cook and their ship has been badly damaged on a coral reef. It is now beached while repairs are made. The sailors are in a strange land where the plants and animals are unfamiliar to their eyes. They notice many palm-like plants growing nearby (see figure 7.7a), some of which have large brownish seeds described as 'nutts about the size of a large chestnut and rounder' (from the *Endeavour Journal of Joseph Banks*, vol. 2, p. 115) (see figure 7.7b). Thinking that the seeds are edible, some sailors eat them. A few hours later, these men are suffering from painful stomach cramps and are vomiting explosively. The ship's captain later writes in his journal that the sailors had thought the seeds to be edible and:

> . . . those who made the experiment paid dear for their knowledge of the contrary, for they [the seeds] operated as an emetic and cathartic with great violence . . .

Source: Hawksworth, 1785, *An Account of the Voyages for Making Discoveries in the Southern Hemisphere, Vol. IV*, 3rd ed., London, p. 195.

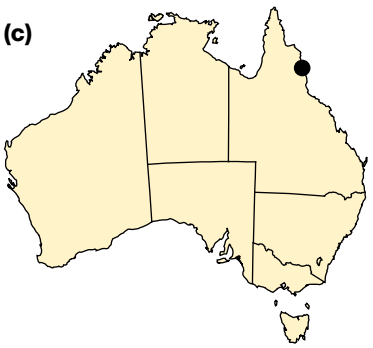


FIGURE 7.7 **(a)** Palm-like plant and **(b)** the seeds of the kind eaten by Cook's sailors. They are not palms but are members of a more ancient group of plants. This particular kind is common along the warm temperate and tropical regions of the east coast of Australia. **(c)** Map showing the location in Queensland where the *Endeavour* was beached in 1770

ODD FACT

Starch-rich cycad seeds were an important part of the diet of Aboriginal people in some regions of Australia. Prior to eating them, Aboriginal people used techniques such as roasting the seeds and then soaking the kernels for many days to wash out the poisons.

The plants involved in the poisoning of the British sailors were unknown to them. While these plants are palm-like, they are not palms. They belong to a group known as **cycads** (pronounced 'sigh-cads') that occur naturally in tropical and warm temperate regions. **Modern cycads are the living survivors of a very ancient group of plants** that existed before the dinosaurs and the flowering plants evolved. Worldwide, nearly 300 different kinds of cycad have been identified and all produce toxic compounds. Eating fresh cycad seeds produces severe gastroenteritis and, if sufficient seeds are eaten, death can result. In fact, pigs were taken on board the *Endeavour* in Tahiti as a source of fresh meat and, when they were fed cycad seeds, several of them died.

Identification is important

The effects of the cycad seeds on British sailors in 1770 are a reminder that accurate **identification** is important. Did the cycad seeds look a bit like chestnuts? Yes, but this was not what they were.

FIGURE 7.8 Australian native plants include both edible and poisonous plants. Not many plants are poisonous but, if eaten, those that are can have serious or even fatal effects on people and farm animals. The attractive plant with red pea flowers in this photo is commonly called crinkle-leaf poison. What does this suggest about this plant?

The native vegetation of Australia consists of many different kinds of plant. Nearly 20 000 different **vascular plants** (e.g. flowering plants, cone-bearing plants and ferns) have been identified in Australia. Many of these plants have edible parts, such as roots, seeds, fruits and leaves; only a relatively small number of native plants are poisonous (see figure 7.8).

Knowing the difference between poisonous and harmless plants is critical. This was particularly important for the early European settlers in Australia who farmed sheep and cattle in pastures where the vegetation was unfamiliar. Their stock sickened and often died after eating poisonous native vegetation; for example, cattle sometimes developed an incurable condition known as 'staggers' that usually led to death. It was later found that this condition occurred when cattle ate the leaves and other parts of cycads.

As well as cycads, many other plants can be the source of poisoning of cattle and sheep. In Western Australia, for example, a group occurs of 43 closely related shrubs with pea flowers. Of these shrubs, 27 are poisonous and have toxic flowers, seeds and leaves. (These shrubs are commonly known by names such as crinkle-leaf poison, narrow-leaf poison and wallflower poison.) Over time, farmers learned to identify poisonous plants and distinguish them from closely related non-toxic plants that could provide good grazing for their herds and flocks. Identification matters!

ODD FACT

The poisonous agent in the toxic Western Australian pea-flowered shrubs is mono-fluoro-acetate, more commonly known as 1080 (ten-eighty). While 1080 is toxic to introduced animals such as cattle and sheep, it is not toxic to native mammals of the region where these plants naturally occur.

The native animal life of Australia consists of many different kinds. About 140 different kinds of marsupial mammal (e.g. kangaroos and wallabies), more than 800 different kinds of bird and about 900 different reptiles (e.g. snakes and lizards) have been identified. Most of these occur nowhere else in the world. Among the reptiles are about 140 different kinds of land snake that include nonvenomous blind snakes, pythons that constrict their prey and elapid snakes, such as taipans and tiger snakes, whose venom acts on the nervous systems of their prey. Knowing the difference between deadly and harmless snakes is critical. Identification matters!

It is important that living organisms can be accurately identified for many reasons, including:

- personal safety — to distinguish harmless from harmful organisms (see figure 7.9)
- quarantine — to recognise animals or plants and their products that are banned imports; for example, imported cargo unloaded from planes and ships can have unwanted 'living passengers'
- medicine — to identify particular kinds of infectious bacteria or fungi so that effective drug treatment can be prescribed
- conservation — to recognise endangered kinds of plants and animals so that their habitats can be preserved
- forensics — to identify plant or animal material that may be used in the identification and conviction of a lawbreaker. For example, **palynology** is the study and identification of pollen. Pollen grains from different kinds of plant have distinctive shapes so that pollen found on a person's clothes can indicate where that person has been. Evidence of this type can link a person to the site of a crime.
- agriculture and horticulture — to identify pests of crops so that effective control measures can be introduced.

FIGURE 7.9 These fungi are just a few of the species found in Australia. Are any of these fungi edible? Accurate identification is important in order to avoid poisonous species.

What's needed for identification?

It is not always necessary to have an entire organism in order to identify it. Identification can be based on a study of:

- a whole specimen (actual or recorded as an image or as a verbal description)
- part of a specimen and macroscopic fragments
- microscopic fragments
- genetic material
- indirect evidence.

In each case, identification will depend on precise observations of the available material. The next step may be:

- recognition of a particular set of features in the unknown organism that allow it to be identified as identical to or closely related to a known species
- careful comparison of a key feature of the unknown organism with a database of relevant material from known specimens until a match is made: 'It looks like this one!'
- examination of the genetic material (DNA) to see if it is a match to specific DNA sequences in a known species.

Whole specimens

Identification can be based on a whole specimen that is living, preserved, fossilised or recorded as an image. Artists were key members of the scientific parties who came to Australia in the 1700s and 1800s, and they drew images of the plants and animals of the southern continent, such as that shown in figure 7.10.

FIGURE 7.10 Drawing of King Island emus (*Dromaius ater*) made by the French artist Charles Le Sueur who was on a French expedition to Australia between 1801 and 1804. This species is now extinct.

Photographs and electronic images can record features of organisms that assist in their identification, and verbal descriptions are useful. The following description was written in Sydney in 1808. Can you identify the organism?

> It is commonly about two feet [61 cm] long and one [30 cm] high; in girth about one foot and a half [45 cm]; it is covered with fine soft fur, lead coloured on the back, and white on the belly. The ears are short, erect and pointed . . . it bears no small resemblance to the bear in the fore part of its body; it has no tail; its posture for the most part is sitting.

Bits and pieces: macroscopic and microscopic

Identification may depend on a view of part of a specimen such as the **tail flukes** of a whale (see figure 7.11).

In other cases, **macroscopic** fragments of a specimen may be available, such as feathers, hairs, teeth, bones, shells, leaves, flowers or fruits. This type of material can be used to identify an organism, often to the level of species.

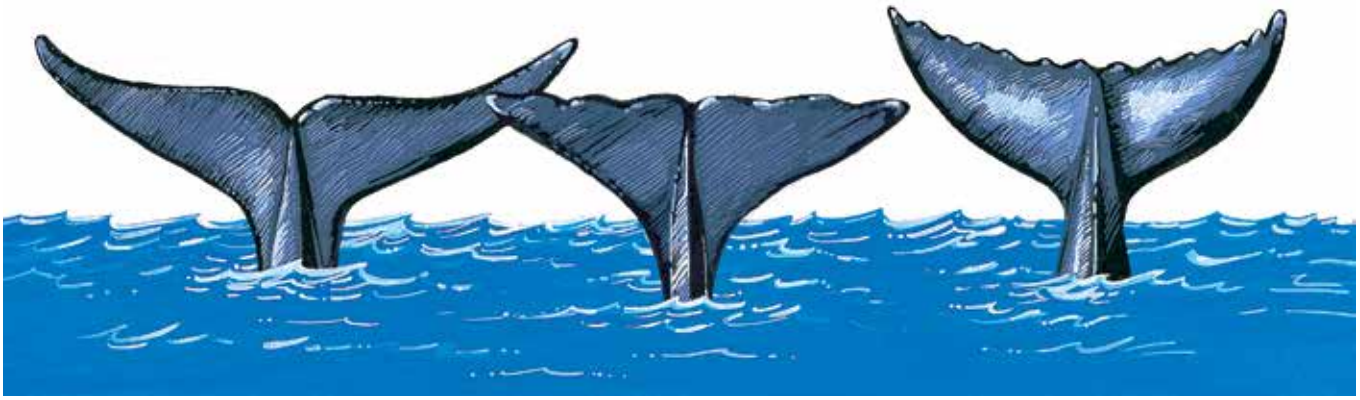


FIGURE 7.11 Distinctive tails of three whale species (left to right): right, sperm and humpback whales. As well as recognising different species, particular nicks and marks on the outer edge of the tail flukes are sufficiently distinctive and permanent to allow individual whales to be identified.

Identification sometimes relies on specimens that must be examined at a microscopic level. Because plant cell walls are resistant to chemical breakdown, plant cells may be identified after passage through the digestive tract of an animal. This means that fragments of material taken from an animal's gut may be sufficient to identify the plants that it eats.

Microscopic examination of plant material, either living or fossilised, can reveal distinctive features, such as cell wall patterns, leaf vein patterns, pollen grain appearance and seed shape. These provide valuable clues to the identification of the plants. Databases of diagnostic features of many plant genera and species are available. Features of an unknown species can be compared with features of known specimens on the database until a match is made. Bingo! The unknown plant material is identified. Even burnt wood (charcoal) can be identified.

Animal cells are, in general, less hardy than plant cells but parts of some animals, such as hair, are resistant to chemical breakdown. Hair and fur from different mammals are distinctive. The shape of hairs in cross-section and the arrangement of scales on the outer surface of a hair fibre may be used to identify the species from which the sample came (see figure 7.12). In addition, hairs in the faeces (**scats**) produced by predatory mammals, such as foxes, or in the pellets regurgitated by owls and **raptors** (eagles, falcons and hawks) can be examined to identify their mammalian prey.

ODD FACT

If a bird is sucked into the air intake of a jet engine, little remains of it apart from feathers. It is possible, however, to identify a bird species from a single feather.

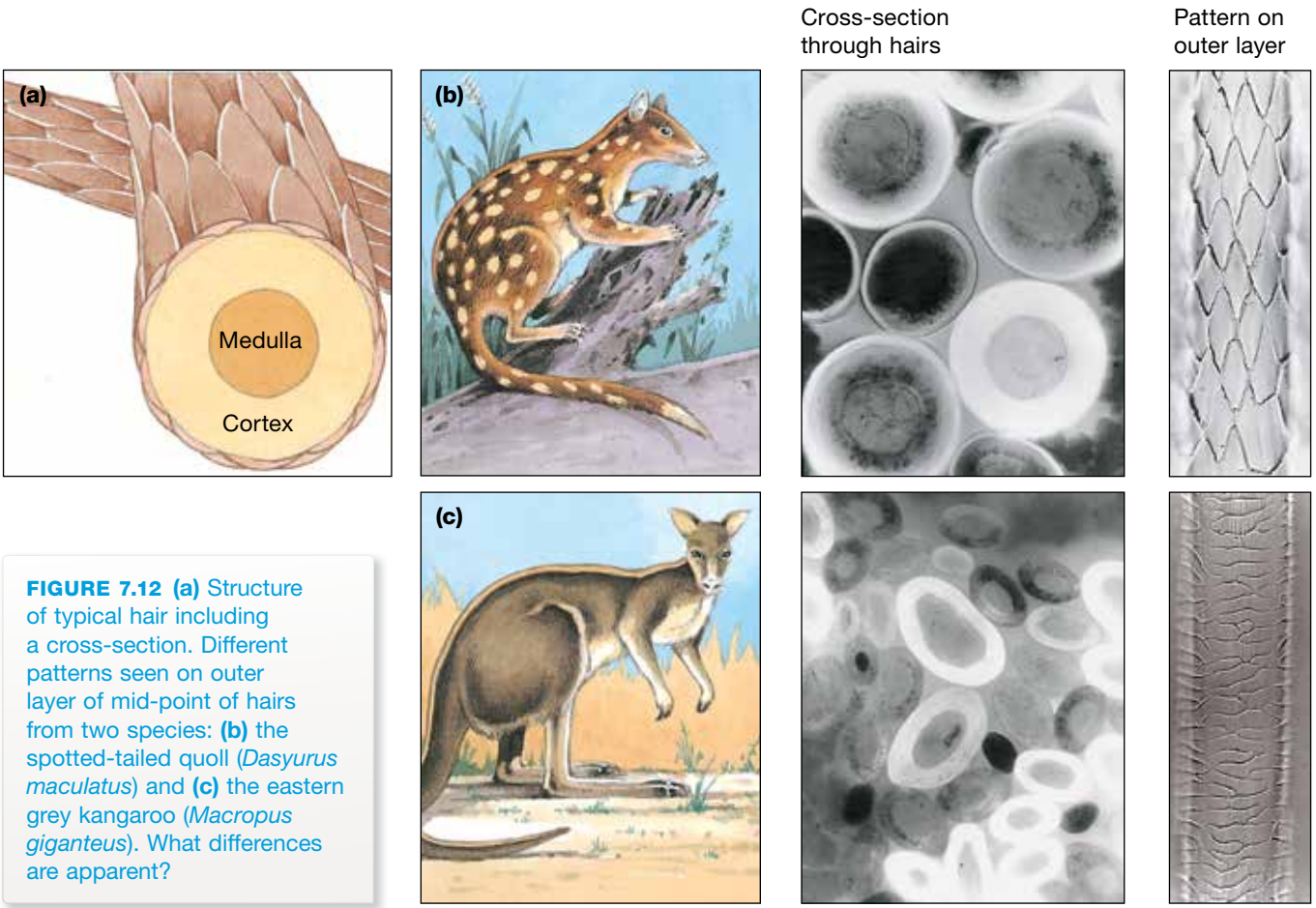


FIGURE 7.12 **(a)** Structure of typical hair including a cross-section. Different patterns seen on outer layer of mid-point of hairs from two species: **(b)** the spotted-tailed quoll (*Dasyurus maculatus*) and **(c)** the eastern grey kangaroo (*Macropus giganteus*). What differences are apparent?

FIGURE 7.13 A *Faunatech* hair-tube trap set up in the litter layer of a forested area. A mammal can freely enter and leave the trap. What advantage does this technique of obtaining hair samples have over capturing a mammal and taking a hair sample from it?

Hair traps are used to collect hairs from living native mammals in their natural environment. A hair trap typically consists of a tube or funnel with adhesive material on the internal surface (see figure 7.13). A bait likely to attract most mammals is placed in the trap. This is a non-invasive sampling method and, of course, the trap does not capture the mammal, it just captures a sample of its hair as the mammal passes through the hair trap.

Genetic material

Increasingly, identification to species level is based on molecular analysis of genetic material, DNA (deoxyribonucleic acid). For identification, samples of genetic material are examined for the presence of known markers that are distinctive in particular species.

Genetic material for identification can be isolated from hair follicles, blood stains, scats (see the box, p. 288) and from any cellular or tissue fragments.

Indirect evidence

Identification can be based on indirect evidence of an organism. In the case of mammals and birds, these might include tracks, burrows or nests, scratchings, scats and calls or songs. Figure 7.14 shows the distinctive tracks of two animals: the dingo (*Canis familiaris*) and the koala (*Phascolarctos cinereus*).

FIGURE 7.14 Impressions of front and rear foot of: **(a)** a koala and **(b)** a single paw print a dingo

SCATTY CLUES FOR IDENTIFICATION

It is claimed by some local residents that at night a catlike beast roams Bodmin Moor in Cornwall, England, and is the cause of strange deaths among cattle and sheep. The most recent investigations have involved study of the scats (faeces) that are supposed to have been left by the 'beast', which many locals assert is some sort of 'big cat', such as a leopard or puma.

When faeces are produced, they carry, on their outer surface, cells dragged from the lining of the digestive tract. These cells can be washed from the surface of the faeces and the DNA present in the cells can be separated out and examined. DNA from different species can be distinguished and scats are thus a valuable source of cells from which DNA can be extracted and used for identification. It is important that care is taken to obtain cells only from the outside of the scat.

Scats claimed to have been produced by the Bodmin Moor beast have been analysed. The first sample was collected by a person who said he had seen the 'beast'. The DNA from this sample was found to match that of both dog and sheep. This result was interpreted as being due to a dog defecating on sheep droppings. The DNA from another sample collected at a different time showed that it was from a domestic cat.

To date, local rumours that the beast of Bodmin Moor is one of the 'big cats', remain unsubstantiated.

In another instance, a scat was claimed to be that of the Abominable Snowman. When analysed, the DNA isolated from this scat showed that it was from a fox! Faeces can also be used to identify the number of individuals in a population. DNA can be distinguished not only from different species, but also from different individuals. In one American study, DNA obtained from faeces was used to estimate the number of coyotes in the population in a given area. DNA from such sources can also be used to identify the sex of individual members of the species.

Tools to assist identification

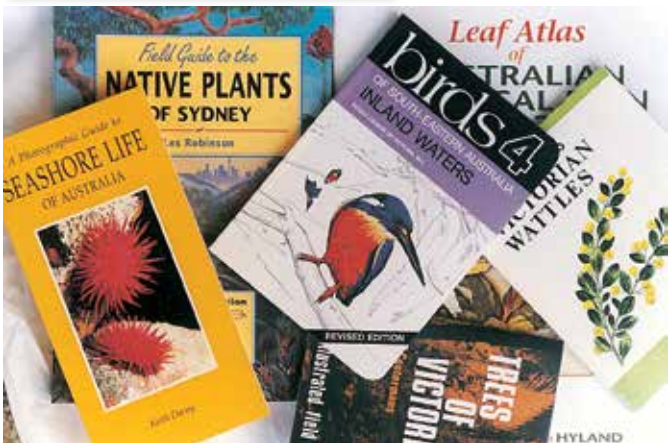
Many tools are available to assist in the identification of unknown organisms. They include:

- field guides
- keys
- reference collections
- databases.

Field guides

Field guides are commonly used for identification purposes by bird watchers, bush walkers, and amateur naturalists. A field guide typically contains pictorial and verbal descriptions of one or more particular kinds of organism from a nominated area, for example, *The Mammals of Victoria* or *Ferns of Victoria and Tasmania* or *Common Australian Fungi.* While field guides are commonly available in print form (see figure 7.15), they are also available as DVDs and as apps for smart phones and tablets.

FIGURE 7.15 Field guides, both printed and in electronic form assist in identification of organisms. Can you suggest a limitation of field guides for identification?



Keys

A means of identifying specimens is through the use of **keys**. Keys involve making decisions about the presence (or absence) of certain features in the specimen to be identified (see figure 7.16). **When each decision involves choosing between just two alternatives, the key is called a dichotomous key (from Greek *dichotomia* = cutting into two).**

eBook*plus*

Interactivity
Dichotomous keys
int-3033

The simple dichotomous key in figure 7.16 shows how seven molluses can be identified using a dichotomous key. Each decision involves a choice between two easily recognised features.

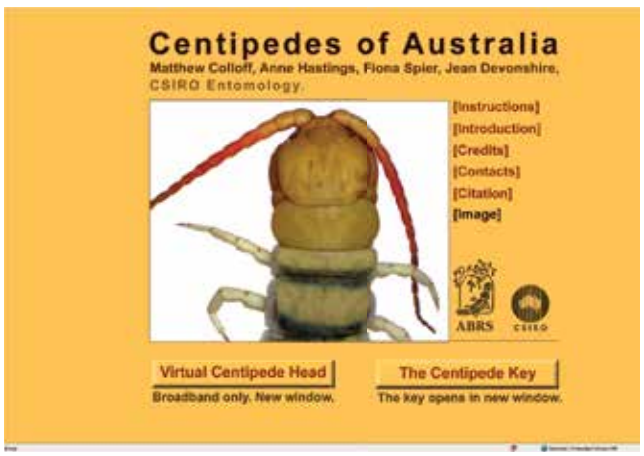
DECISION	1a	Hard outer covering or shell over part or all of body..... Go to 2	DECISION	4a	Both valves convex ..... **mussel**	
	or			*or*		
	1b	No hard outer covering ..... Go to 5		4b	One valve flat, and one convex ..... **scallop**	
DECISION	2a	Single shell..... Go to 3	DECISION	5a	Tentacles or 'arms' present ..... Go to 6	
	or			*or*		
	2b	Shell comprises more than one valve..... Go to 4		5b	No tentacles ..... **slug**	
DECISION	3a	Rounded shell with circular opening ..... **snail**	DECISION	6a	Eight 'arms' present ..... **octopus**	
	or			*or*		
	3b	Cylindrical shell with long opening..... **cone shell**		6b	Ten arms present ..... **squid**	

FIGURE 7.16 A dichotomous key for identifying various groups within the phylum Mollusca. What feature is the basis for the first decision? What is one limitation of a key?

Keys for identification of various organisms can be accessed via the internet. Some examples are:

- Centipedes of Australia (www.ento.csiro.au/biology/centipedes/centipedeKey.html) (see figure 7.17) is a dichotomous key that enables identification of centipedes to the family level and then to the level of order.
- The Discover Life (www.discoverlife.org) website has a key that enables identification of any insect to the level of order.
- The Cycad Pages (http://plantnet.rbgsyd.nsw.gov.au/PlantNet/cycad) website has both a multi-entry key and a dichotomous key for identification of cycads to the species level.

(a)



(b)

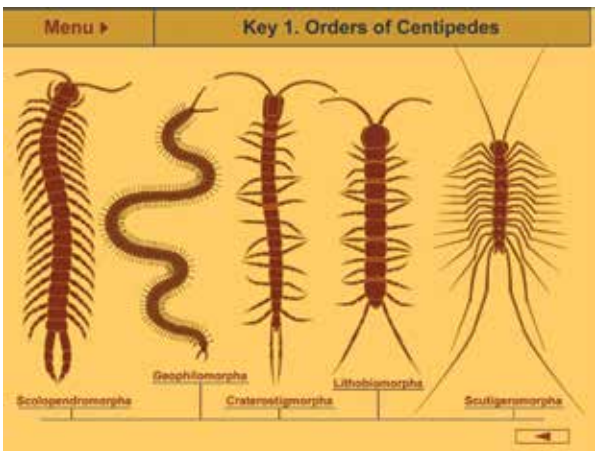


FIGURE 7.17 Screen displays from *Centipedes of Australia*, an identification resource maintained by CSIRO Entomology **(a)** Introductory page **(b)** First page of the identification key in which centipedes are distinguished by appearance

Reference collections

Museums and herbaria (singular: **herbarium**) are institutions where **reference collections** of animal species and plant species, respectively, are held. If an unknown specimen of an animal or plant is to be identified, this process may involve comparison of the unknown specimen with reference specimens held in museums (for animal species) or in herbaria (for plant species).

Reference collections are held in Australian museums and other institutions. Some important reference collections in Australia are:

- the fish collection at the Australian Museum in Sydney, which contains almost 1 million specimens (see the Biologist at work about Mark McGrouther, p. 292)
- the native plant collection, which includes the world's largest collection of eucalypts, at the Australian National Herbarium, which is maintained in Canberra by CSIRO Plant Industry
- the insect collection at the University of Queensland, which contains more than 1 million specimens of insects, in particular beetles, flies and bees, from across Australia, with a small number of foreign specimens.

Reference collections are increasingly being digitised, enabling useable access via the internet.

Databases

Biological **databases** are large organised sets of information stored in computers and accessible for various uses by groups such as research scientists, managers, students and the general public, with the information flowing freely across national boundaries.

Some examples of electronic databases are:

- FishBase (www.fishbase.org) contains diverse biological information on 33 000 fish species. Searches can be started using either the common name of a fish, such as clown anemonefish, or a scientific name, *Amphiprion ocellaris* (see figure 7.18).

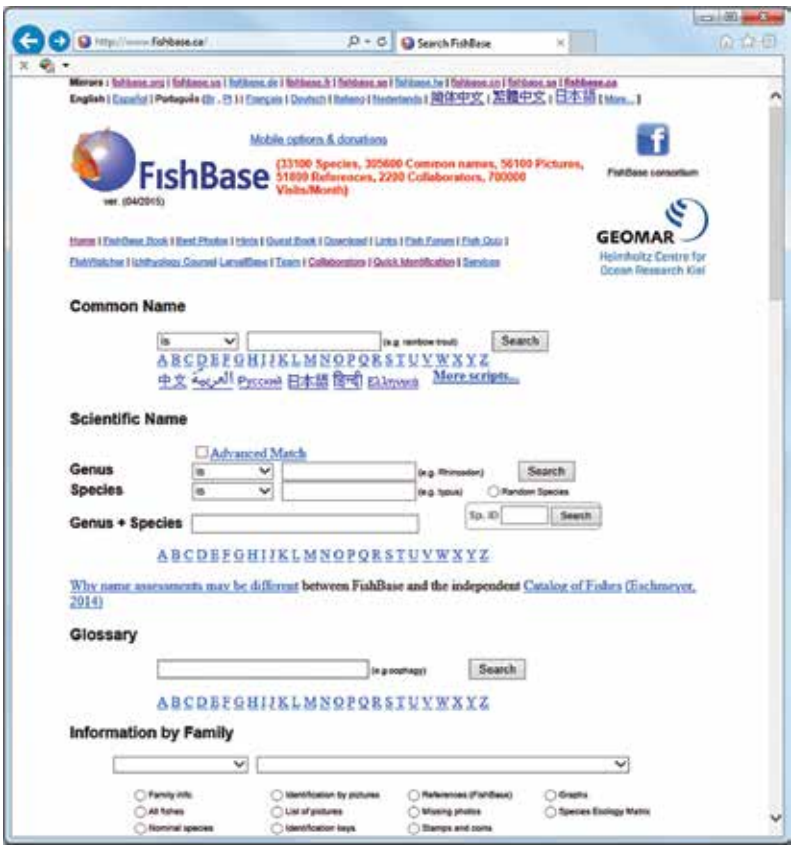


FIGURE 7.18 Search page for the FishBase database. A feature that makes it useful for students is the ability to search using the common name.

- The World Register of Marine Species (WoRMS) (www.marinespecies.org) database has entries for about 230 000 different sea-dwelling species, including microbial species.
- The Australian Faunal Directory (www.environment.gov.au/biodiversity/abrs/online-resources/fauna/afd/home) contains taxonomic and biological data on all animal species (more than 120 000 species/subspecies) known to occur within Australia.

The database that best captures the Earth's biodiversity is the Catalogue of Life (www.catalogueoflife.org) database. This is the most comprehensive database presently in existence. As at April 2015, the Catalogue of Life has about 1.6 million entries that provide the names and distributions of all the known species of animals, plants, fungi and microbes on Earth (see figure 7.19).

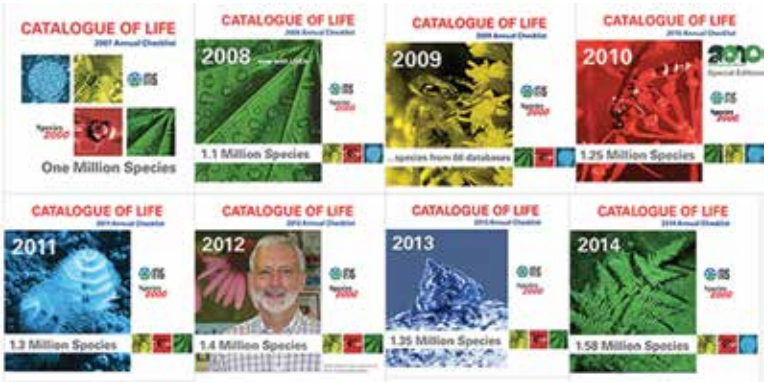


FIGURE 7.19 The 2015 Catalog of Life has almost 1.6 million entries of different living organisms. Each year it publishes a checklist of species online and as a DVD. Note the growth in the number of recognised species.

ODD FACT

Worldwide, so far, more than 270 000 different species of flowering plant have been identified and more than 30 000 bony fish.

Level of identification

Look at the organisms in figure 7.20a and b. **The most precise level of identification is to give each organism its binomial scientific name, thus identifying it to species level.** This identification would be 'Organism 1 is the golden wattle (*Acacia pycnantha*) and organism 2 is the true clown anemonefish (*Amphiprion percula*)'. However, identification can also be less precise and identify larger and more inclusive classification levels. Look at figure 7.20c. The statement 'That is a banksia' in fact identifies this plant to the level of genus since this is the saw-leafed banksia (*Banksia serrata*). Statements such as 'This is a flowering plant' or 'That is a bony fish' identify organisms very broadly to the level of class.

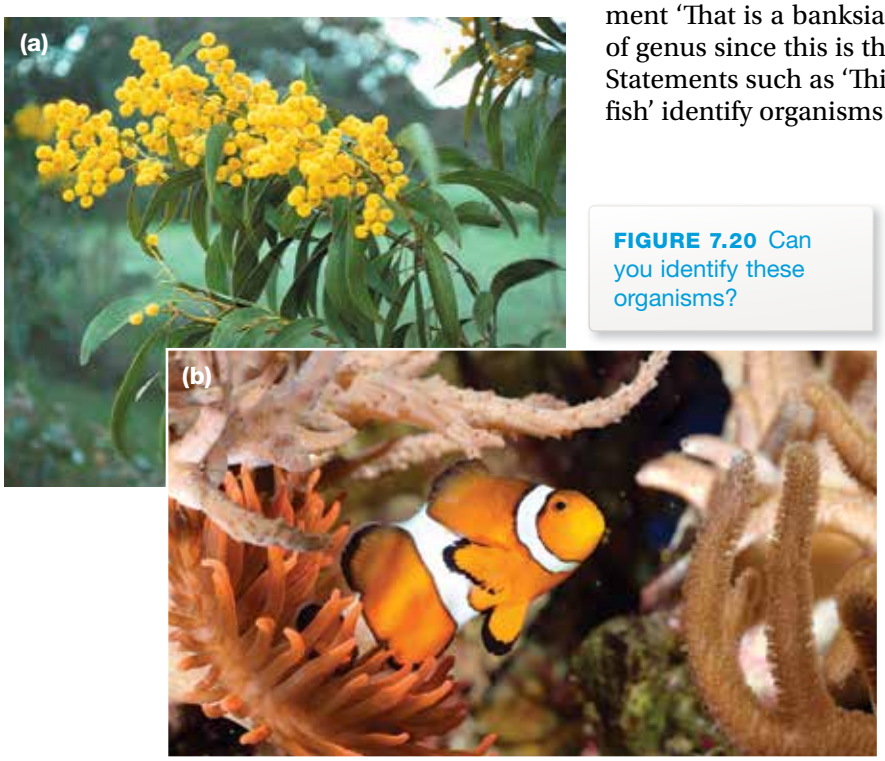


FIGURE 7.20 Can you identify these organisms?

BIOLOGIST AT WORK

Mark McGrouther — collection manager

'Mention the words "marine biologist" and most people think of diving in crystal clear waters on the Great Barrier Reef. My role as collection manager of the Fish Research Collection, which is kept by the Australian Museum does involve some exciting fieldwork, but there are also many duties that do not fit the popular image of a marine biologist.

'The collection manager's role is to manage and develop the fish collection of the Australian Museum. It is a fascinating job with roles as diverse as supplying fishes for research, participating in fieldwork, preparing pages for posting on the internet and answering enquiries from the public about strange fishes.

'The collection contains over a million specimens and serves many functions. One of the most important is scientific research. Researchers who wish to study the anatomy, taxonomy, diet or reproductive biology of a type of fish can use specimens from the collection. In this way, it is used like a library with specimens being loaned to ichthyologists world wide. Just about every fish you can imagine is stored in the collection, both marine and freshwater, from tiny fish eggs to great white sharks.

'So where do all these fish come from? Some are brought to the museum by the public, who find them washed up on a beach, or caught on hook and line. Others are collected by professional fishers or other research institutes, and many are collected by staff during fieldwork.

FIGURE 7.21 Mark McGrouther

'Fieldwork can vary from one day assessing the fauna of a local stream to a month or more away in remote locations assessing fish biodiversity. Staff have participated in expeditions to many countries including French Polynesia, Vanuatu, the Solomon Islands, Papua New Guinea and Madagascar.

'The collection needs to be large enough to provide adequate representation of each species, by covering variations in form, size, age, location, depth ranges and other variables. Of course, amassing a large collection and storing it is not an end in itself. The collection has to be utilised and well documented. The entire collection is recorded in computer databases. These data are constantly being updated and made available to researchers.

'Considerable effort has gone into posting information on the internet. The Australian Museum's fish pages contain a host of information, which caters to the interests of scientists and the public. It seems everyone has a passion for fish.'

Use the **AustMus fish pages** weblink in your eBookPLUS to find out more about the Australian Museum's fish collection.

eBook*plus*

KEY IDEAS

- Accurate identification of different kinds of organism (species) is important for many purposes, including conservation, medicine and forensic investigation.
- Identification may be based on direct or indirect evidence of various kinds.
- Identification can be made from a variety of material ranging from whole organisms to microscopic fragments.
- Identification is enabled through the use of resources such as reference collections and keys.

ODD FACT

On seeing lions, tigers, leopards or other big cats at the zoo, young children readily recognise their essential 'catness' by calling 'Puss, puss, puss' to them.

QUICK CHECK

1 Identify whether each of the following statements is true or false.
   - **a** Australia has more than 800 different kinds of bird.
   - **b** It is necessary to have an entire organism in order to identify it.
   - **c** Reference collections are held in institutions, such as museums and herbaria.
   - **d** Dichotomous keys identify any organism to the species level.

2 Give one example of why accurate identification to species level is important.
3 List two different biological materials by which a species might be identified.
4 List two purposes for using hair samples in identification.

Identification involves naming

Human learning involves putting labels on classes of objects in the world around us. As toddlers, we begin to learn to classify objects in the world around us and to give a distinctive verbal label (for example, 'dog', 'book', 'apple', 'chair') to each class. Young toddlers can recognise a large, fawn great Dane, a small, black and white Jack Russell terrier, a golden labrador and a black greyhound as having an essential 'dogness', in spite of differences in shape, size and colour. Toddlers know that cats are not dogs (see figure 7.22). Through labels or names, we can make sense of the world around us and can communicate our thoughts to others in a concise manner. When we name something, we are identifying some of its essential and distinguishing characteristics. If something has the label of 'bird', you know that it has feathers, not fur.

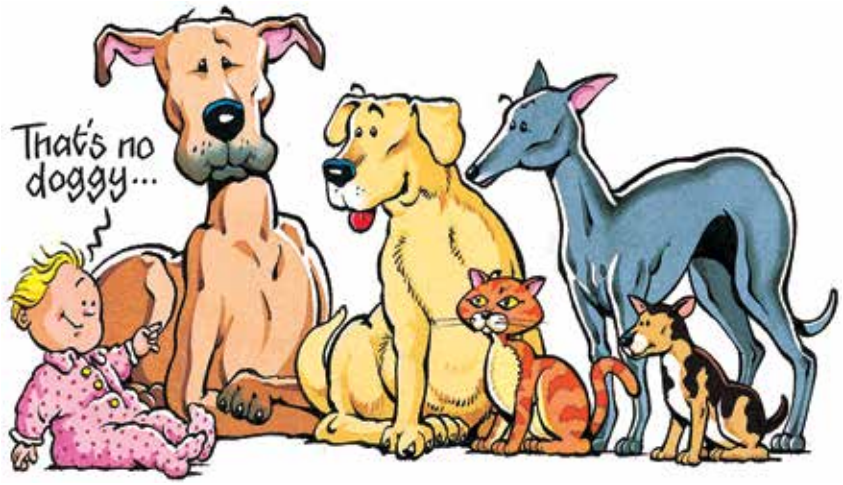


FIGURE 7.22 Learning involves identifying classes of objects in the world around us with verbal labels.

Two-part names and rules

Putting labels or names on living organisms is an important area of biology. **Each different kind or species of living organism presently known has a two-part (binomial) scientific name** (see figure 7.23). You and every other person have the scientific name *Homo sapiens*, while your cat and every other domestic cat is *Felis catus*. The cycad species that poisoned the British sailors in 1770 has the scientific name *Cycas media* (refer to figure 7.7, p. 283).

The naming of various species occurs according to rules. Rules for the naming of new animal and new plant species appear in publications called the International Code of Zoological Nomenclature (ICZN) and the International Code for Botanical Nomenclature (ICBN) respectively. But, what is a species? The box on pages 297–8 explains how species are differentiated.

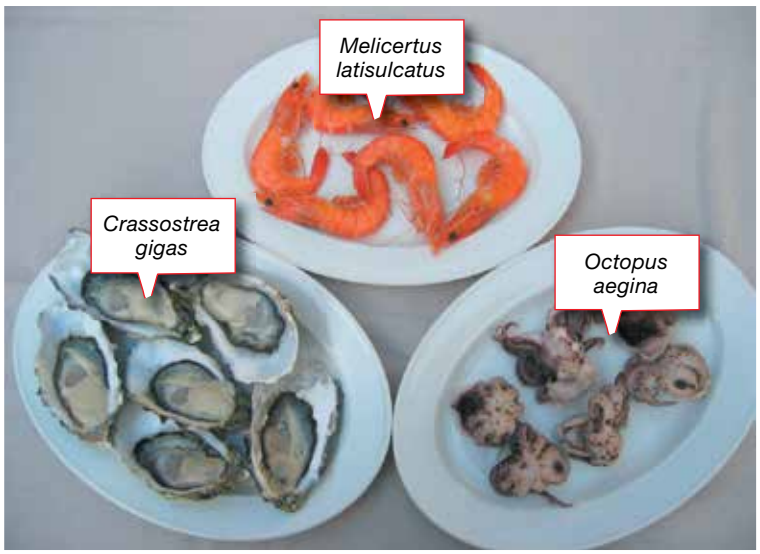


FIGURE 7.23 Each kind of organism has a unique scientific name. How many parts are in each name?

FIGURE 7.24 Carolus Linnaeus is shown on this Linnean Society Silver Medal.

ODD FACT

By the time of his death in 1778, Linnaeus had described and given binomial scientific names to more than 9000 species of plants, nearly 2000 mollusc species, 2100 insect species and 477 fish species.

ODD FACT

Sometimes a person may know the name of the genus to which an organism belongs, for example, a tree belonging to genus *Eucalyptus*, but may not be sure of the specific name. In this case, the tree can be identified simply as *Eucalyptus* sp.

FIGURE 7.25 Sign in a university garden in China. Notice the scientific name amid the Chinese characters.

Linnaeus' binomial system

Let us now look in more detail at the binomial system of naming species that was introduced by the Swedish biologist, Carl von Linné (1707–1778), also known by the Latinised form of his name, as Carolus Linnaeus. In 1758, Linnaeus (see figure 7.24) introduced a new and uniform way of naming different kinds of organism by giving each species a two-part scientific name. This is the **binomial system of naming** (from the Latin *binomius*, meaning 'having two names'). Linnaeus' important contribution to biology was to apply the use of binomial scientific names to all organisms in a systematic way.

The first part of a binomial scientific name is the **generic name** or the name of the genus to which the organism belongs; the generic name always begins with a capital letter. The second part always begins with a lowercase letter and identifies the particular member that belongs to the genus. This second part is known as the **specific name**. **This binomial scheme for naming species continues to be used by all biologists throughout the world today.**

The Linnean binomial system replaced a number of clumsy systems of naming organisms that had developed during medieval times. An early **polynomial system** gave organisms names that were descriptions. For example, the common buttercup was once known by the polynomial: *Ranunculus calycibus retroflexus, pedunculis fulcratus, caule erecto, foliis compositus*. This name described the plant as follows: buttercup with sepals bent back, with supporting flower stalk, with straight main stem, and with composite leaves. Linnaeus gave the common buttercup its binomial scientific name, *Ranunculus repens*.

Another significant feature of the Linnean binomial system is that binomial names are informative about the relationships between organisms. Where close relationships exist between organisms, the Linnean binomial system identifies this feature by giving them the same generic name. For example, Linnaeus gave the scientific name *Cervus elaphus* to the red deer and called the closely related fallow deer *Cervus dama*. Their close relationship is advertised by their having the common generic name *Cervus*.

The specific part of a scientific name does not denote any degree of relationship. So the organism *Balaenoptera musculus* is not at all closely related to *Mus musculus* — the former is the blue whale and the latter is the house mouse!

Advantages of scientific names

Scientific names look more complex than common names. Wouldn't it be easier to stick with common names? Surely words like 'cat', 'koala' and 'numbat' are preferable to tongue twisters such as *Felis catus, Phascolarctus cinereus* and *Myrmecobius fasciatus*! In spite of their tongue-twisting nature, **scientific or species names have several advantages over common names.**

1. *Common names vary from language to language, but scientific names are universal.* The domestic cat is the English *cat*, the Italian *gatto*, the German *Katze*, the French *chat* and the Hebrew *chatul*. In contrast, the scientific name, *Felis catus*, is recognised and used by all biologists, regardless of nationality. Figure 7.25 shows a sign from a university garden in China.
2. *The same common name is sometimes used to label different species.* People who speak the same language may mean different things when they use the same common name. Look at figure 7.26. Which is the robin? The answer depends on the nationality of the person answering the question. The common name 'robin' is used by Australians to refer to small flycatchers, such as the scarlet robin (*Petroica multicolour*). In contrast, the name 'robin' is used by North Americans to refer to a different and larger bird, with a dull orange breast. The scientific name of this larger bird is *Turdus migratorius*.

ODD FACT

The fish *Argyrosomus japonicus* is found around the Australian coast. In Victoria, it is known as the mulloway, in South Australia as the butterfish, in Queensland and New South Wales as the jewfish, and in Western Australia as the kingfish or river kingfish.

FIGURE 7.26 The same common name 'robin' is used both by Australians and Americans for different kinds of bird. **(a)** Australian robins belong to the genus *Petroica*. Is this true of **(b)** North American robins?

In Western Australia, the common name 'prickly Moses' is used for one kind of wattle, *Acacia pulchella*. In New South Wales, the same common name refers to a different species, *Acacia ulicifolia*. In Victoria and Tasmania, the common name 'prickly Moses' refers to yet a different species of wattle, *Acacia verticillata*. A scientific name refers to one kind of organism only.

3. *Scientific names give an indication of the degree of relatedness of different organisms.* Closely related organisms share the same generic name, for example, *Macropus*. So, there is *Macropus rufus*, the red wallaby, and its close relatives, including *Macropus giganteus*, the eastern grey kangaroo and *Macropus fulginosus*, the western grey kangaroo. These three kinds of kangaroo have similarities in physical structure (morphology), in functioning (physiology and biochemistry) and in their evolution (phylogeny). This shared similarity is expressed in the first part of their scientific names — the generic name, *Macropus*.

   In contrast, common names cannot be used as a guide to the degree of relatedness of different kinds of organism. Consider the long-tailed mouse (*Pseudomys higginsi*), the spinifex hopping mouse (*Notomys alexis*) and the heath rat (*Pseudomys shortridgei*). Their common names suggest, perhaps, that the two mice are the most closely related. However, the heath rat and the long-tailed mouse are the most closely related pair.
4. *Common names may be misleading, suggesting relationships that are not valid.* Some common names given to organisms are misleading. In spite of their common names, cuttlefish are not fish, they are molluscs; likewise, starfish are not fish but echinoderms; reindeer moss is not a moss but a lichen and the sea tulip is not a plant but an animal. Early European settlers gave Australian animals common names that suggested relationships that did not exist. Figure 7.27 shows the animal that was given the common name of 'tiger cat' by early European settlers. This animal, the spotted-tailed quoll (*Dasyurus maculatus*) is not a close relative of the domestic cat (*Felis catus*) and it does not even belong to the same family or order as the domestic cat.

FIGURE 7.27 Spotted-tailed quoll (*Dasyurus maculatus*). What common name did early settlers give to this animal? Why might this common name be used?

Sources of scientific names

A person seeing a scientific name, such as *Phascolarctos cinereus,* might say: 'It looks foreign to me!' **Many of the words used in scientific names do come from Greek and Latin words.** The scientific name of the koala is

built from the Greek words *phaskolos* meaning 'pouch', *arktos* meaning 'bear', and the Latin word *ciner* meaning 'ash-coloured'. So *Phascolarctos cinereus*, the scientific name given to the koala in 1816, simply means 'ash-coloured, pouched bear'.

Some scientific names are shown below, along with their meanings.

Macropus rufus = big-foot (Gk), red (L)
Acrobates pygmaeus = acrobat (Gk), pygmy (L)
Thylacinus cynocephalus = pouched-dog (Gk), dog-head (Gk)
Ornithorhynchus anatinus = bird-snout (Gk), duck-like (L)

The big-footed red animal is the red kangaroo.

Try to match the other scientific names to the Australian native animals shown in figure 7.28.

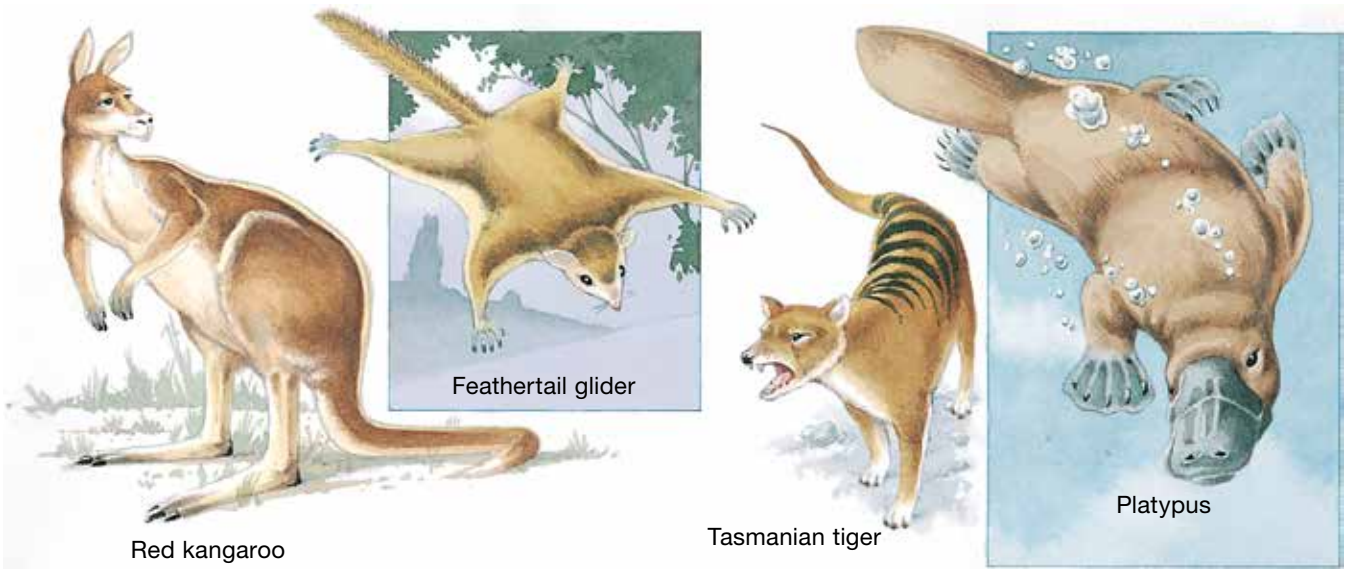


FIGURE 7.28 Which of these animals might have a scientific name that means 'bird-snout, duck-like', 'pouched-dog, dog-head' or 'acrobat, pygmy?

Other languages have contributed to scientific names; for example, the name of the plant genus *Pandanus* comes from the Malay language.

The generic names of some Australian native marsupial mammals are derived from Aboriginal words or phrases; for example the genus *Bettongia* is named from an Aboriginal word 'bettong' meaning small wallaby. Four marsupial species now have the generic name *Bettongia* including the brush-tailed bettong, *B. penicillata*, and the burrowing bettong, *B. lesueur*.

Scientific names of organisms may come in part from the names of people involved with their discovery or description. Names are usually 'Latinised' by adding an appropriate suffix. Some examples are given in table 7.1.

ODD FACT

Scientific names sometimes have an extra bit, such as the messmate tree (*Eucalyptus obliqua* L'Hér), the koala (*Phascolarctos cinereus* Goldfuss) and the blue whale (*Balaenoptera musculus* Linnaeus — often shown as simply 'L'). This addition identifies the name of the person who first described the organism.

TABLE 7.1 Parts of scientific names based on people

Scientific name	Common names	Source of name(s)
Banksia serrata	saw-leafed	Joseph Banks, English naturalist on Cook's *Endeavour* voyage
Wollemia nobilis	Wollemi pine	Dave Noble, who discovered this species in 1994 (see p. 306)

WHAT IS A SPECIES?

Species can be defined in different ways, including:
1. classic definition — the use of structural similarities
2. biological definition — the ability to interbreed
3. modern definition — the use of DNA.

Classic definition of species

The classic definition of a species is based solely on similarities in appearance. If two organisms look sufficiently similar, they are defined as the same species; if they look sufficiently different, they are defined as different species. One problem with this definition is that different species may look virtually identical. For example, the snow petrel (*Pagodroma nivea*) and the white tern (*Gygis alba*) are very similar in appearance but are different species. Butterflies and moths of different species can also be very similar in appearance. Another problem is that members of the same species may show enough variation to cause them to be mistakenly identified as different species, for example:

- different sexes of the same species may vary markedly, as seen in the *Electus* parrot (see figure 7.29a)

FIGURE 7.29 **(a)** The two sexes of the *Electus* parrot (*Electus roratus*) differ greatly. The adult male (left) is mainly bright green in colour while the female (right) is red and purple. For many years these two sexes were mistakenly thought to be different species. **(b)** The green python (*Chondropython viridis*) shows developmental or age variation. Shown here are an adult python that is lime green and a juvenile that is typically bright yellow. **(c)** The dark and the white variants of adult southern giant petrels (*Macronectes giganteus*)

(continued)

- members of the same species at different ages may show striking variation, as seen in the green python (*Chondropython viridis*) (see figure 7.29b)
- members of the same species, regardless of sex and age, may look different because of inherited variation. For example, the southern giant petrel (*Macronectes giganteus*) has two variants: the common dark and a rarer white (see figure 7.29c).

The classic definition of a species is useful for fossil species. When two fossil organisms are very similar, they are identified as members of the same species. Figure 7.30 shows three fossil trilobites that are recognised as different species because of significant differences in aspects of their size and shape. Likewise, the classic definition can apply to organisms that reproduce only asexually. (Why?)

Biological definition of species

The biological definition of species **identifies a species as members of a group of similar organisms that are capable of interbreeding under natural conditions to produce viable and fertile offspring**. This definition allows two different species to be recognised even when they appear superficially similar.

Lions (*Panthera leo*) and tigers (*Panthera tigris*) can mate but they fail the 'biological test' because (i) their offspring, known as ligers, are infertile and (ii) such matings occur only under captive conditions.

The biological definition of a species has limited application. It cannot be used for species that reproduce asexually.

Modern definition of species

Species are now recognised through criteria such as:

- the number and shape of chromosomes present in their cells
- molecular data, in particular, the genetic information contained in their genomes.

This procedure can assist in separating, as distinct, two different species that look the same!

In the case of microbes, molecular analysis is used to identify various species. To be the same species, the DNA of the microbes concerned must match to a high degree. This test is very useful for microbes that cannot be cultured in the laboratory. More recently, it has been proposed that all species be DNA barcoded (see pp. 306–8).

FIGURE 7.30 Three different trilobite species identified because of differences in their shape and structure: **(a)** *Elrathia kingii* (top) and *Agnostus pisiformis* (bottom); **(b)** *Phacops africanus*

KEY IDEAS

- Identifying classes of objects involves giving them names.
- Each different kind of organism or species has a unique scientific name.
- Scientific names are binomial: the first part is the generic name, the second part is the specific name.
- Identification can be at several levels with the most precise identification being at species level.

QUICK CHECK

5 Identify whether each of the following statements is true or false.
- **a** The systematic use of the binomial system of naming organisms was introduced by Linnaeus.
- **b** Each different species has a unique scientific name.
- **c** Some, but not all, domestic cats have the scientific name *Felis catus*.
- **d** Two different species could have the same scientific name.
- **e** A species found in New Guinea must have the same scientific name as the same species found in northern Australia.

6 If a black labrador dog has the scientific name *Canis familiaris*, what scientific name would be given to a white highland terrier?

7 Two organisms are similar in appearance. Will they have the same generic name?

How many different kinds?

ODD FACT

Rainforests cover less than 10 per cent of Earth's land surface but contain about half of our planet's species.

ODD FACT

In the period 1863–78, the first published collection of Australian plants, entitled *Flora Australiensis*, listed 8000 plants. Since then, more than 13 000 new species have been described.

All the different species of living organisms (animals, plants, fungi, protists and microbes) comprise the biological diversity (biodiversity) of planet Earth. The species is the basic unit of the living world and the box on pages 297–8 explains how species are defined. To date, around 1.6 million different species have been identified and their descriptions and scientific names published.

The biologists who specialise in identifying, naming, describing and classifying organisms are called **taxonomists**. Their area of study is called **taxonomy** and it is part of a broader area of study known as **systematics**, which aims to describe relationships between different groups of organisms and to understand the evolutionary history of life on Earth. Taxonomists tend to specialise in one particular group of organisms. Read about Bruce Maslin, a taxonomist and the world's expert on plants of the genus *Acacia,* on page 302.

Describing each different kind of organism and giving each a unique scientific name creates an enormous amount of data. Imagine that the description and the name of each of the 1.6 million different species already identified were put into a book, *Life on Earth*, with one page for each different species. Such a book would be a multi-volume series that would form a stack more than 75 m high! However, the total number of different kinds of living organism on planet Earth is far more than the number so far identified and named. In addition, the species living today are just a tiny fraction of large numbers of different species that have existed since life first appeared on this planet. These species, now extinct and occurring only as fossils, could also be added to the book *Life on Earth* — in the 'past life' section.

How many different kinds (species) of organism live on Earth today? A simple question, but with no simple answer. Past estimates have ranged wildly from 3 to 100 million!

A careful study in 2011 by a group of scientists from the United Nations Environment Program (UNEP) produced an estimate of 8.7 million, plus or minus 1.3 million, for the total number of eukaryotic species living on Earth. Of these, about 6.5 million species are believed to be land-based and about 2.2 million live in the seas. (This study, however, does not accommodate the prokaryotic groups of bacteria and archaea.) If these UNEP estimates are correct,

this means that about 86 per cent of all land-based eukaryotic species and about 91 per cent of those in the seas are yet to be discovered, described and named!

In 2013, another group of scientists reported an estimate of 5 million, plus or minus 3 million, species for the number of eukaryotic species living on Earth.

One recent estimate of the number of prokaryotic species on Earth is between 120 000 to 150 000. However, no consensus exists on this issue and other estimates identify a much higher figure.

Table 7.2, based on the UNEP estimates of eukaryotic species, shows the comparison between the estimated numbers of different kinds of organism and the known numbers of these kinds. 'Known' means that the organism has been identified, described and named.

TABLE 7.2 Comparison between the estimated and known numbers of different kinds of organism on Earth. The last column gives an estimated percentage of the species yet to be identified, described and named. Note that plants are the group of organisms for which the record is most complete.

Eukaryote group	Estimated number	Known number	Percentage yet to be described
animals	~7.700 000	953 434	88%
plants	~298 000	215 644	28%
fungi	~611 000	43 271	93%
protists (protozoa)	~36 400	8 118	78%
protists (chromista)	~63 900	13 033	54%

What about Australia? Table 7.3 shows a sample of the biodiversity in Australia in terms of the numbers of different kinds (species) of organism in various groups. Most of these organisms are **endemic** to Australia, that is, are unique to this country and do not occur naturally in any other part of the world. Figures 7.31 to 7.35 show a small sample of Australia's endemic marsupial species.

TABLE 7.3 Numbers of different kinds of organism in Australia

Taxonomic group	Number of Australian species	Taxonomic group	Number of Australian species
mammals	386	plants	
• monotremes	2	• flowering plants	18 706
• marsupials	140	• conifers	120
		• ferns	498
		• mosses	1 846
birds	828	fungi	11 846
reptiles	917	algae	~3 545
• lizards	520		
• snakes	172		
amphibians	227	protists	> 1 346
fish	~5 000		
echinoderms	1 475		
insects	98 703		
spiders	6 615		
molluscs	~8 700		
crustaceans	7 266		
earthworms	2 192		
sponges	>1 346		

Source: Adapted from Chapman, 2009, *Numbers of Living Species in Australia and the World,* 2nd ed., Australian Biodiversity Information Services, Toowoomba.

Endemic species that occur nowhere else in the world provide a contrast to introduced, invasive or exotic species. These species have been introduced, either deliberately or accidently, to Australia. Examples include rabbits, cane toads and prickly pear.

FIGURE 7.31 The Tasmanian devil (*Sarcophilus harrisii*) is a nocturnal carnivorous marsupial. It feeds both as a scavenger, eating carrion (dead animals), and as a predator of small mammals.

FIGURE 7.32 The koala (*Phascolarctos cinereus*) feeds by day exclusively on leaves of a few eucalypt species.

FIGURE 7.33 The kultarr (*Antechinomys laniger*) is a noctural hunter that feeds mainly on insects.

FIGURE 7.34 The feather-tailed glider (*Acrobates pygmaeus*) is an omnivore that feeds on small insects, nectar, pollen and sap; it is active by night and can glide for distances in excess of 15 m.

FIGURE 7.35 The marsupial mole (*Notoryctes typhlops*) lives underground in sandy areas, is blind and has no external ears.

BIOLOGIST AT WORK

Bruce Maslin — taxonomist and *Acacia* specialist

Bruce Maslin is a research scientist with the Department of Parks and Wildlife in Perth, Western Australia (see figure 7.36a). He is a botanist and expert on the plants of the genus *Acacia*, commonly known as wattles.

Acacia is the largest group of woody plants in Australia with over 1000 different kinds (species) currently recognised. Formerly, *Acacia* was a larger genus but recent research has shown that most of the 300 species occurring outside Australia should be referred to other groups (genera). Bruce was involved in a robust international debate that resulted in the name *Acacia* being retained for the group that predominates in Australia. Acacias have great symbolic significance to Australians because wattle (*Acacia pycnantha*) is our national floral emblem, the predominant colours of wattles (green and gold) are our national colours often worn by athletes, and the Order of Australia medal, our most important honour, is based on a single wattle blossom.

Bruce has spent many years studying the taxonomy of wattles, and practical applications of his knowledge include finding ways to incorporate wattles into landcare, conservation and economic activities.

Bruce completed a Bachelor of Science (Honours) and a Master of Science degree at the University of Western Australia, but his specialist knowledge of Australian wattles has developed from 'on-the-job' experience. Western Australia, particularly the southwest, contains one of the world's richest floras.

As a taxonomist, Bruce classifies and formally names wattles as well as studying their evolutionary relationships. He observes plants in the field and collects specimens that are preserved in botanical museums (herbaria). He gathers data on the shapes, sizes and forms (morphology) of different kinds of wattle from herbarium collections and also uses data published by other taxonomists in scientific journals.

Bruce has described and named around 350 previously unknown species of wattle. Scientific names are important because they enable people to communicate information about organisms and this, in turn, provides the foundation for applied areas of biology, including forestry, horticulture and conservation. Because accurate identification is critical, Bruce has developed interactive electronic tools (keys) that guide users to the correct names for various wattles. Use the **Wattles** and **What plant is that?** weblinks in your eBookPLUS for help in identifying wattle species.

eBook*plus*

Weblink
Wattles
What plant is that?

Bruce's taxonomic work is used to develop conservation strategies. The geographic distribution and the conditions under which each kind of *Acacia* lives are documented so that rare and geographically restricted kinds have been identified. Bruce's department and other organisations responsible for land management can use this information to formally declare (gazette) these endangered kinds so that they and their habitats are protected.

Bruce's taxonomic work is also used in applied areas. Australian *Acacias* are used for a wide range of environmental, social and commercial purposes worldwide. For example, *Acacia mearnsii* (black wattle) is an important source of tannin for the leather industry and is cultivated especially in South Africa and Brazil, while *Acacia mangium* (brown salwood) is grown in Indonesia, Vietnam and Malaysia for its wood, which is used in furniture and paper manufacture. Coojong (*Acacia saligna*) is used extensively for fodder and soil conservation purposes in north Africa (see figure 7.36b). Australian Aborigines used wattles for medicines, weapons and food, for example, seeds of wirewood (*Acacia coriacea*) (see figure 7.36c). Around 50 species of *Acacia* have potential for cultivation in southern Australia as part of the fight against increasing salinity, a serious environmental threat in Australia.

FIGURE 7.36 **(a)** Bruce Maslin, botanist and taxonomist **(b)** Coojong (*Acacia saligna*), one of the most promising species for use in the fight against salinity in southern Australia **(c)** Pods and seeds of wirewood (*Acacia coriacea*)

Biodiversity: a medicine cabinet and more

The biodiversity of the natural world represents a rich source of organic substances that have the potential to play a role in curing or preventing disease.

Think about established or historical drugs, such as:

- aspirin derived from the bark of the willow (*Salix alba*)
- digitalis extracted from foxgloves (*Digitalis* spp.) (see figure 7.37a)
- penicillin from a fungus (*Penicillium chrysogenum*) (see figure 7.37b)
- Taxol®, a commonly prescribed cancer drug originally derived from the Pacific yew (*Taxus brevifolia*)
- quinine, an antimalarial drug from the bark of *Cinchona* species.

These examples provide ample evidence that organisms are a potential source of new pharmaceuticals.

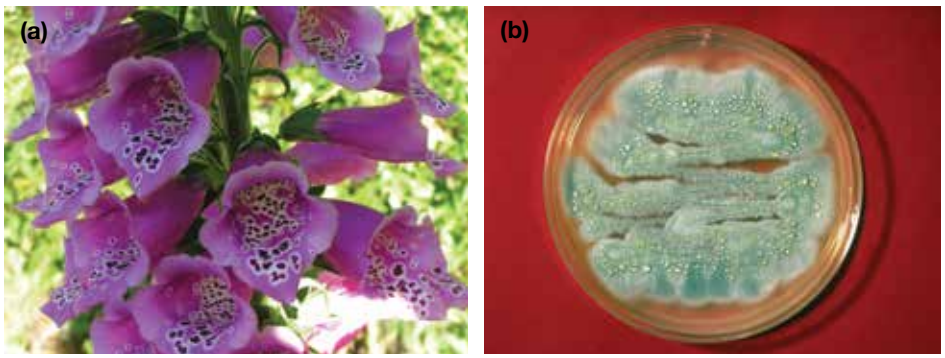


FIGURE 7.37 **(a)** The common foxglove (*Digitalis purpurea*), a source of the drug called digitalis that is used in the treatment of heart conditions **(b)** The *Penicillium chrysogenum* fungus is the source of the antibiotic, penicillin.

Research has shown that traditional plant remedies used in the Middle Ages that were believed to have particular curing properties do indeed contain chemicals with biological activity. For example, the feverfew plant (*Tanacetum parthenium*), used as a traditional remedy, has been shown to contain two chemicals with anti-inflammatory properties.

Sweet wormwood (*Artemesia annua*), an endangered weed, is the only source of the drug artemisinin, which is highly effective and fast-acting against malaria caused by *Plasmodium falciparum*.

A sea squirt or tunicate (*Ecteinascidia turbinate*) from West Indian seas is the source of a drug that is under investigation for use in the treatment of soft tissue sarcomas, one type of cancer. It has been approved for clinical use in Europe under the trade name Yondelis.

These few examples illustrate the value of biodiversity as a source of drugs and the potential for it to be a source of new drugs in the future. Loss of biodiversity is a potential loss of a disease-curing drug.

Plants in the wild and some bacterial species represent valuable sources of genetic material that might confer resistance to particular diseases, to drought or to high-salt conditions, or have the ability to produce a particular chemical such as a vitamin. Incorporation of these genes into existing crop plants would be expected to produce benefits including yields of greater quantity or quality.

The biodiversity of the plant world also represents a resource from which new foods may be identified.

New species continue to be found

It is not surprising that new species are found every year. More than 1200 new species of plant and animal were found in the Amazon region of

FIGURE 7.38 Rusticles on the iron railings of RMS Titanic. In 2011, a new bacterial species was identifed from these rusticles.

South America in the 10-year period from 1999 to 2009. Worldwide, about 17 000 new species are discovered each year. Discoveries of new species are not necessarily made in remote and unpopulated areas. For example in 2002, scientists found a new species of centipede in a pile of leaf litter in Central Park in New York City.

Discovery of a new species is sometimes a result of advanced-technology deep-sea explorations or the result of expeditions by scientific teams into rainforests. Figure 7.38 shows the bow of the wreck of RMS *Titanic* lying almost 4 km below the surface of the North Atlantic Ocean. Note the 'rusticles' that have formed on the iron railings. A sample of a rusticle was collected by *Mir*, a Russian self-propelled deep submergence vehicle, in 1991. Later analysis revealed the presence of many organisms in the rusticle. One of the organisms identified was a new bacterial species that was given the scientific name *Halomonas titanicae*. However, advanced technology is not always involved in the identification of new species. Discoveries of new species are often made by individuals with keen skills of observation, an enquiring mind and a sense of curiosity who notice something different, such as occurred with Dave Noble who discovered the Wollemi pine (see the box on p. 306).

Below is list of some new species discovered in recent years.

FIGURE 7.39 A new species of glass frog discovered in Costa Rica in 2015 by Brian Kubicki of the Costa Rican Amphibian Research Centre and his co-researchers. Its scientific name is *Hyalinobatrachium dianae* and its common name is Diane's bare-hearted glass frog. (Image courtesy of Brian Kubicki, Costa Rican Amphibian Research Center)

2015

A new transluscent glass frog *(Hyalinobatrachium dianae)* was found in a tropical wet forest in Costa Rica. Figure 7.39 shows the ventral view of this beautiful animal and illustrates vividly why it is a member of a group of frogs called glass frogs. (You will explore more about this frog in the Biochallenge at the end of this chapter.)

2014

- A new species of river dolphin (*Inia araguaiaensis*) in Brazil
- A new fish species, the aquitanian pike (*Esox aquitanicus*) in France
- A new species of wild banana (*Musa arunachalensis*) in India
- A new species of sea anemone (*Edwardsiella andrillae*) that hangs upside down from ice into the waters below the Ross Ice Sheet in Antarctica
- A new species of small marsupial, the black-tailed antechinus (*Antechinus arktos*) that was discovered in an area of high rainfall and high altitude near the NSW/Queensland border. This species of antechinus differs from other related species living nearby; it is distinguished from them by the yellow-orange markings around its eyes and on its rump and by its black feet and tail.

Other exciting recent discoveries in late 2014 and early 2015 were those of three new species of peacock spider in Queensland. The new species have been given the scientific names *Maratus elephans*, *M. jactatus* and *M. sceletus*. The tiny male peacock spiders are less than 5 mm long and are brightly coloured or vividly patterned. They perform elaborate courtship displays to attract females to mate with them. Figure 7.40 shows an image of one of the newly discovered peacock spiders (*Maratus jactatus*) that has been given the nickname Sparklemuffin.

It is perhaps not surprising that many small organisms are discovered each year. What is surprising is that even new species of large organisms, such as mammals and reptiles, are also discovered each year. This raises the question of how many species will be lost before they have even been discovered because of habitat destruction or natural disasters.

FIGURE 7.40 Image of the tiny peacock spider (*Maratus jactatus*) also known as Sparklemuffin. As he eyes a potential mate, he starts a courtship dance during which he waves his rear leg. These spiders are found only in Australia. (Image courtesy of Jürgen Otto)

Each species is important in its own right as a member of the ecosystem in which it lives and to which it contributes. In addition, from a human-centred viewpoint, the loss of any species represents a potential loss of new pharmaceutical products, or the loss of a biomimicry inspiration that can lead to new processes or products, or the loss of a potential new food source, or the loss of valuable gentic material, or simply the loss of a living organism of amazing beauty.

Using technology to discover and identify new species

Technology is an important tool in the discovery and identification of new species, for example:

- Both manned submersibles and remotely operated submersible vehicles (ROVs) (see figure 7.41) have revealed new species in the ocean depths.
- Global positioning satellite technology allows scientists to identify positions with high precision so that the location of new discoveries can be accurately mapped (a handy tool when you are wandering through a large, unmapped rainforest!).
- Digital recordings of the calls of birds and monkeys have been the first clues to the existence of new species.
- DNA technology is used to identify microbial species that cannot be cultured (grown) in laboratories.
- DNA technology is used to distinguish between related species by enabling comparison of multiple DNA regions.
- Computer technology enables the storage, rapid retrieval and organisation into databases of the enormous amounts of information concerning Earth's biodiversity.

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Weblink
Spider courtship dances

FIGURE 7.41 ROV *Tiburon*, a remotely operated submersible vehicle of the Monterey Bay Aquarium Research Institute, is lowered into the ocean to undertake exploratory research. It can operate to a depth of up to four kilometres below the ocean surface and is equipped with various sensors and cameras that scientists control with remote technology on the ship.

In some cases, new species result when one existing species is split into two species. For example, dolphins from Central and South America that were classified as a single species are now recognised to include a river-dwelling species (*Sotalia fluviatilis*) and a coastal marine species (*S. guianensis*).

BIOLOGIST AT WORK

Dave Noble — ranger

'I am a ranger for the National Parks and Wildlife Service of New South Wales. I work in the Gardens of Stone and Wollemi National Parks about 100 km to the west of Sydney. My job involves doing a variety of duties including fighting fires, picking up rubbish, search and rescue, wildlife surveys and writing reports. To get a job as a ranger, I completed a degree in park management at Charles Sturt University in Albury. After many interviews and lots of temporary work, I succeeded in getting a permanent position.

'I am very much an outdoors person and enjoy climbing, caving, bushwalking and canyoning. As I am a keen botanist, I am always looking at the plants around me. It was the combination of my outdoor activities and interest in plants that led me to discover the Wollemi pine in 1994. I was walking down a canyon in a remote part of Wollemi National Park when I saw a plant that I didn't recognise. I was interested to find out what type of plant it was and took a small cutting home.

'After looking through several books I gave up and decided to take it to a good friend and experienced botanist, Wyn Jones. Wyn didn't seem impressed and said it was some kind of fern. I remarked it was a large tree and left the specimen with him for a couple of days. We later visited the site to collect further specimens. The tree became known as the Wollemi pine (*Wollemia nobilis*); it was not just a new species but a whole new living genus dating from the time of the Gondwana supercontinent.

'I enjoy my work as a ranger and the surprise aspect of the job. You never know where you will end up when you turn up for work.'

In October 2005, over 100 'first generation' pines, grown from cuttings from the original trees discovered by Dave Noble, were auctioned to the public. The auction yielded more than $1 million.

In order to safeguard this unique species, no public access is permitted to the gully where the Wollemi pine was discovered — not even Dave Noble can visit the site!

FIGURE 7.42 Dave Noble

FIGURE 7.43 Just a thought!

Quick species ID: DNA

We cannot know what species exist on Earth until they have been identified, but we do know that:

- a very large number of Earth's living species have yet to be discovered, named and identified
- species are becoming extinct at a very rapid rate through factors such as habitat destruction and many may be lost before they have been discovered
- the process of identifying, describing and naming species through traditional methods is a time-consuming process.

In light of these facts, **one group of scientists is using DNA technology as a new and fast way of identifying new species of any kind** — this new technology is called **DNA barcoding**.

Supermarkets keep track of their stock and of their sales through a barcode system called Universal Product Code. Barcodes on supermarket items are machine-readable digital labels, typically a series of stripes that uniquely identifies each different type of product. In a similar way, this group of scientists proposes that all species could be identified using a short stretch of their genetic material, DNA, that would serve as a unique identifier for the species. The barcode is a particular sequence of bases (A, T, C and G) present in DNA (see figure 7.43).

For animals, the barcode is a sequence of 650 bases from the **CO1** gene (cytochrome oxidase 1) that is present in the mitochondria of all eukaryote cells.

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WoRMS World register of Marine species

For example, the unique barcode for the deepbody boarfish *Antigonia capros* (see figure 7.44) is as follows:

GCACTCCTAGGAGATGACCAAATCTACAATGTTGTAGTTACAGCACATGCCTTTG-
TAATAATTTTCTTTATAGTAATACCAATTATAATTGGAGGATTTGGAAACTGACTAAT-
TCCTTTAATGATTGGAGCCCCCGATATAGCATTCCCCCGAATGAACAATATGAGCT-
TCTGACTACTTCCACCCTCTTTTTTACTTCTCCTTGCCTCTTCTATAGTAGAAGCAG-
GGGCGGGCACTGGATGAACAGTTTACCCCCCTCTAGCTGGGAACCTGGCCCATGC-
CGGGGCATCAGTTGACTTAACAATTTTTTCTCTCCACTTAGCAGGGATTTCCT-
CAATCCTTGGGGCCATCAACTTTATCACAACTATTATTAATATGAAACCTCCCGC-
TATTTCCCAGTACCAAACTCCCCTGTTTGTTTGAGCAGTACTAATTACTGCAGTTCT-
TCTTCTCCTCTCCCTTCCCGTCCTTGCTGCCGGAATTACAATACTTCTTACAGAC-
CGAAACTTGAACACCACCTTCTTTGACCCAGCCGGAGGAGGAGACCCGATTCTTTAT-
CAACATCTATTCTGATTTTTTGGG

Different genes are being considered for plant species. The plant genes used are the **rbcL** gene and the **matK** gene.

FIGURE 7.44 The deepbody boarfish (*Antigonia capros*). Check out its details using the search engine at WoRMS, www.marinespecies.org.

Instead of the letters A, T, C and G, a DNA barcode can also be displayed as a pattern of coloured bands where A = green, T = red, C = blue and G = black. With colours, the distinctive patterns for various animal species are quite apparent (see figure 7.45).

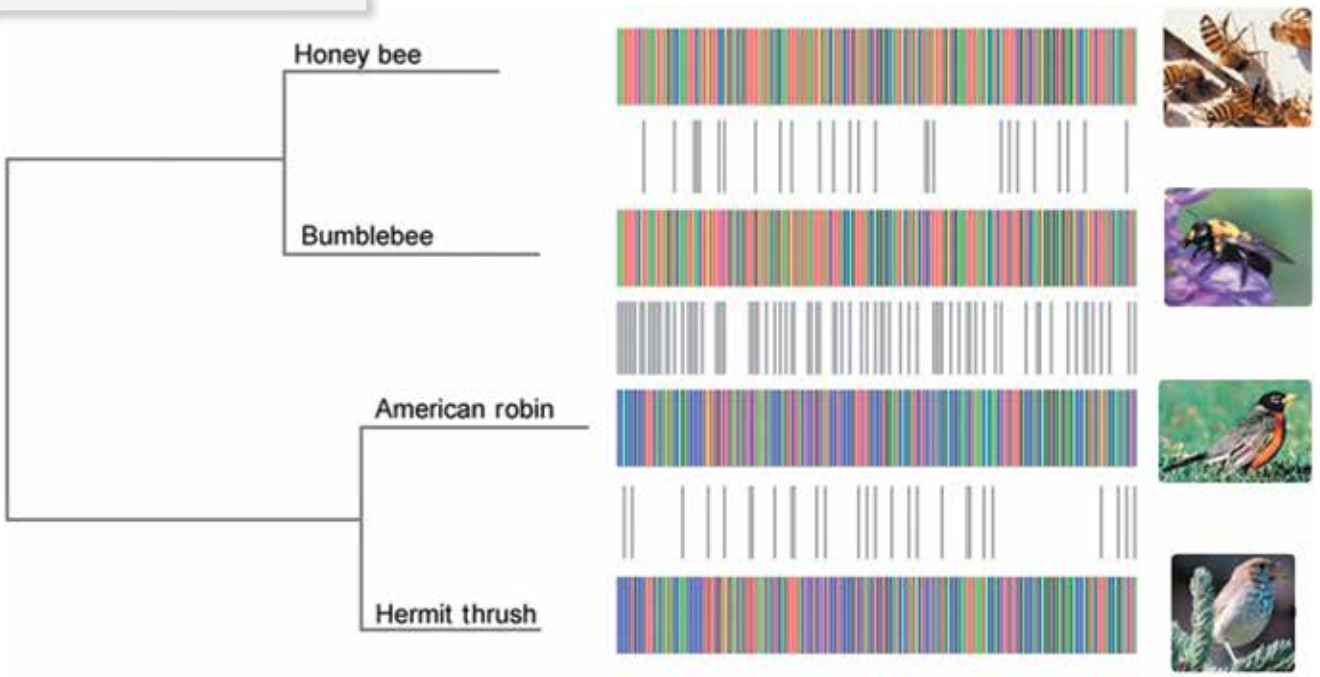

FIGURE 7.45 Part of the DNA barcodes of four different species. Each barcode is unique for the species. What do the colours represent?
Source: www.plosbiology.org.

ODD FACT

DNA barcoding requires only small samples that can be taken from living specimens or from museum specimens and can be used on fragments of biological material, such as hair, skin cells and stomach contents.

Applications of DNA barcoding include:

- identifying and separating animal species that are presently regarded as a single species because of similarity in appearance
- identifying whether a specimen is a new or an existing species.

The validity of DNA barcoding as a tool for identification is being tested. In one test reported in 2004, scientists took museum samples and showed that each of the 260 different bird species had a unique DNA barcode. This test also showed that, in one case, a bird species was in fact two distinct species. In future, it is possible that each species will have:

- its binomial name, based on a time-consuming study of structural and behavioural features using traditional taxonomy
- a DNA barcode, based on its unique genetic make-up, which is rapidly obtained.

Unlike traditional taxonomy, DNA barcoding can be done much more quickly, and will speed up species identification. Not all scientists agree that DNA barcoding can deliver reliable identification but the technique is being applied, particularly in animals, and a database of DNA barcodes has been established. This database is the Barcode of Life Database (BOLD).

Because the DNA barcodes of species are distinctive, these barcodes can be used for various purposes, including identifying:

- cases of species substitution in fish markets (and in restaurants), where cheaper fish fillets are labelled (or served) as more expensive species
- invasive pest species at quarantine checkpoints
- whether meat and leather come from farmed animals or from protected wildlife.

In addition, the DNA of a species can show detectable variation over the geographic range of the species. Where such variation exists, DNA barcodes can be used to identify the region of origin of tissues of the species. This means that barcodes can be used to identify whether timber imported into Australia comes, as is claimed, from a sustainable plantation, say in Papua, or instead from a native forest in another region.

FIGURE 7.46 The extinct dinosaur, *Muttaburrasaurus*. Where has evidence of its past existence been found?

Extinction: loss of diversity

Kinds of organism that no longer live on planet Earth are said to be **extinct**. The fossil record indicates that over geological history, many kinds of organism have become extinct.

Some organisms have been extinct for a very long time. Figure 7.46 shows the plant-eating dinosaur, *Muttaburrasaurus langdoni*, that once lived in regions that are now part of Queensland. This animal became extinct more than 65 million years ago. Other **extinctions** occurred tens of thousands of years ago. *Diprotodon*, the largest known marsupial that ever lived in Australia, was about the size of a rhinoceros and appears to have become extinct more than 10 000 years ago.

Recent extinctions

An organism is presumed to be extinct if 50 or more years have passed since the last reliable sighting. Australia holds the sad record of having lost, since the time of European settlement, more mammals through extinction than any other continent or country on Earth. Table 7.4 lists some Australian animals that are presumed to be extinct. Plants, too, have been affected with nearly 100 kinds of Australian plant presumed to have become extinct in the same period. The loss of each kind of organism represents loss of part of Australia's unique biodiversity.

TABLE 7.4 Australian vertebrate animals presumed to be extinct. When was the last reliable sighting of the desert bandicoot?

Animal	Last recorded sighting
Mammals	
thylacine, *Thylacinus cynocephalus*	1936
desert rat-kangaroo, *Caloprymnus campestris*	1935
lesser stick-nest rat or djooyalpi, *Leporillus apicalis*	1933
central hare-wallaby, *Lagorchestes asomatus*	1932
desert bandicoot, *Perameles eremiana*	1931
lesser bilby, *Macrotis leucura*	1931
Gould's mouse or koontin, *Pseudomys gouldii*	1930
crescent nailtail wallaby, *Onychogalea lunata*	1930s
toolache wallaby, *Macropus bernadus*	1924
pig-footed bandicoot, *Chaeropus ecaudatus*	1907
short-tailed hopping mouse or yoontoo, *Notomys amplus*	1896
Birds	
paradise parrot, *Psephotus pulcherrimus*	1922
rufous bristlebird, *Dasyornis broadbenti*	1906
dwarf emu, *Dromaius diemenianus*	1840s

FIGURE 7.47 The loss of thylacines from planet Earth provides warning that action to conserve the life forms of this planet can come too late. When were thylacines declared a protected species?

The last known thylacine or Tasmanian tiger (*Thylacinus cynocephalus*) (see figure 7.47), was a male named Benjamin that died in 1936 at Hobart Zoo. Not many years before that, bounties were paid for thylacine scalps. The bounty was removed on 14 July 1936 about the time Benjamin died. In 1938, the Tasmanian Government declared the thylacine a protected animal. The decision was far too late. Your great-grandparents, and even your grandparents, could have seen the beauty of a living thylacine, but you will never see one.

ODD FACT

The first clue that the Adelaide skink was not extinct came in October 1992 when a biologist found an eastern brown snake that had been killed by a car. The snake had recently eaten and the lump in its stomach was found to be an adult Adelaide skink! Later, live specimens of the skink were found.

Back from the brink!

Occasionally, kinds of organism that were regarded as extinct have been rediscovered, such as the organisms listed below.

- The mountain pygmy possum (*Burramys parvus*) was found in 1966 in a ski hut on Mount Hotham in Victoria. It was previously known only from fossil bones.
- The bridled nailtail wallaby (*Onychogalea fraenata*) was presumed extinct in the 1950s. In 1973, however, a small population was discovered near Dingo, Queensland.
- The Adelaide skink (*Tiliqua adelaidensis*) had been seen only twice in the twentieth century, the last time in 1959. It was presumed extinct; but was rediscovered in 1992.

FIGURE 7.48 The Alice Springs mouse or djoongari (*Pseudomys fieldi*), thought to be extinct, can still be found on Bernier Island off the coast of Western Australia. (Image courtesy of W Lawler, Australian Wildlife Conservancy)

- The Alice Springs mouse or djoongari (*Pseudomys fieldi*) (see figure 7.48) was thought to be extinct, having last been seen in 1895. In 1998, biologists realised that the Alice Springs mouse was identical with the Shark Bay mouse that lives on Bernier Island off the west coast of Western Australia. So, the Alice Springs mouse survives today, but about 2000 km from the place after which it was named! Figure 7.48 was taken at Faure Island Wildlife Sanctuary, a protected area where the Australian Wildlife Conservancy are reintroducing the species.
- The wrinkled button plant (*Leptorhynchos gatesii*), last seen in 1922, was found again in 1983.

Stopping the loss

At present, various kinds of living thing on Earth are becoming extinct at a rate that is estimated to be faster than ever before. The Australian Museum in Sydney estimates that various kinds of plant and animal are becoming extinct at the rate of several kinds every hour. Many organisms will become extinct before they have been discovered, studied, classified and named by biologists. Why has the rate of extinction increased?

Living things are dependent on their surroundings, which include both physical and other kinds of living thing. Actions that change, degrade or destroy an environment affect the survival of all living things in that region, increasing the risk of extinction for rare kinds of organism and contributing to the extinction of organisms whose range is restricted to that region alone. Such actions include:

- excessive clearing of native grasslands and unsustainable loss of old growth forests
- overgrazing
- changed frequency of fire
- degradation of water quality in rivers, lakes and estuaries
- introduction of exotic plants, predators and diseases
- unregulated exploitation of terrestrial and marine wildlife.

Because of the interdependence of living things, the loss of one kind of organism does not stop there. If it is a source of food or shelter for other kinds of organism, they too will be at risk, and so on.

Stopping the loss of biodiversity depends on taking action to reverse or repair damage already done and to compensate for (or slow to sustainable rates) the consequences of actions identified above.

study on

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Topic 2
Concept 2

Maintainence of biodiversity
Concept summary and practice questions

KEY IDEAS

- Earth's biodiversity is variously estimated to comprise less than 10 million species.
- Discovery of many new species continues every year.
- Taxonomy is the science of systematically identifying, naming and describing species and organising them into related groups.
- Species can be defined in various ways, with each definition having different applications and limitations.
- DNA barcoding is a new tool for the rapid identification of species.
- Extinction refers to the permanent loss of all members of a particular kind (species) of living organism from Earth.

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QUICK CHECK

8 Identify whether each of the following statements is true or false.
- **a** Most living organisms on Earth have been identified, described and named.
- **b** The classic definition of a species is useful for fossil species.
- **c** Only a few species remain to be discovered.
- **d** More species of insect are estimated to exist than species of bird.

9 Species can be defined in different ways. Which of the ways is most useful in the case of a fossil specimen?

10 List two ways that technology has assisted the discovery of new species.

11 Give one example of the successful use of DNA barcoding in species identification.

12 If a species of possum has disappeared completely from a large area, but a small population is later found on a distant island, is this an example of extinction? Briefly explain.

Classification: forming groups

The biodiversity of planet Earth comprises millions of different species. How can this enormous amount of biological data be organised in a meaningful way? This is done through the process of **classification**, which involves:

1. naming and describing each different kind of organism or species
2. organising closely related species into groups
3. combining these groups to form larger, more inclusive groups.

We have already seen how species are named (see pp. 297–8) and we will now explore how species are organised into groups. As we saw on page 299, the rules and principles of classification are part of the special area of biology known as **taxonomy, the science of systematically identifying and describing species and organising them in related groups.** Let us look first at the principles of classification and then at biological classification.

Principles of classification

Consider the following people: Shane is sorting stamps to put in a new album, Rosie is adding some new releases to the display of CDs in her music store and Tracey wants to locate a biology book from a library. A botanist, Tran, looks at a plant and says 'That's a fern.' What do these people have in common?

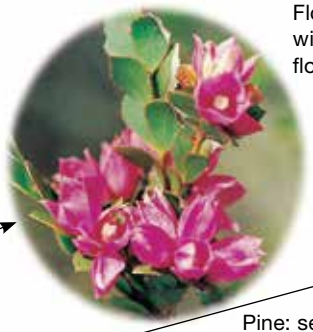
Each of these people is involved with an aspect of classification.

- Shane is *creating* a classification scheme by separating his stamps into groups by country of origin. The basis on which groups are formed is known as a **criterion** — in this case, 'country of origin.'
- Rosie, the music storekeeper, is *adding* new items to an existing classification scheme by putting new CDs to a display, previously arranged in separate areas by type of music (classical, rock etc.) and, within each area, alphabetically by name of the composer or performer(s).
- Tracey is *retrieving* an existing book from a library organised according to the Dewey classification scheme. She goes to the 500s section for biology.

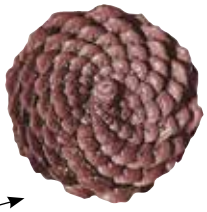
The classification of stamps, CDs and books involves their physical separation into groups. In contrast, the classification used by Tran, the botanist, is an intellectual exercise in which mental categories of objects are formed.

Tran organises plants into different groups according to the presence or absence of various features. Seeing a particular green plant having distinctive fronds with spores on their undersurface, Tran identifies it as belonging to the category labelled 'fern.' Tran uses a series of decisions, known as a dichotomous key (see figure 7.49), to organise the plants into groups.

DECISION	1a	Plant produces seeds	Go to 2
	or		
	1b	Plant produces no seeds	Go to 3
DECISION	2a	Seeds enclosed with ovaries	It's a flowering plant!
	or		
	2b	Seeds exposed on scales of cones	It's a conifer!
DECISION	3a	Dominant stage of life cycle is the diploid stage that produces spores	It's a fern!
	or		
	3b	Dominant stage of life cycle is the haploid stage that produces gametes	It's a moss!



Flowering plant: seed producer with seeds produced in ovaries of flowers



Pine: seed producer, with seeds carried on cones

Fern: spore-producing stage dominant (the dark lines on the undersurface are small brown spore-producing structures)

Moss: gamete-producing stage dominant

FIGURE 7.49 These plants are organised into four major groups using a dichotomous key as shown.

Features of classification schemes

- *Classification schemes can vary depending on their function.* There is no single correct way of classifying a group of items. Classification schemes can use different criteria to organise the same set of items. A plant nursery owner might classify plants on the criterion of size and group them into 'trees', 'shrubs', 'creepers' and 'herbaceous plants'. In contrast, indigenous tribespeople might classify them as 'edible', 'non-edible' and 'poisonous'.
- *Usefulness of classification schemes depends on the criteria selected.* Useful classification schemes involve criteria that are:
  - objective (rather than subjective)
  - meaningful (rather than arbitrary).

An objective criterion is one that has the same meaning for different people; for example, with books, an objective criterion is 'subject matter' while a subjective criterion is 'interest level of contents'. Use of objective criteria in classification gives reproducible and predictable results, no matter who uses it. A meaningful criterion conveys useful information about what members of a particular group have in common, in contrast to an arbitrary criterion. For classical CDs, 'composer' is a meaningful criterion that provides useful information, in contrast to an arbitrary criterion such as 'colour of CD label'.

- *Classification schemes are not fixed but can change as new information becomes available.*
- *Classification schemes can be single or multi-level.* Shane organised his stamps into a single-level scheme using one criterion. Rosie used two criteria and produced a multi-level scheme (see figure 7.50). A multi-level scheme is also called a hierarchical scheme. We will see later (pp. 314–16) that biological classification involves a hierarchical scheme.

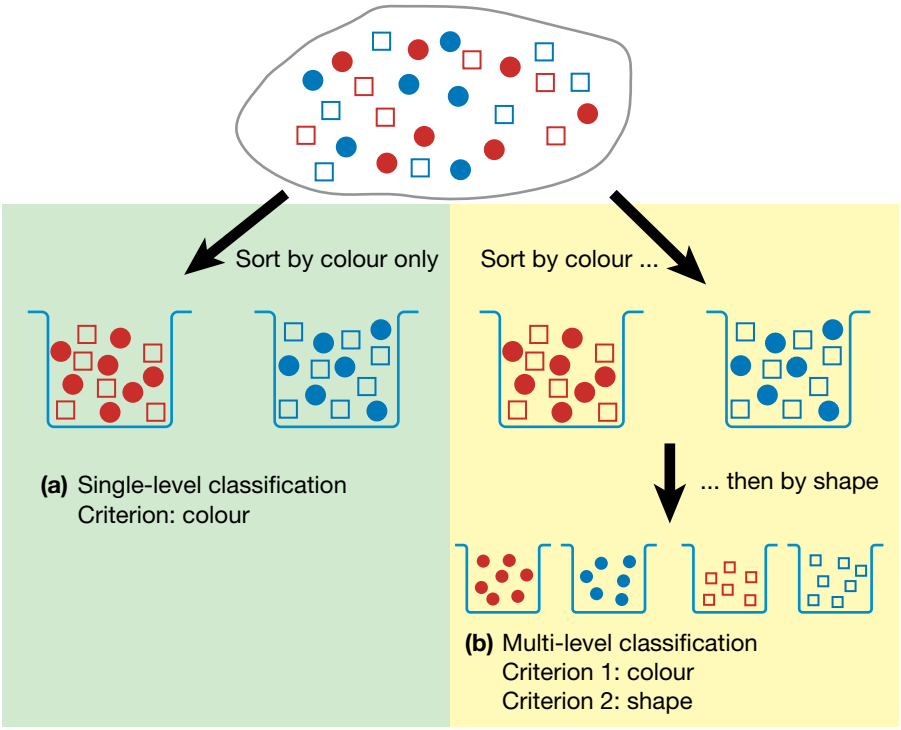


FIGURE 7.50 **(a)** Single-level classification schemes use one criterion. **(b)** Multi-level classification schemes use two or more criteria. How many criteria are used in this scheme?

ODD FACT

The Great Herball, a book published in 1526, has the following classification of fungi: 'Musheroons: There be two manners of them; one manner is deadly and slayeth them that eateth them and be called tode stools, and the other doeth not'. What criterion was used to group the fungi?

FIGURE 7.51 Knowledge of classification allows biologists to make predictions about a kind of organism — but *not* about its pet name!

Benefits of classification

Think about trying to find a phone number if the entries in a phone book were not organised alphabetically. Think about finding a book in a library if the books were just shelved in order of date of delivery. Think about communicating information about biodiversity if every organism, both living and fossil, was treated as an individual, unrelated item: aardvark, ammonite, armadillo, artichoke, avocado, and so on, to zebra, zebu, zinnia, zokor, zorro.

Classifying or organising different kinds of organism into a smaller number of groups using objective and meaningful criteria produces benefits.

- It is easier to deal with a smaller number of groups than a very large number of separate items. For example, the group 'family Felidae' refers to all members of the cat family including lions, leopards, cheetahs, jaguars, pumas, lynxes, ocelots and domestic cats.
- Classification can provide information. For example, what are zokors? Zokors are members of the order Rodentia and this label conveys the information that zokors are mammals closely related to mice and rats.
- New items can be added in a predictable way. For example, when a new kind of organism is discovered, it is compared with known groups and is classified as part of an existing group with which it shares key similarities.
- Information about items can be easily retrieved. For example, if a scientist wishes to access data about the group of invertebrate animals with soft bodies enclosed within paired shells of equal size, this can be done by accessing data about the animal group known as class Bivalvia.
- Predictions can be made about an item based on knowledge of its classification (see figure 7.51). If, for example, biologists read that a newly discovered fossil specimen has been classified as a member of the class Mammalia, they can confidently predict that its skull will show features characteristic of all members of that group, including a lower jawbone made of a single bone and teeth differentiated into various types. Examine figure 7.52. Can you identify the mammalian skull? The lower jaw of the reptile is made of several bones and its teeth are not differentiated into incisors, canines, premolars and molars, as is the case in mammals.

FIGURE 7.52 Two fossil skulls. Only one can be classified as belonging to the group known as Class Mammalia. Can you select which? (The other belongs to the group known as Class Reptilia.) You are a mammal. What prediction can you make about your lower jawbone?

Biological classification: forming a hierarchy

The system of biological classification forms a nested hierarchy of levels from species to phylum (see figure 7.53). Any level of classification — species, genus and so on — can be called a **taxon** (plural: taxa). The species level is the least inclusive and contains just one kind of organism. In contrast, the phylum level may contain a large number of organisms; for example, the phylum Mollusca contains more than 85 000 accepted species.

The closer the evolutionary relationship between two organisms, the more similar their classification. Two organisms that belong to the same genus are more closely related than two organisms that share only the same family membership.

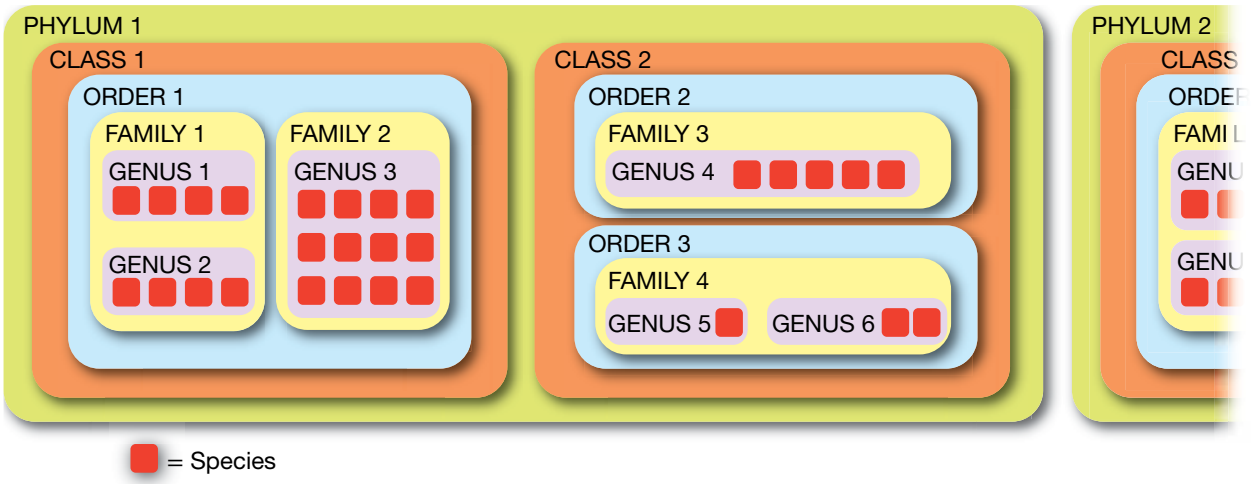


FIGURE 7.53 Classification schemes for organisms form a hierarchy.

Each different kind of organism, living or extinct, is known as a species, which is the basic level of classification. Examples of species include:

- domestic cat (*Felis catus*)
- tiger (*Panthera tigris*)
- lion (*Panthera leo*)
- great white shark (*Carcharodon carcharias*)
- polar bear (*Ursus maritimus*)
- chimp (*Pan troglodytes*)
- emu (*Dromaius novaehollandiae*)
- dog (*Canis familiaris*).

Figure 7.54 shows key features of their classification. Note that:

- Closely related species form a group known as a **genus** (plural: genera). Lions and tigers are both members of the genus *Panthera*; the other species belong to different genera.
- Groups of related genera form a group known as a **family**. Cats, lions and tigers are all members of the family Felidae. The others belong to different families: family Canidae for dogs, family Ursidae for bears and family Hominidae for chimps.
- Related families form a group known as an **order**. With the exception of chimps that are members of order Primates, the other five species are members of order Carnivora.

- Groups of related orders form a group known as a **class**. Six of the species are members of class Mammalia (which have fur/hair and produce milk for their young).
- Related classes form a group known as a **phylum**. Mammals, birds and sharks are some of the classes that are grouped into phylum Chordata (see figure 7.55). What are the other classes?

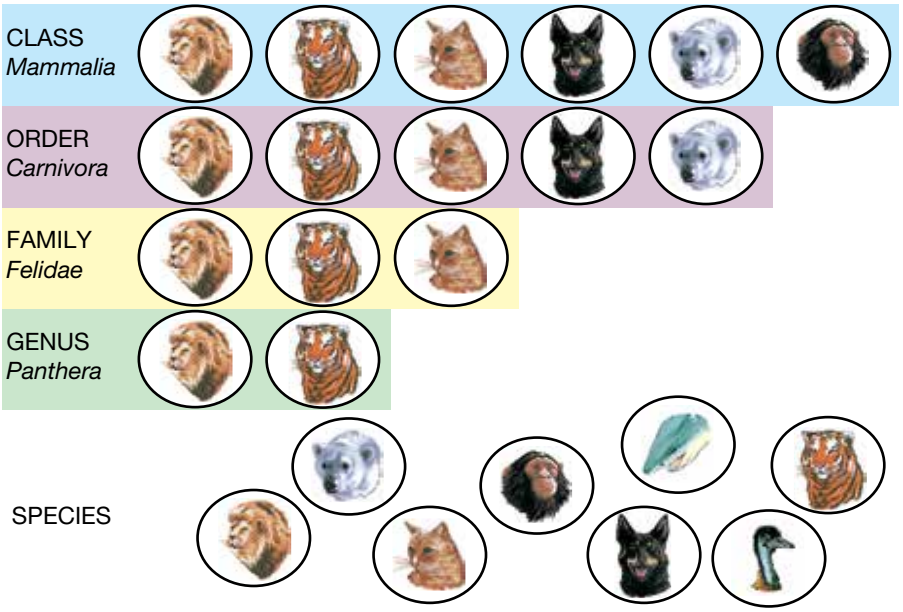


FIGURE 7.54 The hierarchical (multi-level) system of classification of organisms. Observe how, as one moves to higher levels in the hierarchy, each group becomes more inclusive and contains more species.

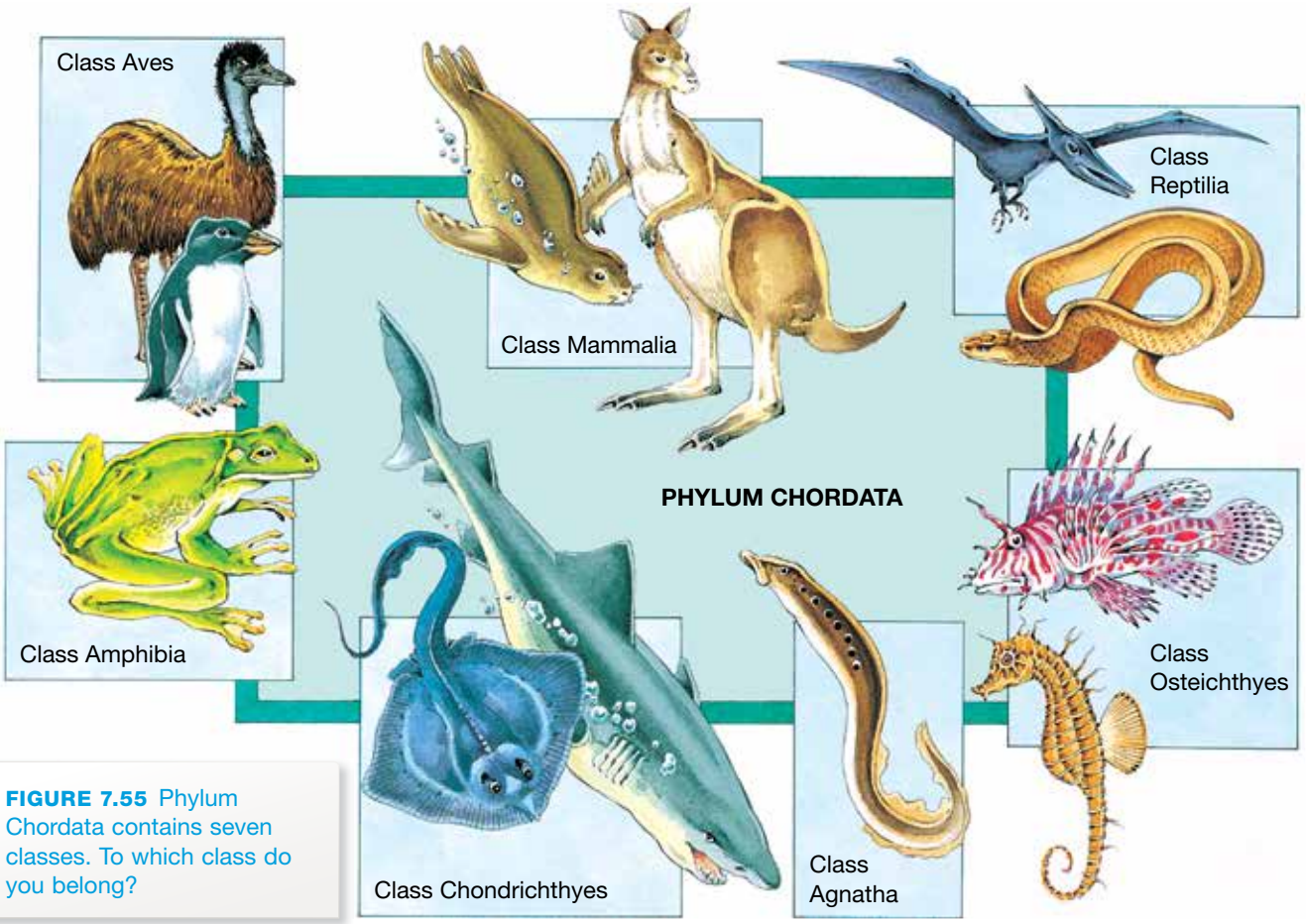
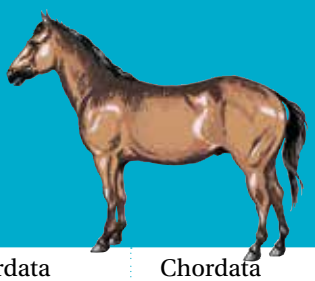


FIGURE 7.55 Phylum Chordata contains seven classes. To which class do you belong?

The classification of five animal species, including an extinct species of ammonite, is shown in table 7.5.

TABLE 7.5 Classification of five animal species. Based on this information, which two are most closely related?

	Human	Horse	Black rhinoceros	Dog	Ammonite
					
phylum	Chordata	Chordata	Chordata	Chordata	Mollusca
class	Mammalia	Mammalia	Mammalia	Mammalia	Cephalopoda
order	Primates	Perissodactyla	Perissodactyla	Carnivora	Ammonitida
family	Hominidae	Equidae	Rhinocerotidae	Canidae	Dactylioceratidae
genus	*Homo*	*Equus*	*Diceros*	*Canis*	*Dactylioceras*
species	*Homo sapiens*	*Equus caballus*	*Diceros bicornis*	*Canis familiaris*	*Dactylioceras commune*

Classification also applies to plants and table 7.6 shows the identification and classification of the peppermint gum.

TABLE 7.6 Classification of peppermint gum, one of the eucalypts whose leaves are eaten by koalas. What kind of fruit would *Eucalyptus marginata* have?

division	Spermophyta	It produces seeds.
class	Magnoliidae	It is a flowering plant having an embryo with two seed leaves or cotyledons.
order	Myrtales	It belongs to a group that includes some members with dry fruit and some with fleshy fruits; water-conducting tissue (xylem) in the stem is internal to the sugar-conducting tissue (phloem).
family	Myrtaceae	It produces aromatic oil from glands in the leaves, and has dry woody fruits, known as nuts.
genus	*Eucalyptus*	It is one of the eucalypts with each flower bud covered by a woody cap.
species	*Eucalyptus radiata*	It is the common peppermint gum tree, with grey fibrous bark and narrow leaves.

Classifications can change

Biological classifications can change. Organisms originally identified as belonging to a single species may later, as a result of further study, be split into two different species. Traditional classifications were based on structure and organisms were grouped because of similarities in their structures. Major changes in classification can occur as a result of **DNA sequencing** and **protein sequencing**. Technological advances in the last decade have made it possible to sequence DNA segments, specific genes and proteins very quickly and cheaply. Sequence data are held in a database that can be accessed by scientists worldwide and have become new tools in classification.

One example of a changed classification involves the Australian mountain brush-tailed possum, found in forests in eastern Australia from Queensland to Victoria (see figure 7.56). It was originally believed that this possum was a single

species with the scientific name *Trichosurus caninus*. Based on extensive studies of the structural and molecular features of these possums, it was concluded in late 2002 that the northern and the southern populations were in fact two different species. The northern species has retained the scientific name *Trichosurus caninus* but has been given the common name of short-eared possum. The Victorian species now has the scientific name *Trichosurus cunninghamii* and is commonly known as the mountain brush-tailed possum. One species has become two!

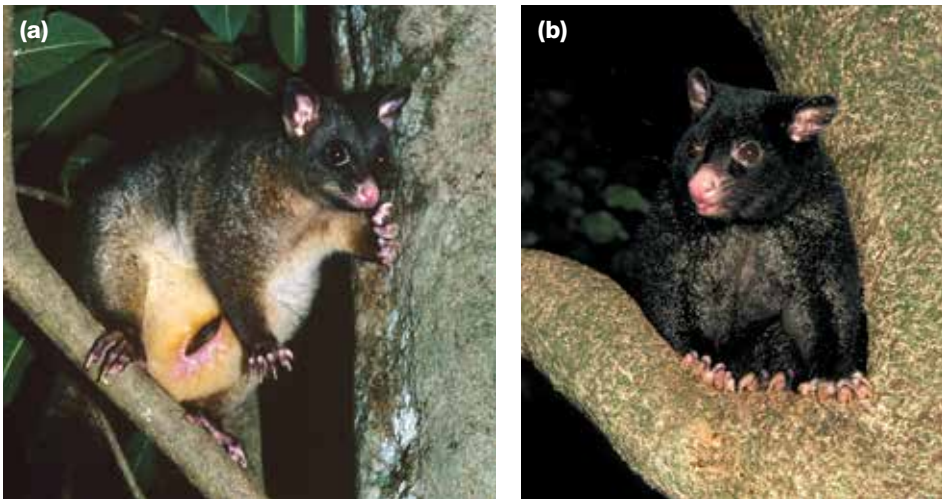


FIGURE 7.56 These possums, once thought to be a single species, are now classified as two species: **(a)** the short-eared possum in the north (*Trichosurus caninus*) and **(b)** the mountain brush-tailed possum in the south (*Trichosurus cunninghamii*). This was first reported in 2002 in *Australian Journal of Zoology*, vol. 50, p. 369.

FIGURE 7.57 One of the Asian tree shrew species, *Tupaia glis*. Two major changes have occurred in their classification. To which order do they now belong?

Tree shrews are a group of small mammals (see figure 7.57) that live in tropical rainforests in Asia; about 30 different species have been identified. Oriental tree shrews are not shrews and most do not live in trees! Tree shrews were originally classified as members of the order Insectivora, which includes hedgehogs, moles and shrews (real ones!). In 1945, tree shrews were reclassified as members of the order Primates, which includes lemurs, monkeys and apes. However, DNA technology showed later that tree shrews are not closely related to primates and they have now been reclassified as the only members of a new group known as Order Scandentia.

How are groups formed?

Taxonomists have organised all the known animal species presently living on Earth into nearly 40 phyla. These animal phyla are subdivided into about 80 different classes and nearly 400 orders. All the plant species on Earth have also been organised into phyla (also known as divisions). Among the plants, there are more than 260 000 different species of flowering plants and taxonomists have classified them into two classes, more than 200 orders and more than 500 families.

How are decisions made about what should be included within the various groupings? Organisms that are directly descended from a common ancestor are placed in the same genus. But which genera should be grouped into the same family? What other mammals should be included with dogs in the family Canidae? Biologists wish to group organisms according to inferred degrees of evolutionary relationship (see figure 7.58). One approach to identifying the relationships between various organisms and deciding which organisms should be included in particular groups, such as genus, family and order, is **cladistics**.

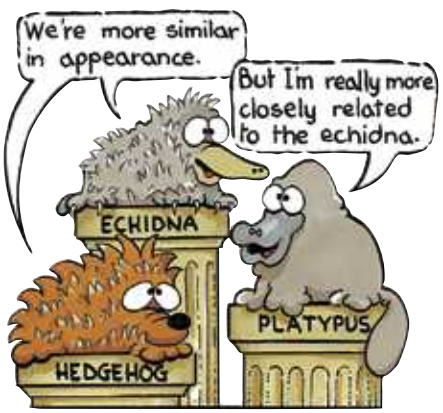


FIGURE 7.58 Which two animals appear more closely related? The most closely related pair is the echidna and the platypus.

Cladistics: recognising relationships

Cladistics asks the question 'How many derived features do they share?' to identify which organisms should be included in a particular genus, family or order.

Characters seen in a particular group of organisms can be identified as primitive or derived. For a particular group, **primitive characters** are features that were present in their common ancestor and so appear in all members of the group. In a group of mammals, for example, a primitive or ancestral feature is the presence of fur. Why? Because this feature was present in the common ancestor of all mammals. **Derived characters** are advanced or modified features that evolved later and appear *in some members only* of the group in question. In a group of mammals, for example, a derived feature is the presence of nails on fingers and toes. Why? The hands and feet of the common ancestor of all mammals had claws so this is the primitive state; nails evolved later in one group of mammals, the primates, so this is the derived state.

In cladistics, only *shared* derived features can be used. (Derived features that are present in one member only of a group being studied cannot be used in cladistics.) The result of a cladistics analysis is shown in a diagram known as a **cladogram** (see figure 7.59). Branching points (forks) occur on the cladogram each time a derived character appears in some members of the group. A cladogram shows the evolutionary relationship between particular organisms based on the derived characters that they share. Various groups containing all organisms descended from a common ancestor are formed and these groups are used as the basis for various levels of classification.

Cladistics can also be used to identify the relationships between genera within a family, such as family Equidae, the horse family. Using various derived features, living and extinct horses can be related, as shown in figure 7.68 on page 325.

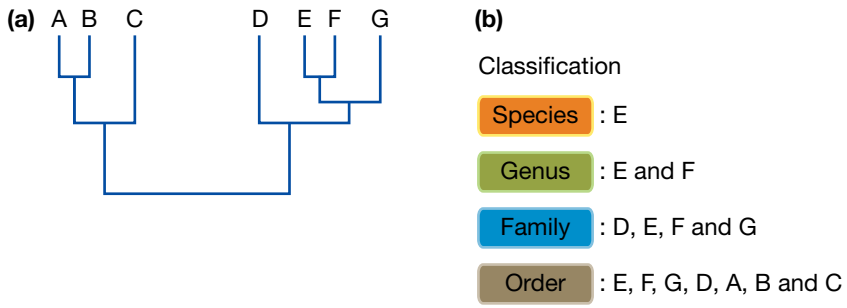


FIGURE 7.59 **(a)** A cladogram showing the presumed relationship **(b)** From this cladogram, classification groups can be formed. Organisms grouped in the same genus are the most closely related, for example, E and F. Families are formed from the next most closely related organisms, for example, E, F and G.

Cladograms show evolutionary relationships but do *not* give the evolutionary history of the organisms (or groups) since they all appear at the end of the branches and no ancestral organisms are identified.

Beyond the phylum

The species biodiversity of Earth is made up of several million different kinds of organism. We have seen that this biodiversity can be progressively organised into larger groups up to the level of phylum (plural: phyla). Phylum comes from the Greek *phylon* = tribe.

- Animals are organised into more than 30 phyla, but the majority (about 95%) of animal species fall into about 9 phyla.
- Plants are organised into 12 divisions or phyla.
- Fungi are organised into 6 phyla.
- Bacteria are organised into at least 29 phyla.
- Archaea are organised into 5 phyla.

FIGURE 7.60 Sea pens belong to the class Anthozoa ('flower animals'), a group that also includes anemones and corals. This sea pen (*Sarcoptilus grandis*) is a sessile (nonmotile) marine animal. It occurs in eastern Australian seas and grows to a maximum length of about 40 cm. Why does this not fit the Linnean definition of an animal?

What lies beyond the level of phylum?

The entire biodiversity of planet Earth has been organised by various biologists at different times into a small number of major groups. The most important are the:

- two-kingdom system of Linnaeus
- three-kingdom system of Haeckel
- five-kingdom system of Whittaker
- three-domain system of Woese.

Kingdoms: 2 to 3 to 5

The Swedish biologist Carolus Linnaeus (1707–78) classified the living world into two **kingdoms** — vegetables (plants) and animals — so identifying every species as either a plant or an animal. Linnaeus stated that members of the Animal Kingdom 'have life, sensation and the power of locomotion', while members of the Plant Kingdom 'have life and not sensation'. The Linnean two-kingdom system lasted for about one hundred years, but organisms such as bacteria and single-celled eukaryotes like *Amoeba* did not fit well into the two-kingdom system. In addition, some animals and plants are atypical, such as sea pens, which are immobile (sessile) animals (see figure 7.60).

In 1866, a German biologist, Ernst Haeckel (1834–1919), proposed a three-kingdom system that comprised Kingdom Animalia (animals), Kingdom Plantae (plants and fungi) and Kingdom Protista (everything else). The Protista kingdom created by Haeckel included bacteria and single-celled eukaryotes.

In 1969, an American biologist, Robert H Whittaker, proposed a five-kingdom system (see figure 7.61). Whittaker created two new kingdoms. One was Kingdom Fungi, which separated fungi from plants, and the other was Kingdom Monera, which encompassed all prokaryotic organisms, such as bacteria. Kingdom Protista, as was the case for Haeckel, was a 'left-over' group that accommodated those unicellular eukaryotic organisms, such as *Amoeba* and *Paramecium*, that were not plants, animals, fungi or bacteria.

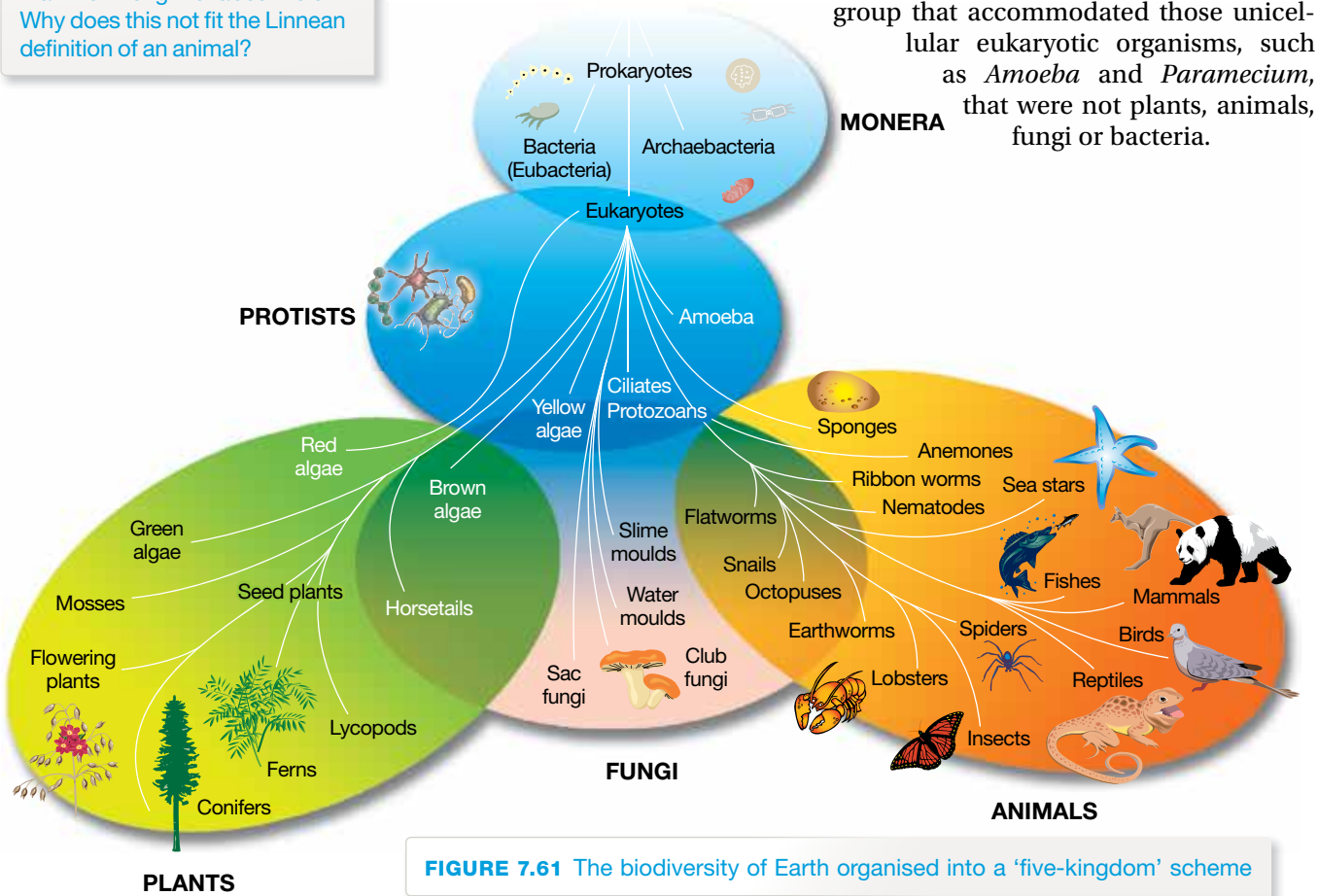
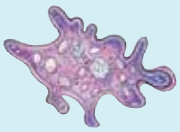


FIGURE 7.61 The biodiversity of Earth organised into a 'five-kingdom' scheme

Table 7.7 gives more detail of the five-kingdom scheme and compares the different kingdoms in terms of some key features, in particular, modes of nutrition. Which kingdom has members that display the greatest variety of obtaining energy and matter for living? How do fungi differ from plants?

TABLE 7.7 The five-kingdom system proposed by Whittaker in 1969

Five kingdoms					
Name	**Monera**	**Protista**	**Fungi**	**Plantae**	**Animalia**
Examples	• cyanobacteria • gram-positive bacteria	• *Amoeba* • *Paramecium* • *Volvox*	• moulds • yeasts • toadstools	• mosses • ferns • cycads	• sponges • lobsters • birds
Cell type	prokaryotic	eukaryotic	eukaryotic	eukaryotic	eukaryotic
Other cell features	cell walls with complex carbohydrates		cell walls with chitin	cell walls with cellulose	no cell walls
Cell number	• unicellular	• unicellular • colonial • multicellular	• unicellular • multicellular	• multicellular	• multicellular
Reproduction	• binary fission	• asexual: mitosis • sexual: meiosis	• asexual: mitosis • sexual: meiosis	• asexual: mitosis • sexual: meiosis	• asexual: mitosis • sexual: meiosis
How energy and matter for life are gained	• autotrophic – photosynthesis – chemosynthesis • heterotrophic	• autotrophic – photosynthesis • heterotrophic – ingestion	• heterotrophic – absorption	• autotrophic – photosynthesis	• heterotrophic – ingestion
					

Kingdoms: 5 to 6

In 1977, two researchers (Woese and Fox) published a scientific paper showing that members of Kingdom Monera included some microbes that were very different from typical bacteria. These researchers examined one group of microbial species, termed *methanogens*, that produce methane (CH_4) as a product of their metabolism (e.g. *Methanococcus* and *Methanothermobacter*).

Woese and Fox noted that:

1. the cell walls of methanogens lacked the complex carbohydrate present in the cell walls of typical bacteria
2. the base sequence of the ribosomal RNA (rRNA) of methanogens differed significantly from that of typical bacteria.

Based on this, Woese and Fox proposed that Kingdom Monera be split into two Kingdoms, namely Eubacteria and Archaebacteria (later called Archaea), producing a six-kingdom scheme. However, Woese recognised weaknesses in this scheme because its groupings gave the same weighting to differences between two eukaryotic groups, such as fungi and animals, as to differences between a prokaryotic group, such as bacteria, and a eukaryotic group, such as animals.

Domains: a new level of classification

In 1990, a more radical classification for all living organisms was proposed by Woese. To classify organisms, earlier schemes used physiological features, such as modes of nutrition, and structural features (morphological criteria), such as whether the organisms were built of prokaryotic or eukaryotic cells. Woese and his colleagues created a new classification scheme for the living world that used molecular criteria. They compared the order of bases in particular genes,

such as ribosomal RNA genes and other genes that code for specific proteins found in all organisms.

Based on these molecular comparisons, Woese proposed a radical new classification system that organised living things into different **domains**:

- Bacteria
- Archaea
- Eukarya.

Domains are a higher level of classification than kingdoms. Each domain is subdivided into lineages or kingdoms shown as twigs branching from the main lines (see figure 7.62).

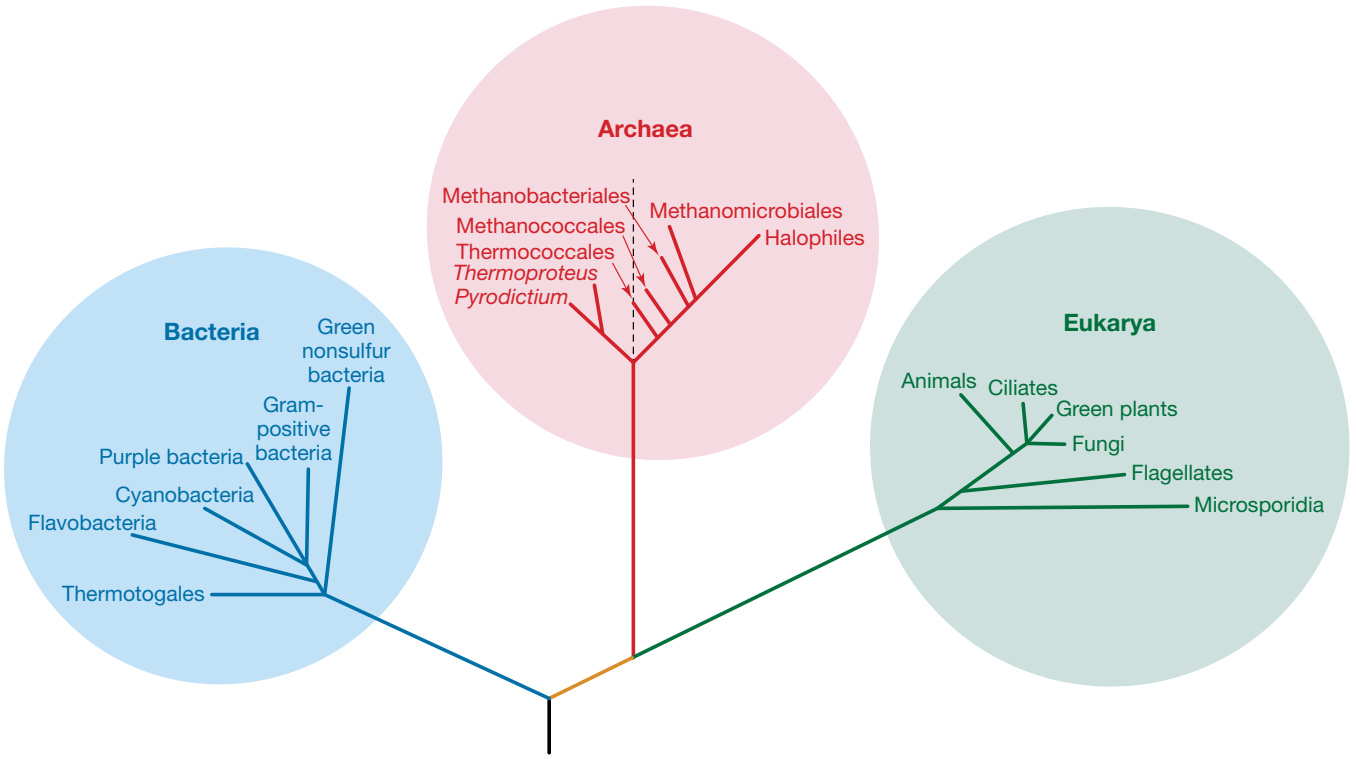


FIGURE 7.62 Phylogenetic tree showing Woese's three domains of life based on differences in rRNA sequences. Some of the lineages (kingdoms) within each domain are identified. The order of the branches and their lengths are based on comparisons of rRNA sequences. (Woese et al., *PNAS*, vol. 87, pp. 4576–9, 1990)

The Woese molecular classification:

- recognises the importance of the prokaryote–eukaryote split in evolution
- acknowledges the long evolutionary history and the separation of bacteria and archaeans
- downplays the significance of distinctions between multicellular eukaryotic groups.

The Woese classification system can assist in reconstructing major events in the evolution of life. Comparisons of the same gene from different organisms allow us to infer that, after the first forms of life evolved, a split occurred, perhaps at about 3700 million years ago, to produce two distinct lines, the Bacteria line (shown in figure 7.62 in blue) and a second line (shown in orange). The second line later split to produce the Archaea line (shown in red) and the Eukarya line (shown in green).

Carl Woese's three-domain system of classification was revolutionary. This system recognised that, while all microbes were prokaryotic, not all microbes were bacteria. Molecular studies showed that, among the microbes, two major groups could be distinguished — typical bacteria that form the **Bacteria domain** and different microbes that form the **Archaea domain**.

FIGURE 7.63 Cows release methane as a result of the methanogens that live in their stomachs.

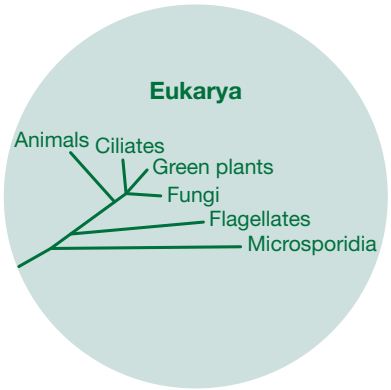


FIGURE 7.64 The Eukarya domain comprises many lineages.

studyON

Unit 1
AOS 2
Topic 2
Concept 1

Classification systems
Concept summary and practice questions

The third domain in the Woese classification system puts all other organisms — animals, plants, fungi, protists — as part of the **Eukarya domain**.

The Bacteria domain contains all the bacterial species and includes the cyanobacteria that were the earliest forms of life to capture the energy of sunlight; the **nitrogen-fixing bacteria** that can convert atmospheric nitrogen to ammonium (NH_4^+); and the **gram-positive bacteria**, many of which are heterotrophic bacteria that cause diseases of humans and other mammals. This domain is typically 'out-of-sight', except when their presence is expressed through a disease such as cholera or bacterial meningococcal disease.

The Archaea domain contains all the archaeal species, many of which are extremophiles. They thrive in extreme environments such as salt lakes, water more acidic than vinegar, water more alkaline than cloudy ammonia, oxygen-free mud of marshes and swamps. This domain includes the methane-producing archaea, known as **methanogens**, that produce methane from carbon dioxide and hydrogen and can survive only in oxygen-free environments such as swamps and in the stomachs of ruminant mammals such as cows (see figure 7.63). Another group of archaea are the thermophiles (heat-lovers) found in hot springs.

The question is often asked: do archaea cause any human diseases? Recent research published in 2013 concludes that there is no evidence that archaea are responsible for any human diseases.

Look around you — **almost all the living organisms that you see are members of the Eukarya domain.** This domain comprises all animals, plants, fungi and the various lineages of protists (see figure 7.64), and unlike the other domains is visible and not 'out-of-sight'.

KEY IDEAS

- Classification is the process of organising objects or data into groups according to one or more criteria.
- Classification schemes may be single-level or multi-level (hierarchical) depending on whether one or more criteria are used.
- Taxonomists organise Earth's biodiversity into a series of taxa that form a hierarchical, multi-level system.
- Biological classification begins with the species level and then moves through more inclusive groups such as families and phyla.
- Levels of classification above phylum are kingdoms and domains.
- The three-domain system of classification introduced in the 1990s organised all living organisms into three domains: Bacteria, Archaea and Eukarya.

QUICK CHECK

13 Identify whether each of the following statements is true or false.
- **a** Classification gives reproducible results when objective criteria are used.
- **b** A phylum is a more inclusive group than a family.
- **c** A species consists of just one particular kind of organism.
- **d** Taxonomy is the study of the biology of particular species.
- **e** Organisms in the same order must be members of the same genus.
- **f** A taxonomist stated that she had published details of two new taxa so this must mean that she published details of two new species.

14 Identify two benefits that can result from classification.

15 You are told that an organism is a member of class Bivalvia. List one prediction that you can confidently make about this organism.

16 A plant fossil is found to have many features in common with modern eucalypts. Into which family should this fossil plant be placed?

17 Identify a classification scheme that:
- **a** groups all microbes in Kingdom Protista
- **b** separates prokaryotes into two different taxa.

BIOCHALLENGE

Use the **Glass frog** webink in your eBookPLUS, where you will find the abstract of a scientific paper published in February 2015 that describes a new species of glass frog found in the wet tropical forests of Costa Rica (see figure 7.65). This new discovery becomes the fourteenth glass frog species found in this small Central American country (see figure 7.66).

eBook*plus*

FIGURE 7.65 The new species of glass frog first described in 2015. In the popular press it has been likened to Kermit of *The Muppets*. (Image courtesy of Brian Kubicki, Costa Rican Amphibian Research Center)

FIGURE 7.66 Map showing the location of Costa Rica in relation to nearby countries

Read the abstract and answer the following questions.

1 The description of the new glass frog species was based on six specimens collected at three different sites. Suggest why six specimens were used in preparing this description rather than a single frog.

2 a To what genus does the new glass frog belong?
b To what genus would those species that are most closely related to the new species belong?

3 How many features were identified as distinguishing the new species from other species of glass frog?

4 a The distinguishing features of the new species fall into three different categories. What are these three categories?
b In total, how many points of distinctive differences have been identified?

5 a A particular gene was used to measure the relationship of the new species to existing glass frog species. Which gene was this?
b Which other species of glass frog is most closely related to the new species?
c What degree of difference was found between these two species?
d The gene in part (a) has a particular application in animals (outlined earlier in this chapter). What is this use?

Chapter review

Key words

Archaea domain
Bacteria domain
binomial system of naming
biodiversity
cladistics
cladogram
class
classification
criterion
cycads
database
derived character
dichotomous key
DNA barcoding
DNA sequencing
domain
ecosystem diversity
endemic
Eukarya domain
extinct
extinction
family
field guide
generic name
genetic diversity
genus
gram-positive bacteria
herbarium
identification
keys
kingdom
macroscopic
methanogens
microscopic
nitrogen-fixing bacteria
order
palynology
phylum
polynomial system
primitive character
protein sequencing
raptor
reference collection
scats
species
species diversity
specific name
systematics
tail fluke
taxon
taxonomist
taxonomy
vascular plant

Questions

1 **Making connections** ➜ Use of last eight of the chapter key words to draw a concept map. You may use other words in drawing your map.

2 **Applying understanding** ➜ Consider the following items: cat, dog, cow, canary, budgerigar, kangaroo, emu, wallaby, platypus, elephant and tiger.
   - **a** Identify an objective criterion to divide these items into groups.
   - **b** How would you test whether your criterion is objective?

3 **Communicating your understanding** ➜ Horses and donkeys can interbreed but their offspring, known as mules, are infertile or sterile. A student stated that, because they can interbreed, horses and donkeys must be members of the same species. Do you agree? Explain.

4 **Analysing information** ➜ Three different organisms (D, E and F) belong to Kingdom Animalia.

   Animals D and E belong to the same class but to different orders.

   Animals E and F belong to the same genus but are different species.

   Classify the following statements as either 'true', 'false' or 'can't say'.
   - **a** The degree of relationship between organisms D, E and F is equal.
   - **b** The first part of the scientific names of animals D and E must be identical.
   - **c** Animals D and F must belong to the same class.
   - **d** Animals E and F must belong to the same order.

5 **Evaluating alternatives** ➜ For this question, use the 'five kingdom' classification scheme.
   - **a** Consider each statement in table 7.8 about organism X in turn and indicate what conclusions can be made about the kingdom(s) to which it might belong.

TABLE 7.8

Statement	Possible kingdom(s)
Organism X is built of cells.	
These cells each have a distinct nucleus bounded by a nuclear envelope.	
These cells have cell walls.	
These cell walls contain chitin.	

   - **b** At which point may a definite decision be made about the kingdom to which organism X belongs?
   - **c** What prediction can be made about how organism X obtains the energy and matter required for living?

6 **Applying understanding** ➜ Photographs of two different birds, A and B, are selected from a book *Birds of the World*. Photograph A is shown to a biologist who says: 'It's a magpie. Its scientific name is *Pica pica*.' Photograph B is shown to a second biologist who says: 'It's a magpie. Its scientific name is *Gynorhina tibicen*.' Could both biologists be correct? Explain.

7 **Using scientific conventions** ➜ Examine the following list showing some whale species.

Common name	Scientific name
fin whale	*Balaenoptera physalus*
southern right	*Eubalaena australis*
humpback	*Megaptera novaeangliae*
sei whale	*Balaenoptera borealis*

a How many different species are shown in this list?
b How many different genera do these whales represent?
c Identify the two most closely related whales.

8 Analysing information and making predictions ➜ Figure 7.67a shows a creeper-like plant (P). The undersurface of one of its leaves is shown in figure 7.67b. A different plant (Q) is shown in figure 7.67c.

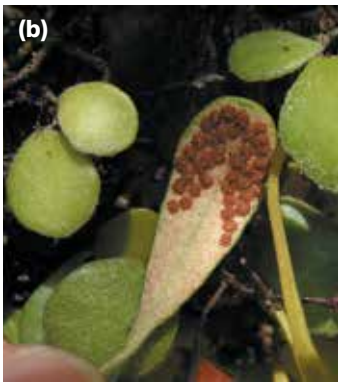


FIGURE 7.67 (a) Plant P **(b)** Undersurface of leaf of plant P **(c)** Plant Q

a Refer to the dichotomous key (figure 7.49) on page 312. On the basis of the information in figure 7.67a only, can plant P be identified?
b Using the information in figure 7.67b, can plant P be identified?
c To what level of classification have you identified this plant? (Refer if necessary to appendix C.)
d List two resources you might use to make a more precise identification.
e Now consider plant Q. You are told that it is a member of the same group as plant P. In light of this, what prediction can you confidently make about its classification?

9 Applying your understanding ➜ The diagram in figure 7.68 shows the relationship between various horse species as produced by a cladistics study (refer to p. 317). Of the horse species concerned, one is living (Equus) and the other six are extinct.
a What name is given to this type of diagram?
b Identify one primitive (ancestral) character that would apply to this group.
c Are primitive characters used in cladistics studies? Explain.
d Does this diagram show the evolutionary history of the horses?
e What shared derived feature was used to group species P and Q?

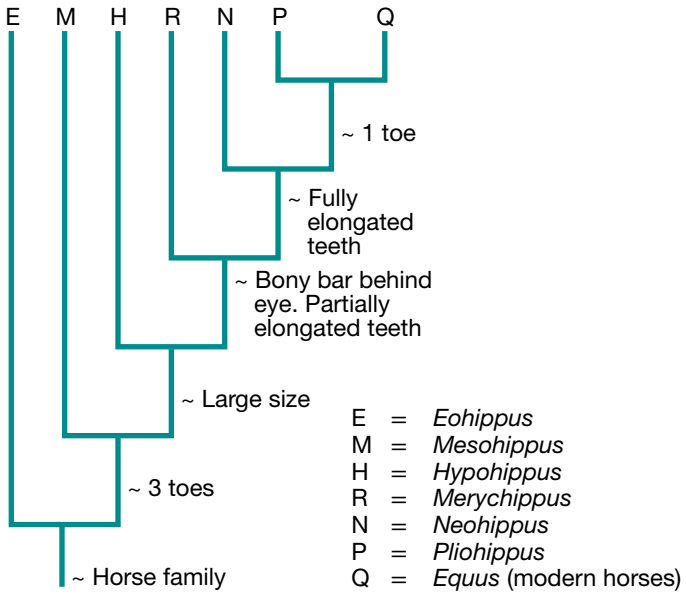


FIGURE 7.68

10 Discussion question ➜ Consider that a previously unknown kind of monkey is discovered in a tropical forest. Identify at least three steps that might be taken in order to decide whether this monkey is a new species within an existing genus or whether it should be assigned to a new genus.

11 Biodiversity has many values. These can be expressed in many terms such as:
- economic
- social
- aesthetic.

One example of the economic value of biodiversity is the value of the role of pollinators, such as bees, in providing a service to agriculture. No pollinators = no crops.

In discussion with your classmates, identify other values of biodiversity relating to any of the above categories.

CHAPTER

8 Relationships within an ecosystem

FIGURE 8.1 Part of the living community in a marine habitat. Communities consist of populations of different species living in the same habitat at the same time. Many interactions occur between members within a community and between members of a community and their environment. In this chapter we will explore communities in ecosystems and some of the interactions and relationships that occur in ecosystems.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- develop understanding of the nature of ecosystems, with particular emphasis on their living communities
- become aware of the different ecological roles of members of an ecosystem
- recognise that ecosystems require a continual input of energy, but that matter recycles within ecosystems
- recognise the inter-dependence and interactions between different members of an ecosystem
- develop knowledge and understanding of the factors that influence population size and growth
- become aware that various populations differ in their intrinsic growth rates.

A day in the life of krill

It is late summer in Antarctica and the sun shines from a cloudless sky onto the clear blue waters. While these seas appear clear, they are in fact a concentrated soup of phytoplankton, which is a mixture of hundreds of different species of single-celled microscopic algae such as diatoms, dinoflagellates and silicoflagellates. These tiny organisms possess coloured pigments that capture the energy of sunlight during the long daylight hours of an Antarctic summer. The radiant energy captured by the phytoplankton is transformed from non-material sunlight to chemical energy in carbohydrates, such as glucose. These floating phytoplankton themselves represent succulent morsels of chemical energy for hunters — such as krill.

Hunters of all sizes lurk in the Antarctic waters. The smallest are an army of zooplankton, which comprise a biodiverse mixture — tiny protists, jellyfish, fish larvae, tunicates known as salp and various crustaceans, including copepods and krill (shrimp-like organisms). Antarctic krill (*Euphausia superba*) are the most abundant organisms in the zooplankton found in these waters. Individual krill reach an adult length of about 6 cm (see figure 8.2a) and gather in swarms so dense that at times the sea water becomes red (see figure 8.2b). These enormous aggregates or super-swarms can contain more than two million tonnes of krill spread over an area of 450 km^2.

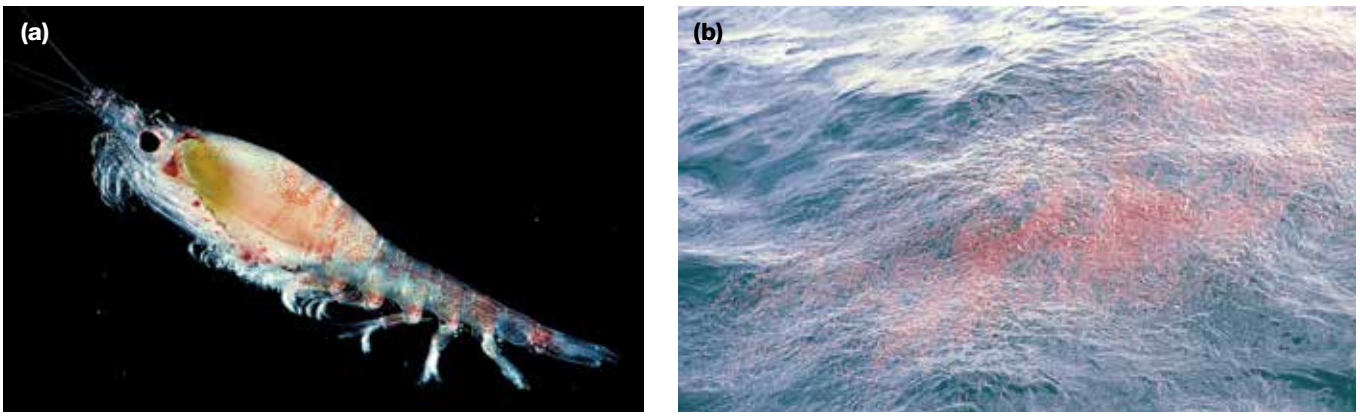


FIGURE 8.2 **(a)** One *Euphausia superba* from a swarm of Antarctic krill. Notice the bristle strainer formed by the 'feeding' limbs around the anterior end. What function might it serve? **(b)** Part of a swarm of krill colouring the Antarctic waters

ODD FACT

The term *krill* is Norwegian for 'whale food' and refers to a group of more than 80 species of shrimp-like organisms whose habitats are the tropical, temperate and polar oceans of this planet. Antarctic krill are the most numerous of all krill species. Antarctic female krill spawn twice a year, on each occasion producing several thousand eggs that fall to the sea bed where they hatch.

By day, the krill swarm typically stays in deep water. As the light dims, the swarm approaches the surface to feed on phytoplankton. Krill have five pairs of jointed limbs for swimming and other paired limbs, including six pairs of specialised 'feeding' limbs, located around their mouths, which are covered with long fine bristles — just like a built-in strainer! To capture their food, the krill enclose a quantity of water within their feeding limbs and strain it by squeezing the water through the bristle network. Small organisms, particularly phytoplankton, are trapped in the net formed by the bristles and this material is eaten. The radiant energy originally trapped by the phytoplankton has now been captured by the krill.

Suddenly, the krill swarm becomes the target of larger hunters. Adelie penguins (*Pygoscelis adeliae*) (see figure 8.3a) returning from a foraging trip have detected the swarm. They move in, swallowing the krill whole. Adelie penguins must obtain food not only for themselves, but also for the young hatched in December that wait onshore in the creche area of the penguin rookery. The young penguins are close to fledging, the period when they will replace their fluffy down

with adult feathers. Having taken as many krill as they can store in their crops, the Adelie parents begin the return journey to their rookery. Here they will regurgitate from their crops a fishy stew, known as barf, to feed their young. One Adelie penguin, however, will not complete this journey. As the penguins approach the shore, a leopard seal (*Hydrurga leptonyx*) that has been waiting for the return of the penguins dives deep into the water. Suddenly changing direction, the seal accelerates upward, seizing one of the penguins. The leopard seal vigorously shakes the dying penguin, stripping the skin from its body. The seal now eats the exposed flesh and, in feeding, obtains the chemical energy it needs for living.

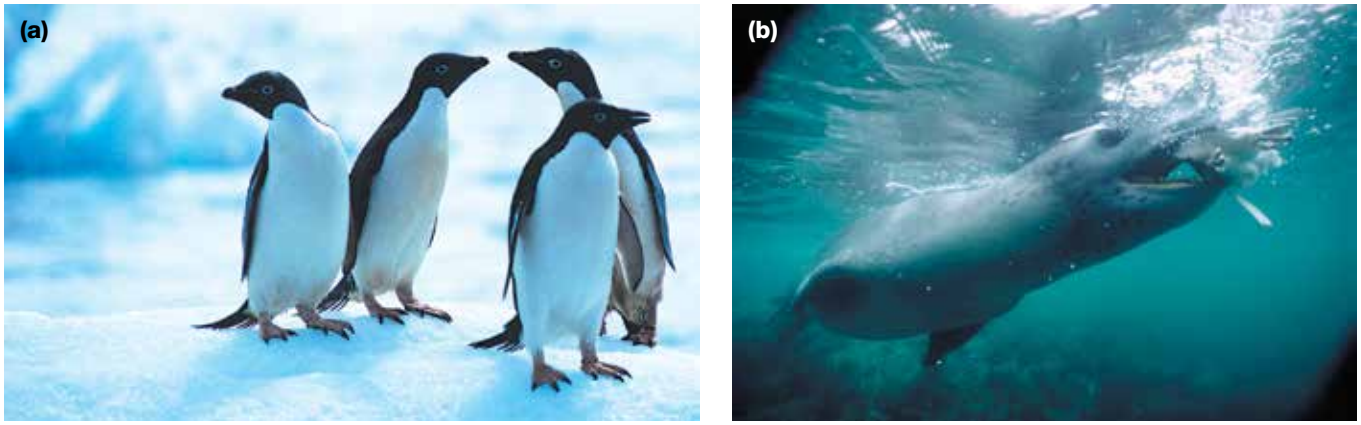


FIGURE 8.3 **(a)** Adelie penguins are consumers within the Antarctic marine ecosystem. Krill is a major source of chemical energy for them. From where do krill obtain their energy? **(b)** Adelie penguins themselves are food for higher level consumers in the Antarctic marine ecosystem. Here we see a leopard seal that has caught a penguin.

Other animals also feed on the krill swarm. Crab-eater seals (*Lobodon carcinophagus*) sieve krill from the water through their multi-lobed teeth (see figure 8.4). (In spite of their name, they do *not* eat crabs, but feed mainly on krill.) The adult crab-eater seals that feed on the krill are survivors of a much larger group of crab-eater seal pups whose numbers were reduced in part by the feeding activities of hunters such as leopard seals and killer whales (*Orcinus orca*).

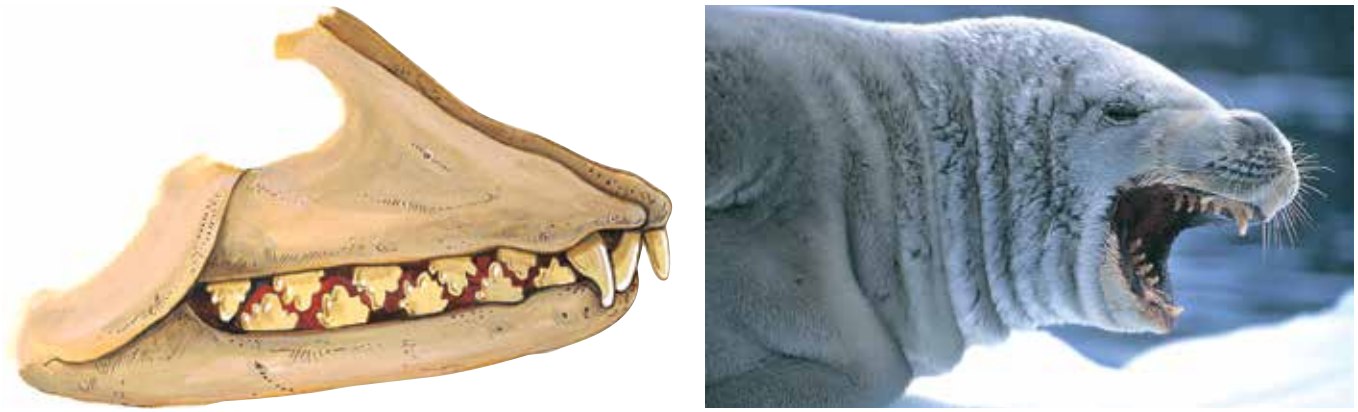


FIGURE 8.4 A crab-eater seal. Its unusual multi-lobed teeth (see inset) enable it to sieve krill from water.

The krill swarm re-aggregates after the attack by the Adelie penguins. It now becomes the subject of massive feeding activity by a pod of humpback whales (*Megaptera novaeangliae*) that circle the dense swarm at depth and then rise vertically through it, with open mouths, engulfing quantities of krill-rich water from which they filter the krill.

The krill swarm continues to feed on phytoplankton but the krill also become food for other animals, such as squid and fish. The squid, in turn, become food for flying birds (albatrosses, petrels), penguins and toothed whales. The fish are hunted by seals — Weddell seals (*Leptonchotes weddellii*), southern elephant seals (*Mirounga leonina*), Ross seals (*Ommatophoca rossii*) and Antarctic fur seals (*Arctocephalus gazella*). In spite of the feeding activities of so many hunters, the krill population over time is largely unaffected because of its high reproductive rate.

The living **community** in Antarctic seas in summer, which includes toothed and baleen whales, various sea birds, penguins and seals, depends on the seas for their food. A simplified version of the feeding relationships between these animals is shown in figure 8.5. Note the importance of krill as a direct and indirect food resource for this community. The krill, in turn, depend on phytoplankton as their food source (see figure 8.6).

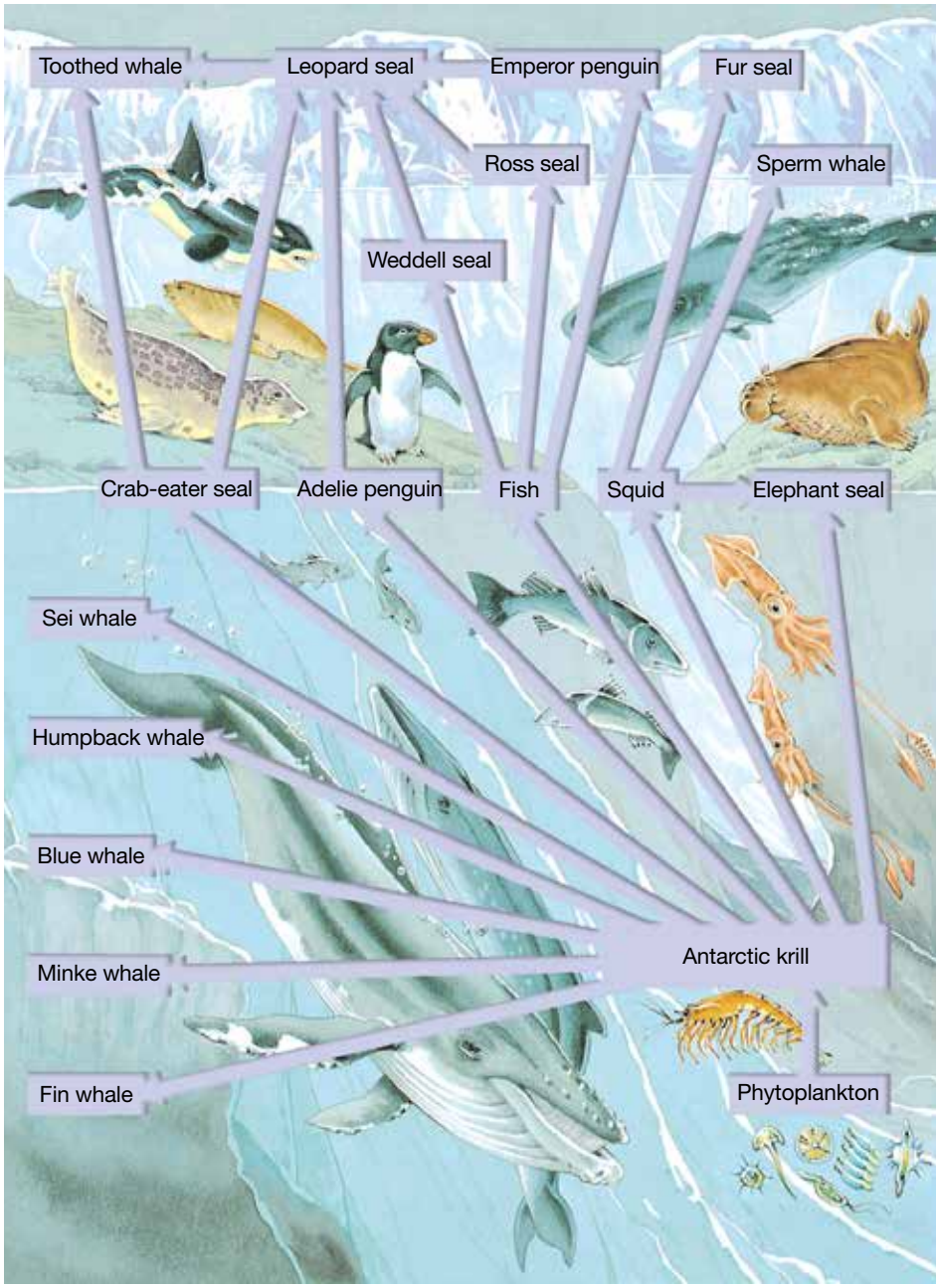


FIGURE 8.5 Feeding relationships (food web) in an Antarctic ecosystem. Arrows denote the flow of chemical energy as one organism feeds on another kind. How does energy enter this ecosystem?

FIGURE 8.6 Phytoplankton are a mixture of various microscopic organisms of different types, including bacteria, protists and algae. All are autotrophic organisms that can carry out photosynthesis.

What is an ecosystem?

Each **ecosystem** includes a living part and a non-living part. The living part is a community that consists of the **populations** of various species that live in a given region. The non-living part consists of the physical surroundings. However, an ecosystem consists of more than living organisms and their non-living physical surroundings.

Look at some definitions of an ecosystem:

- a biological community living in a discrete region, the physical surroundings **and the interactions that maintain the community**
- an assemblage of populations grouped into a community **and interacting with each other and with their local environment**.

Each definition conveys the idea that an ecosystem consists not only of a living community and the non-living physical surroundings but also the interactions both within the community and between the community and its non-living surroundings.

We can develop an understanding of the concept of an ecosystem using an analogy with a hockey game. A hockey game has a 'living part' made up of players, coaches, umpires and time keepers — these are like the living community. A hockey game also has its 'non-living part' that includes a pitch, line markings, hockey sticks, goal nets and scoreboard — these are like the non-living surroundings of an ecosystem. A hockey game also includes interactions that occur within the 'living part' and between the 'living part' and the 'non-living' surroundings. These are like the interactions occurring in an ecosystem.

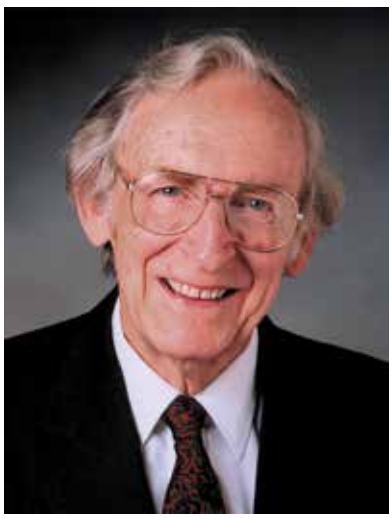


FIGURE 8.7 Professor Eugene Odum (1913–2002) was a world-famous ecologist who received many honours for his research and wrote many scientific publications and books on ecology.

The continuation of an ecosystem depends on the intactness of the parts and on the interactions between them. An ecosystem depends on its parts and may be destroyed if one part is removed or altered. This idea was expressed by Professor Eugene Odum, the world-famous ecologist (see figure 8.7), who wrote: 'An ecosystem is greater than the sum of its parts'. This is another way of saying that an ecosystem is a functioning system, not just living things and their non-living surroundings.

When you think about any ecosystem, remember its three essential parts:

1. a living community consisting of various species, some of which are microscopic
2. the non-living surroundings and their environmental conditions
3. interactions within the living community and between the community and the non-living surroundings.

Ecosystems can vary in size but must be large enough to allow the interactions that are necessary to maintain them. An ecosystem may be as small as a freshwater pond or a terrarium or as large as an extensive area of mulga scrubland in inland Australia. An ecosystem may be terrestrial or marine.

In studying biology, it is possible to focus on different levels of organisation. Some biologists focus on the structures and functions of cells. Other biologists focus on whole organisms, others on populations. Different levels of biological organisation are shown in figure 8.8. An ecosystem is the most complex level of organisation.

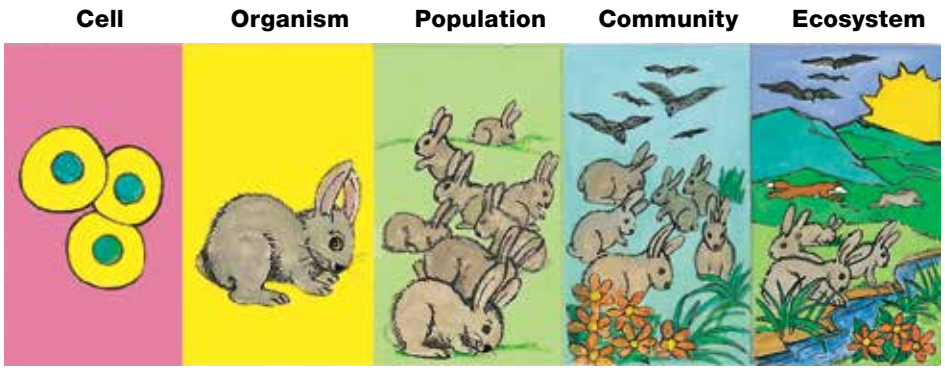


FIGURE 8.8 Different levels of biological organisation, from the most basic unit of life, the cell, to the complex unit of an ecosystem

The study of ecosystems is the science known as **ecology** (*oikos* = home or place to live; *logos* = study).

Let's now look at some living communities in their non-living physical surroundings.

BIOLOGIST AT WORK

Professor Alison Murray — microbial ecologist

Professor Alison Murray has an interdisciplinary background including undergraduate studies in (bio) chemistry, a masters degree in Cell and Molecular Biology and a PhD earned at the University of California, Santa Barbara, in the Ecology, Evolution and Marine Biology Department where she studied molecular microbial ecology in Antarctic and coastal Californian ecosystems. She is currently a research professor at the Desert Research Institute (DRI) in Reno, Nevada, United States, where she studies life in natural, but often extreme, habitats found at both poles. Since joining the DRI in 2001, Alison has made significant contributions to molecular and cellular biology, advancing ecological understanding of microbial life with respect to ecosystem variability, function and geochemistry. Her work has helped answer questions about how microbes function and survive in extremely cold environments and how environmental changes (e.g. global climate change) may affect the functioning and diversity of these organisms, as well as potential feedbacks that might affect the sustainability of cold-environment ecosystems.

Recently, Alison worked as part of an interdisciplinary team of scientists (including planetary scientists, paleolimnologists and organic and stable isotope geochemists) to study a very unusual lake in Antarctica — Lake Vida. Lake Vida lies in the Victoria Valley, one of the higher elevation valleys found in the McMurdo Dry Valleys. It is the largest of the lakes in these dry valleys and, uniquely, the team's research showed, although it is essentially frozen, the lake ice below 16 metres harbours a network of liquid brine with very unusual chemistry, which, it is suspected, extends to depths well below where the team has been able to sample thus far (perhaps below 50 m).

Alison Murray setting up microbial activity assays in the laboratory at McMurdo Station, Antarctica. (Photo courtesy of Peter Rejeck)

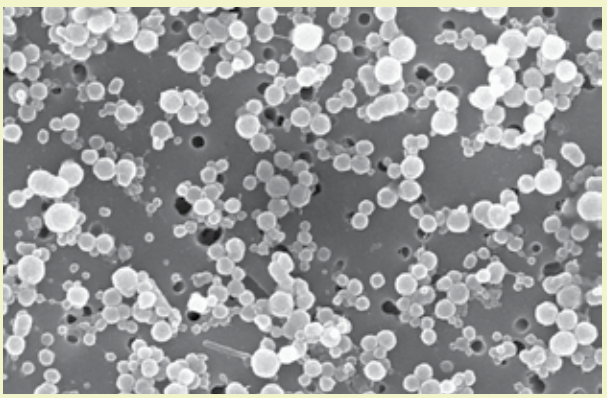
Discussing these findings, Alison remarked, 'Though still liquid, the brine is very salty — with a concentration more than six times that of sea water, and the temperature is –13.4 °C — a frigid place to call home if you are one of the micro-organisms living in the brine!' She went on to discuss her role in the project:

'From our field camp on top of the frozen lake, we drilled to 27 m, collecting and logging the ice core along the way. I helped design a strategy for accessing the brine to ensure that we did not contaminate it. My primary role in the project was to determine if there was biological life in the brine, and if so, whether it was metabolically "alive". The answers

to both questions turned out to be 'Yes' — and to our surprise, the cell densities were actually quite high. We observed two size classes of cells under the microscope at the field camp. One class contained typically sized bacteria — around 0.5 microns. Bacteria in the other class were more abundant but they were barely visible — even using fluorescent cell-stains that make cells easier to see — these were in the order of 0.2 microns or smaller. Because the brine was anoxic, with high levels of iron that would precipitate if exposed to air, it was pumped directly into chambers that had nitrogen atmospheres. This made things challenging, but it was necessary in order to preserve the brine in its native condition. We also did everything possible to keep the brine at the in situ temperature of around –13.5 °C, and preserved samples for at least 10 different laboratories that we were collaborating with to study the brine chemistry. The brine was transported by helicopter to McMurdo Station to conduct activity assays and to collect the cells and their DNA and RNA. The activity assays revealed that the cells were metabolically active — though they were metabolising at some of the lowest rates on record. Research in my lab now is focused on studying the genomes of the brine microbes and their adaptations to this unusual habitat, which is the first of its kind found on Earth. I'm motivated to understand how they survive in Lake Vida, since this type of habitat could also be found on the icy moons in the solar system, such as Europa and Enceladus, where liquid oceans exist under icy shells. Thus, our research at Lake Vida provides a very relevant analogue for planetary astrobiology studies.' More information about the Lake Vida Project can be found at http://lakevida.dri.edu.

Drillers centring the ice-coring apparatus (Gopher) designed by Jay Kyne (pictured on the right) and his assistant Chris Fritsen, Desert Research Institute. (Photo courtesy of Alison Murray)

Lake Vida ice cover in early December when most of the snow has melted, leaving a blue colour reflecting the sky. The McMurdo Dry Valleys is a polar desert region, which is the largest ice-free area in Antarctica. (Photo courtesy of Alison Murray)



Scanning electron micrograph of Lake Vida brine microbial cells. The pore size of the filter underlying the cells is 0.2 micron, which provides a good scale indicating that there are many cells in that size range. (Photo courtesy of Clint Davis and Chris Fritsen)

Ecological communities

What is a community? Each community is made up of all the populations of various organisms living in the same location at the same time. Community 1 = population 1 + population 2 + population 3 and so on.

A population is defined as all the individuals of one particular species living in the same area at the same time. So, we can talk about the population of giant tubeworms (*Riftia pachyptila*) in the **hydrothermal vent** community and the population of clams (*Calyptogena magnifica*) in the same community. Just as the hydrothermal vent has its own living community, other habitats, such as coral reefs, sandy deserts and tussock grasslands, also have their own living communities.

Different communities can be compared in terms of their **diversity**. Diversity is not simply a measure of the number of different populations (or different species) present in a community. When ecologists measure the diversity of a community, they consider two factors:

1. the richness or the number of different species present in the sample of the community
2. the evenness or the relative abundance of the different species in the sample.

As richness and evenness increase, the diversity of a community increases.

How many populations in a community?

A journey to the Ross Sea in summer will take us to locations such as Cape Adare, which is located 71 °S of the equator. As we approach land, a stunning sight will greet us — a rookery of thousands of Adelie penguins (*Pygoscelis adeliae*) (see figure 8.9). As well as this sight, your other senses will register much noise and a strong fishy smell. While large in numbers, all these penguins are members of just one population: that is, members of one species living and reproducing in the same region at the same time.

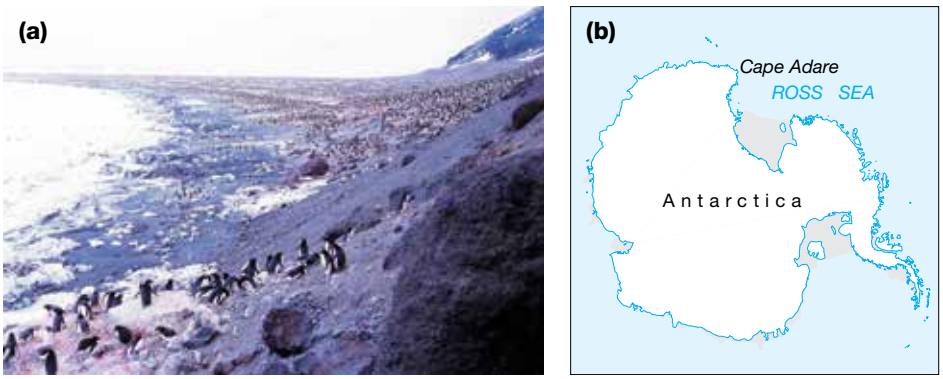


FIGURE 8.9 **(a)** The Adelie penguin rookery at Cape Adare in Antarctica during summer
(b) Location of Cape Adare, Antarctica

Different communities vary in the number of populations that they contain. The community at Cape Adare in Antarctica is dominated by one population, that of the Adelie penguins. The situation in a coral reef community is very different, with a very large number of different populations present. Since each population is made up of one discrete species, the number of populations in a community corresponds to the number of different species or the species richness of the community.

Factors that affect the number of species (or populations) in a community include:

- the physical area in which the community lives
- the latitude (or distance, north or south, from the equator).

Physical area affects species richness

The number of different populations in terrestrial communities in the same region is related to the physical size of the available area. For example, the Caribbean Sea contains many islands that differ in their areas. Figure 8.10 shows the results of a study into the relationship between the sizes of the islands and the numbers of species of reptiles and amphibians (and hence the number of different populations) found on them. In general, if an island has an area 10 times that of another in the same region, the larger island can be expected to have about twice the number of different species.

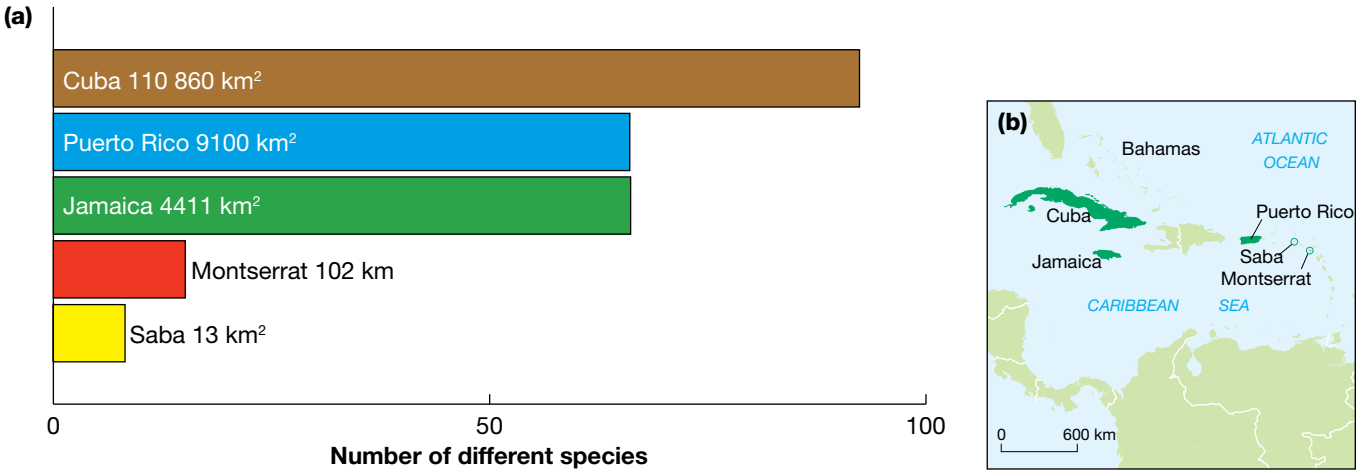


FIGURE 8.10 **(a)** Relationship between the area of an island and the number of populations of different species that it contains (based on data from RH MacArthur and EO Wilson 2001,*The Theory of Island Biogeography*, Princeton University Press) **(b)** Location of the islands in the Caribbean Sea

Latitude affects species richness

The number of different populations in a terrestrial area is also related to the latitude or distance from the equator. For example, terrestrial Antarctica covers about 14 000 000 square kilometres and the continent lies south of latitude 60 °S. Most of the Antarctic continent is an ice desert — dry and covered with ice.

The temperature and light levels in Antarctica vary greatly between the extremes of winter and summer. Only three species of flowering plant survive in this habitat — they live along the west coast of the Antarctic Peninsula (see figure 8.11). These are two species of grasses, *Deschampsia parvula* and *D. elegantula*, and a cushion plant, *Colobanthus crassifolius*. Other plants found in terrestrial Antarctica are mosses, as well as many species of lichen, which are partnerships of fungi and algae (see figure 8.12). Terrestrial algae, such as *Prasiola* sp., grow on open ground and damp rocks, and there is also a pink snow alga (see figure 8.13).

ODD FACT

Australia has a land area of about 7 600 000 km² and the mainland lies between latitudes 10°S (Cape York) and 39°S (Wilson's Promontory).

FIGURE 8.11 Location of the Antarctic Peninsula

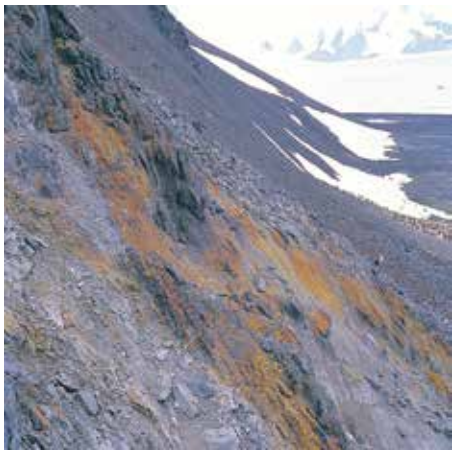


FIGURE 8.12 Vegetation in terrestrial Antarctica in summer. What would a winter picture show?

FIGURE 8.13 A biological scientist examines 'pink snow' in an area of melting ice on Antarctica's fringe. The pink effect is caused by algae, mainly *Chlamydomonas nivalis*.

ODD FACT

In contrast to Antarctica, the island of Madagascar lies in the tropical zone about 20° south of the equator and has a land area of about 580 000 km^2. It has an estimated 13 000 plant species — more than one thousand times the number in Antarctica.

ODD FACT

Twice per month, at new moon and at full moon, spring tides occur when high tide is at its highest and low tide is at its lowest. At the first and third quarter phases of the moon, neap tides occur when the tidal movement is at its minimum.

Only a few animal species survive on terrestrial Antarctica, and these include insects, such as species of springtails (*Cryptopygus antarcticus*), wingless flies (*Belgica antarctica*) and midges. There are also other invertebrates such as species of mites, *Alaskozetes antarctica* and *Tydeus tilbrooki*, as well as brine shrimps and nematodes. Why are seals and penguins excluded from this list?

In general, as we move from the poles to the equator, species richness of terrestrial communities increases. This means that more species and hence more populations exist in a given area of a tropical rainforest ecosystem than in a similar area of a temperate forest ecosystem. In turn, an area of temperate forest ecosystem has more populations than a similar area of a conifer (boreal) forest ecosystem in cold regions of the northern hemisphere. For example, a two-hectare area of forest in tropical Malaysia has more than 200 different tree species while a similar area of forest 45° north of the equator contains only 15 different tree species.

Let's now look at some different communities.

The community of a littoral zone

The **littoral (intertidal) zone** of a rocky seashore (see figure 8.14) has a living community that includes various populations of green and brown algae and sponges that are situated at the low tide mark. Higher up in the intertidal zone, animals including arthropods (such as barnacles and crabs), molluscs (such as periwinkles and mussels) and echinoderms (such as starfish) are found.

FIGURE 8.14 **(a)** The intertidal or littoral zone of a rocky shoreline. The living community of this ecosystem is most apparent at low tide and includes many organisms, such as: **(b)** barnacles (*Tetraclitella purpurascens*); **(c)** starfish or sea star (*Nectria ocellata*); and **(d)** brown algae such as the strapweed (*Phyllospora comosa*), which may be seen at the low-tide mark.

The littoral (or intertidal) zone is the narrow strip of coast that lies between the low-water mark (LWM) of low tide and the high-water mark (HWM) of high tide. This zone is affected by the tides, being exposed at each low tide and submerged at each high tide.

The littoral zone can be a near-vertical cliff face; in other locations, it can be a near-horizontal rock platform.

The littoral zone is often subdivided into lower, middle and upper regions. Note that these are artificial subdivisions and there is no sharp boundary delimiting each region. The 'splash zone' lies above the upper region (see figure 8.15a).

The various species living in the littoral zone are exposed to a wide range of environmental conditions varying from total submergence to total exposure to the air. At low tide when the littoral zone is exposed, organisms must cope with drying air and heat from the sun. They may be exposed to fresh water during periods of heavy rain. At high tide, when the littoral zone is submerged, organisms are returned to conditions where they are affected by water currents.

The various species found in the littoral community are not distributed uniformly throughout the zone. This suggests that the various species differ in their tolerance to exposure to the air and risk of **desiccation** (drying out). One species may tend to be found higher up in the littoral zone than another species; for example, periwinkles are typically found much higher in the littoral zone than algae.

Several species of rock barnacles, including the six-plated barnacle (*Chthamalus antennatus*) and the surf barnacle (*Catomerus polymerus*), can be found in the littoral zone. During low-tide periods when they are exposed to the air, barnacles are protected against desiccation by the presence of hard valves that seal each barnacle into its moist chamber (see figure 8.15b).

ODD FACT

Barnacles begin life as free swimming larvae. The adults are sessile (fixed) and live adhering to rock surfaces. Barnacles are hermaphrodites, each animal having both male and female reproductive organs. Cross-fertilisation occurs in barnacles.

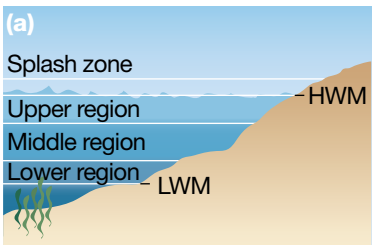


FIGURE 8.15 **(a)** The littoral zone can be subdivided into a number of regions: lower, middle and upper. The splash or spray zone lies above the upper region. Tide heights vary during the month: LWM = low-water mark; HWM = high-water mark. **(b)** Periwinkles are common in the splash zone of rocky shores on Australia's east coast. These periwinkles of family Neritidae are often seen clustered in depressions or along cracks in rocks.

The community of an open forest

The plant community living in one open forest (see figure 8.16a) consists of:

- an upper storey made of the leafy tops (canopies) of various trees, such as the narrow-leaved peppermint (*Eucalyptus radiata*), the messmate (*E. obliqua*) and the manna gum (*E. viminalis*)
- a middle storey consisting of shrubs, including the black wattle (*Acacia mearnsii*)
- a ground cover of various herbs and hardy ferns.

Other members of this open forest community include various fungi and, within the soil, many microbe populations (see figure 8.16b).

The open forest community includes many animal populations. Hidden in tree hollows are possums, which are active at night (see figure 8.16c). Various bird species feed in the forest, some kinds in the upper canopy, others in the middle storey and some are ground feeders. Tiny skinks sun themselves on rocks and scurry into the litter layer when disturbed. The litter layer and the underlying pockets of soil also contain populations of invertebrates, such as centipedes and beetles.

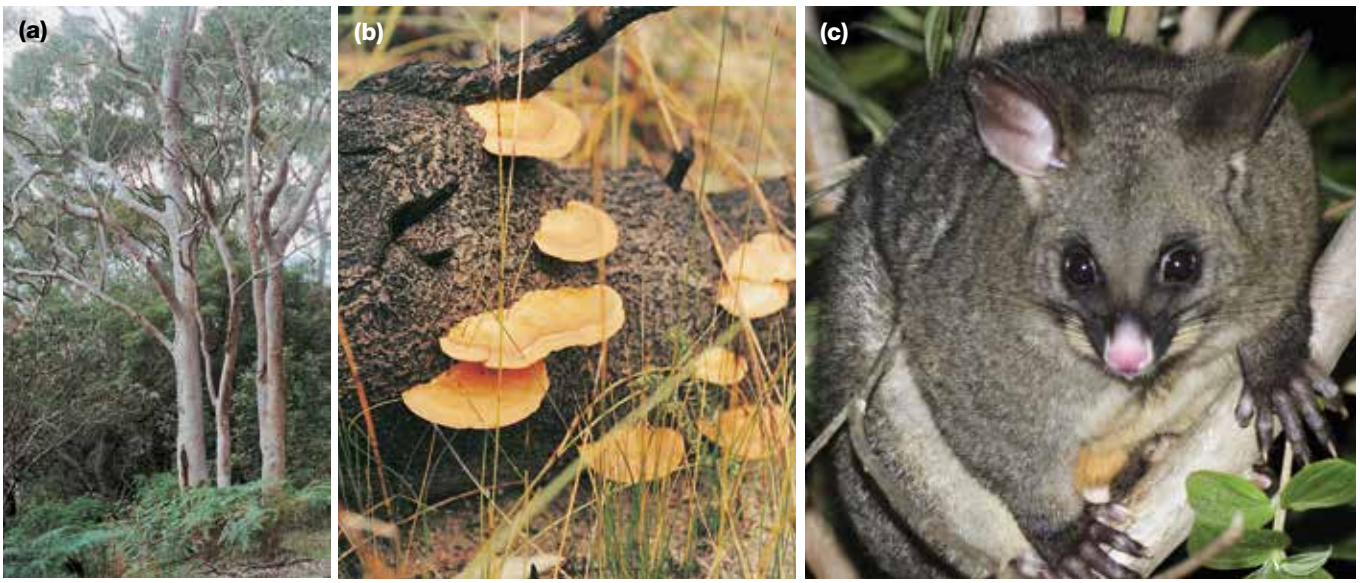


FIGURE 8.16 Part of an open forest ecosystem. Which members of its living community are most prominent? The living community of this ecosystem includes: **(a)** various species of *Eucalyptus* and wattles of the genus *Acacia* as well as **(b)** many small plants and fungi **(c)** various animals. What component of an ecosystem cannot be easily shown in a photograph?

The community of a mallee ecosystem

If we visit the Little Desert National Park in north-west Victoria, we would find ourselves **in the Mallee, a region of low rainfall, with sandy soils that in some areas are salty**. The Little Desert National Park covers an area of 132 000 hectares. The living community in this mallee ecosystem includes more than 670 species of native plants and more than 220 species of birds, including the endangered mallee fowl (*Leipoa ocellata*) (figure 8.17c).

The living community of this mallee ecosystem includes many reptiles, including geckos, skinks, snakes and lizards, such as the shingleback lizard (*Trachydosaurus rugosus*) (figure 8.17b), many birds including the mallee fowl and the musk lorikeet (*Glossopsitta concinna*) (figure 8.17d), and many mammals including Mitchell's hopping mouse (*Notomys mitchelli*). Near waterholes or after rain, some of the frogs of this ecosystem can be seen and heard, such as the eastern banjo frog (*Limnodynastes dumerillii*). A diversity of plant species lives in a mallee ecosystem, including many multi-stemmed eucalypts (figure 8.17a) such as green mallee (*Eucalyptus viridis*) and red mallee (*E. calycogona*). Other plants include the drooping she-oak (*Allocasuarina verticillata*) (see figure 8.18) and the buloke (*Allocasuarina luehmannii*), and native conifers, such as slender cypress pine (*Callitris preissii*) and Oyster Bay pine (*Callitris rhomboidea*). Invisible bacteria that are present in the soil form an important part of this ecosystem.

ODD FACT

The foliage of she-oaks (*Allocasuarina* spp.) does not consist of typical leaves. Fine green branches, known as **cladodes**, do the photosynthetic work of leaves. The true leaves are reduced to very small pointed scales at the nodes of these branches.

FIGURE 8.17 Part of a mallee ecosystem of the Victorian Little Desert. The living community includes various plants and animals. **(a)** Note the multi-stemmed nature of the mallee eucalypts, which differs from the single trunk seen in most other eucalypts. **(b)** A shingleback lizard (*Trachydosaurus rugosus*). **(c)** A mallee fowl (*Leipoa ocellata*). **(d)** A musk lorikeet (*Glossopsitta concinna*).

FIGURE 8.18 Jointed stems (cladodes) of a species of *Casuarina* sp.

Keystone species in ecosystems

An ecological community typically has many populations, each composed of a different species. Within an ecosystem, each species has a particular role — it may be as producer, or consumer or decomposer; it may be as a partner or player in a particular relationship with another species. Some species have a disproportionately large impact on, or deliver a unique service to, the ecosystem in which they live. In some cases, their presence is essential for the maintenance of the ecosystem.

These species are termed **keystone species** for their particular ecosystems. The importance of keystone species is highlighted by the fact that their loss would be expected to lead to marked and even radical changes in their ecosystems, compared with the potential impact of the loss of other species.

On the great grasslands of Africa, elephants (*Loxodonta* sp.) are a keystone species. Through their feeding activities, elephants consume small *Acacia* shrubs that would otherwise grow into trees. They even knock over and uproot large shrubs as they feed on their foliage. Through these activities, elephants control the populations of trees on the grassland, maintaining the ecosystem as an open grassland. The herbivores of the grasslands, including species of wildebeest, zebra and antelope, feed by grazing and depend on the existence

of these grasslands. Similarly, the **predators** of the grasslands, such as lions, hyenas and painted hunting dogs, depend on the open nature of the grasslands for hunting and catching **prey**. Removal of the elephants would, over time, lead to the loss of grasslands and their conversion to woodlands or forests.

In some marine ecosystems, starfish are keystone species because they are the sole predator of mussels. If starfish were removed from such ecosystems, in the absence of their only predators, mussel numbers would increase markedly and they would crowd other species. The presence of starfish in such an ecosystem maintains the species diversity of the ecosystem.

In the tropical rainforests of far north Australia, cassowaries *(Casuarius casuarius)* are a keystone species. Cassowaries eat the fruits of some rainforest plants that are indigestible to all other rainforest herbivores. After digesting the fruits, cassowaries eject the seeds in their dung, thus playing a unique role in the dispersal of these plants (see figure 8.19). Because cassowaries wander widely through the rainforest, the seed dispersal is widespread. If cassowaries were to be lost from rainforest ecosystems, these ecosystems would be in danger of extinction.

FIGURE 8.19 **(a)** A cassowary in a rainforest in Far North Queensland **(b)** Fruits of a rainforest tree species **(c)** Fruits of another rainforest tree species **(d)** Cassowary dung. Note the many seeds in this dung that are left after the cassowary has digested the fleshy fruit, leaving viable seeds that can germinate at a distance from the tree that produced the fruit.

KEY IDEAS

- An ecosystem consists of a living community, its non-living physical surroundings, and the interactions both within the community and between the community and its physical surroundings.
- The study of ecosystems is called ecology.
- Ecosystems are the most complex level of biological organisation.
- A community is composed of several populations.
- Each ecosystem has a living community composed of several populations.
- A keystone species is one that has a disproportionately larger effect on the ecosystem in which it lives, relative to other species.

QUICK CHECK

1 Identify whether each of the following statements is true or false.
   - **a** A population of plants is an example of an ecosystem.
   - **b** The water in a lake is an example of an ecosystem.
   - **c** An ecosystem is a more complex level of biological organisation than a community.
   - **d** A population is composed of several different species.

2 Identify five species you would expect to find in a mallee community.

3 **a** Give an example of a keystone species.
   b Identify an action of your example species on its ecosystem that makes it a keystone species.

Ecosystems need energy

FIGURE 8.20 The radiant energy of sunlight is the source of energy for virtually all ecosystems on Earth. This sunlight energy travels a distance of about 150 million kilometres to Earth where a small fraction is captured by **autotrophs** such as green plants and phytoplankton, and transformed to chemical energy in organic molecules, such as sugars.

Every ecosystem must have a continual input of energy from an external source. Imagine a city with no energy supplies — no electricity, no gas, no petroleum and diesel. Such a city would have no lighting, no artificial heating, no refrigeration, no industrial activity and no mass transportation of people or goods. It would be unable to operate and would cease to be recognised as a functioning city.

Just as the operation of a complex unit like a city requires an input of energy, an ecosystem requires an input of energy for its operation. Energy is not recycled in an ecosystem — it must be supplied continually. So, from where does this energy come?

The external source of energy for almost all ecosystems on Earth is the radiant energy of sunlight (see figure 8.20). In these ecosystems, sunlight energy is brought into the ecosystem by autotrophic organisms, such as plants, algae, phytoplankton or cyanobacteria. These organisms capture sunlight energy and transform it into the chemical energy of sugars, such as glucose, through the process of **photosynthesis**. In these sunlit ecosystems, for example, a mangrove forest ecosystem (see figure 8.21a), life is sustained by photosynthesis:

$$6CO_2 + 12H_2O \xrightarrow[\text{light}]{} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

However, some ecosystems lie beyond the reach of sunlight and are in permanent darkness, such as the hydrothermal vent ecosystems many kilometres below the ocean surface (see figure 8.21b and refer to chapter 3, p. 110), and the Movile Cave ecosystem in Romania (refer to chapter 3, p. 109). The energy source for hydrothermal vent ecosystems comes from the chemical energy in inorganic chemicals, such as hydrogen sulfide, which are released

from the vent. Similarly, in the Movile Cave ecosystem, the energy source is the chemical energy present in inorganic compounds, such as hydrogen sulfide, that rise from thermal areas deep below the caves. This energy is brought into these ecosystems by microbes that use the chemical energy of these simple inorganic compounds to build organic compounds through the process of chemosynthesis. In these sunless ecosystems, life is sustained by chemosynthesis.

For example, in ecosystems in permanent darkness, chemosynthesis occurs as follows:

$$6CO_2 + 24H_2S + 6O_2 \rightarrow C_6H_{12}O_6 + 24S + 18H_2O$$

carbon dioxide + hydrogen sulfide + oxygen → sugar + sulfur + water

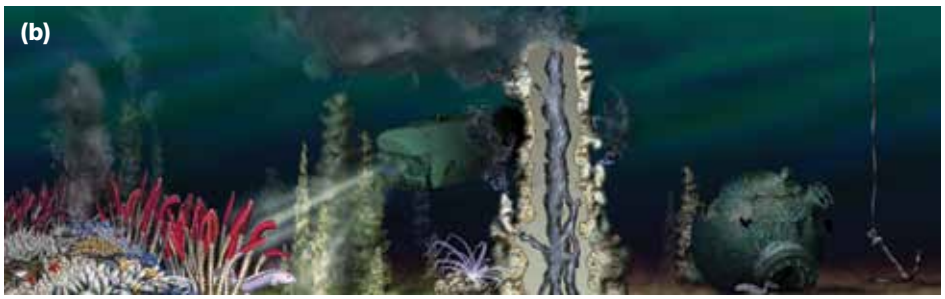


FIGURE 8.21 Ecosystems in light and darkness **(a)** A mangrove forest ecosystem derives its energy from sunlight and is sustained by photosynthesis. **(b)** A hydrothermal vent ecosystem in permanent darkness derives its energy from inorganic chemicals released by the vent (shown on the right in longitudinal section) and is sustained by chemosynthesis.

For the remainder of this chapter, we will use the term ecosystem to refer to a sunlight-powered ecosystem.

Who's who in an ecosystem community?

In an ecosystem, the members of the living community can be identified as belonging to one of the following groups: **producers**, **consumers**, or **decomposers**.

Producers: the energy trappers

Producers are those members of an ecosystem community that bring energy from an external source into the ecosystem. Producers capture sunlight energy and transform it into chemical energy in the form of sugars, such as glucose, making it available within the community. Examples of producers are autotrophic organisms, such as plants, algae, phytoplankton and photosynthetic microbes. Although they are microscopic, phytoplankton are visible on a global scale because of their accumulated mass (see figure 8.22).

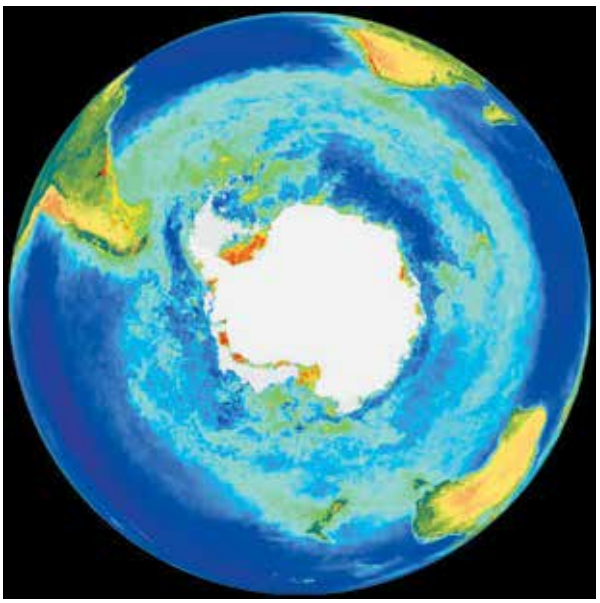


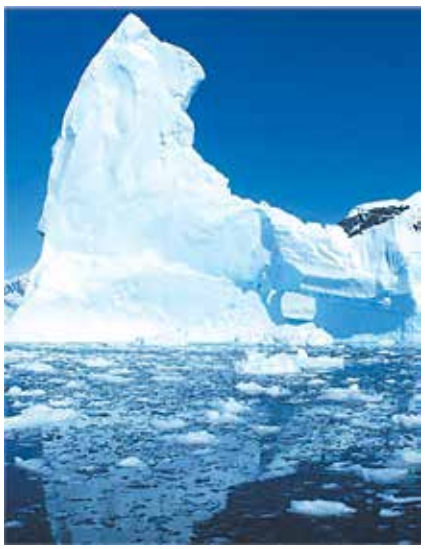
FIGURE 8.22 Colour-coded satellite image of surface chlorophyll from the presence of phytoplankton in the Southern Ocean around Antarctica in summer. Purple areas have little phytoplankton; orange areas have the highest concentration of phytoplankton. Note the high concentration of chlorophyll (and hence of phytoplankton) over the continental shelf surrounding the Antarctic continent.

The organic compounds made by producer organisms provide the chemical energy that supports their own needs. In addition, these organic compounds also provide the chemical energy that supports, either directly or indirectly, all other community members of the ecosystem (see figure 8.23). No ecosystem can exist without the presence of producers. In short, no producers equals no ecosystem.

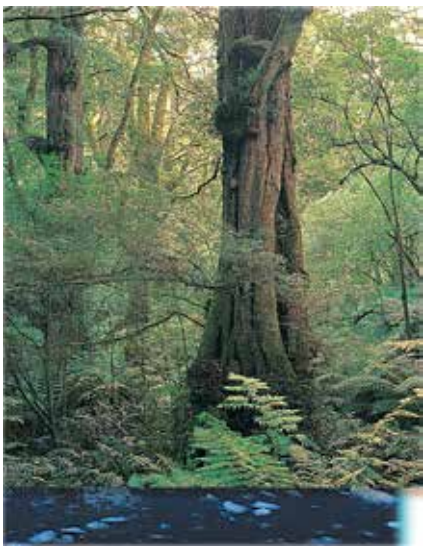
In aquatic ecosystems, such as seas, lakes and rivers, the producers are microscopic phytoplankton, macroscopic algae and seagrasses.

In terrestrial ecosystems, producer organisms include familiar green plants. These, in turn, include trees and grasses, other flowering plants, cone-bearing plants such as pines, and other kinds of plant such as ferns and mosses (see figure 8.23). All of these producers convert the energy of sunlight into the chemical energy of glucose through the process of photosynthesis.

Ecosystem: temperate marine kelp forest
Producers: algae, including the string kelp, Macrosystic angustifolia



Ecosystem: Antarctic marine ecosystem
Producers: many species of phytoplankton



Ecosystem: temperate closed forest
Producers: various woody flowering plants, ferns and mosses

FIGURE 8.23 Producers from a range of ecosystems

In some ecosystems, various species of bacteria, such as cyanobacteria, are also among the producers (see figure 8.24). Cyanobacteria have a form of chlorophyll and can carry out photosynthesis. While individual cells of cyanobacteria are microscopic, under certain favourable conditions the cell number can increase exponentially — this is a so-called 'bloom'.

FIGURE 8.24 Some bacteria, such as cyanobacteria, can transform the energy of sunlight to the chemical energy of sugars, such as glucose. Here we see a so-called 'bloom' of cyanobacteria (either *Anabaena* sp. or *Microcystis* sp.) in a river. Would you predict that cyanobacteria possess a type of chlorophyll?

Consumers in an ecosystem

Another group typically present in the living community of an ecosystem are the consumers. Consumers are **heterotrophs** that rely directly or indirectly on the chemical energy of producers (see figure 8.25).

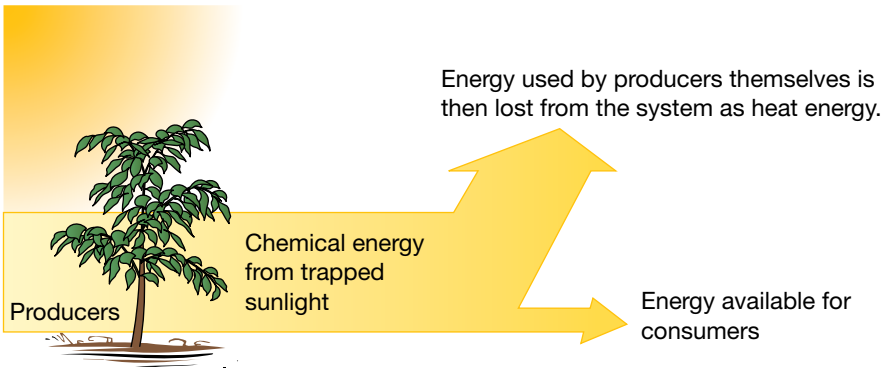


FIGURE 8.25 The chemical energy in sugars from sunlight energy trapped by producers is used mainly by the producers themselves for staying alive. A small amount of this energy is available to consumers in the ecosystem.

Consumers or heterotrophs are those members of a community that must obtain their energy by eating other organisms or parts of them. All animals are consumers and, in aquatic ecosystems, examples of consumer organisms include: fish, which graze on algae; sharks, which eat fish; and crabs, which eat dead fish. In terrestrial ecosystems, consumer animals include: wallabies, which eat grass; koalas, which eat leaves; snakes, which eat small frogs; eagles, which eat snakes; echidnas, which eat ants; numbats, which eat termites; and dunnarts, which eat insects (see figure 8.26).

FIGURE 8.26 Examples of consumer animals in a terrestrial ecosystem **(a)** The koala (*Phascolarctos cinereus*), an Australian marsupial, is a herbivore. It consumes the leaves of certain species of Eucalyptus. **(b)** The common dunnart (*Sminthopsis murina*) is a small Australian marsupial mammal. It is a carnivore and feeds mainly on insects.

ODD FACT

The dietary habits of the little crow, *Corvus bennetti*, which lives in inland Australia, show that its diet is typically composed of insects (48%), plant material (26%) and carrion (26%).

Consumer organisms can be subdivided into the following groups:

- **herbivores**, which eat plants, for example, wallabies and butterfly caterpillars
- **carnivores**, which eat animals, for example, numbats, snakes, and coral polyps
- **omnivores**, which eat both plants and animals, for example, humans and crows
- **detritivores**, which eat decomposing organic matter, such as rotting leaves, dung or decaying animal remains, for example, earthworms, dung beetles and crabs.

Fragments of dead leaves and wallaby faeces on a forest floor, pieces of rotting algae and dead starfish in a rock pool are all organic matter, which contains chemical energy. Particles of organic matter like this are called **detritus**. The organisms known as detritivores use detritus as their source of chemical energy. Detritivores take in (ingest) this material and then absorb the products of digestion. Detritivores differ from decomposers (see below) in that decomposers first break down the organic matter outside their bodies by releasing enzymes and then they absorb some of the products.

Decomposers: the recyclers

Typical decomposer organisms in ecosystems are various species of fungi and bacteria (see figure 8.27). Decomposers are heterotrophs, which obtain their energy and nutrients from organic matter; in their case, the 'food' is dead organic material. Decomposers are important in breaking down dead organisms and wastes from consumers, such as faeces, shed skin and the like. These all contain organic matter and it is the action of decomposers that converts this matter to simple mineral nutrients. Decomposers differ from other consumers because, as they feed, decomposers chemically break down organic matter into simple inorganic forms or mineral nutrients, such as nitrate and phosphate. These mineral nutrients are returned to the environment and are recycled when they are taken up by producer organisms. So, decomposers convert the organic matter of dead organisms into a simple form that can be taken up by producers.

FIGURE 8.27 **(a)** Clusters of fruiting bodies of the fungi *Coprinus disseminatus*, found on rotting wood that is its food **(b)** Fungal growth on apples. What is happening?

Of the three groups described — producers, consumers and decomposers — only two are essential for the functioning of an ecosystem. Can you identify which two? One essential group comprises the organisms that capture an abiotic source of energy and transform it into organic matter that is available for the living community. Who are they? The second essential group is the one that returns organic matter to the environment in the form of mineral nutrients. Who are they?

KEY IDEAS

- Every ecosystem must have a continual input of energy from an external source.
- The organisms in an ecosystem can be grouped into the major categories of producers, consumers and decomposers.
- Producers use the energy of sunlight to build organic compounds from simple inorganic materials.
- Consumers obtain their energy and nutrients from the organic matter of living or dead organisms.
- Consumers can be subdivided into various groups.
- Decomposers break down organic matter to simple mineral nutrients.

QUICK CHECK

4 Identify whether each of the following statements is true or false.
- **a** Producer organisms in an ecosystem must be green plants.
- **b** Every functioning ecosystem must have producer organisms.
- **c** Decomposer organisms are important in breaking down organic matter to simple inorganic compounds.
- **d** Every ecosystem requires a continual input of external energy.

5 Three ecosystems were identified in figure 8.23. Choose one ecosystem and give an example of an organism in that community that is likely to be identified as: (a) a producer; (b) a consumer; (c) a decomposer.

Energy flows through ecosystems

The chemical energy that is generated by producers is available as energy for living for the producers themselves and is also available for all consumers in an ecosystem. Chemical energy can be transferred from one organism to another. When consumers feed, chemical energy is transferred from one organism (the one eaten, in whole or part) to another (the eater) (see figure 8.28).

So next time you eat potatoes, consider the fact that you are taking in chemical energy produced by the photosynthetic activity of the leaves of the potato plant that transformed sunlight energy to glucose. This glucose was converted to sucrose that was transported through the phloem of the plant to underground stems (tubers) where it was stored as starch.

FIGURE 8.28 This bird, a secondary consumer, has captured the chemical energy of a caterpillar, a primary consumer. In turn, this caterpillar obtained its chemical energy from the plant on which it fed. From where did this plant obtain its chemical energy?

Consumers that feed directly on the organic matter of producers are termed **primary consumers**, including leaf-eating caterpillars (see figure 8.29) and other sap-sucking insects and herb-eating wallabies. Consumers that feed on primary consumers are termed **secondary consumers**, such as birds that eat caterpillars. Eagles that eat these carnivorous birds are termed **tertiary consumers** or top carnivores. Decomposers cannot be identified easily as primary or secondary consumers since they feed on the dead remains of both plants and animals.

FIGURE 8.29 Sometimes herbivores or primary consumers themselves are not visible, but the results of their feeding activities can be seen.

Feeding levels in a community

The feeding level or **trophic level** (from *trophe* = food) of an organism within a community depends on what the organism eats. Producer organisms that make their own food occupy the first trophic level. Table 8.1 identifies the various trophic levels that can exist in an ecosystem. Organisms that are classified as omnivores (refer to p. 344) do not fit neatly into one trophic level. (Why?)

TABLE 8.1 Different trophic levels may exist in an ecosystem. What level is occupied by a primary consumer? Why is it difficult to include decomposers in this table?

Trophic level	Organisms at that level	Source of chemical energy or 'food'
first	producers	make organic matter (food) from inorganic substances using energy of sunlight
second	primary consumers (herbivores)	eat plants or other producers
third	secondary consumers (carnivores)	eat plant-eaters
fourth	tertiary consumers (top carnivores)	eat predators

Figure 8.30 shows the types of organism in a community that might be present at different trophic levels.

The transfer of chemical energy is not 100 per cent efficient — at every transfer, some energy is 'lost' as heat energy that cannot be used as a source of energy for living. A rough rule of thumb used by ecologists for the transfer of energy between trophic levels is the 10-per-cent-rule: that is, only about 10 per cent of the energy going into one trophic level is available for transfer to the next trophic level.

ODD FACT

For every 100 kg of pasture that beef cattle eat, they produce about 4 kg of meat.

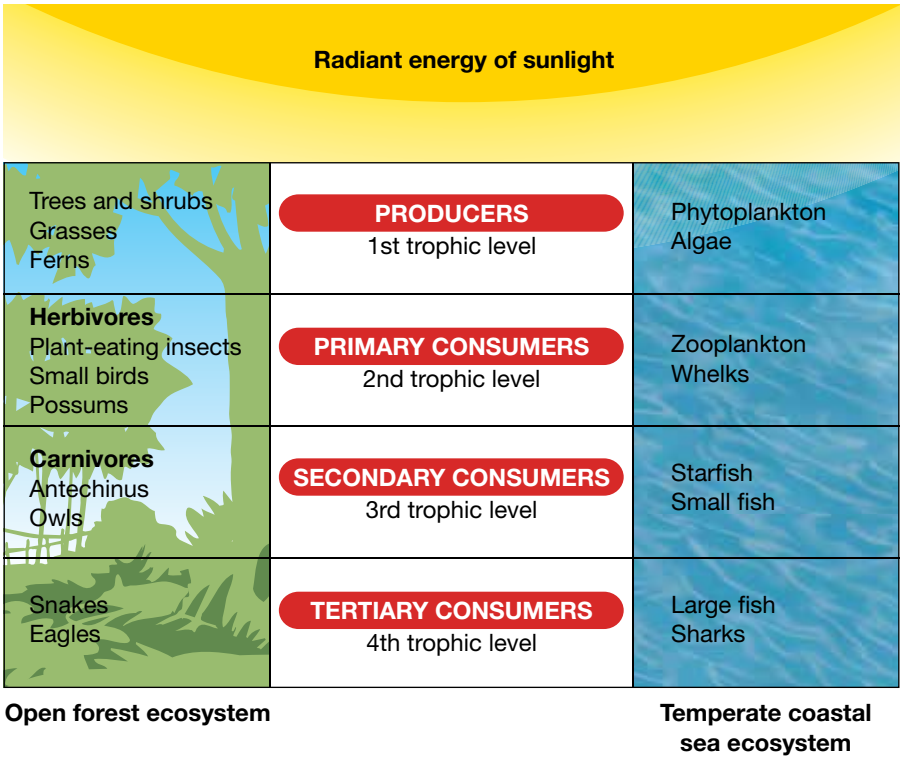


FIGURE 8.30 Comparison of producers and consumers in a terrestrial and an aquatic ecosystem. Which organisms are the producers in each? What is the energy source for organisms at the third trophic level?

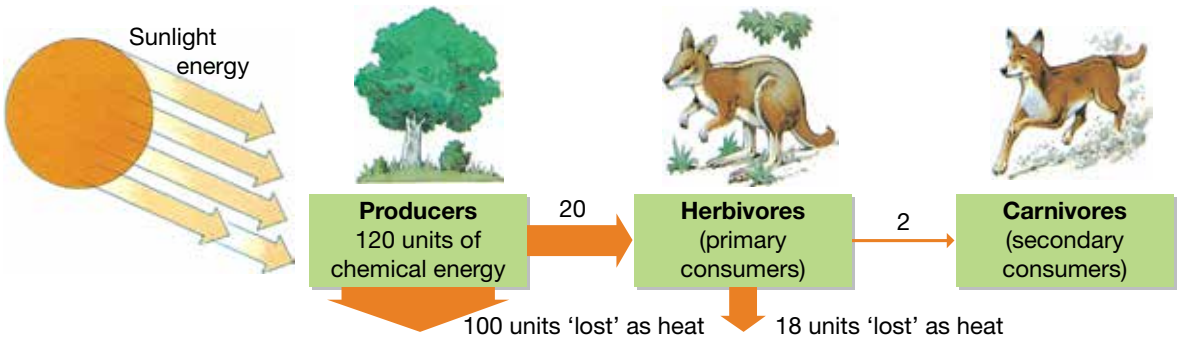


FIGURE 8.31 Energy flow in an ecosystem. The values are averages. Is the amount of energy that enters a trophic (feeding) level equal to the amount that flows to the next level?

Several important conclusions arise from the fact that energy is lost as heat energy at each trophic level in an ecosystem.

1. The number of trophic levels in ecosystems is limited, with many ecosystems having only three levels.
2. The higher the trophic level of organisms, the greater the energy cost of production of their organic matter. So, the production of carnivore organic matter requires more energy than the production of an equal amount of herbivore organic matter.
3. Energy must be supplied continually to an ecosystem, because it flows in a one-way direction and is not recycled.

People are primary consumers when they obtain chemical energy from eating cereal crops and are secondary consumers when they obtain chemical energy from eating beef. A consequence of conclusion 2 above is that larger human populations can be supported on cereal crops grown on a given area of land than can be supported on beef from cattle reared on this same area of crop.

Similarly, it is not surprising that very large numbers of herbivores, such as wildebeest (*Connochaetes taurinus)* and the plains zebra (*Equus. quagga*) can be sustained on the African grasslands (see figure 8.32) but the carnivores, such as lions, that feed on them exist in much smaller numbers.

FIGURE 8.32 The vegetation of the African grasslands supports large numbers of herbivores, which occupy the second trophic level in this ecosystem. In contrast, carnivores at the third trophic level are sustained in much lower numbers.

The following box outlines a study that showed how much chemical energy in the form of fish is needed to produce a penguin chick.

WHAT IS THE ENERGY COST OF PRODUCING A CHICK?

There are significant challenges in answering this question, such as: how much chemical energy in food is required to rear an Adelie penguin chick from hatchling to fledging? However, Australian scientists have developed technology to help answer this question.

Adelie penguins (*Pygoscelis adeliae*) are the most common penguin species living in Antarctica. The major part of their diet is krill. It is important that the feeding behaviour of Adelie penguins is understood. To do this in a way that minimises handling the penguins, a team led by Dr Knowles Kerry developed an automated penguin monitoring scheme (APMS) that is being used with a colony of Adelie penguins consisting of 1800 breeding pairs. The colony is located on Bechervaise Island near Mawson Station, Antarctica.

The APMS is an automated scheme that involves a weighbridge that penguins must cross when they enter or leave the colony (see figure 8.33). By measuring the mass of the penguin on exit from the colony and its mass on return from a feeding trip, an estimate can be made of the success of its feeding activity.

As well as recording their mass, the APMS also logs individual birds into and out of the colony. This outcome involves implanting an electronic identification tag under the skin along the lower backs of a selected sample of penguins. As the penguin crosses the weighbridge, a nearby antenna detects and records the specific tag. The direction that the penguin is travelling can be identified because the bird must cross two infra-red beams. The order in which the beams are cut identifies the direction.

FIGURE 8.33 An Adelie penguin returning to the colony via a weighbridge

By weighing particular penguins as they leave their breeding colony and as they return, it is possible to estimate the mass of krill that these penguins are bringing back to the colony to feed their young. From these measurements, it was estimated that raising a penguin chick to fledging required 45 kg of food. The weight of an Adelie penguin at the time of fledging is about 3.1 kg. What happened to the other 41.9 kg of food?

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Interactivity
Food chains
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Showing energy transfers

The transfers of chemical energy in an ecosystem may be shown in various ways, such as:

- **food chains**
- **food webs**.

In both representations, arrows show the direction of energy transfer from eaten to eater, but the amount of energy transferred is not shown.

Food chains

The flow of chemical energy can involve more than two kinds of organism. In a mulga scrub ecosystem in the Flinders Ranges, part of the chemical energy present in the organic matter of grass is transferred to yellow-footed rock wallabies (*Petrogale xanthopus*) when they feed. In turn, some of this chemical energy is transferred to the wedge-tailed eagles (*Aquila audax*) that prey on young rock wallabies.

This one-way energy transfer can be shown as a simple diagram known as a food chain (see figure 8.34). Arrows show the direction of flow of chemical energy from the eaten to the eater.

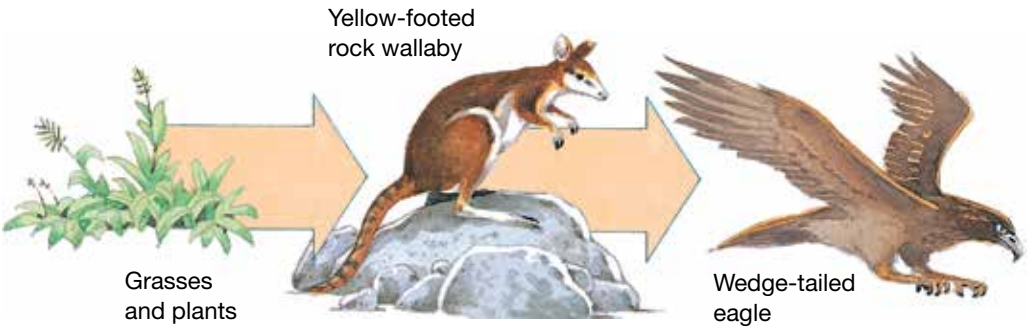

FIGURE 8.34 A simple food chain in an ecosystem. What do the arrows denote?

The energy flow in an ecosystem is more complex than can be shown with a food chain. Food chains have certain limitations.

- Food chains may suggest that a particular consumer obtains its chemical energy from a single source, but this is not always the case. The flow of chemical energy to wedge-tailed eagles is not only from rock wallabies, but also from rabbits and small birds.
- Food chains may suggest that a particular consumer always occupies the same position in terms of energy flow. This is not always the case; for example, yellow-bellied gliders (*Petaurus australis*) obtain chemical energy from both producers (sap, nectar) and consumers (insects).
- Food chains may suggest that chemical energy flows from one kind of organism to only one kind of consumer. This is not always the case. One kind of organism may be eaten by several other kinds. The chemical energy in grasses flows not only to rock wallabies, but also to other herbivores in the same ecosystem.
- Food chains often do not show the energy flow from dead organisms, from parts of organisms or their waste products.

Food webs

The flow of chemical energy in an ecosystem can also be shown using a representation known as a food web, such as the one in figure 8.35.

The producer organisms in an ecosystem are usually shown at the base of a food web diagram. Arrows show the direction of flow of chemical energy in an ecosystem from the eaten to the eater. In a food web, the flow of chemical energy from the organic matter of dead organisms can be included.

You will notice that a food web includes many food chains. Can you identify a food chain from grasses to wedge-tailed eagles through a primary and a secondary consumer?

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Unit 1 AOS 2 Topic 2 Concept 5

Food webs
Concept summary and practice questions

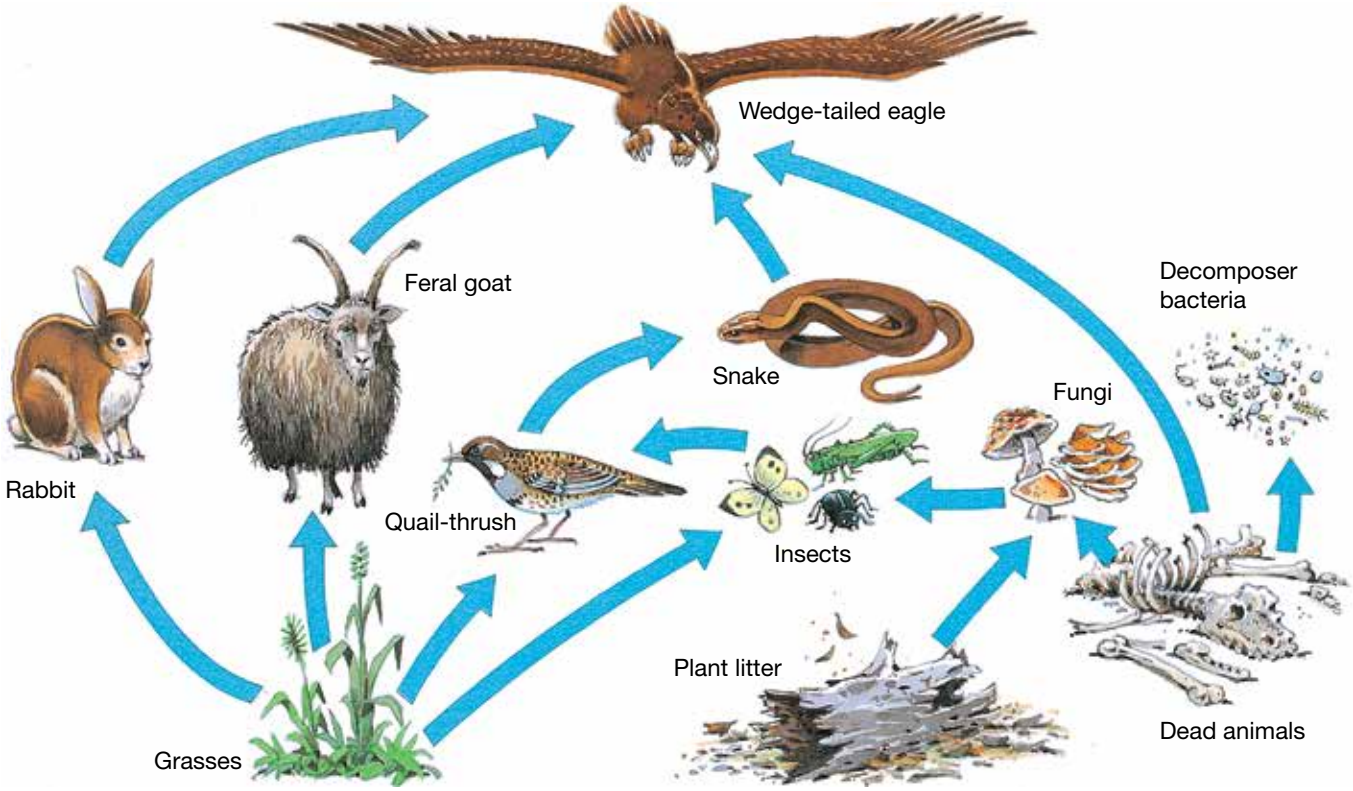

FIGURE 8.35 A food web showing the flow of chemical energy through the different kinds of organism in an ecosystem

KEY IDEAS

- **Chemical energy flows through ecosystems when consumers feed.**
- **Organisms in an ecosystem community can often be assigned to different trophic (feeding) levels.**
- **Chemical energy from organism at one trophic level passes to organisms at a higher trophic level, with loss of heat energy at each level.**
- **Only a small fraction of the energy taken in by consumers in their food appears as organic matter in their tissues.**
- **A rough rule-of-thumb is that the fraction of chemical energy transferred between trophic levels is about one-tenth, or 10 per cent.**
- **Energy transfers within an ecosystem can be shown as food chains and food webs.**

QUICK CHECK

6 Identify whether each of the following statements is true or false.
- **a** Producers occupy the first trophic level in an ecosystem.
- **b** Energy is gained at each higher trophic level in an ecosystem.
- **c** In an ecosystem, herbivores would be expected to occur in greater numbers than carnivores.

7 **a** In an ecosystem, which energy flow would be greatest:
- **i** energy flow from primary to secondary consumers
- **ii** energy flow into producers
- **iii** energy flow from secondary to tertiary consumers?

b Which energy flow would be least?

8 Which has the higher energy cost of production: one gram of herbivore tissue or one gram of carnivore tissue?

9 Consider food chains and food webs. Which representation gives a more complete picture of the feeding interactions within an ecosystem? Briefly explain your choice.

Interactions within ecosystems

Interactions are continually occurring in ecosystems as follows:

- between the living community and its non-living surroundings through various interactions, such as plants taking up mineral nutrients from the soil and carbon dioxide from the air, and animals using rocks for shade or protection
- within the non-living community through interactions such as heavy rain causing soil erosion, and high temperatures causing the evaporation of surface water from a shallow pool
- within the living community through many interactions between members of the same species and between members of different species.

In the following section we will explore some of the interactions that occur within the living community of an ecosystem.

Competition within and between species

In an ecosystem, certain resources can be in limited supply, such as food, shelter, moisture, territory for hunting and sites for breeding or nesting. In situations where resources are limited, organisms compete with each other for them.

Competition may be between members of the same species. For example, pairs of parrots of the same species compete for suitable hollows in old trees for nesting sites. Competition between members of the same species for resources is termed **intraspecific competition**.

Members of a population of one species also compete with members of populations of other species and this is termed **interspecific competition**. For example, members of different plant populations in the same ecosystem compete for access to sunlight, and different animal species may compete for the same food source.

Competition occurs when one organism or one species is more efficient than another in gaining access to a limited resource, such as light, water or territory, for example:

- faster growing seedlings will compete more efficiently in gaining access to limited light in a tropical rainforest than slower growing members of the same species; the faster growers will quickly shade the slower growers from the light and deprive them of that resource
- when soil water is limited, a plant species with a more extensive root system will compete more efficiently for the available water than a different plant species with shallow roots and deprive it of that resource.

Figure 8.36 shows an example of competition for space between two species of anemones. The competitive interaction between the two anemones is very visible to an observer. This is also the case for other competitive interactions, such as when a number of smaller birds of one species 'mob' a larger bird of another species that enters their nesting territory.

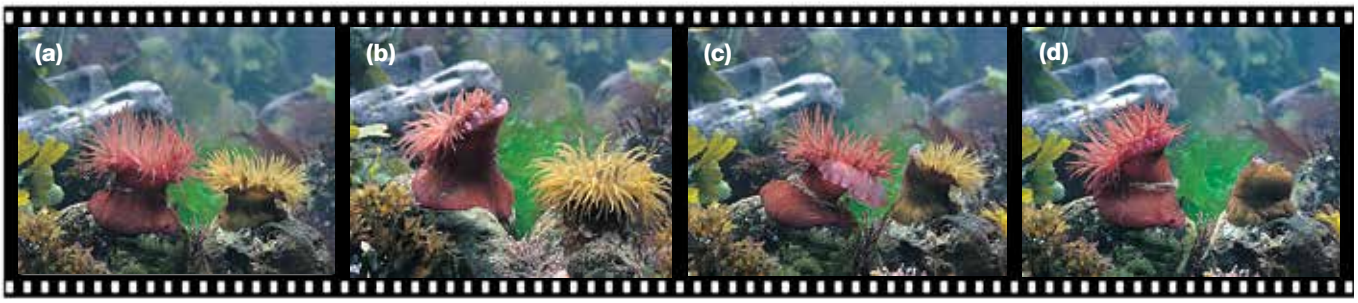

FIGURE 8.36 Anemones compete for space and food. **(a)** If an anemone encroaches too closely to another, **(b)** the original occupant will inflate its tentacles and **(c)** release poisoned darts from stinging cells. The intruder may retaliate and return fire. **(d)** Eventually one of the anemones retires from the fight.

ODD FACT

Some fungi produce chemicals that prevent the growth of bacteria. One such fungus is the green mould (*Penicillium notatum)*, which is often seen growing on stale bread. The chemical that it produces is the antibiotic penicillin.

FIGURE 8.37 Aerial view showing wallow holes and trails made by water buffalo (*Bubalus bubalis*) that create channels which let fresh water drain away and allow salt water to enter, killing the natural vegetation

Amensalism: bad luck for you, but I'm OK

Amensalism is any relationship between organisms of different species in which one organism is inhibited or destroyed, while the other organism gains no specific benefit and remains unaffected in any significant way.

Examples of amensalism include the foraging or digging activities of some animals, such as wild pigs, that kills soil invertebrates or exposes them to predators. While soil invertebrates may be destroyed by the foraging of pigs, the pigs do not benefit from these deaths. Other similar examples are the destruction of pasture plants by the trampling actions of hard-hoofed mammals, such as cattle or sheep, and the destruction of natural vegetation by the wallowing behaviour of water buffalo (see figure 8.37).

Another type of amensalism occurs when one species secretes a chemical that kills or inhibits another species, but the producer of the chemical is unaffected and gains no benefit from these deaths. This occurs with the *Penicillium chrysogenum* mould, which produces an antibiotic that kills many other bacterial species (see figure 8.38). The mould gains no benefit from the bacterial deaths caused by the antibiotic released by the mould.

FIGURE 8.38 *Penicillium* mould growing on lemons

Some plant species also produce chemicals that inhibit the germination or growth of other plant species. Chemical inhibition of this type is termed **allelopathy**. The inhibitory chemicals are known as **allelochemicals** and they are made in various parts of a plant, such as roots, leaves or shoots. Plants known to produce allelochemicals include:

- crop plants such as barley (*Hordeum vulgare*), wheat (*Triticum* spp.), sorghum (*Sorghum bicolor*) and sweet potatoes (*Ipomoea batatas*)
- the black walnut tree (*Juglans nigra*) that secretes the chemical juglone, which destroys many plants within its root zone
- many species of pine.

The area under a pine tree that is covered with fallen needles is bare of plant growth (see figure 8.39). Why? When the pine needles fall, they release allelochemicals that inhibit germination of other plant species.

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FIGURE 8.39 Pine needles contain allelochemicals that inhibit the growth of weeds around the base of pine trees.

Predator-prey relationships

In an open forest ecosystem after rain, a frog leaps towards a shallow pond. It pauses momentarily beside a clump of dense vegetation. A sudden movement occurs as an eastern tiger snake (*Notechis scutatus*) strikes. The frog collapses, its muscles paralysed by neurotoxins in the snake's venom. The snake eats the frog that has become a source of nutrients and energy for the snake. This is just one example of the **predator–prey relationships** in ecosystems. **A predator–prey relationship is one in which one species (the predator) kills and eats another living animal (the prey)**.

Predators or carnivores have structural, physiological and behavioural features that assist them to obtain food. These features include the web-building ability of spiders, claws and canine teeth of big cats, heat-sensitive pits of pythons, poison glands of snakes, visual acuity of eagles and cooperative hunting by dolphins.

Vacuuming, grasping, netting, ambushing, pursuing, piercing, filtering, tearing, engulfing, spearing, constricting, luring and biting — these are some of the different ways that predators capture and eat their living prey. Can you identify predators that obtain their food in some of these ways?

Think about the labels 'carnivore' and 'predator'. On land, these tend to call up an image of an animal such as a lioness (*Panthera leo*) equipped with strong teeth, sharp claws and powerful muscles, which stalks its prey, pursues it over a short distance and then overpowers and kills it. However, a net-casting spider (*Deinopis subrufa*) is equally a predator; it waits for its living prey to come to it to be snared on its web (see figure 8.40).

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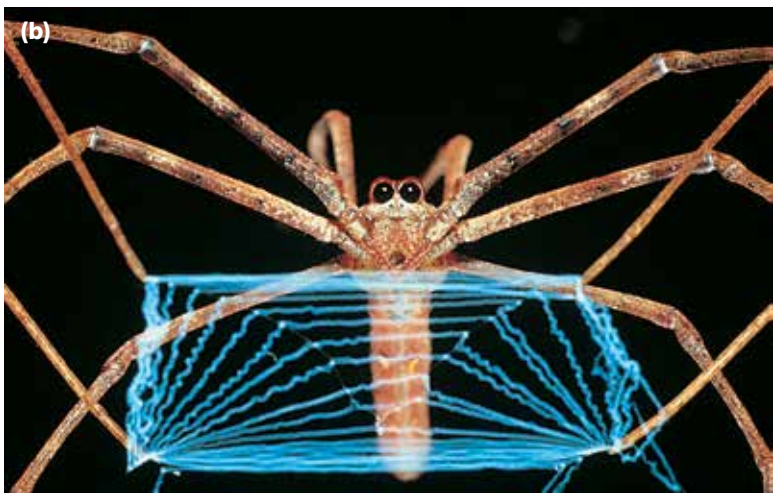

FIGURE 8.40 **(a)** A net-casting spider pulling out silk threads and crafting them into a net **(b)** Spider with a completed net. In Australia, nine species of spider within the genus *Deinopis* are distributed across most states.

If you were asked to name a predator of the seas, the powerful white shark (*Carcharodon carcharias*), which actively hunts its prey, would probably spring to mind. However, the coral polyp (see figure 8.41b), which uses a 'sit-and-wait' strategy, is also a carnivore, equipped not with teeth but with tiny stinging cells (see figure 8.41a).

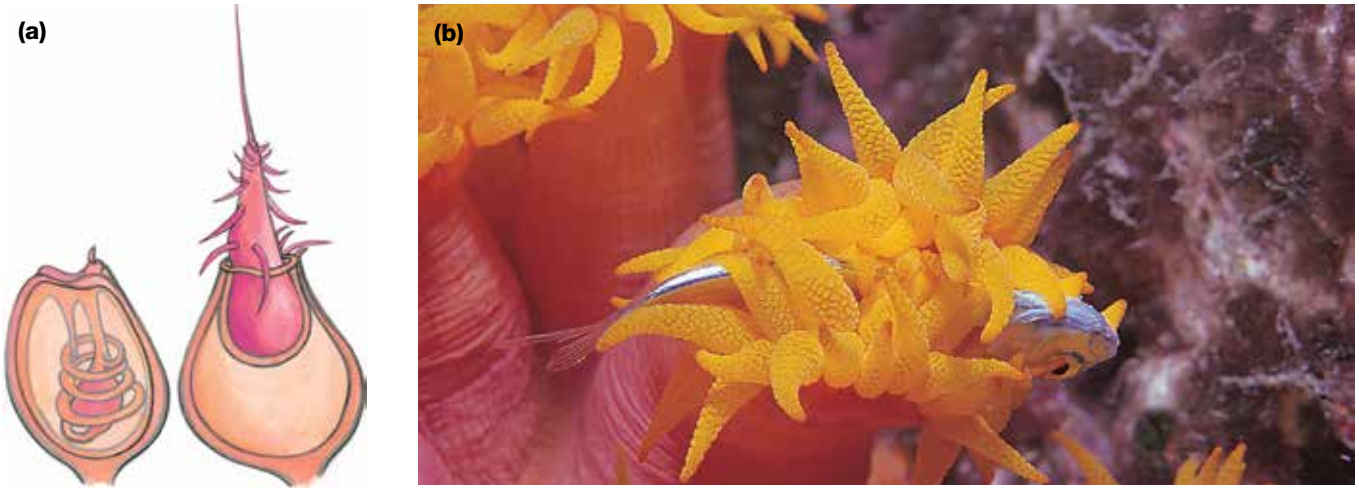

FIGURE 8.41 **(a)** Stinging cells or nematocysts (left: charged; right: discharged). The hollow coiled thread when discharged penetrates the prey and injects a toxin. **(b)** Coral polyps capture their prey, including fish, using the stinging cells on their 'arms'.

Predators come in all shapes and sizes and different species obtain their prey using different strategies. Let's look at three snake species. Snakes are a remarkable group of predators — legless but very efficient!

- The copperhead snake (*Austrelaps superbus*) lies in wait for its prey, such as a frog or a small mammal. When the prey comes within striking distance, the copperhead strikes, injecting its toxic venom.
- The desert death adder (*Acanthophis pyrrhus*) (see figure 8.42a) attracts its prey by using its tail as a lure. The death adder partly buries itself in sand or vegetation and wriggles its thin tail tip. When its prey is attracted by the 'grub' and comes close, the death adder strikes and injects its venom.
- The green python (*Chondropython viridis*) actively hunts its prey by night in trees (see figure 8.42b). Its prey includes bats, birds and tree-dwelling mammals. The python locates its prey in the darkness using its heat-sensitive pits, located mainly on the lower lip under the eye, and it kills its prey, not by toxic venom but by constriction.

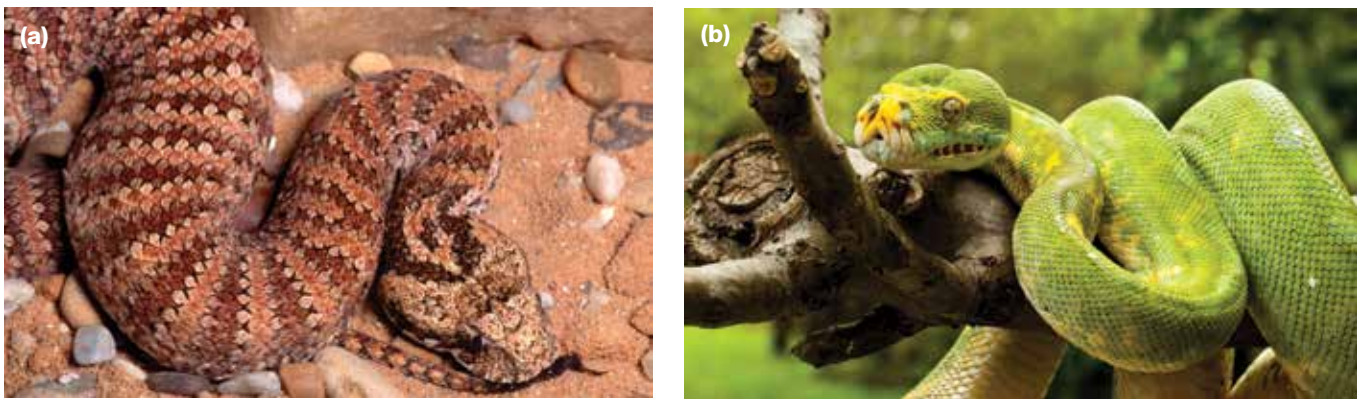

FIGURE 8.42 **(a)** The death adder has a short thick body but its tail tip is thin and is used as a lure to attract prey. Note how the snake positions its tail tip close to its head. What advantage does this behaviour have? **(b)** A green python on the hunt. Like most members of the family Boidae, the green python has heat-sensitive pits that can detect temperature differences as small as 0.2 °C between objects and their surroundings. By moving its head and responding to information from these sense organs on either side of its head, a python is able to locate a source of relative warmth such as a bird or a mammal. Can you see the pits along its lower lip?

Figure 8.43 tells an interesting story. Notice the Adelie penguins (*Pygoscelis adeliae*) that are lined up eager to enter the water but holding back. They must enter the water to feed on krill and small fish for themselves and for their chicks that are in a rookery away from the water. The penguins are reluctant to enter the water because of the leopard seal (*Hydrurga leptonyx*) on the ice. Leopard seals are major predators of Adelie penguins.

FIGURE 8.43 Adelie penguins waiting to enter the sea to feed. On the left is one of their major predators — a leopard seal. The leopard seal on land is slow and cumbersome and the penguins are safe. In fact, they can come quite close to the seal. In the water, however, the leopard seal becomes a swift, agile and efficient predator of these penguins. Also present is a bird, a south polar skua (*Stercorarius maccormicki*), that will feed on fragments left by the leopard seal.

FIGURE 8.44 Meerkats on sentry duty while a pup is feeding

Response of prey species to predators

In the living community of an ecosystem, predators are *not* always successful in obtaining their prey. Various prey species show structural, biochemical and behavioural features that reduce their chance of becoming a meal for a potential predator. Following are examples of some features that protect prey.

Structural features

- **Camouflage**: look like something else! Some insects in their natural surroundings look like green leaves, dead leaves or twigs, for example, the stick insect.
- **Mimicry**: look like something distasteful! Viceroy butterflies (*Limentitis archippus*) mimic or copy the colour and pattern of monarch butterflies (*Danaus plexippus*), which are distasteful to birds that prey on butterflies.

Behavioural features

- Stay still! Prey animals such as some rodents and birds reduce their chance of being eaten by staying still in the presence of predators.
- Keep a lookout! Meerkats gain protection from predators by having one member of their group act as a sentry or lookout when the rest of the group is feeding (see figure 8.44). The lookout signals the approach of a predator, such as an eagle, and the group immediately flees to shelter.
- Schooling — safety in numbers! Individual organisms in a large group, such as a school of fish, have a higher chance of not being eaten than one organism that is separated from the group.

FIGURE 8.45 A monarch butterfly in its caterpillar stage

Biochemical features

- Produce repellent or distasteful chemicals! Larvae of the monarch butterfly (*Danaus plexippus*) (see figure 8.45) feed on milkweeds that contain certain chemicals that cause particular predator birds to become sick. The larvae store these chemicals in their outer tissues and the chemicals are also present in adult butterflies. Predator birds that are affected by this chemical rapidly learn that the monarch butterflies are not good to eat. In fact, monarch butterflies advertise that they are distasteful with bright **warning colouration**.

Herbivore–plant relationships

One of the most common relationships seen in living communities is a **herbivore–plant relationship**. Herbivores are organisms that obtain their nutrients by eating plants. Herbivores include many mammals, such as kangaroos, koalas and cattle, but the most numerous herbivores are insects, such as butterfly larvae (caterpillars) (see figure 8.45), bugs, locusts, aphids and many species of beetle. Plants under attack from herbivores cannot run, hide or physically push them away. What can plants do?

Plants can protect themselves from damage by herbivores by physical means, such as thorns and spines, as seen in cacti, and also by means of stinging hairs, as in nettles. Various plant species also produce allelochemicals that either protect the plant from attack by herbivores or limit the damage done by them.

- Some plants produce chemicals that deter or poison insect herbivores; for example, some clovers (*Trifolium* spp.) produce cyanide.
- Some plants produce chemicals that interfere with the growth or development of insects; for example, an African plant known as bugleweed (*Ajuga remora*) produces a chemical that causes serious growth abnormalities in herbivorous insects.

Parasite–host relationships in animals

In a temperate forest, a wallaby hops through the undergrowth. A close examination shows this wallaby is carrying some 'passengers' in the form of ticks that are attached to the animal's face, near its eyes. The passengers in this case are adult female paralysis ticks (*Ixodes holocyclus*), which are native to Australia. The female ticks are noticeable because they are fully engorged after feeding on their **host**'s blood (see figure 8.46).

FIGURE 8.46 Life-size representations of a tick. A female paralysis tick is smaller than a match head before it feeds on its host. As a tick feeds, it increases from about 3 mm in length to about 12 mm in length when it is fully engorged. Notice that a tick has eight legs and this makes it a member of the Class Arachnida, which includes other eight-legged arthropods, such as mites and spiders.

This is just one example of the many **parasite–host relationships** that occur in ecosystems. In a parasite–host relationship, one kind of organism (the **parasite**) lives on or in another kind (the host) and feeds on it, typically without killing it, but the host suffers various negative effects in this relationship and only the parasite benefits. A variety of animals are parasitic, including insects, worms and crustaceans. (In addition, other kinds of organism — plants, fungi and microbes — can also be parasites.) It is estimated that parasites outnumber free-living species by about four to one.

Parasites that live *on* their host are called **exoparasites**, while those that live *inside* their host are termed **endoparasites**. Fleas, ticks and leeches are examples of exoparasites that feed on the blood of their host. Other external parasites are fungi, such as *Trichophyton rubrum*, a fungus that feeds on moist human skin causing tinea and athlete's foot.

Some exoparasites, such as fleas, live all of their lives on their host. Others, such as ticks, attach to and feed from their hosts at specific times only; at other times, they are off the host. The life cycle of the paralysis tick, for example, has three stages: larva, nymph and adult (see figure 8.47). Each stage must attach

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to a host and feed on the host's blood. Tick larvae hatch from eggs and must attach to a host and feed on its blood. After feeding, the larvae drop off the host to the ground where they moult and become tick nymphs. A nymph then attaches to a host and feeds, after which it drops to the ground and moults to become an adult. The adult must also attach to a host and feed. After an adult female tick has fed, she drops off her host, lays several thousand eggs and dies. The eggs hatch after about two months.

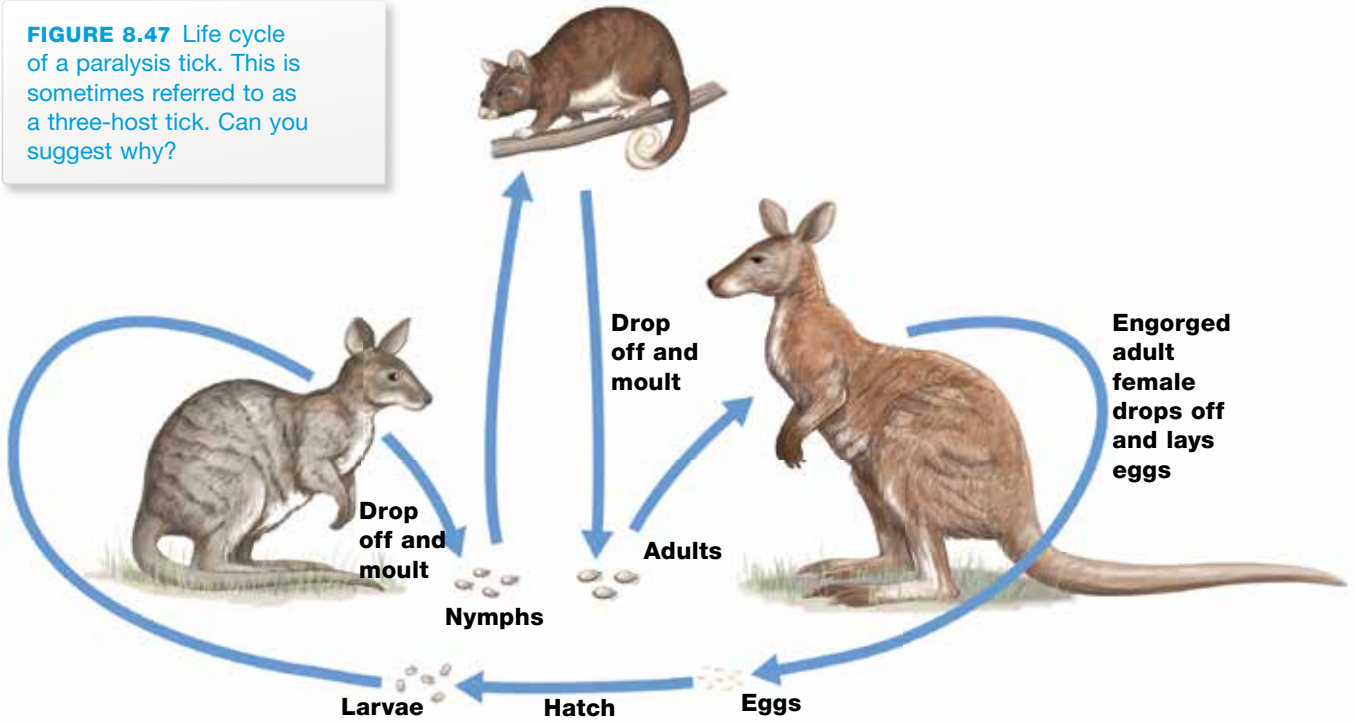

FIGURE 8.47 Life cycle of a paralysis tick. This is sometimes referred to as a three-host tick. Can you suggest why?

FIGURE 8.48 Mouth of a wide-mouthed lamprey (*Geotria australia*) showing large teeth above the mouth and radiating plates with smaller teeth around the mouth

Parasites are also found in freshwater and marine ecosystems. Parasitic lampreys have round sucking mouths with teeth arranged in circular rows (see figure 8.48). Lampreys attach themselves to their host's body using their sucker mouth and rasp the skin of the host fish and feed on its blood and tissues (figure 8.49). Other examples of parasite–host relationships include roundworms and tapeworms that are endoparasites in the gut of mammals, such as the beef tapeworm, *Taenia saginata* and the pork tapeworm, *T. solium*.

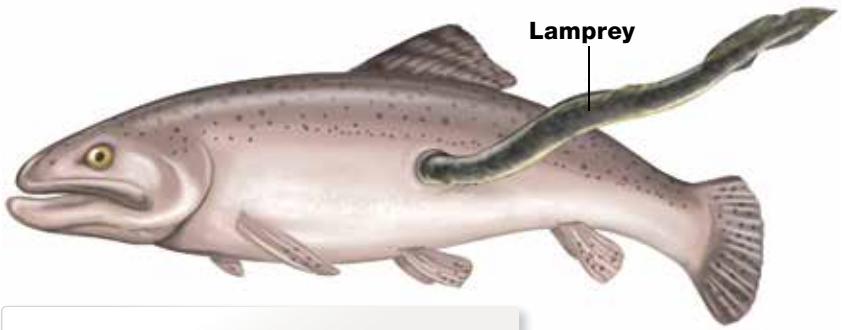

FIGURE 8.49 Lamprey attached to its host

Parasitoids are a varied group of organisms, mainly small wasps and flies, that are like parasites. (The suffix *-oid* means 'like'.) Parasitoids kill their hosts, which are usually another kind of insect. A predator–prey relationship is of short duration with the death of the prey occurring quickly. In contrast, a parasitoid–host relationship has a longer duration before the host dies. In addition, unlike parasites, only the adult female wasp or fly is a parasitoid.

A parasitoid, such as an adult female wasp, lays one or more eggs on or in the body of her specific host. The host is usually the immature stage (larva or caterpillar) of another kind of insect such as a fly or butterfly (see figure 8.50). The parasitoid wasp larva that hatches from the egg then slowly eats the host from inside and, when the vital organs are eaten, the host finally dies. Read the box on pages 364–5 for an example of parasitoids in action in horticulture.

FIGURE 8.50 Eggs of a parasitoid wasp on the caterpillar or larval stage of its host insect. What happens when the eggs hatch?

Parasite–host relationships in plants

Parasite–host relationships also exist in the Plant Kingdom. Two kinds of parasite–host relationship can be recognised, namely:

1. **holoparasitism**, in which the parasite is totally dependent on the host plant for all its nutrients
2. **hemiparasitism**, in which the parasite obtains some nutrients, such as water and minerals, from its host but makes some of its own food through photosynthesis.

Holoparasitism

Holoparasitism in plants is rare. One striking example of holoparasitism is seen in 15 plant species belonging to the genus *Rafflesia*. These species occur only in the tropical rainforests of Borneo and Sumatra. *Rafflesia* plants are remarkable — they have no leaves, stems or roots and, most of the time, they grow as parasites hidden inside the tissues of one specific vine (*Tetrastigma* sp.). They obtain all their nutrients from their host vines.

At one stage, a *Rafflesia* parasite forms a bud on the roots of its host vine and, over a 12-month period, the bud swells until finally it opens out into a single giant flower (see figure 8.51) that has the smell of rotting meat. (Why?) *Rafflesia* flowers are either male or female. The pollinators for *Rafflesia* flowers are flies and beetles that usually feed on dead animals (carrion).

FIGURE 8.51 Giant flower of *Rafflesia arnoldii*. This holoparasitic species produces the largest single flower in the world, measuring about one metre in diameter and weighing about 10 kg. A flower lasts for about one week. What are the pollinating agents for this plant? What is its host?

ODD FACT

The parasitic plant *Rafflesia arnoldii* was first reported to the scientific world in 1816, when it was discovered by Sir Stamford Raffles and Dr Joseph Arnold in Sumatra — hence the scientific name of this species. Raffles Hotel in Singapore is named after the same Raffles.

Species of another group of holoparasites, known as dodder, have a worldwide distribution, including some species that occur in Australia. Dodders belong to the genus *Cuscuta* and our native species include the Australian dodder, *C. australis*, and the Tasmanian dodder, *C. tasmanica*. Dodder plants have no leaves and are parasites on the stems of many different host plants, including crops such as clover, lucerne and potato, and ornamental plants such as dahlia and petunia.

Dodders obtain the water and nutrients they need for survival and for reproduction from their host plants. Initially, a young dodder seedling has roots but, as soon as it attaches to a host, the roots die and the dodder simply consists of a mass of thin intertwining yellowish stems (see figure 8.52a). At various points, there are thickenings in the dodder stems and these are the sites where the dodder parasite penetrates the tissues of the host plant (see figure 8.52b).

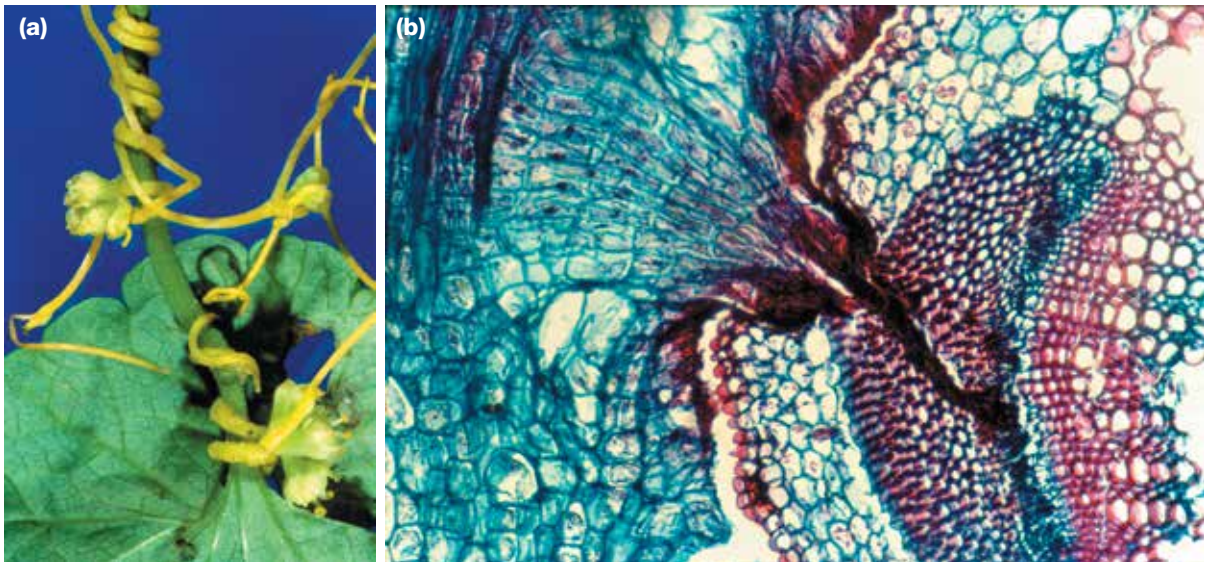

FIGURE 8.52 **(a)** Dodder parasite on its host. Note the intertwining yellow stems of the dodder and the occasional thickened regions of the dodder stem. What is happening here? **(b)** Photomicrograph showing tissue of one species of dodder (*Cuscuta campestris*) penetrating the tissue of its host plant (right). The thin strand of parasite tissue that forms the connection with the host is known as a haustorium (plural: haustoria).

Hemiparasitism

Hemiparasitism (*hemi* = 'half') is best known to most people through plants known as mistletoes. Australia has many species of mistletoe that are parasitic on different host plants (see table 8.2). Mistletoes form connections (known as haustoria) with their host plants and the parasites obtain water and mineral nutrients from their hosts through the **haustoria** (see figure 8.53).

TABLE 8.2 Mistletoe species and their common hosts

Mistletoe species	Hosts
sheoak mistletoe (*Amyema cambagei*)	various sheoaks, especially *Casuarina cunninghamiana*
paperbark mistletoe (*Amyema gaudichaudii*)	various paperbarks especially *Melaleuca decora*
grey mistletoe (*Amyema quandong*)	*Acacia* species in dry woodlands
drooping mistletoe (*Amyema pendulum*)	*Eucalyptus* species in forests and woodland
Amylotheca dictyophleba	various rainforest tree species

FIGURE 8.53 Here we see a mistletoe stem (right) and its host plant (left). Note the connections between the parasite and its host. These connections (haustoria) are modified roots.

ODD FACT

The largest plant parasite in the world is the Christmas bush (*Nuytsia floribunda*), which is native to Western Australia. This species is parasitic on the roots of other plants.

FIGURE 8.54 Lichen on a tree trunk. Which two organisms form the lichen partnership?

How do mistletoes reach their host plant since their seeds are large and fleshy? We get a clue from the word 'mistletoe', which comes from two Anglo-Saxon words: *mistel* = 'dung' and *tan* = 'twig'. This name arose from the mistaken belief that mistletoes spontaneously arose from bird dung on trees. We now know that seeds of many mistletoe species are dispersed by birds. For example, in Australia, mistletoe seeds are spread by the mistletoe bird (*Dicaeum hirudinaceum*) (see **Mutualism**, below).

Mutualism

Mutualism is a prolonged association of two different species in which both partners gain some benefit. Examples of mutualism include:

- *mistletoe birds (Dicaeum hirudinaceum) and mistletoe plants*. The birds depend on mistletoe fruits for food and, in turn, act as the dispersal agents for this plant. The birds eat the fruit but the sticky seed is not digested. It passes out in their excreta onto tree branches where it germinates. An interesting behaviour is that, before voiding excreta, the birds turn their bodies parallel to the branch on which they are perching so that their droppings plus seeds lodge on the branch rather than falling to the ground.
- *fungi and algae that form* **lichens** (see figure 8.54). The fungus species of the lichen takes up nutrients made by the alga and the alga appears to be protected from drying out within the dense fungal hyphae.
- *fungi and certain plants*. A dense network of fungal threads (hyphae) becomes associated with the fine roots of certain plants to form a structure known as a **mycorrhiza** (see figure 8.55). Plants with mycorrhizae are more efficient in the uptake of minerals, such as phosphate, from the soil than plants that lack mycorrhizae. This is because the mycorrhiza increases the surface area of root systems. The fungal partner gains nutrients from the plant.

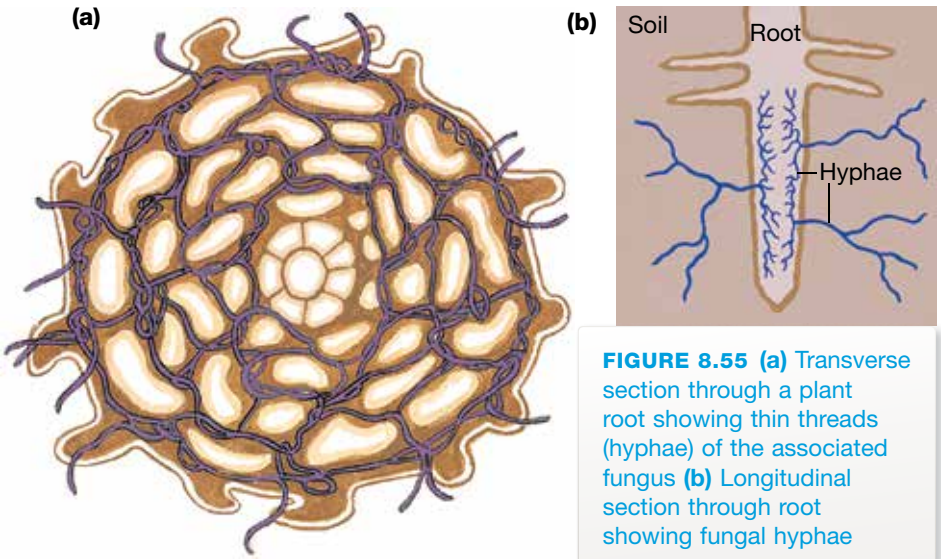

FIGURE 8.55 **(a)** Transverse section through a plant root showing thin threads (hyphae) of the associated fungus **(b)** Longitudinal section through root showing fungal hyphae

- **nitrogen-fixing bacteria** *and certain plants*. Plants require a source of nitrogen to build into compounds such as proteins and nucleic acids. Plants can use compounds such as ammonium ions (NH^{4+}) and nitrates (NO^{3-}) but cannot use nitrogen from the air. However, bacteria known as nitrogen-fixing bacteria can convert nitrogen from the air into usable nitrogen compounds. Several kinds of plants, including legumes (peas and beans) and trees and shrubs such as wattles, develop permanent associations with nitrogen-fixing bacteria. These bacteria enter the roots and cause local swellings called nodules (see figure 8.56). Inside the nodules, the bacteria multiply. Because of the presence of the bacteria in their root nodules, these plants can grow in nitrogen-deficient soils.

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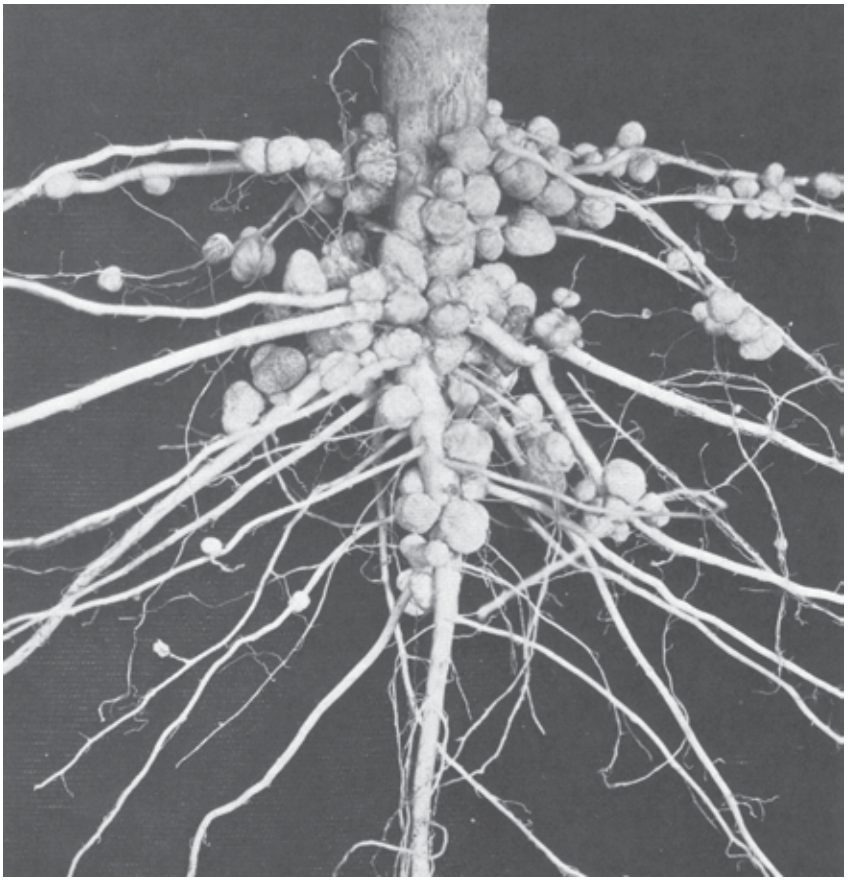

FIGURE 8.56 Root nodules contain large numbers of nitrogen-fixing bacteria. These nodules occur on the roots of several kinds of plants. How does each partner in this association benefit?

One stunning example of mutualism on the Great Barrier Reef involves small crabs of the genus *Trapezia* and a specific kind of coral (*Pocillophora damicornis*). The crab gains protection and small food particles from the coral polyps. The coral receives a benefit from the crab. Look at figure 8.57 and you will see a tiny *Trapezia* crab defending the coral polyps from being eaten by a crown-of-thorns starfish (*Acanthaster planci*). The crab repels the starfish by breaking its thorns.

To date, we have dealt with sunlight-powered ecosystems. However, a striking example of mutualism exists in deep ocean hydrothermal vent ecosystems. **Sulfur-oxidising producer bacteria** bring energy into these ecosystems through chemosynthesis, using energy released from the oxidation of hydrogen sulfide to build glucose from carbon dioxide. These producer bacteria form microbial mats around the vents that release hydrogen sulfide (refer to figure 3.33). In addition, some producer bacteria form relationships with other organisms in the ecosystem, including mussels, clams, and giant tubeworms (see figure 8.58a). Giant tubeworms (*Riftiapachyptila*) have no mouth, no digestive system and no anus. These tubeworms have plumes that are richly supplied with blood and they possess an organ known as a **trophosome** (*trophe* = food; *soma* = body). Chemosynthetic bacteria live inside the cells of the trophosome (see figure 8.58b). The tubeworms absorb hydrogen sulfide, carbon dioxide and oxygen into blood vessel in their plumes; from there, it is transported via the bloodsteam to trophosome cells where it is taken up by the bacteria living inside those cells.

FIGURE 8.57 *Trapezia* crab repelling a crown-of-thorns starfish from eating coral polyps

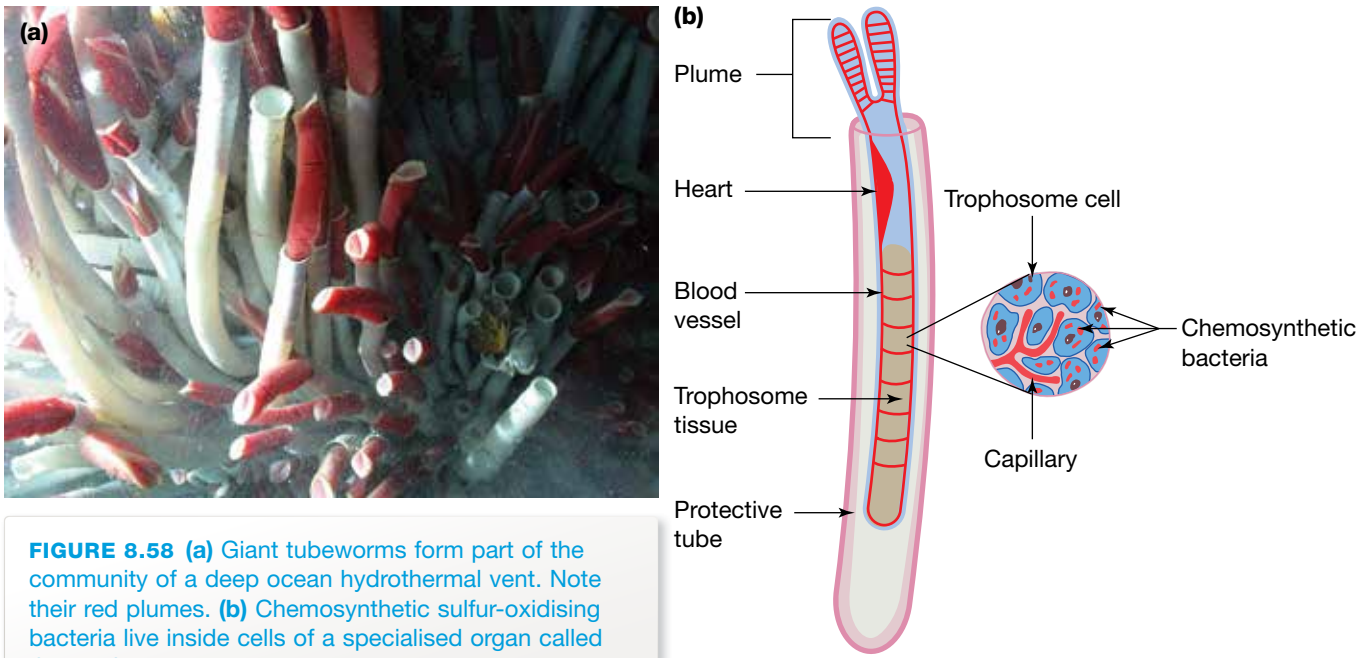

FIGURE 8.58 **(a)** Giant tubeworms form part of the community of a deep ocean hydrothermal vent. Note their red plumes. **(b)** Chemosynthetic sulfur-oxidising bacteria live inside cells of a specialised organ called the trophosome.

Commensalism

Commensalism ('at the same table') refers to the situation in which **one member gains benefit and the other member neither suffers harm nor gains apparent benefit**. An example of commensalism is seen with clownfish and sea anemones (see figure 8.59). The clownfish (*Amphiprion ocellaris*) lives among the tentacles of the sea anemone and is unaffected by their stinging cells. The clownfish benefits by obtaining shelter and food scraps left by the anemone. The anemone appears to gain no benefit from the presence of the fish.

FIGURE 8.59 The clownfish (*Amphiprion ocellaris*) lives among the tentacles of a sea anemone in tropical seas and is unaffected by the anemone's stinging cells.

FIGURE 8.60 **(a)** Commensalism from nearly 400 million years ago! Inside the branched arms of this fossil crinoid can be seen part of a small shell. The animal that lived in this shell ate wastes produced by the crinoid. Part of the segmented stalk of the crinoid is also visible. Compare this crinoid fossil with the living specimen illustrated in (b). **(b)** Diagram of a living crinoid. Note the fine detail of the branched arms that wave about creating currents that carry food particles to the crinoid.

Interactions such as parasitism, mutualism and commensalism are all examples of close associations between two species that have evolved over geological time.

Figure 8.60 shows an example of commensalism from about 400 million years ago. In the seas of that time lived many animals known as crinoids or sea-lilies. They were sessile animals fixed to the sea floor by long stalks. At the top of each crinoid stalk were branched arms surrounding its mouth. Many fossil crinoids have been found with small, shelled molluscs within their branched arms. These molluscs fed on wastes produced by the crinoid. Figure 8.60a shows the shell of one of these waste-eating animals (*Platyceras* sp.) within the arms of the crinoid (*Arthroacantha carpenteri*).

Interactions such as parasitism, mutualism and commensalism are sometimes grouped under the general term **symbiosis** ('living together'), which is defined as a prolonged association in which there is benefit to at least one partner. Table 8.3 summarises these symbiotic relationships in terms of benefit or harm or neither to each of the species concerned. Is amensalism an example of symbiosis?

TABLE 8.3 Summary of symbiotic relationships

Interaction	Species 1	Species 2
parasitism	parasite: benefits	host: harmed
mutualism	species 1: benefits	species 2: benefits
commensalism	species 1: benefits	species 2: neither harm done nor benefit gained

USEFUL PARASITOIDS IN HORTICULTURE

It may be surprising to discover that parasitoids play a valuable role in the horticulture industry. Plant crops, whether ornamental flowers or fruits, that are grown in glasshouses have an added value if they can be advertised as 'pesticide free' or 'organically grown'. Labels of this type mean that flowers and fruit have not been exposed to chemical pesticides.

A tiny wasp (*Encarsia formosa*) can act as a living 'pesticide' that operates in glasshouses where ornamental plants and fruits, including tomatoes,

cucumbers and eggplants, are grown. The tiny wasp, just 0.6 mm long, is a parasite of whiteflies (*Trialeurodes vaporariorum*), which are the most common and damaging insect pest found in glasshouses. In this relationship, the whitefly is the host.

One *Encarsia* female wasp can produce 50 to 100 eggs. A female wasp injects one egg into the pupa of a whitefly. She then flies off to parasitise another wasp from her supply of eggs. The wasp larva that hatches from each egg eats the whitefly pupa from inside, eventually killing it. In the meantime, the *Encarsia* wasp larva develops into a pupa inside the remains of the whitefly pupa that is now just a black scale. When the adult *Encarsia* wasp emerges, it flies off to find a mate, after which the female wasp will look for a whitefly into which it can inject an egg.

To use *Encarsia* wasps in pest control, horticulturalists purchase envelopes that contain numbers of parasitised whitefly nymphs. These are the black scales, each of which encloses a pupa of the *Encarsia* wasp. The envelopes are placed on various plants throughout the glasshouse (see figure 8.61). A female wasp that emerges from a black scale will fly around the glasshouse, actively seeking out whitefly pupae that she can parasitise.

FIGURE 8.61 Envelope on an ornamental plant in a glasshouse. The envelope contains parasitised whitefly pupae that are visible as black scales, each of which encloses an *Encarsia* wasp pupa. The adult wasp that emerges from each pupa will spread around the glasshouse.

KEY IDEAS

- Interactions occur continuously between and within the various components of an ecosystem.
- Relationships between different species in the living community of an ecosystem can be grouped into different kinds, with effects on species involved being beneficial, harmful or benign.

QUICK CHECK

10 Identify whether each of the following statements is true or false.
- **a** In a parasite–host relationship, the host is always killed by the parasite.
- **b** A predator–prey relationship is an example of mutualism.
- **c** In lichens, the interacting species are a fungus and an alga.
- **d** Endoparasites live on the outside of their hosts.
- **e** In mutualism, both partner organisms gain some benefits.

11 Give an example of each of the following.
- **a** A plant that is hemiparasite
- **b** A fungus that is a parasite
- **c** Two partners with a relationship of mutualism

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Looking at populations

Ecological communities are composed of populations of different species. Each population can be characterised in terms of several attributes, including:

- size that refers to the actual number of individuals in a population
- density that refers to the number of individuals per unit area
- distribution that refers to the pattern of spacing of a species within a defined area
- abundance that refers to the relative representation of a population in a particular ecosystem
- age structure of the population
- birth and death rates
- immigration and emigration rates
- rate of growth.

In addition to these attributes, the study of a particular population also involves consideration of other specific features, such as habitat requirements, breeding season and reproductive strategy.

In this section, we will examine some of the attributes of populations and the impact on populations of various factors — intrinsic factors that are part of a population itself (such as growth rate), and extrinsic factors that are external to a population (chance environmental events, such as drought or bushfire).

Abundance of populations

Abundance refers to the relative representation of a population in a particular ecosystem or specified area.

Abundance can be expressed qualitatively, for example, in order of increasing abundance, as:

- rare
- occasional
- frequent
- common
- abundant (see figure 8.62).

Any statement about abundance of a species relates to a particular physical setting or defined area.

Refer back to figure 8.9. In qualitative terms, how would you describe the abundance of the Adelie penguins? Abundance can also be expressed in quantitative terms. For animals, abundance is typically expressed as the number of individuals per sample of an area. For plants, abundance is most commonly expressed as the relative area of a plot covered by the plant species. So, for example, one study identified 54 Tasmanian devils (*Sarcophilus harrisii*) living in an area of 80 km^2 in Tasmania. In the case of organisms living in soil or water, the population abundance can be expressed as the number of organisms per unit volume of a sample of soil or water.

To measure abundance, it is sometimes possible to carry out a **total count** or **true census** of a population by counting every member of a population that occurs in a given area. Total counts can be done with populations of animals that are large or conspicuous (such as ground-nesting birds on an island or seals on an isolated beach) or animals that are slow moving or sessile (such as limpets or barnacles on rocks in the intertidal zone). Likewise, total counts can be done of populations of large plant species.

Carrying out a total count of a population, however, generally poses difficulties. A true census is not possible for small, shy or very mobile animals because many animals will probably be missed. In any case, the cost of a total census in time and personpower may be unacceptably high, especially if a large area of a habitat is involved. Instead, when an entire population cannot be counted, **sampling** techniques are used. Typically one or more samples are

FIGURE 8.62 Abundance can be expressed in qualitative terms such as *rare* or *abundant*.

taken randomly from a population and the samples are assumed to be representative of the entire population. Sampling from a known area allows biologists to make estimates of both the abundance of a population and the size of the population. The abundance of a population cannot usually be based on just one count because of the chance of sampling errors. In order to avoid sampling errors, counts of population are typically repeated several times. The following box outlines some techniques for sampling populations.

SAMPLING TECHNIQUES

Techniques for sampling populations for use in estimating the abundance and size of populations include:

- the use of quadrats
- the use of transects
- mark–recapture.

Quadrats are square areas of known size, such as 1 m × 1 m, or 20 m × 20 m. A quadrat may be subdivided into smaller units and can be used to estimate the abundance or population density of plants, of sessile animals like oysters (see figure 8.63), mussels, limpets and anemones, and of slow-moving animals such as chitons and snails.

FIGURE 8.63 Sampling a population of oysters using a quadrat

A **transect** is a line or a strip laid across the area to be studied. Line transects are particularly useful in identifying changes in vegetation with changes in the environment, such as across a sand dune on a beach or along a sloping hillside. While many transect lines or strips are laid out on the ground where the population under study lives, transects can also be carried out from the air or under the sea.

Aerial strip transects are used to estimate the abundance of populations of species that are distributed across broad areas of open flat habitat and are active by day, for example, kangaroo species. The procedure involves a trained observer in an aircraft that flies at a speed of 185 km per hour and at an altitude of 76 m above the ground. Use of global positioning receivers and altimeters enable the aircraft to maintain constant height and speed.

An observer records the numbers of a particular kangaroo species seen between two markers on the aircraft that represent 200 m width (0.2 km) on the ground. Over a 97-second period, the plane travels 0.5 km. A strip transect that is 0.2 km wide and 0.5 km long encompasses an area of 0.1 km^2, so each 97-second period of flight corresponds to 0.1 km^2 (see figure 8.64). By counting the target species over many 97-second periods, the observer surveys many km^2 of habitat.

Strip transects can also be performed underwater. These transects have been important in studying the abundance of the crown-of-thorns starfish (*Acanthaster planci*) on the edges of reefs in the Great Barrier Reef.

To do a strip transect, a snorkel diver holds a so-called manta board that is attached to a boat by a long rope (17 m) (see figure 8.65a and b). The diver is towed at a constant speed of about 4 km per hour for a 2-minute period. The diver counts crown-of-thorns starfish numbers on the reef below and at the end of that period the diver records the data (on waterproof paper, of course!). Each year about 100 reefs are surveyed using this method.

(continued)

Knowing the population abundance of the crown-of-thorns starfish is important. When the population reaches a density of greater than one starfish per 2-minute tow over a particular reef, the situation is identified as an 'active' outbreak or start of a population explosion.

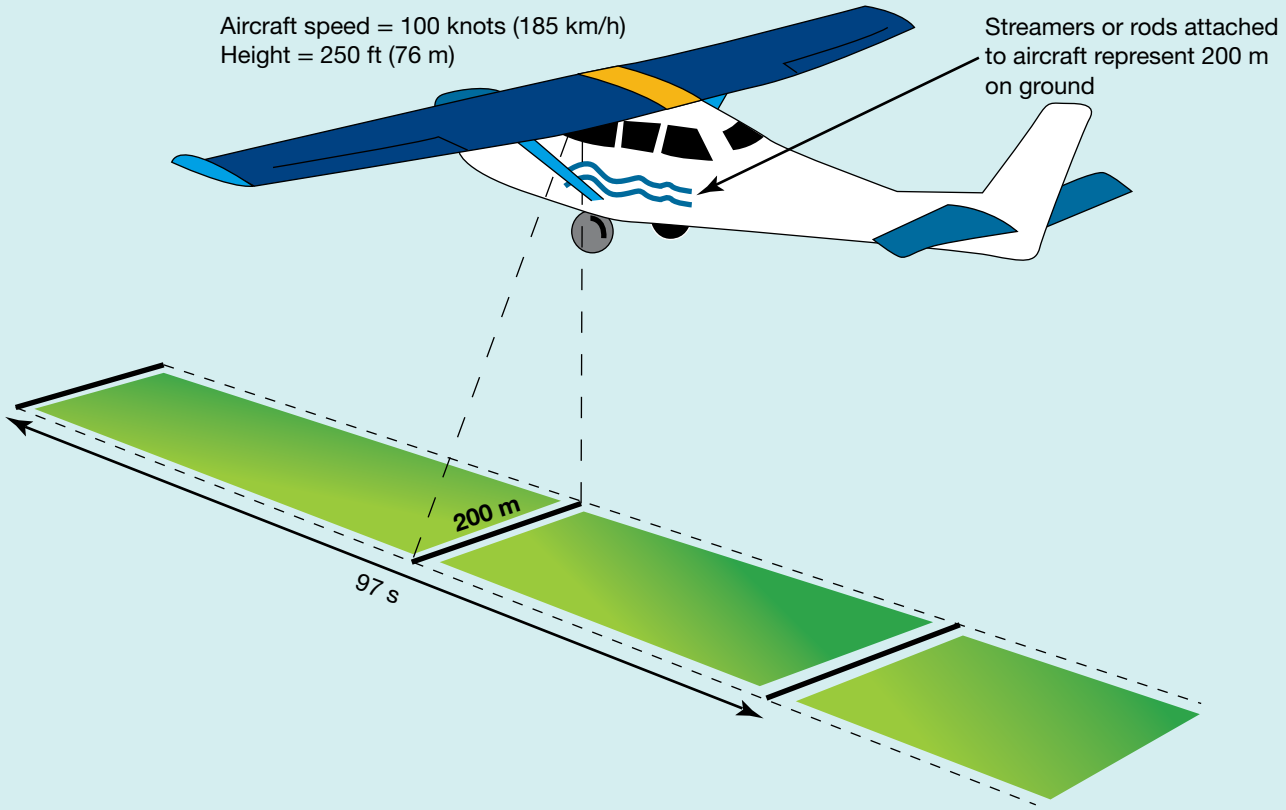

FIGURE 8.64 Procedure for aerial surveying of a population using a strip transect method. Would this procedure be useful for a small wallaby that shelters by day in rocks and emerges to feed at night?

The **mark–recapture technique** involves collecting a sample of an animal population under study, for example, by trapping with mist nets in the case of birds, or by use of light traps in the case of moths. The trapped animals are marked in some way (leg bands for birds, tiny spots of harmless paint for moths) and are then released. Later, another sample of the population is trapped. From these data, it is possible to estimate the size of the population.

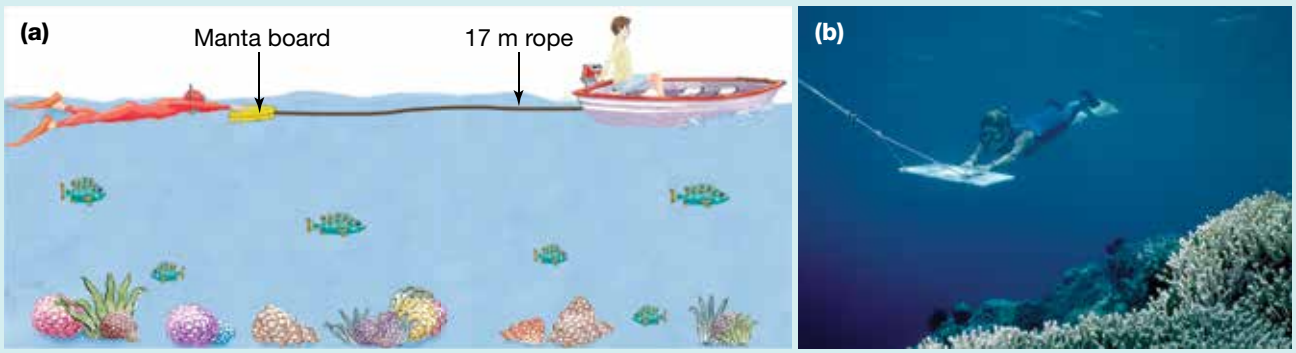

FIGURE 8.65 **(a)** Arrangement for an underwater strip transect using a tow **(b)** A diver under tow. The diver can ascend or descend by changing the angle of the board.

Changes in the abundance of a species can occur over time owing to factors such as migration and breeding patterns. For example, orange-bellied parrots (*Neophema chrysogaster*) migrate annually from south-west Tasmania (where they breed from about October to March) to the southern coast of Victoria and South Australia (where they over-winter from about April to October) (see figure 8.66). In order to measure the abundance of this population in its Victorian breeding grounds, the population must be surveyed at the right time of year when all the members of the population have returned from south-west Tasmania.

FIGURE 8.66 **(a)** The orange-bellied parrot **(b)** Annual migratory path of the orange-bellied parrot. Where would you expect to find this parrot in summer? in winter?

As well as changing over time, the abundance of a population can change over space. The geographic area where a population occurs is termed its range. The abundance of a population over its range is not necessarily constant and may vary. Figure 8.67 shows the abundance of three tree populations over an area that differs in soil moisture, from a moist valley floor up an increasingly dry slope. Note that the three tree populations differ in abundance. The abundance of population A is highest in the valley, while that of population B is highest on the mid-slope, and that of population C is highest at the top of the slope.

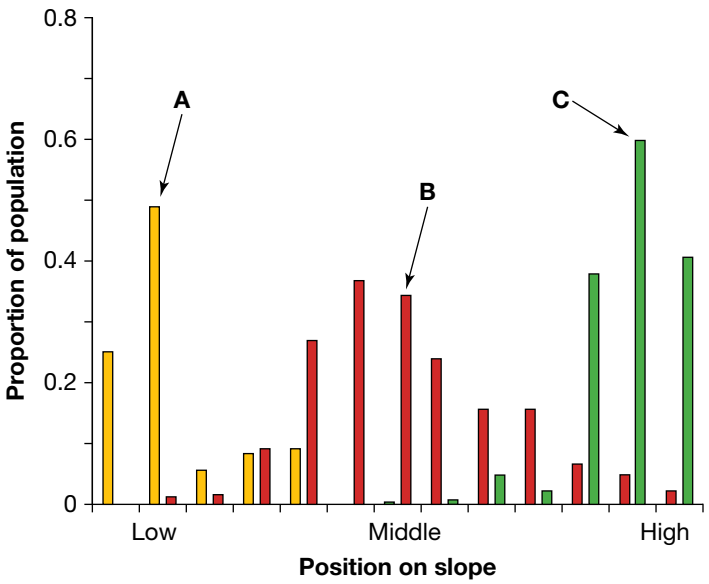

FIGURE 8.67 Abundance of three tree populations in an area sloping from a low moist valley floor up an increasingly dry slope. Which tree species appears to have the greatest requirement for soil moisture? Which tree species is most tolerant of drier soil conditions?

Why measure population abundance? Biologists are interested in the abundance of populations for various reasons; for example:

- Biologists concerned with conservation must measure the abundance of populations of endangered species over time to decide if the populations are stable, increasing or decreasing in abundance. If the abundance of the population of an endangered species falls, the risk of extinction increases. For example, regular counts of the population of the endangered orange-bellied parrot are carried out to see if conservation measures are succeeding in rebuilding this population.
- Biologists concerned with the control or elimination of exotic (non-native) pest species need to monitor changes in their abundance and range. For example, the northern Pacific sea star (*Asterias amurensis*) is native to waters of the north Pacific and is now found in Port Phillip Bay in Victoria and in the Derwent estuary in Tasmania (see figure 8.68a). This pest is spread as tiny larvae in the ballast water of ships. In order to identify the risk that this pest could spread further around Australia via this means, biologists measured the population density of Pacific sea star larvae in water samples (see figure 8.68b).

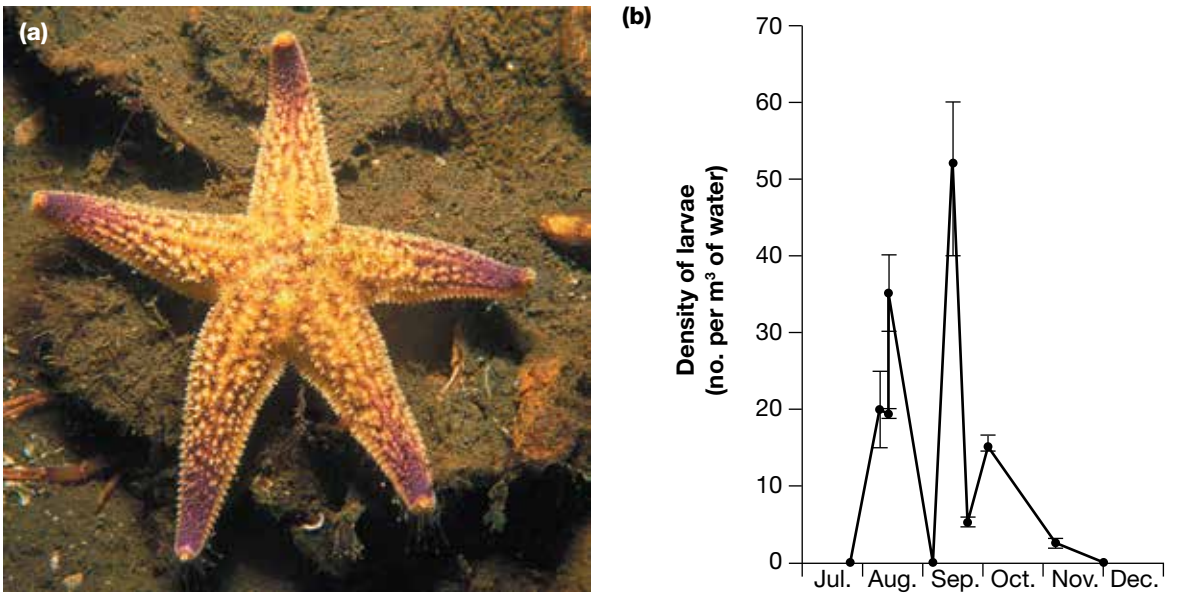

FIGURE 8.68 **(a)** The northern Pacific sea star, an introduced pest in areas of south-eastern Australian waters. How did this species, which is native to the north Pacific, reach Australia? **(b)** Abundance of Pacific sea star larvae in samples from the Derwent River during 2001. Abundance is given in number of larvae per cubic metre of water. Note the variation in larval density over time. (Data from Craig Johnson et al., in Report to the Department of Sustainability and Environment, Victoria, 2004)

ODD FACT

In 1979, at Green Island in the Great Barrier Reef, the population of crown-of-thorns starfish exploded to reach about 3 million. Each crown-of-thorns starfish consumes between 5 m^2 and 6 m^2 of coral each year.

- Biologists interested in understanding why some populations can 'explode' or sharply increase in numbers measure population abundance regularly in order to detect patterns and identify possible causes of these explosions. On the Great Barrier Reef, populations of the crown-of-thorns starfish (*Acanthaster planci*) periodically explode. The increased numbers of starfish cause great damage to the corals by eating the coral-producing polyps (see figure 8.69). Refer to the box on page 371, to read about Ian Miller, a marine biologist at the Australian Institute of Marine Science (AIMS), who describes aspects of his research on sampling populations of marine species of the Great Barrier Reef.

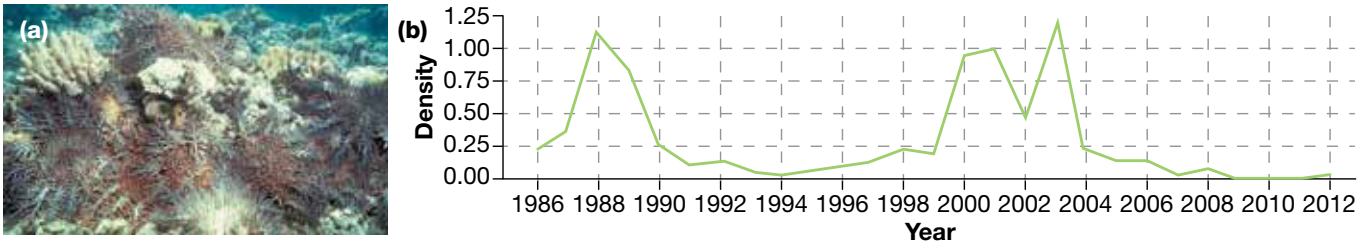

FIGURE 8.69 **(a)** A cluster of crown-of-thorns starfish on coral. How many can you count in this small area? The white areas are 'feeding scars' consisting of dead coral that remains after the living coral polyps have been eaten. **(b)** Average crown-of-thorns starfish density (number per tow) across the Great Barrier Reef. Note the changes in population density over time. (*Source:* Australian Institute of Marine Science)

BIOLOGIST AT WORK

Ian Miller — monitoring crown-of-thorns starfish on the Great Barrier Reef

Ian Miller is an experimental scientist employed at the Australian Institute of Marine Science (AIMS). He writes:

'I work as a marine biologist. In my role as coordinator of broadscale surveys, I am responsible for the day-to-day management of the crown-of-thorns starfish (COTS) component of a larger Long Term Monitoring Program (LTMP). The LTMP was set up in 1992 and is an extension of a previous monitoring initiative that began in 1985 to describe the pattern and extent of COTS activity on the Great Barrier Reef (GBR). This groundbreaking program was the first to sample the GBR over its entire geographic range on an annual basis. I joined the program in 1989 after obtaining a BSc in Marine Biology from James Cook University. Monitoring the GBR has proven to be an exciting and challenging career.

'COTS outbreaks remain a major management problem on the GBR and are responsible for more coral mortality than any other factor. To determine the pattern and extent of COTS activity on the GBR, we use the manta tow technique. This is a plotless transect survey method, where the scale of interest is the whole reef or large parts of the reef (i.e. kilometres). Data on COTS counts are collected and visual estimates of live coral, dead coral and soft coral are made. Approximately 100 reefs are surveyed by manta tow annually from Cape Grenville in the north to the Capricorn Bunker Reefs to the south. The method relies on making visual estimates and provides observers with a thrilling ride as they are towed around the reef. By tilting the manta board you can dive to a depth of up to 10 metres and literally fly through the reef environment. Stunning vistas of drop-offs on the reef fronts and bommie fields on the reef backs provide a unique experience. The broad range of reef habitats encountered has given me a greater appreciation of how the GBR changes through time and space.

'The manta tow surveys have provided an unprecedented record of change on the GBR and are an invaluable resource for reef managers and scientists alike. The results have led to a greater understanding of the pattern and extent of COTS activity and their effects on coral reefs. The results also provide insight into the dynamic nature of coral reef ecosystems and highlight their vulnerability to large-scale impacts that include not only COTS infestation but also other factors such as cyclones, floods, disease and coral bleaching.

FIGURE 8.70 Ian Miller in the 'office'

'As a team member of the LTMP, I also participate in site-specific surveys of nearly 100 reefs from Cooktown in the north to Gladstone in the south. These surveys involve scuba diving on fixed transects,

(continued)

usually on the northeastern flanks of reefs, to gather detailed information on corals, algae and fishes. Each survey consists of three fixed sites, which in turn are composed of five 50-metre transects. At each site, visual counts of reef fish (some 200 species) are conducted along the transects as belts, 5 metres wide for large roving demersal species and 1 metre wide for small habitat dependent species. Bottom dwellers are sampled on each transect by video (for later analysis in the laboratory) and factors causing coral mortality are also recorded along 2-metre-wide belts using visual counts. These fine-scale surveys allow the monitoring team to define small-scale changes in community structure through time and pinpoint factors that are driving these changes. Results have shown that the reef environment is a far more diverse and dynamic system than was previously imagined and that, following a disturbance, reefs can and do recover to their previous condition depending on the size of the initial disturbance and given enough time before the next disturbance.

'As part of the AIMS LTMP, I look forward to being at the forefront of defining the pattern and extent of impacts from new and emerging threats to the GBR, such as coral bleaching and disease. In the immediate future, the LTMP will be a major contributor to defining the role that water quality plays in shaping the fate of inshore reefs on the GBR, which is a current topic of extreme interest for coral reef managers.

'I continue to find my job an exciting and challenging one where I can make a real contribution to extending our knowledge of coral reefs.'

Distribution of populations

Distribution refers to the spread of members of a population over space. Populations may have identical densities but their distributions can differ. Figure 8.71 shows three populations with identical densities but their horizontal distributions differ, being uniform in A, random in B and clustered or clumped in C. Clumped and uniform distributions are both non-random patterns. The most common pattern observed in populations is a clumped distribution. (What pattern is apparent in the Adelie penguins seen in figure 8.9?)

Changes in the distribution of populations can occur over time. Animal populations that have a random distribution at one period, such as the non-breeding season, may show a different distribution during the breeding season.

A clumped distribution of a plant population may indicate that some areas only within a sample area are suitable for germination and survival of a plant species and that areas without plants are unsuitable for survival because of the pH of the soil or the lack of water or the ambient temperature.

Mosses grow in open forests. Their distribution, however, is far from random; they are confined to damp, sheltered areas. A distribution map of mosses in a forest corresponds to the distribution of damp, sheltered areas.

Likewise, some parts of a habitat may be more shaded or more protected or closer to water than other parts. Animal populations aggregate in the more favourable parts, producing a clumped distribution (see figure 8.72). Clumped distributions are also seen in populations of mammals that form herds or schools as a strategy for reducing predation. Clumped distributions are also seen in populations of plant species that reproduce asexually by runners or rhizomes, with new plants appearing very close to the parental plant.

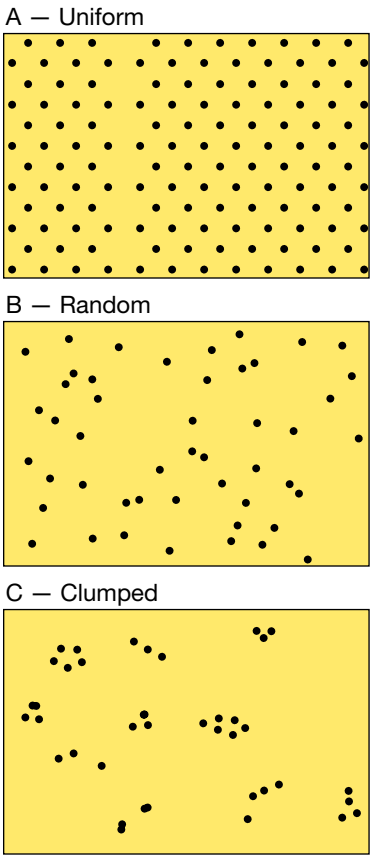

FIGURE 8.71 Three populations, A, B and C, with different distributions. What might cause a clumped distribution?

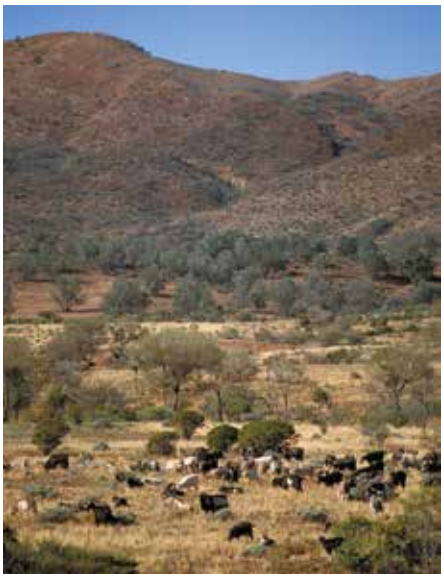

FIGURE 8.72 A group of feral goats in central Australia — an example of clumped distribution

FIGURE 8.73 Spinifex covers the level ground and hills of this area of Western Australia — an example of uniform distribution.

A uniform distribution may indicate a high level of intraspecific competition so that members of a population avoid each other by being equidistant from each other. Uniform spacing is seen in plants when members of a population repel each other by the release of chemicals (see figure 8.73). In animals, uniform distribution occurs when members of a population defend territories.

A random distribution is expected (1) when the environmental conditions within the sample area are equivalent throughout the entire area and (2) when the presence of one member of a population has no effect on the location of another member of the population. Both of these conditions rarely occur and, as a result, a random distribution pattern of members of a population is rare in nature.

Age structure of populations

In a population, individual members vary in their ages and lifespans. The age structure of a population identifies the proportion of its members that are:

- at pre-reproductive age (too young to reproduce)
- at reproductive age
- at post-reproductive age (no longer able to reproduce).

The age structure of a population is important since it indicates whether the population is likely to increase over time. Where the majority of individuals in a population are at reproductive age or younger, that population is expected to increase over time. If a population has most members at post-reproductive stage, then, regardless of its size, this population will decline.

The age structure of populations can be plotted as a series of bars whose lengths indicate the relative numbers in each group or cohort. When the low bars are longest, more members of the population are at or below reproductive age and that population will increase. The age structure plot of such a population, with most members at or below reproductive age, is a 'pyramid' shape (see figure 8.74a). In contrast, a population whose age structure is a 'vase' shape is either at zero population growth or is decreasing (see figure 8.74b).

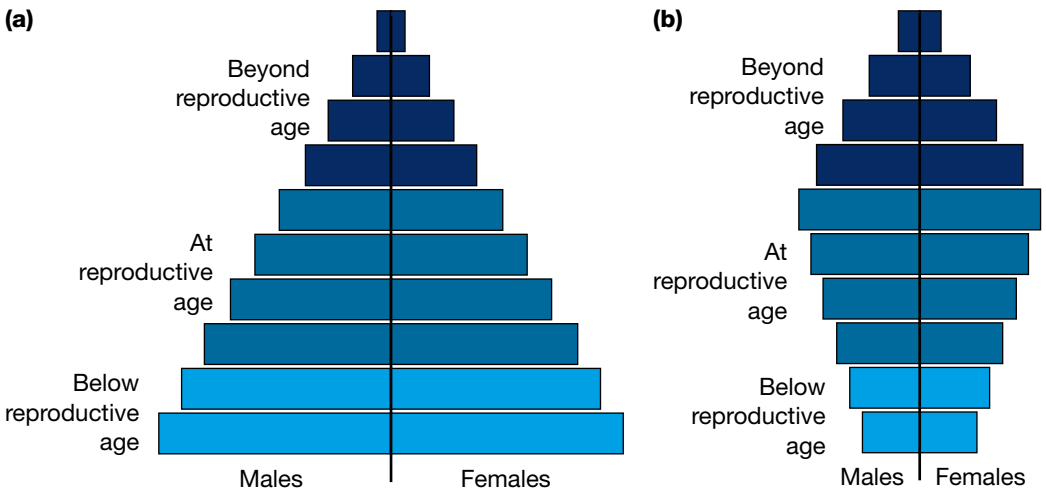

FIGURE 8.74 Age structures of two populations
(a) Population with a broad base with most individuals being at reproductive age or younger. Is this population expected to grow?
(b) Population with a narrow base. Is this population expected to grow?

In human populations, where lifespans are long, the population structure is generally shown in terms of both age and sex. Figure 8.75 shows the contrasting age–sex structures of the populations of two countries, Australia and Nigeria.

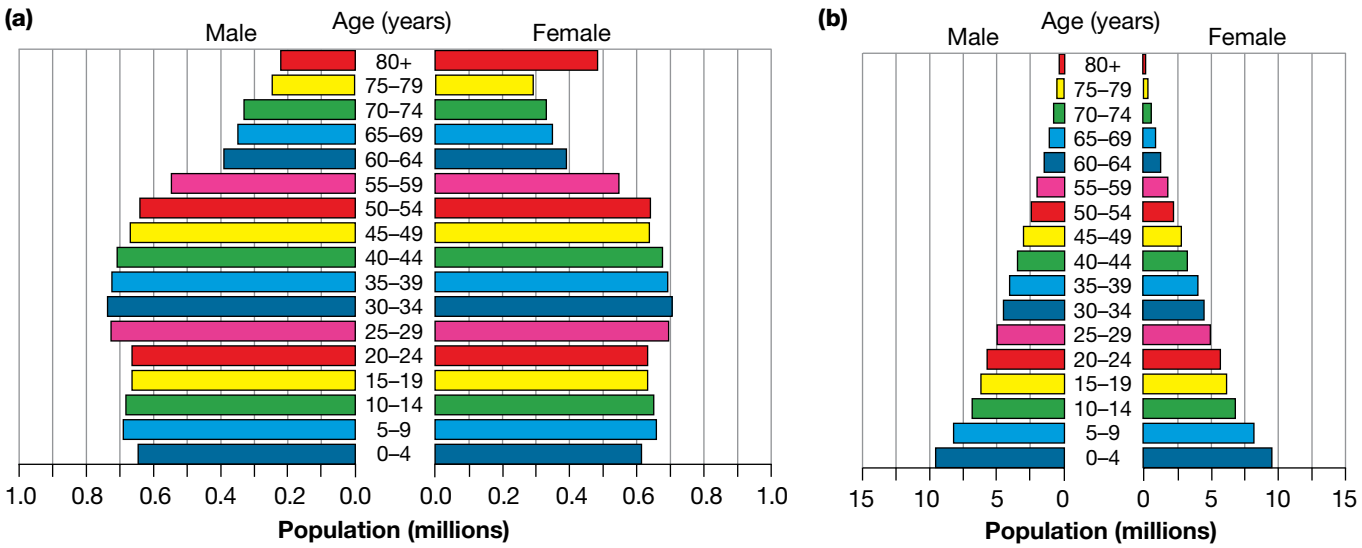

FIGURE 8.75 Age–sex structures for **(a)** Australia and **(b)** Nigeria. Note the different shapes of the age–sex structures for the two countries and note the different x-axis scales. Which population will be expected to increase?

KEY IDEAS

- The abundance of a population refers to relative representation of a population in a specified area.
- The abundance of a population can vary over time and space.
- Either total counts or sampling techniques are used to assess abundance of a population in a specified location.
- The distribution of a population identifies how members of a population are spread over space.
- The shape of the plot of the age structure of a population indicates its reproductive capacity.

QUICK CHECK

12 Identify whether each of the following statements is true or false.
- **a** A total count or true census of a population is less commonly carried out than the use of a sampling technique.
- **b** An age structure with a pyramid shape is indicative of a growing population.
- **c** The abundance of a population would be expected to be constant across its range.

13 Give a possible explanation for a population showing a clumped distribution.

14 Identify one possible reason that a biologist studies the abundance of a population over time.

Variables affecting population size

The size of the population of a particular species in a given area is not always stable. Fluctuations can occur — a population may decline or it may suddenly explode, such as has occurred from time to time with the crown-of-thorns starfish population in the Great Barrier Reef. What determines the size of a population?

Four primary events determine population size

The four **primary ecological events** that determine population size are:

1. births
2. deaths
3. immigration, movement of individuals *into* the population
4. emigration, movement of individuals *out of* the population.

The combined action of these four primary events produces changes in the size of a population over time.

This may be represented by the equation:

change in population size = (births + immigration) − (deaths + emigration)

If the sum (births + immigration) is greater than (deaths + emigration), the population will increase in size.

If the sum (births + immigration) is less than (deaths + emigration), the population will decrease in size.

The change in population size expressed in terms of a period of time is the **growth rate** of the population.

The growth rate is positive when population size increases over a stated period, for example, 200 organisms per year. The growth rate is negative when the population size decreases over a stated period. When gains by births and immigration match losses by deaths and emigration over a stated period, a population is said to have **zero population growth**.

A population is defined as either *open* or *closed* depending on whether migration can occur. Migrations into or out of **closed populations** is nil, unlike **open populations**. Closed populations are isolated from other populations of the same species, for example, a lizard population on an isolated island. Other closed populations include monkey populations in closed forests on various mountains where the mountains are separated by open grassland and desert that the monkeys cannot cross. Closed populations are less common among bird species. Why?

Many other factors can affect population size. These include both **biotic factors**, such as predators or disease, and **abiotic factors**, such as weather. These factors are called **secondary ecological events** because they influence one or more of the primary events of birth, death, immigration and emigration. For example, events such as droughts, cyclones, bushfires and outbreaks of disease increase deaths in a population. In contrast, events such as favourable weather conditions, removal of predators and increased food supply would be expected to increase births in a population.

One striking example of the impact of a secondary event on population size can be seen with the red kangaroo (*Macropus rufus*). From 1978 to 2004, populations of red kangaroos were surveyed over a large area of South Australia using aerial belt transects. Over that time, the population size varied from a high of 2 175 200 in 1981 to a low of 739 700 in 2003. The major factor affecting the numbers of red kangaroos was drought.

ODD FACT

The heatwave that affected Victoria in January 2014 was believed to be responsible for the doubling of the number of deaths reported to the coroner.

Density-independent or density-dependent?

Some of these secondary events, such as weather events, are said to be **density-independent factors**. This means that they affect all individuals in a population, regardless of the size of the population. So, a sudden frost will kill a high percentage of members of a population of frost-sensitive insects. It does not matter if the population size is small or large. Both the small and a large population would experience the same mortality (death) rate. Likewise a population of plants in a forest, whether large or small, will be equally affected when a bushfire races through their habitat. Other density-independent events include cyclones, flash floods and heatwaves (see figure 8.76).

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FIGURE 8.76 Cooling down during a heatwave

In contrast, other secondary events are said to be **density-dependent factors**. These are events that change in their severity as the size of a population changes. The impact of density-dependent factors varies according to the size of a population. One example of a density-dependent factor is the outbreak of a contagious disease. The spread of this disease will be faster in a large, dense population than in a small, sparsely distributed population. As a result, the impact of the disease outbreak is greater in the large population as compared with the small population. Predation is another example of a density-dependent facto. Predators are more likely to hunt the most abundant prey species, rather than seek out prey from a small population.

Competition for resources is another density-dependent factor. Members of a population need access to particular resources. In the case of plants, these resources include space, sunlight, water and mineral nutrients. In the case of animals, necessary resources include food, water and space for shelter and breeding. These resources are limited in supply.

As a population increases in size, the pressure on these resources increases because of competition between members of the same population for these resources, as well as competition from members of other populations that live in the same habitat and compete for the same resources (see figure 8.77). The impact of competition on individuals in a population depends on the population size. When a population is small, the impact of competition is low or absent. However, when a population becomes large, competition has a major impact on each member of a population and survival and reproductive success are threatened.

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FIGURE 8.77 Inter-specific competition for food. The lioness is trying to defend her prey from her successful hunt from a pack of hyenas.

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Unit 1 AOS 2 Topic 3 Concept 9 **Limits to population growth** Concept summary and practice questions

Models of population growth

A new species is introduced to an island where it has no predators, diseases that might affect it are absent, and food and other resources are in plentiful supply. What will happen to the size of the population?

Two models of population growth in a closed population can be identified:

- the exponential or unlimited growth model
- the logistic or density-dependent model.

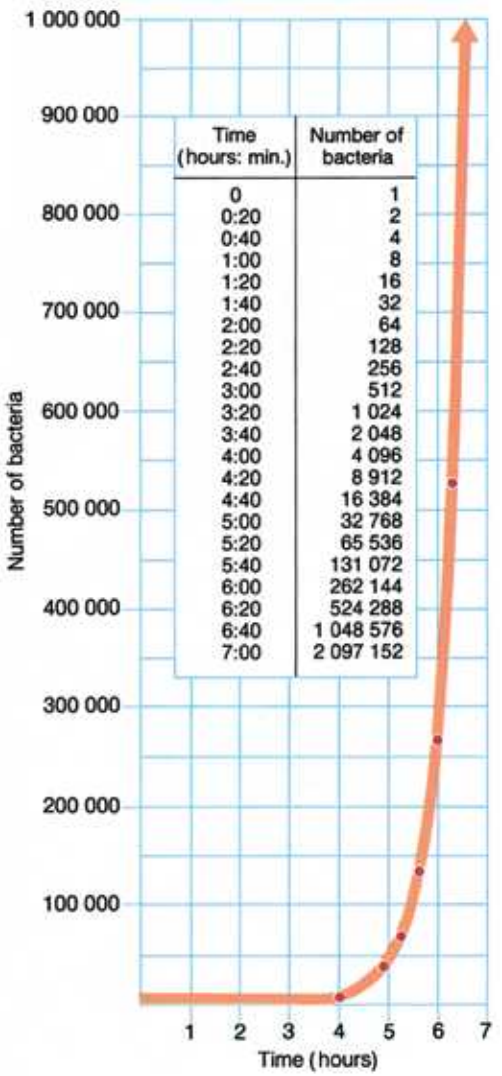

FIGURE 8.78 Exponential growth of bacteria over a 7-hour period, starting with a single cell

Exponential growth: the J curve

Exponential growth is seen in the growth of bacteria over a limited period of time. For example, consider a bacterial species in which each cell divides by asexual binary fission to give two cells every 20 minutes. Figure 8.78 shows the theoretical outcome of this pattern of growth starting with a single bacterial cell.

Consider the Australian bushfly (*Musca vetustissima*). Let's start a population with just one female bushfly and her mate. Assume that she lays 100 eggs and dies soon after. Of the eggs, assume that 50 develop into females with a generation time of 8 weeks. Table 8.4 shows the growth in the bushfly population that would occur if the population could grow exponentially.

TABLE 8.4 Exponential growth in a bushfly population over eight generations

Generation	Total population
0	2
1	100
2	5 000
3	250 000
4	12 500 000
5	625 000 000
6	31 250 000 000
7	1 562 500 000 000
8	78 125 000 000 000

With exponential growth, the increase in population size over each generation is not identical. As the population increases in size, the growth over each generation also becomes larger.

If exponential growth occurred, this single female bushfly and her mate would have 31 billion descendants in just under one year! In reality, however, this number *cannot* materialise because exponential growth of populations cannot occur indefinitely. The conditions required for exponential growth — unlimited resources such as food and space — can last for only a few generations. Every habitat has limited resources and can support populations of only a limited size. So, let's look at another model of population growth that has a better fit with reality.

ODD FACT

In bacterial populations, population growth will slow and stop because of the build-up of bacterial waste products in their living space.

Density-dependent growth: the S curve

A pair of rabbits in a suitable habitat with abundant food and space initially multiplies and, over several generations, the population grows faster and faster; this is a period of exponential growth. However, this rate of growth cannot continue. As the population increases in size, the pressure on resources increases, competition grows, and the population growth slows, and then stops. At this point, the so-called carrying capacity of the habitat is reached.

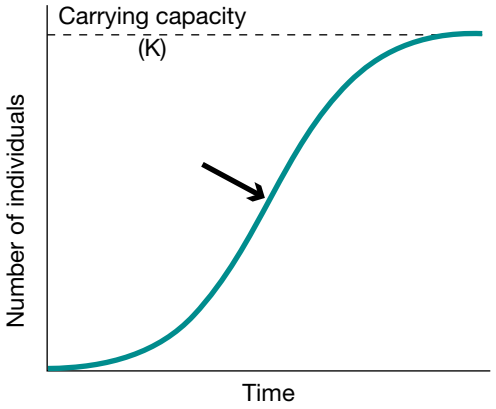

FIGURE 8.79 An S-shaped curve that is typical of the growth of most populations. The upper limit of this curve is determined by the carrying capacity of the habitat. The arrow marks the point of maximum growth of the population.

The carrying capacity is the maximum population size that a habitat can support in a sustained manner.

The growth of a population under the density-dependent condition is shown in figure 8.79. The growth is at first like the exponential growth pattern, but, as the population grows, the rate of growth slows and finally stabilises at the carrying capacity. This pattern is known as an S-shaped curve.

Populations affect other populations

The population size of one species can be affected by the size of the population of another species. For example, the size of a plant population is affected by the sizes of the populations of herbivores that feed on that plant.

Other density-dependent factors that influence the size of one population include the sizes of populations of its parasites and its predators. Let's look at how predator and prey populations interact and the impacts on their population sizes.

Predator and prey population numbers

The population size of a prey species can be affected by the size of the population of a predator species that feeds on it. Over time, several outcomes are possible:

- If the predators are absent, the prey population will increase exponentially but will eventually 'crash' when its numbers become too high to be supported by the food resources in the habitat.
- If the prey population is too small, the predator population will starve and die.

In some cases, cycles of 'boom-and-bust' can be seen in both populations, with the peak in the predator population occurring after the peak in the prey population. Why? Figure 8.80 shows the theoretical expectation of these boom–bust cycles while figure 8.81 shows the result obtained in an actual experimental study.

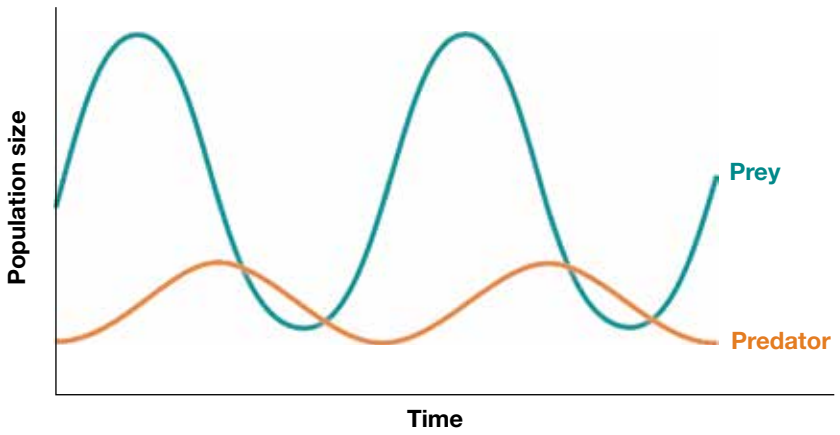

FIGURE 8.80 Fluctuations in population size in a prey population and in the predator population that feeds on it. Which population peaks first in each cycle: predator or prey? Can you suggest why?

In the next section we will see how the different intrinsic rates of growth of populations can affect their ability to colonise new habitats and their ability to re-built numbers after a population crash.

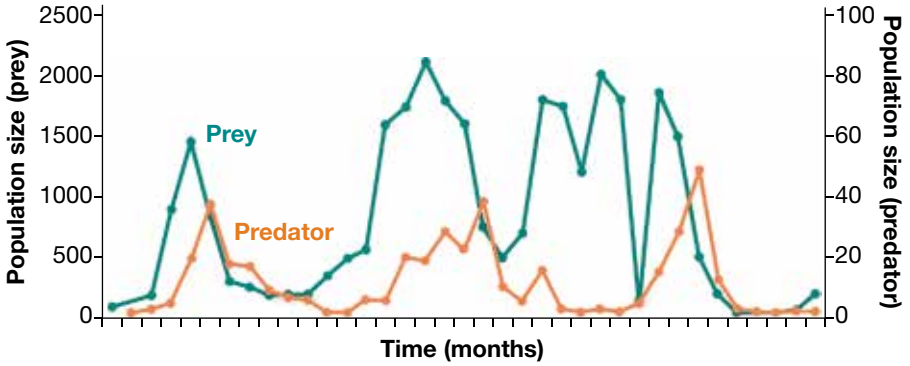

FIGURE 8.81 Results from an actual study of boom–bust cycles in predator and prey populations

KEY IDEAS

- Population size is determined by four primary events: birth, death, immigration and emigration.
- Population size is also affected by secondary events that impact on the rate of births and deaths.
- The impact of some secondary events depends on the size of a population and these are said to be density dependent.
- Exponential population growth follows a J-shaped curve but cannot continue indefinitely.
- Logistic population growth follows an S-shaped curve that levels off at the carrying capacity of the ecosystem concerned.
- The populations of one species may be affected by the population size of another species in the community.

QUICK CHECK

15 Identify whether each of the following statements is true or false.
- **a** Floods are an example of a density-independent environmental factor.
- **b** Immigration is one of the primary events that determine population size.
- **c** Increases in prey population size are expected to be followed by decreases in its predator population size.
- **d** When gains by births and immigration exceed losses by deaths and emigration, a population is said to have zero population growth.
- **e** Exponential growth of a population follows a J-shaped curve.

16 Identify a density-dependent factor that would be expected to limit population growth.

17 Give one cause for the 'crash' of a prey population.

18 What is the difference between an open and a closed population?

19 Give an example of a closed population.

Intrinsic growth rates

In the previous section we looked at growth of populations in general. Populations of different species vary in their intrinsic rates of increase, typically denoted by the symbol 'r'.

Populations of some species are short-lived and produce very large numbers of offspring. Species that use this 'quick-and-many' strategy put their energy into reproduction and are said to be **r-selected**. Examples of r-selected species include bacteria, oysters, cane toads, crown-of-thorns starfish, many species of reef fish, clams, coral polyps, many weed species, rabbits and mice. **In general, r-selection is directed to *quantity* of offspring.**

At the other end of the spectrum are populations of species that produce small numbers of offspring at less frequent intervals. Species that use this 'slower-and-fewer' strategy put their energy into the care, survival and development of their

offspring and are said to be **K-selected**. Examples of K-selected species include gorillas, whales, elephants, albatrosses, penguins, southern bluefin tuna and many shark species. **In general, K-selection is for *quality* of offspring.**

Table 8.5 identifies some of the differences between the extremes of r-selected and K-selected species. Not every species displays all the features of one strategy and many have intermediate strategies.

TABLE 8.5 Extremes of reproductive strategies compared

Feature	r-selected strategy	K-selected strategy
general occurrence	commonly seen in oysters, clams, scallops, bony fish, amphibians, some birds and some mammals, such as mice and rabbits	commonly seen in sharks, some birds, such as penguins, and some mammals, such as whales and gorillas
lifespan	shorter lived	longer lived
number of offspring	many	few
energy needed to make an organism	smaller	greater
survivorship	very low in young	high in young
growth rate	faster	slow
age at sexual maturity	early in life	late in life
parental care	little, if any	extensive
adapted for	rapid population expansion	living in densities at or near carrying capacity
relative energy investments	higher investment into numbers of offspring; lower into rearing offspring	lower investment into numbers of offspring; higher into rearing offspring

FIGURE 8.82 The spawn of cane toads can be readily distinguished from those of native frogs by their appearance as black eggs embedded in long jelly-like strings. How many eggs are produced on average in a cane toad spawning?

r-selected growth strategy

Populations of species that operate using the 'quick-and-many' strategy can show major fluctuations in population sizes. When resources are plentiful and other environmental conditions are favourable, the numbers of an r-selected species can increase very rapidly because of their short generation times and the large numbers of offspring that they produce. A short generation time means that the growth of an r-selected population occurs much more quickly (weeks) than in a K-selected species, where generation times may be several years. When conditions become unfavourable, the very low survival rates of offspring mean that population numbers drop sharply. These r-selected populations, however, can recover quickly because of their high growth rates.

The r-selected populations are adapted for life in 'high risk' and unstable environments, where factors such as flood and drought operate, and in 'new' habitats such as on fresh lava flows, or new land elevated from the sea as a result of earthquake or volcanic activity, or even a cleared patch of land in the suburbs. (Most weeds are r-selected.)

The following examples identify the numbers of offspring produced by some r-selected species:

- Cane toads (*Rhinella marina*) are an introduced pest species. They spawn twice yearly and, at each spawning, one mature female cane toad produces an average of 20 000 eggs, which are fertilised externally. Within one to three days, fertilised eggs (see figure 8.82) hatch into tadpoles that metamorphose into small toads very quickly. Within a year, these toads are ready to reproduce and do so for a period of several years.

ODD FACT

Cane toads are estimated to live from 10 to 40 years (data from Honolulu Zoo).

ODD FACT

Crown-of-thorns starfish can reach more than 80 cm in diameter. Some have been kept in captivity in aquaria for up to 8 years but their lifespan in the wild is probably 3 to 4 years.

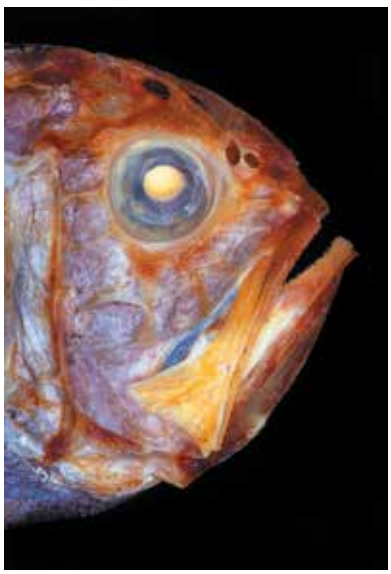

FIGURE 8.83 The orange roughy (*Hoplostethus atlanticus*)

ODD FACT

How can you tell the age of a fish? It is possible to tell the age of fish from an examination of the growth rings of their scales or from the stony otoliths in their ears. Using this method, some orange roughy have been identified as more than 70 years old.

- The crown-of-thorns starfish (*Acanthaster planci*) (refer back to figure 8.69) breeds in the waters of the Great Barrier Reef when water temperatures reach about 28 °C. Female starfish release eggs into the water where they are fertilised by sperm released by nearby male starfish. In one spawning season, a female crown-of-thorns starfish may release up to 60 million eggs. Water currents disperse the fertilised eggs and larval development is completed over a two-week period. The tiny larvae settle on coral reefs and develop into juvenile starfish about 0.5 mm in size. These juveniles feed on algae for about 6 months and then, when they are about 1 cm in diameter, they begin to feed on coral polyps. Sexual maturity is reached after about two years.

K-selected growth strategy

Populations of species that operate using the 'slower-and-fewer' strategy live in habitats in stable environments and with their population sizes at or near the carrying capacities of their habitats. K-selected species are adapted to cope with strong competition for resources. If the population size of a K-selected species drops sharply as a result of fire, habitat loss or over-harvesting, the population will not recover quickly because of their long generation times and their low rates of increase. K-selected species are at great risk of extinction if their population numbers fall because their initial rate of replacement is very slow.

The following examples identify some species that are K-selected in terms of their reproductive strategy.

- In late autumn and winter each year, humpback whales (*Megaptera novaeangliae*) migrate up the east coast of Australia to breeding grounds in tropical or semitropical waters. It is here that the whales mate and it is also here that pregnant females give birth during the southern hemisphere winter. Humpback whales show many of the features of a K-selected species as follows:
  - sexual maturity in humpback whales does not occur until whales are about five years old
  - gestation (pregnancy) in humpback whales lasts about 11.5 months
  - each female gives birth to just one calf every one or two years
  - for an average of 10 months after its birth, a mother suckles her calf on milk
  - the lifespan of humpback whales is up to 50 years.
- The orange roughy (*Hoplostethus atlanticus*) (see figure 8.83) is a species of fish found in deep waters off south-east Australia. This species is slow-growing and does not reach sexual maturity until it is about 30 years old. At this stage, the fish has a length of about 30 cm.

Not all species dovetail into r-selected or K-selected species. For example, green turtles (*Chelonia mydas*) exhibit r-selection in terms of the numbers of eggs produced and the lack of parental care but they also show some K-selection through features such as their slow growth rates, the period required for sexual maturity (estimated at 40 to 50 years) and their long lifespan (estimated at 70 years).

A female green turtle (see figure 8.84a) lays a clutch of about 100 eggs on a sandy beach at night, covers them with sand and returns to the water (see figure 8.84b). During the breeding season, she returns to the same beach about every 2 weeks and may lay three to nine clutches of about 100 eggs per clutch. About 2 months later, baby turtles hatch from the eggs, dig their way out of the nest and make their way to the sea (see figure 8.84c).

FIGURE 8.84 **(a)** Green turtles are common in the waters of the Great Barrier Reef. This species has a worldwide range in tropical and semi tropical waters. **(b)** Female green turtle laying eggs. The temperature at which the eggs develop determines the sex of the turtles; lower temperatures produce males, while higher temperatures produce females. **(c)** Turtle hatchlings making their way to the sea. If this occurs during the day, predators such as sea birds and crabs take many of the hatchlings before they reach the sea.

KEY IDEAS

- Populations differ in their intrinsic rates of growth.
- Species can be identified as being r-selected or as K-selected.
- r-selection and K-selection are the extremes of a range.
- r-selected species are adapted for living in newly created and in unstable habitats.
- K-selected species are adapted for living in stable habitats and at densities at or near the carrying capacity of a habitat.

QUICK CHECK

20 Which species, r-selected or K-selected, would be expected to:
- **a** recover more quickly after its population was reduced
- **b** be at greater risk of extinction through habitat destruction?

21 Contrast r-selection and K-selection in terms of:
- **a** number of offspring
- **b** growth rates
- **c** age at sexual maturity.

22 Give an example of:
- **a** a K-selected species
- **b** an r-selected species.

BIOCHALLENGE

Figure 8.85 is a diagrammatic representation of an ecosystem that shows energy inputs and outputs from the ecosystem and the movement of matter around the ecosystem.

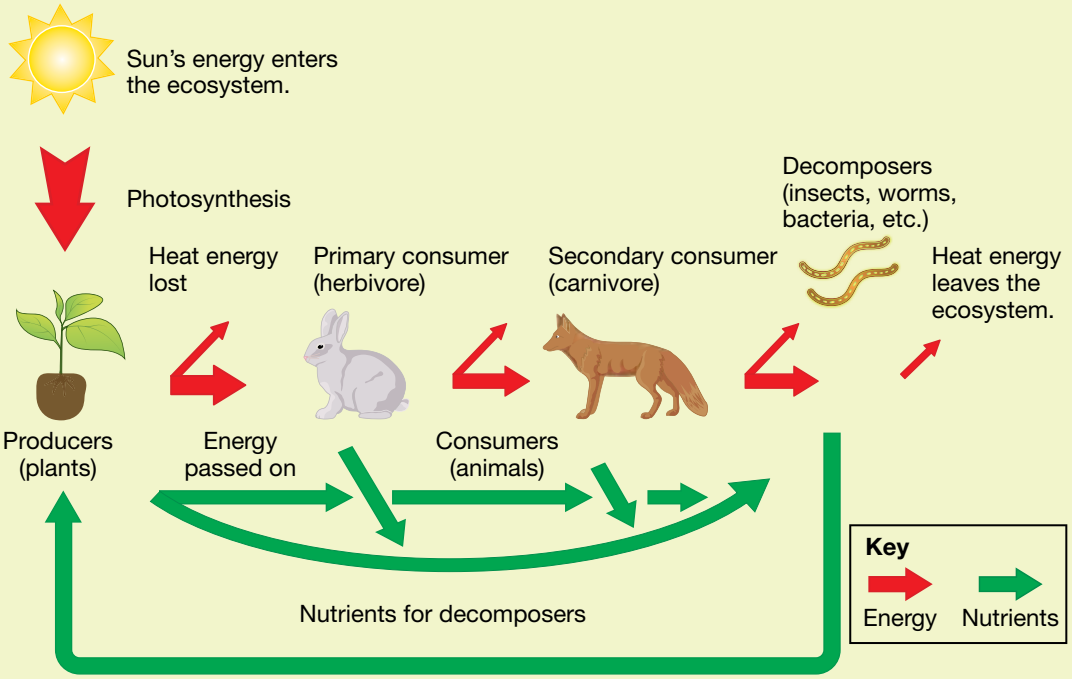

FIGURE 8.85 Diagrammatic representation of a simple ecosystem

1 Consider figure 8.85 and the information in this chapter and answer the following questions.
   - **a** What is the source of the external energy for this ecosystem?
   - **b** How does energy enter an ecosystem?
   - **c** Consider the following sentences:
     - i Energy recycles within an ecosystem.
     - ii Energy lost from an ecosystem is as heat energy.
     - iii Energy gained by an ecosystem is as sunlight energy.
     - iv Energy is transferred within an ecosystem as chemical energy.
     - v Energy transfers within an ecosystem are 100 per cent efficient.

     Identify each of the sentences as either true or false and, if judged by you to be false, re-write the sentence in a 'true' form.
   - **d** In what form do nutrients move within an ecosystem?
   - **e** Some green arrows show the flow of nutrients from consumers to decomposers. Explain how this occurs.

2 Many relationships exist between members of different populations in an ecosystem community as shown in table 8.6. Complete this table by using the following symbols to identify the outcome of the relationship for each species in each case.

   \+ the species receives a benefit

   – the species is killed, inhibited or harmed in some way

   0 the species neither receives a benefit nor is it harmed

TABLE 8.6

Relationship	Species A	Species B
mutualism		
predator-prey		
amensalism		
parasite-host		
herbivore-plant		
commensalism		

Chapter review

studyon
Unit 1 AOS 2 Topic 3
Relationships between organisms within an ecosystem
Sit topic test

Key words

abiotic factor
abundance
aerial strip transect
allelochemical
allelopathy
amensalism
autotroph
biotic factor
camouflage
carnivore
cladode
closed population
commensalism
community
competition
consumer
decomposer
density-dependent factor
density-independent factor
desiccation
detritivore
detritus
diversity
ecology
ecosystem
endoparasite
exoparasite
exponential growth
food chain
food web
growth rate
haustoria
hemiparasitism
herbivore–plant relationship
herbivores
heterotroph
holoparasitism
host
hydrothermal vent
interspecific competition
intraspecific competition
K-selected
keystone species
littoral (intertidal) zone
mark–recapture technique
mimicry
mutualism
mycorrhiza
nitrogen-fixing bacteria
omnivore
open population
parasite
parasite–host relationship
parasitoid
photosynthesis
population
predator
predator–prey relationship
prey
primary consumers
primary ecological event
producer
quadrat
r-selected
sampling
secondary consumers
secondary ecological event
sulfur-oxidising producer bacteria
symbiosis
transect
tertiary consumers
total count
trophic level
trophosome
true census
warning colouration
zero population growth

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map. You may use other words in drawing your map.

2 **Identifying differences** ➜ Identify one essential difference between the members of the following pairs.
- **a** Parasite and parasitoid
- **b** Host and prey
- **c** Predator and parasite
- **d** Symbiosis and commensalism
- **e** Holoparasite and hemiparasite
- **f** Density-dependent and density-independent factors
- **g** Exponential growth and logistic growth of populations
- **h** Commensalism and amensalism

3 **Applying understanding** ➜ Suggest a possible explanation in biological terms for the following observations.
- **a** A common fern produces a chemical that interferes with the development of insect larvae.
- **b** A grower of tomatoes in a commercial glasshouse invests in the purchase of eggs of a particular parasitoid.
- **c** A population initially grows rapidly but then slows and stops.
- **d** An ecosystem cannot exist without producer organisms in its community.
- **e** Some ecosystems exist in conditions of permanent darkness.
- **f** The cost of one kilogram of steak is greater than the cost of one kilogram of rice.

4 **Applying understanding** ➜ Figure 8.86 shows a Morning Glory vine (*Ipomoea purpurea*) that has overgrown plants, some of which can still be seen in the lower right-hand corner.
- **a** What will happen to the underlying plants?
- **b** What name might be given to the relationship between the vine and the plants below it?

5 **Analysing information in new contexts** ➜
- **a** What trophic level can be assigned to each of the following organisms?
  - i Green mosses in a damp gully
  - ii Insects that feed on the mosses
  - iii Birds that feed on the moss-eating insects
  - iv Parasitic mites that live on the birds
- **b** Draw a food chain that shows the energy flow for the organisms above.
- **c** What is the nature of the relationship between each of the pairs of organisms in (ii) to (iv) above?

FIGURE 8.86 Morning Glory vine (*Ipomoea purpurea*)

6 Analysing data and communicating understanding ➜ Pedra Branca lies off the south coast of Tasmania (see figure 8.87). Living on the island and in the surrounding waters is a community that forms part of an ecosystem and includes krill, various species of fish, squid and birds such as the Australasian gannet (*Morus serrator*) and the shy albatross (*Diomedia cauta*).

a Draw a food web showing part of the energy flow in this ecosystem.

b How many trophic levels exist in this ecosystem?

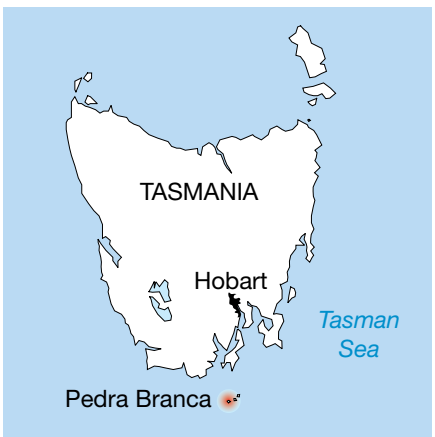

FIGURE 8.87

7 Applying your understanding ➜ Give one example of organisms in an ecosystem that:

a capture and transform radiant energy

b are primary consumers

c occupy the first trophic level

d form part of the producers of ocean ecosystems

e interact in a relationship of commensalism

f interact in a relationship of mutualism.

8 Applying understanding ➜ Explain the following observations in biological terms.

a When fish and mammals can survive on the same food pellets, the cost of producing a given mass of fish is less than the cost of producing the same mass of mammals.

b In an ecosystem, the number of large carnivores is typically far less than the number of herbivores.

c More fish and other consumer organisms are found in a volume of coastal sea than in an equivalent volume of open ocean.

d Tropical rainforests have more trophic levels than a desert scrub.

9 Applying biological principles ➜ A food chain consists of:

leaves → caterpillar → sparrow → eagle

Consider that a caterpillar eats 100 grams of leaf organic matter. Based on the 10-per-cent rule, how much of the chemical energy in this organic matter would be available for consumption by:

a a sparrow

b an eagle?

10 Analysing a situation ➜ Could a fish tank with clean fresh water containing three fish, each of a different species, be regarded as a miniature ecosystem? Explain your decision.

11 Interpreting new information ➜ Consider the lamb shown in figure 8.88.

a What is the trophic level of this herbivorous lamb?

b What percentage of the chemical energy in the food eaten by the lamb is expected to:

i be used in cellular respiration

ii be egested as faeces or excreted as urine

iii appear as new tissue?

c Of every 100 units of chemical energy obtained from grass that is eaten by the lamb, how much goes into producing lamb chops and the like?

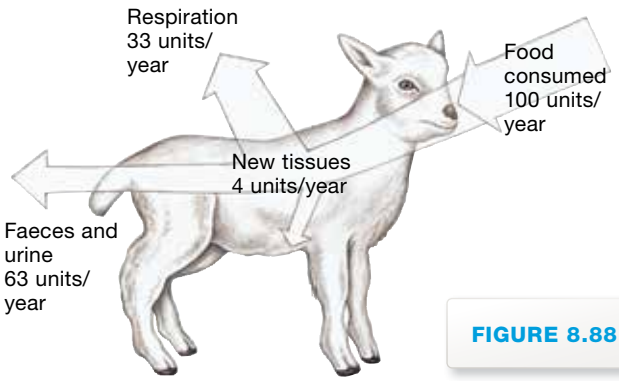

FIGURE 8.88

12 Analysing information and drawing conclusions ➜ Two islands (C and D) in temperate seas differ in their species richness, with island C having twice as many species as D. Of the following four statements, which is the most reasonable explanation?

- **a** No conclusion is possible.
- **b** Islands C and D have the same area.
- **c** Island C has twice the area of island D.
- **d** Island C has about ten times the area of island D.

13 Applying your understanding ➜ Identify the following statements as true or false.

- **a** A population that is large must be increasing in size.
- **b** Quadrats can be used to sample populations of fast-moving animals.
- **c** The presence of more than one crown-of-thorns starfish per two-minute tow indicates the start of a population explosion.
- **d** Exponential growth can occur in a population provided resources are not limited.

14 Discussion question ➜ Consider the following relationships between organisms in a community:

i Termites ingest the cellulose of wood but they cannot digest it. Protozoan organisms living in the termite gut secrete cellulases, enzymes that digest cellulose, releasing nutrients that can be used by the termites.

ii Giant tubeworms (*Riftia pachyptila*) living in deep ocean hydrothermal vents have no mouth or digestive system. Within their cells live chemosynthetic bacteria.

iii Adult barnacles (refer to figure 8.14b) are sessile animals that are filter feeders. Barnacles are generally found attached to rocks. Some barnacles, however, attach to the surface of whales.

iv Bacteria of the genus *Vampirococcus* attach to the surface of bacteria of other species, where they grow and divide, consuming the other bacteria.

In each case:

- **a** identify the type of relationship that exists between the organisms
- **b** briefly describe the outcome of the relationship for each member of the pair of interacting organisms.

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PRACTICAL ACTIVITIES

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ACTIVITY 1.2 Exploring one of the tools of the biologist: the microscope
ACTIVITY 1.3 Viewing and staining cells
ACTIVITY 1.4 What limits the size of cells?
ACTIVITY 1.5 Cells and cell organelles: how big?
ACTIVITY 1.6 Crossing membranes

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ACTIVITY 3.3 Respiration involving oxygen: aerobic respiration
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ACTIVITY 4.2 Blood and its transport
ACTIVITY 4.3 The heart
ACTIVITY 4.4 Grasshoppers, fish and rats: how do they obtain oxygen?
ACTIVITY 4.5 Transport systems in plants: plant pipelines

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ACTIVITY 5.2 Case studies in survival
ACTIVITY 5.3 Making urine: losing water
ACTIVITY 5.4 Physiological adaptations for maintaining water balance in vertebrates
ACTIVITY 5.5 Leaves for survival
ACTIVITY 5.6 Plant responses: phototropism
ACTIVITY 5.7 Plant responses: geotropism
ACTIVITY 5.8 Courtship and reproductive behaviour

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ACTIVITY 6.2 Glucose ups and downs
ACTIVITY 6.3 Hot stuff

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ACTIVITY 7.2 What eucalypt is that?
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ACTIVITY 8.2 A population study: long-nosed bandicoots at North Head, Sydney Harbour National Park
ACTIVITY 8.3 How fast are they growing?

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CHAPTER 10

ACTIVITY 10.1 Vegetative reproduction: reproduction without sex

CHAPTER 11

ACTIVITY 11.1 Human reproduction
ACTIVITY 11.2 Reproduction in mosses

CHAPTER 14

ACTIVITY 14.1 Karyotypes and meiosis
ACTIVITY 14.2 Modelling meiosis
ACTIVITY 14.3 How much do I owe grandma?

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ACTIVITY 15.1 Environmental influences on phenotype

CHAPTER 16

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ACTIVITY 16.2 Two genes at a time
ACTIVITY 16.3 Family portraits: what pattern is this?
ACTIVITY 16.4 Genetics with *Drosophila*

CHAPTER

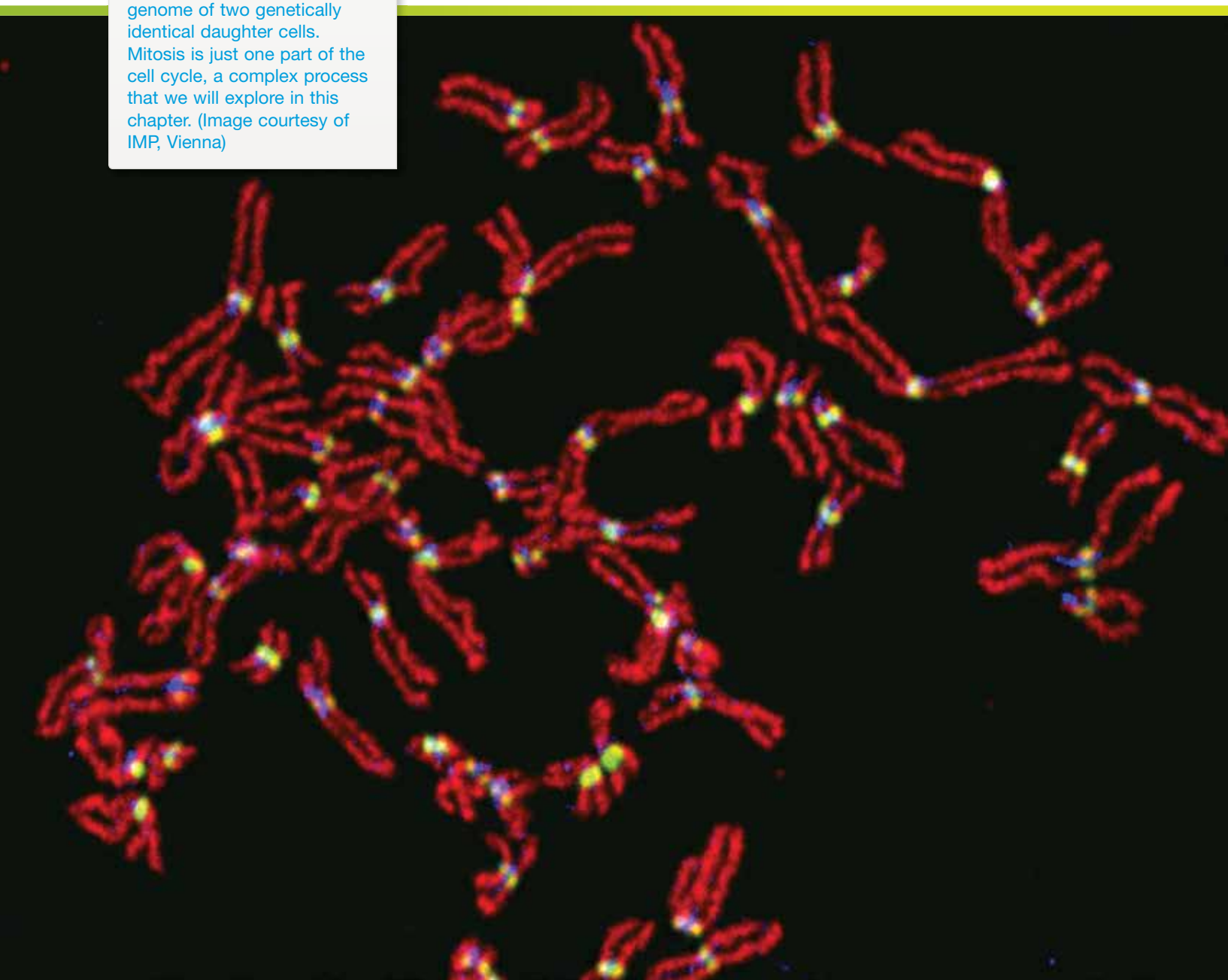
9 Cell cycle

FIGURE 9.1 The duplicated chromosomes (stained red) of a HeLa cell. Each chromosome consists of two sister chromatids, with each chromatid having identical genetic information. When these sister chromatids separate during anaphase of mitosis, they will form the genome of two genetically identical daughter cells. Mitosis is just one part of the cell cycle, a complex process that we will explore in this chapter. (Image courtesy of IMP, Vienna)

KEY KNOWLEDGE

This chapter is designed to enable students to:

- gain understanding of the importance of the mitotic cell cycle in cell production for growth and repair in eukaryotes
- recognise that the cell cycle produces daughter cells that are identical to each other and are clones of the parent cell
- become familiar with the stages of the cell cycle and the chromosomal events that occur at each stage.



Saving burns victims

When Professor Fiona Wood (see figure 9.2) of the Royal Perth Hospital was made 2005 Australian of the Year, it was in recognition of her work related to the treatment of people with severe burns. For about 10 years prior to March 2003 Professor Wood had been developing improved methods for growing replacement skin. When 28 Australians were badly wounded and burnt as a result of a terrorist bombing in Bali, Indonesia, it was decided that they should be returned to Australia as soon as possible for treatment. They were sent to Professor Wood and Australians followed their progress through the daily press. 'Spray-on skin', known commercially as CellSpray, and Professor Wood became famous.

FIGURE 9.2 Professor Fiona Wood AM was awarded 2005 Australian of the Year for her work on developing an improved method of skin-cell regeneration, leading to improved and more rapid treatment for people with skin burns.

Skin: the outer layer

Normal intact skin provides a covering for the human body. The skin is composed of an outer **epidermis** and an underlying **dermis**. The epidermis and the dermis are held together by a non-cellular basement membrane.

The epidermis consists of several cell layers (see figure 9.3):

- an outermost region consisting of layers of flattened dead cells, called the stratum corneum (*strata* = layer, coat; *corneum* = horny). These cells are constantly being shed from the skin surface. This layer is thickest on the soles of the feet and the palms of the hands.
- several layers of living cells called **keratinocytes** that are gradually pushed upwards, becoming flattened and eventually forming part of the outermost region of dead cells. The keratinocytes form the bulk of the epidermis.
- a basal layer which includes stem cells that are constantly dividing. For each two cells produced by division of a stem cell, one becomes a new keratinocyte and the other replaces the stem cell. The continual division of stem cells in the basal layer pushes the overlying keratinocytes towards the skin surface. Another group of cells present in the basal layer are the pigment-producing cells, or **melanocytes**.

The dermis lies below the epidermis. The dermis contains blood vessels, hair follicles, sweat glands, touch-sensitive and pain-sensitive cells, muscle fibres and collagen fibres.

The severity of burn damage to human skin may vary from first-degree burns, such as sunburn, that involve the epidermis only, to second-degree burns, such as scalds, that involve the epidermis and the upper section of the dermis, to severe third-degree or full thickness burns that destroy the epidermis and all or part of the dermis. Burns of this type were those seen in the seriously burnt victims of the Bali bombing and those who are badly burnt in bushfires in this country.

Basement membranes occur throughout the human body. They consist of glycoproteins and provide structural support for tissues.

ODD FACT

It has been estimated that each person replaces, on average, about 18 kg of skin cells during a lifetime. Dandruff, skin cells from our scalps, represents just a fraction of the skin cells we must replace.

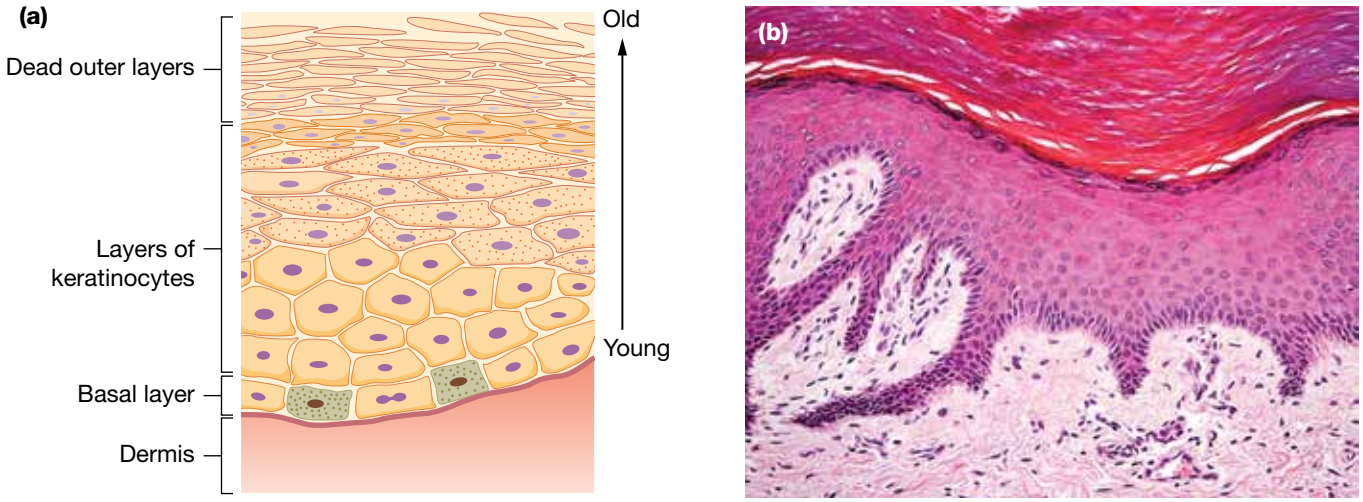


FIGURE 9.3 Section through human skin **(a)** Diagram showing the epidermis that overlays the dermis. The basal layer of epidermal cells includes stem cells that are capable of cell division. As keratinocytes are pushed towards the skin surface, they flatten and eventually become part of the dead outermost layers of skin cells. **(b)** Photomicrograph of stained epidermis of human skin. Note the change in shape of the keratinocytes as they become older and move closer to the outer surface of the skin. What is the origin of the keratinocytes that form the bulk of the epidermal tissue?

When areas of skin are severely damaged by fire, acid or some other trauma, the challenge is to get new skin to grow over the damaged area. In the past, the treatments available for persons suffering third-degree burns included the use of skin grafts taken from an uninjured part of the victim's body. Such a graft is called an **autograft** (*auto* = self) because it is a transplant of healthy skin from one area of a person to a damaged area of the same person. However, a problem with autografts is that the area of the graft must be as large as the area of the burned skin. So, for patients with severe burns over a large area of their skin surface, say 50 per cent or more, there is insufficient unburned skin to be used for grafting. In some urgent cases, skin from another person may be grafted onto the burned area of the victim; such a graft is an **allograft**. A skin allograft is a temporary measure because this graft will be rejected.

Another treatment involved covering a burn area with a thin sheet of skin cells grown in plastic dishes in a laboratory. This procedure used cells harvested from a small area of skin from the patient. A problem with skin grown in plastic dishes is that this procedure takes considerable time, with up to 21 days being needed to produce sheets of skin cells sufficiently large to cover severely burned areas. In addition, the sheets of skin cells are thin and very fragile. Another problem is that the sheets begin to act like skin and the surface cells form keratin and die so that they are less active growers when the transplant is carried out. Scarring tends to be more severe the longer the patient waits to be treated and the longer wait also increases the chance of infection and other complications with the wounds.

Alternatively, synthetic skin can be used for skin grafts. One example is Integra® Template. The outer layer of this artificial skin is a thin film of silicone, and the second layer is made of cross-linked fibrous proteins (collagen) and a complex carbohydrate (glycosaminoglycan). Synthetic skin is used to cover the burnt area where it acts as a scaffold that enables the patient's own dermal cells to regenerate the skin dermis. Then the silicone film is removed and covered with a thin epidermal skin graft, thus replacing the skin epidermis.

Spray treatments for burns

Professor Wood's research first led to the development of a spray-on solution of skin cells, or CellSpray, that contained a suspension of various skin cells. The cells came from skin harvested from unburnt areas of a patient's skin. These cells were first cultured in the laboratory for a period of about 5 days, during which their numbers increased by cell division. Later, when sprayed over a burn area, the cells spread and continued to divide forming a layer of skin.

FIGURE 9.4 Regenerative Epithelial Suspension™ created using ReCell®, developed by Professor Fiona Wood. A small skin sample is processed into an Epithelial Suspension™ using the ReCell® device and is sprayed onto burnt areas where it will continue to grow and form a new skin.

A further development of this technology is ReCell® Spray on Skin® (see figure 9.4), which is marketed as a self-contained kit (see figure 9.5a). The time interval from taking cells from a patient to applying these cells to a burn area on that patient is about 30 minutes. A small area of healthy skin — about 2 cm by 2 cm, about 0.2 mm thick and close to the area of the burn — is taken from a burns patient. The skin sample includes basal stem cells, pigment-producing cells, keratinocytes and fibroblast cells from the epidermis, as well as some cells from the dermis. The skin tissue is treated through a series of steps (see figure 9.5b) that includes treatment with an enzyme which removes the extracellular matrix that holds the skin cells together. The final suspension of skin cells, plus growth factors to stimulate cell division, is delivered directly to the burn site with a special spray applicator.

ReCell Spray on Skin technology is used in conjunction with skin grafts for deep or third-degree burns. In cases of limited thickness or second-degree burns, the technology is used alone and can cover burn areas up to about 1900 cm^2. Once the cell suspension is applied to a burn area, the basal stem cells will multiply through repeated cell cycles and, over time, the skin lost by the burn damage will be replaced.

As well as being used in the treatment of acute burns where donor skin grafts cannot be taken, the ReCell technology can be used to treat other conditions, such as chronic skin ulcers.

The science involved in growing new skin cells is possible because living skin cells are able to regenerate. We continually shed our old skin cells and so we continually need to replace them. **Skin cells are continually being replaced by the cell cycle, a process that results in the production of two new cells, each identical to the parent cell that gave rise to them. Mitosis** is an important part of that cycle and involves the replication of the genetic material in the cell. The cytoplasm of a cell is shared between the two new cells at **cytokinesis**.

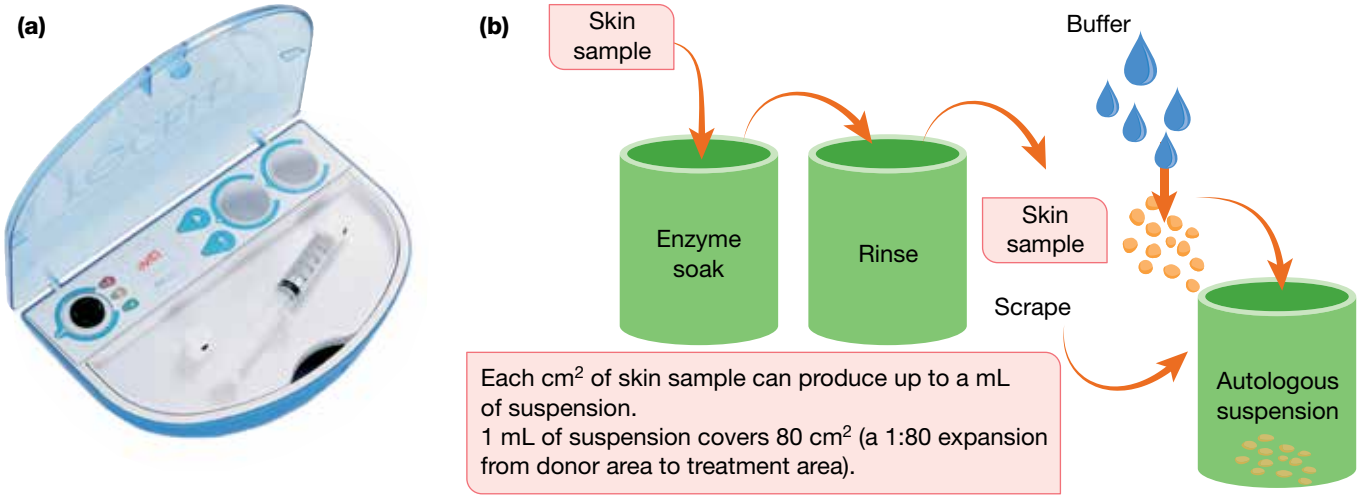


FIGURE 9.5 (a) The self-contained ReCell® Spray on Skin® kit. The sterile chambers and the tray are used for the various procedures involved in preparing a small sample of skin tissue for application to a burn site. What is the size of the patient's skin sample used in this procedure? (Image courtesy of Avita Medical Ltd) **(b)** Diagram showing the procedure that cells pass through with the ReCell kit. Each square centimetre of skin taken from a patient converts to 1 mL of cell suspension, and this can cover 80 cm^2 of burn area. (Image adapted from www.avitamedical.com/wp-content/uploads/2015/03/Avita-Corporate-Presentation-March-2015.pdf)

In this chapter, we consider in some depth the importance of mitosis and cytokinesis. We also explore where these processes occur in a range of animals and plants.

The cell cycle

Cells have evolved complex and exact mechanisms to ensure that genetic information can be passed without error from one cell to two daughter cells of the next generation. It is through the mechanisms of the **cell cycle** that somatic cells of eukaryotes can divide, producing two daughter cells from one parent cell. These daughter cells are genetically identical to each other and genetically identical to the parent cell: a process of natural cloning. To achieve this, eukaryotic cells must first replicate their DNA, then orient their chromosomes in a very precise way, and then separate the sister chromatids.

Key events in the cell cycle

The key events that occur during a cell cycle are summarised in simple terms in table 9.1. These events occur in three distinct phases of the cell cycle: interphase, mitosis and cytokinesis.

TABLE 9.1 A simplified summary of key events during the cell cycle

Cell cycle	What happens	Phase of cell cycle
step 1	replication of DNA of parent cell	interphase
step 2	organisation of chromosomes, followed by their separation into two identical groups at different poles of the parent cell	mitosis
step 3	division of parent cell into two cells	cytokinesis

Let's explore each of these steps in some detail.

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Unit 2 AOS 1 Topic 1 Concept 2

Eukaryotic cell cycle: Interphase
Concept summary and practice questions

Interphase: period of DNA replication

An essential process in the cell cycle is the replication of DNA, the genetic material. DNA replication occurs during a stage of the cell cycle known as the **interphase**. (This stage was once called the 'resting phase', but the cells are far from resting during interphase.) If you looked through a light microscope at cells during interphase, you would see the cell nucleus, but you would not see any discrete chromosomes. In interphase, the chromosomes are decondensed and distributed through the nucleus. However, if you could watch the uptake of the nucleic acids that are the building blocks of DNA, you would see that the cells were busily copying their DNA and performing many other biochemical activities.

In a mammalian cell, a complete cell cycle takes about 24 hours. The time spent by a cell in interphase is far longer than that spent in any other stage of the cell cycle. For example, in mammalian cells about 90 per cent of the time of a complete cell cycle is spent in interphase (see figure 9.6), that is, about 22 hours. This highlights the importance of the activities occurring during interphase.

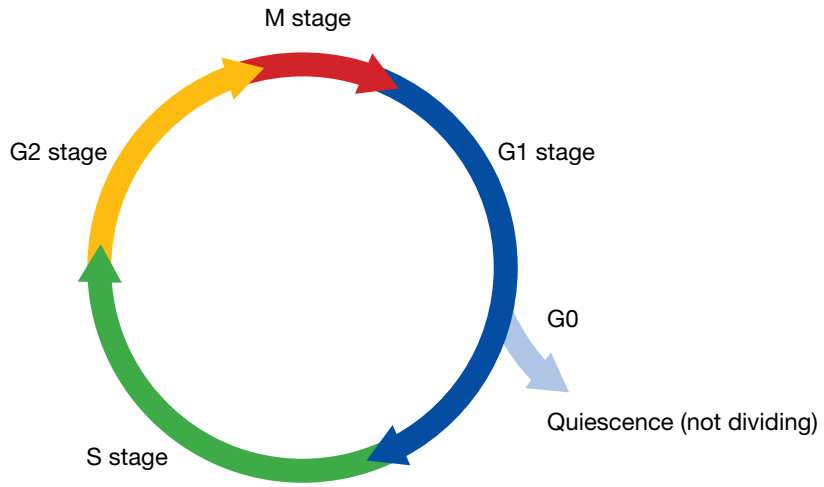

FIGURE 9.6 Stages of the cell cycle. Most of the cell cycle is taken up by the three stages of interphase (G1, S and G2). The M stage is the division stage that includes the division of the nucleus (mitosis) and the division of the remainder of the cell (cytokinesis). What key event takes place during the S stage of interphase?

Interphase is subdivided into three stages:

1. *The G1 or Gap 1 stage*. During the **G1 stage of interphase**, a cell undergoes growth, increasing the amount of cell cytosol. The cell also synthesises proteins that are needed for DNA replication. The mitochondria of the cell divide and, in the cases of photosynthetic plant cells, their chloroplasts also divide. It is near the end of this stage that the cell will either commit to continuing the cell cycle or will drop out and not divide. If the latter occurs, the cell enters a non-dividing quiescent G0 stage.
2. *The S or synthesis stage*. During the **S stage of interphase**, the parent cell synthesises or replicates its DNA, the genetic material of the cell. At the end of the S stage, the parent cell contains two identical copies of its original DNA.
3. *The G2 or Gap 2 stage*. During the **G2 stage of interphase**, further growth of the cell occurs in preparation for division. In addition, the synthesis of proteins occurs, including those that form the microtubules of the spindle. By the end of interphase, the cell has doubled its size.

For a typical human cell that requires 24 hours to complete one cell cycle, the time spent in the various stages might be: G1 stage about 11 hours, S stage about 8 hours, G2 stage about 4 hours and the remainder (mitosis and cytokinesis) about 1 hour. This is in contrast to the rapid process of **binary fission** in prokaryotes that produces two daughter cells within a period of 20 to 40 minutes.

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Unit 2 AOS 1 Topic 1 Concept 3

Eukaryotic cell cycle: mitosis
Concept summary and practice questions

Mitosis: organising and separating chromosomes

The appearance of chromosomes, initially thin and long, and the disappearance of the nuclear membrane mark the start of the part of the cell cycle known as mitosis, the M stage.

eBook*plus*

Interactivity
Mitosis
eles-3027

Mitosis includes a number of different stages:

- **Prophase**. Chromosomes gradually condense — becoming shorter and thicker — and become visible as double-stranded structures (see figure 9.7). The spindle forms and the nuclear membrane breaks down.
- **Metaphase**. The double-stranded chromosomes, also called **dyads**, line up around the equator of the cell.
- **Anaphase**. The sister chromatids separate and are pulled to opposite ends of the spindle by the contraction of spindle fibres (see figure 9.8).
- **Telophase**. A nuclear membrane forms around each separate group of single-stranded chromosomes and the chromosomes gradually decondense. Mitosis completes the division of the nucleus.

Figure 9.9 provides details of the different stages of mitosis.

FIGURE 9.7 False coloured scanning electron microscope image of a human chromosome. At the metaphase stage of mitosis, the chromosome is double-stranded and can be called a dyad. In this image, the two sister chromatids of this chromosome are clearly visible. Each chromatid contains an identical copy of the same DNA molecule. At what stage of the cell cycle did the replication of this chromosome occur?

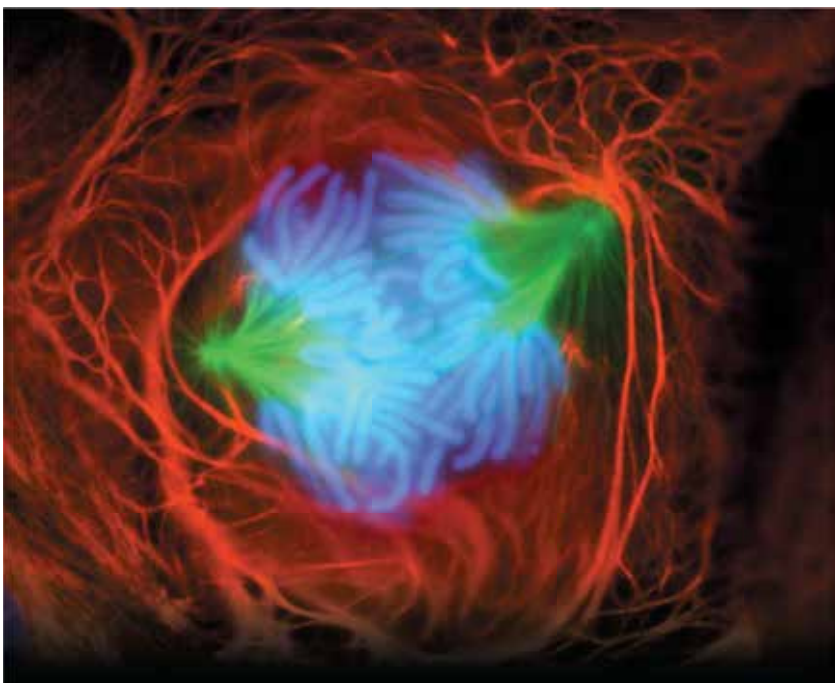
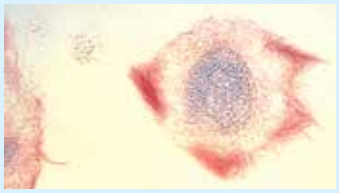


FIGURE 9.8 A dividing cell of a newt (*Notophthalamus* sp.) at anaphase of mitosis. The chromosomes (stained blue) are attached to the microtubules that form the spindle fibres (stained green). A duplicate set of chromosomes is being pulled to opposite poles of the spindle as fibres contract. Keratin fibres (stained red) surround the spindle.

STARTING POINT: One cell containing four single-stranded chromosomes

i. Nucleus is well defined at late interphase. Animal cells have a pair of centrioles in an aster of microtubules close to the nuclear envelope. Chromosomes are not visible but their DNA has already replicated.

Interphase

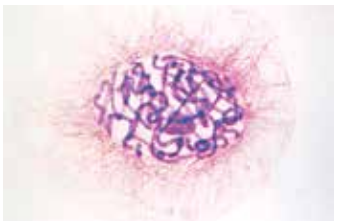


Interphase

MITOSIS

ii. Chromosomes become visible early in mitosis. At first they appear thin and long but gradually become thicker and shorter. Later, the chromosomes can be seen to be double stranded, held together at the centromere. The replicated centrioles move apart; microtubules of the mitotic spindle continue to extend from the centrioles.

Prophase



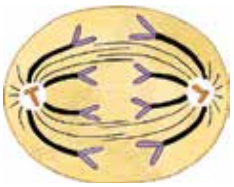
Prophase

iii. Mitotic spindle is fully formed between the pairs of centrioles at the two poles of the spindle. The double-stranded chromosomes (each strand is called a chromatid) line up around the equator of the cell. From the side, they form a line across the middle of the cell. The nuclear membrane has disappeared.

Metaphase

Metaphase

iv. Each centromere divides, so that the single-stranded copies of each chromosome move to opposite ends of the cell as the tubules shorten. This migration is orderly and results in one copy of each chromosome moving toward each end of the spindle.

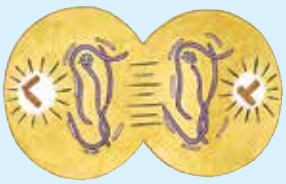


Anaphase

Anaphase

v. The chromosomes become thinner and less obvious. A new nuclear membrane begins to form around each group of chromosomes.

This completes the process of mitosis.



Telophase

Telophase

vi. Division of the cytoplasm by a process called cytokinesis is completed, new membranes form enclosing each of the two new cells (and cell walls in the case of plants), which become interphase cells.

Interphase

Interphase

END POINT: Two cells each containing four single-stranded chromosomes

FIGURE 9.9 Summary of mitosis and cytokinesis. The drawings (middle column) show a stylised version in an animal cell containing four chromosomes. The light micrographs (third column) show mitosis in the endosperm of the seed of an African blood lily, *Scadoxus katherinae* (18 chromosomes in each cell). Chromosomes are stained purple and microtubules are stained pink. Note the changes in chromosomes and the formation and distribution of microtubules and fibres as the cell moves through the cell cycle. Two daughter cells form from each cell by the completion of the cell cycle.

A protein called cohesin holds sister chromatids together. (It appears as a blue stained region in figure 9.1). Cohesin is removed at the metaphase–anaphase transition.

Individual chromosomes first become visible as double, thread-like structures held together in a constricted region. Each of these threads is called a **chromatid** and the position where they are held together is called a **centromere**. The fact that the chromosomes are double-stranded and therefore contain two molecules of DNA indicates that the genetic material in the parent cell has already been replicated.

The chromosomes continue to shorten and thicken and the nuclear membrane disintegrates. At the same time, the very fine protein fibres or microtubules in the cytosol move towards the nucleus. The function of the fibres is to guide the movement of the chromosomes in the cell. The fibres become arranged in the cell, rather like the lines of longitude on a globe, to form a structure called a **spindle**. **The chromosomes become attached by their centromeres around the 'equator' of the spindle.**

Two things then happen. The centromeres split, so that there are pairs of chromosomes, and the spindle fibres contract. The contraction of the spindle fibres is responsible for the movement of the chromosomes towards the poles of the spindle. The movement of the new chromosomes is very ordered. One of the new chromosomes from each pair moves to one end of the spindle; its identical pair moves towards the opposite pole. The end result is a set of chromosomes at each end of the spindle. Because the new chromosomes behave in an orderly way, **the set of chromosomes at one end of the spindle is identical to the set of chromosomes at the other end of the spindle.**

The chromosomes at each end of the spindle begin to lengthen and become less visible as distinct structures. At the same time, the protein fibres disperse back into the cytosol and a nuclear membrane develops around each group.

Remember that mitosis is a continuous process. The stages of mitosis identify key changes in the appearance and the position of chromosomes. Remember also that chromosomes are not routinely visible when viewing cells through a light microscope. Only cells that are capable of division will ever show chromosomes and this will be for only a short period during the cell cycle. The disappearance of discrete chromosomes does not mean that the genetic material has disappeared; rather, the DNA is present as chromatin granules dispersed throughout the nucleus.

WALTHER FLEMMING AND MITOSIS

Walther Flemming (1843–1905) was the German cytologist who discovered chromosomes and their role in cell division. Flemming used newly developed aniline dyes and improved microscopes to study nuclei in cells and found that scattered fragments in the nucleus became highly coloured. He named these fragments 'chromatin'. He found that, during cell division, the chromatin granules coalesced to form thread-like structures that were later called chromosomes (*chroma* = colour; *soma* = body). He showed that, during cell division, chromosomes split lengthwise and separate so that each daughter cell has as much genetic information as the original chromosome. Flemming called this process *mitosis*. The term mitosis comes from the Greek *mitos* = thread and *osis* = process.

study on
Unit 2
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Cytokinesis
Concept summary and practice questions

Cytokinesis: one cell to two cells

At the end of mitosis, the division of the nucleus into two new identical nuclei is complete. However, the cell cycle is completed only after the cytosol and organelles in the cytosol distribute around the new nuclei and become enclosed within an entire plasma membrane. This final process of the cell cycle is called cytokinesis.

In January 2005, the journal *Trends in Cell Biology* (figure 9.10) announced a series of special articles on research into cytokinesis under the title 'Cytokinesis: the great divide'. In the first of these articles, Professor Jeremy Hyams of Massey University wrote:

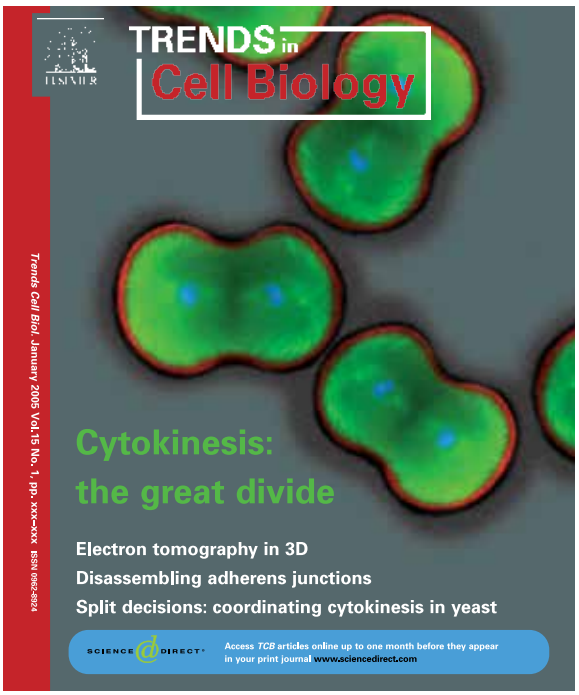

FIGURE 9.10 The front cover of the journal in which research into cytokinesis is discussed

> Cytokinesis brings the curtain down on the cell cycle; it is the final dramatic act in which one cell becomes two.

As the two new nuclei form at the end of mitosis, the cytosol and organelles, such as mitochondria and chloroplasts, surround each nucleus and **cytokinesis occurs**. Minor differences occur during cytokinesis in different organisms. Generally, in animals, the bridge of cytoplasm between the two new nuclei narrows as the plasma membrane pinches in to separate the nuclei and cytoplasm into two new cells (see figure 9.11a). In plant cells, a cell plate forms between the two groups of chromosomes and develops into a new cell wall for each of the newly produced cells (figure 9.11b).

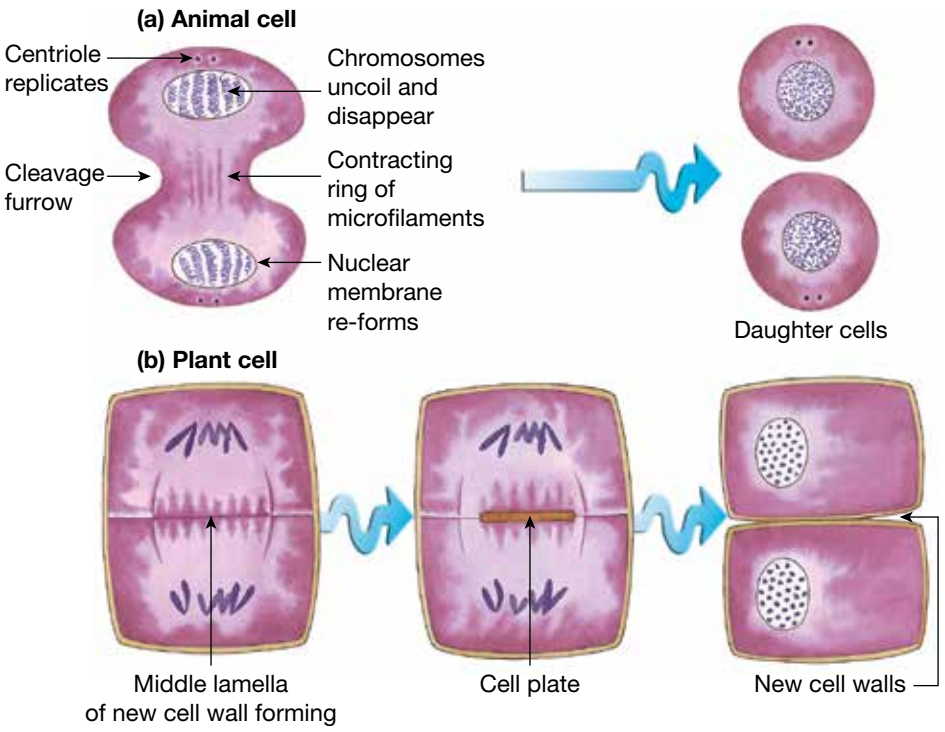

FIGURE 9.11 Minor differences are visible in plant and animal cells during mitosis and cytokinesis. **(a)** An animal cell has a pair of centrioles at each pole of the spindle and a ring of contracting filaments that separates the cytosol and organelles during cytokinesis. **(b)** In a newly replicating plant cell, a cell plate forms between the two groups of chromosomes and gives rise to a new cell wall for each new cell.

Mitosis is essentially the same in plant and animal cells. The small differences that do exist are not related to the genetic material, nor do they have an impact on the biological significance of the process.

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Unit 2 AOS 1 Topic 1 Concept 1

Prokaryotic cell division
Concept summary and practice questions

Cell cycle in prokaryotes

Prokaryotes, such as bacteria and archaea, also have a cell cycle. This is a far less complex process than the cell cycle in eukaryotic cells. Note that bacteria and other microbes have a single circular DNA molecule in contrast to the many chromosomes of eukaryotic cells. The process in microbes is called binary fission and its essential components are shown in figure 9.12.

The process of asexual reproduction by binary fission in bacteria is simpler and faster than asexual reproduction in eukaryotic organisms. Asexual reproduction in eukaryotes involves the more complex process of mitosis followed by division of the cytoplasm (cytokinesis). This process typically takes many hours to complete. Binary fission in bacterial cells can be completed in about 20 minutes at room temperature. This means that, if resources are available, one bacterial cell, through successive binary fissions over an 8-hour period, could produce 16 million descendants! This is an example of **exponential growth** (discussed further in chapter 8) and it reminds us why a bacterial infection, if not treated, can have serious outcomes. Figure 9.13 shows a cell of the bacterial species *Escherichia coli* dividing by binary fission.

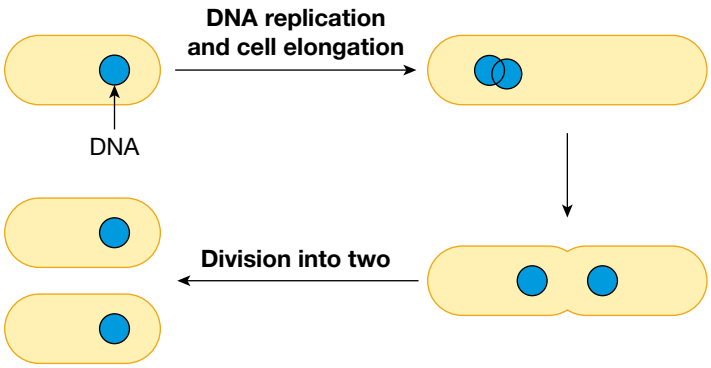


FIGURE 9.12 Diagram showing the essence of the cell cycle in a bacterial cell. The cell cycle in prokaryotes, such as the one shown, is far less complex and much faster than the cell cycle of eukaryotes. What elements of the prokaryotic cell cycle are also present in the cell cycle of eukaryotes?

FIGURE 9.13 Cells of the bacterial species *Listeria* sp., one of which is dividing by binary fission. The circular outlines are cross-sections through bacterial cells. The DNA of the bacterial circular chromosome appears as darkly stained material.

KEY IDEAS

- Eukaryotic cells divide during the cell cycle giving rise to genetically identical daughter cells.
- An essential early process in the cell cycle is the replication of DNA.
- Carefully governed separation of sister chromatids is another essential step in cell division.
- Mitosis is followed by cytokinesis.
- Cell division in prokaryotes involves a relatively simple and rapid process of binary fission.

QUICK CHECK

1 What are the stages of interphase?
2 What is the key event of the S stage of interphase?
3 What is an average time for:
  a a complete cell cycle in a mammal
  b a complete cell cycle by binary fission in a microbe?
4 Identify whether each of the following statements is true or false.
  a Sister chromatids separate at metaphase.
  b During interphase, double-stranded chromosomes are visible.
  c Cytokinesis is the last step in a cell cycle.
  d In a cell cycle, more time is spent in interphase than any other stage.
  e Binary fission does not involve DNA replication.
  f The sequence of stages in interphase is G1 then G2 then S.

FIGURE 9.14 Checkpoints occur at various points in the cell cycle. The G1 and the G2 checkpoints check for the presence of unrepaired DNA or missing DNA. The M checkpoint checks a different feature. What is it?

Checkpoints in the cell cycle

The cell cycle is a complex series of events which, when operating without error, produces two daughter cells that are genetically identical to each other and to their original parent cell. In an error-free cell cycle the complete genome of the parent is accurately duplicated and then distributed to the two daughter cells.

During the cell cycle, there are several checkpoints that function to ensure that a complete and damage-free copy of the genome is transmitted to the two daughter cells. Each checkpoint can detect a particular kind of error. If an error is detected, depending on the type of error, the cell cycle is either aborted or delayed, allowing time for the error to be corrected.

Figure 9.14 shows the location of three checkpoints in the cell cycle.

The **G1 checkpoint** occurs at the G1 (Gap 1) stage of interphase. At this checkpoint, the cell is ready to undergo division so a check of the DNA of the cell occurs. If the DNA of the cell is found to be damaged or incomplete, the cell is stopped from continuing through the cell cycle. Instead, the cell may enter a non-dividing quiescent stage called G0, or it may be targeted for destruction. (The 'security guard' at the G1 checkpoint is a protein known as p53, a tumour-suppressor protein. What do you think might happen if a mutation occurred in the p53 protein so that it could not carry out its normal function?)

If the cell passes the G1 checkpoint, it proceeds into the cell cycle and enters the S stage of interphase. During the S stage, the cell replicates its DNA so that, by the end of the S stage, the cell should have double the amount of DNA and this DNA should be two complete and accurate copies of its genome. The cell now moves to the G2 stage of interphase where it must pass the **G2 checkpoint**.

At the G2 checkpoint, the replicated DNA of the cell is checked for completeness and lack of damage. If the cell passes this checkpoint, it can then advance to the mitosis stage of the cell cycle.

The **M checkpoint** (or spindle assembly checkpoint) occurs at the metaphase stage of mitosis. A check is carried out to ensure that the sister chromatids (i.e. the two strands of each double-stranded chromosome) are attached to the correct microtubules of the spindle. This check is to ensure that the sister chromatids are pulled in opposite directions to different poles of the spindle. If an error is detected, the cell cycle is delayed until the error is fixed.

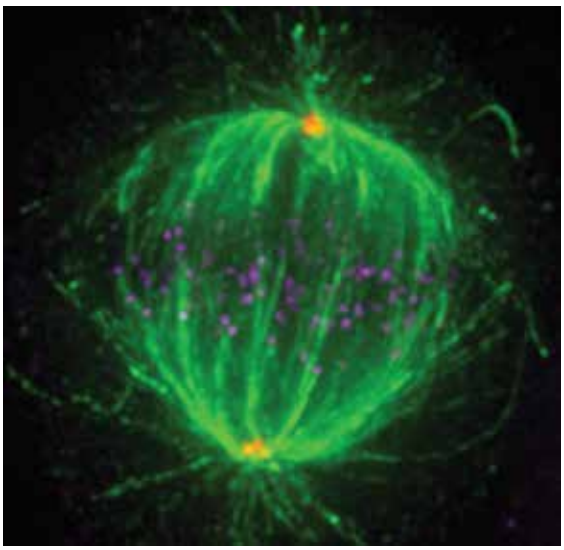


FIGURE 9.15 DeltaVision Widefield microscope image of a HeLa cell undergoing mitosis and treated with various stains. The pericentrin stain shows the centrioles (orange). The ACA stain shows the kinetochores (purple) that are protein complexes located at the centromere and bind each chromosome to the microtubules of the spindle. The A-tubulin stain shows the microtubules of the spindle (green). (Image courtesy A Loynton-Ferrand, IMCF, University of Basel)

The mitotic spindle

The focus in mitosis is typically on chromosomes. However, the positioning and the movement of the chromosomes depend on the presence of a microtubule framework, the spindle.

In animal cells, once mitosis starts, the paired **centrioles** move to opposite ends of the cell where they form the poles of the spindle. Clusters of microtubules grow out from the centrioles towards the middle of the cell. These microtubule clusters are called **spindle fibres**. At metaphase, these fibres anchor the double-stranded chromosomes around the equator of the cell. Each chromatid has a special attachment site called a **kinetochore** by which it links to a spindle fibre (see figure 9.15).

Spindle fibres from one pole attach to one sister chromatid and fibres from the opposite pole attach to its partner chromatid. (What would happen if the two sister chromatids of one chromosome became linked to fibres from the same pole of the spindle?) At the M checkpoint, the connection between chromatid and spindle fibres is checked and, if it is not correct, the cell cycle is delayed until the arrangement is corrected.

Spindle fibres are composed of actin, a contractile protein. At anaphase, the orderly migration of each pair of sister chromatids is achieved by contractions of the fibres that pull these now single-stranded chromosomes to the opposite poles of the spindle.

Mitochondria and chloroplasts also replicate

We have seen that mitosis is followed by cytokinesis. This is essential so that the two new nuclei formed can each be combined with cytosol to give two new cells. Obviously the **organelles such as mitochondria and chloroplasts within the cytosol must also be replicated during the cell cycle,** otherwise cells would contain an ever-decreasing number of these structures.

Just as a nucleus contains DNA that must replicate before two new nuclei are formed, mitochondria and chloroplasts contain DNA that must replicate before the organelles divide. The alga *Mallomonas splendens* (see figure 9.16a) has a single chloroplast composed of two lobes joined by a narrow connection. As a cell of *M. splendens* replicates, its chloroplast must also replicate. During replication of the chloroplast, the narrow connection breaks and each of the two lobes grows and constricts to give two, two-lobed chloroplasts (see figure 9.16b). Organelles such as chloroplasts and mitochondria can arise only from pre-existing organelles. Cells can arise only from pre-existing cells.

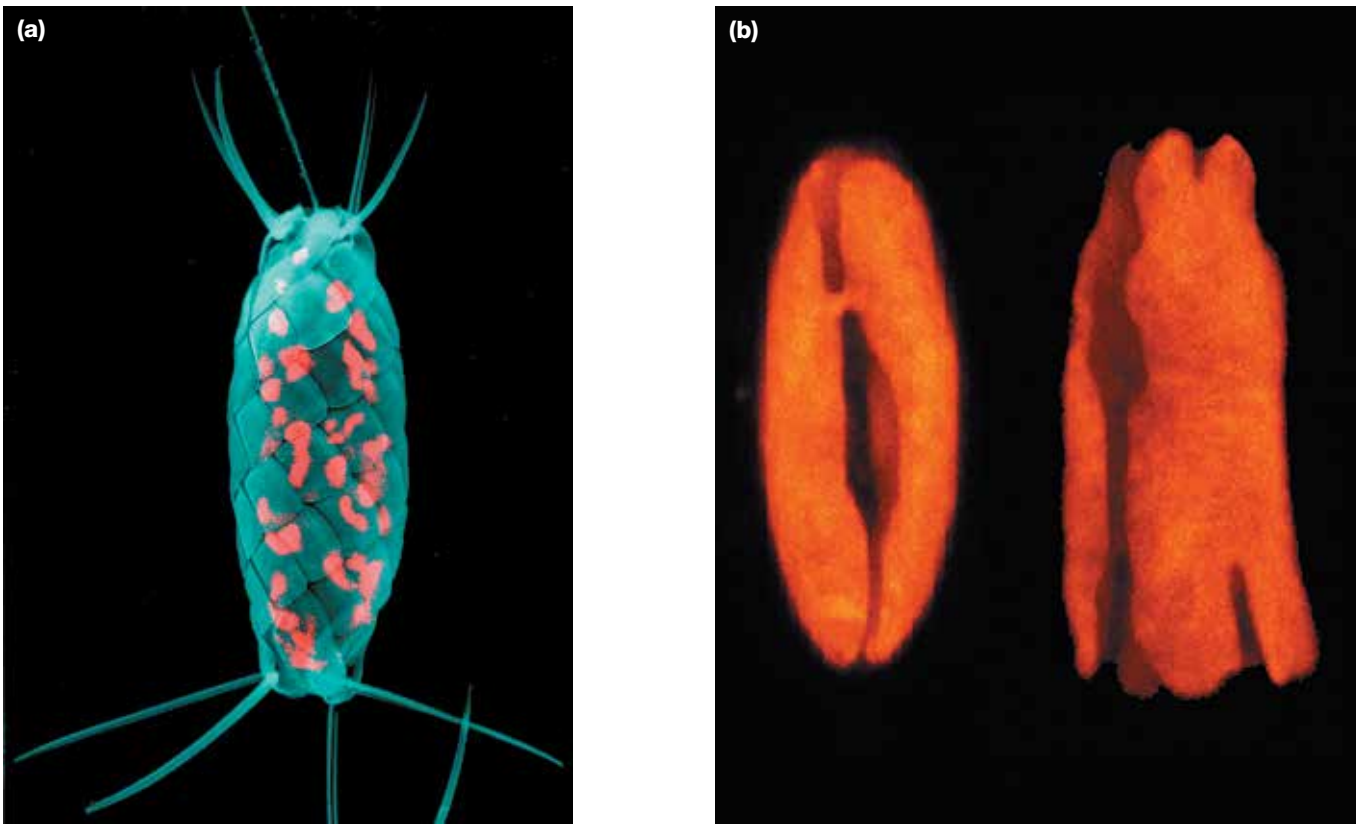


FIGURE 9.16 **(a)** *Mallomonas splendens*, a unicellular alga with scales and bristles, has a single large bilobed chloroplast. **(b)** Confocal microscope image showing autofluorescence of chloroplasts from two cells of *M. splendens*. On the left is a single chloroplast that is composed of two lobes joined by a narrow connection. On the right is a replicating chloroplast. Note that the connection has been broken and the each lobe is replicating to produce two double-lobed chloroplasts.

KEY IDEAS

- Checkpoints occur at various points in the cell cycle.
- Some checkpoints identify damaged or missing DNA and delay or stop the cell cycle.
- The spindle is essential for chromosome arrangement and precise movement during mitosis.
- Sister chromatids must become linked to spindle fibres from opposite poles of the spindle to pass the M checkpoint.

QUICK CHECK

5 What is the role of the M checkpoint?

6 Identify whether each of the following statements is true or false.

a One sister chromatid has just half the DNA of a chromosome.

b Chromosomes move of their own accord because they are made of contractile proteins.

c Mitosis can proceed in the absence of a spindle.

d The spindle is composed of microtubules.

e An accurate separation of sister chromatids during mitosis depends on their being linked to fibres from opposite poles of the spindle.

Cell cycle in action

The cell cycle is a critical process in:

- growth, where the cell cycle produces new cells, resulting in an increase in cell number. This is most prominent during embryonic development of a multicellular organism. Early embryonic cell division is exponential, with one cell dividing to form two cells, these two form four cells, these four form eight cells, and so on. The power of the cell cycle is seen in the fact that a typical human is composed of 37 trillion cells that came originally from a single fertilised egg cell.
- repair and maintenance (regeneration), where the cell cycle produces new cells to replace dead or damaged cells
- reproduction, where the cell cycle produces identical cells, such as spores, that give rise to the next generation.

Not all cells of a multicellular organism are capable of dividing. For example, in the human body, nerve cells generally cannot regenerate. Cells from other organs, such as kidney and liver, may divide occasionally to replace cells lost through injury or death, but, for most of the time, these cells are in the G0 quiescent stage. However, cells of some human tissues produce new cells at a staggering rate. Let's meet some of them.

Cell cycle in mammals

In mammals, such as a human adult, actively dividing cells are found in several tissues, such as the epidermis of the skin, the epithelial lining of the gut and the bone marrow. Cell division normally occurs at a tightly regulated rate, so that the production of new cells matches or balances the rate of cell loss. Tissues with a population of actively dividing stem cells are tissues that have a high and continual level of cell loss or cell death.

Basal stem cells of the epidermis

In human skin, surface cells are constantly being shed and are being replaced by daughter cells produced by division of basal stem cells. Each basal stem cell that undergoes cell division produces two daughter cells. Of these two daughter cells, one becomes a keratinocyte and the other remains in the basal layer as a basal stem cell, replacing the original parent cell. The other daughter cell progressively moves upwards through the epidermis, differentiates into a keratinocyte, and is shed from the skin surface (see figure 9.17). Within a period of about 48 days, the entire epidermis is replaced by new cells. This means that the skin that you have, say, today is made of completely different cells from the skin that you had 2 months earlier.

For a newly produced cell to move from the base of the epidermis where it is formed to the base of the dead layer of cells takes about 2 weeks. To move through the layer of dead cells and be shed takes a further 4 weeks. An estimate of the rate of loss of dead skin cells from an adult person is 30 to 40 thousand per hour. This makes the cell cycle activity of basal stem cells of the epidermis very important.

The ability of the skin to heal after considerable damage, as exemplified by the recovery of burns patients, is due to the presence of stem cells in the basal layer of the epidermis and the stem cells in the dermis.

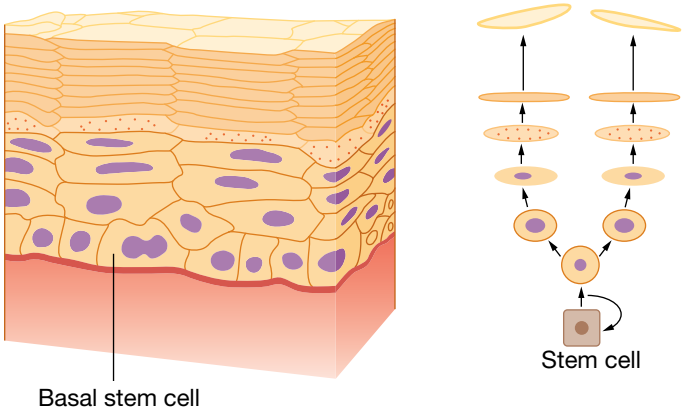


FIGURE 9.17 Cell division in the epidermis of the skin. The basal stem cells divide to produce two cells, one of which replaces the parent stem cell, while the other will differentiate and progressively move to the skin surface and be lost. The cells at the surface become filled with keratin and die.

Intestinal stem cells of the gut

The epithelial lining of the small intestine is regenerated every 4 to 5 days. This means that a person aged 18 years will have experienced more than 1000 replacement cycles of the lining of the small intestine.

As intestinal cells die, they are replaced by new cells produced by intestinal stem cells. These stem cells are located at the base of infoldings, known as **crypts**, that are located between intestinal villi (singular: villus) (see figure 9.18). The replacement cells formed by division of the stem cells take from 2 to 7 days to move from the crypts to the tip of the villi from where they are lost.

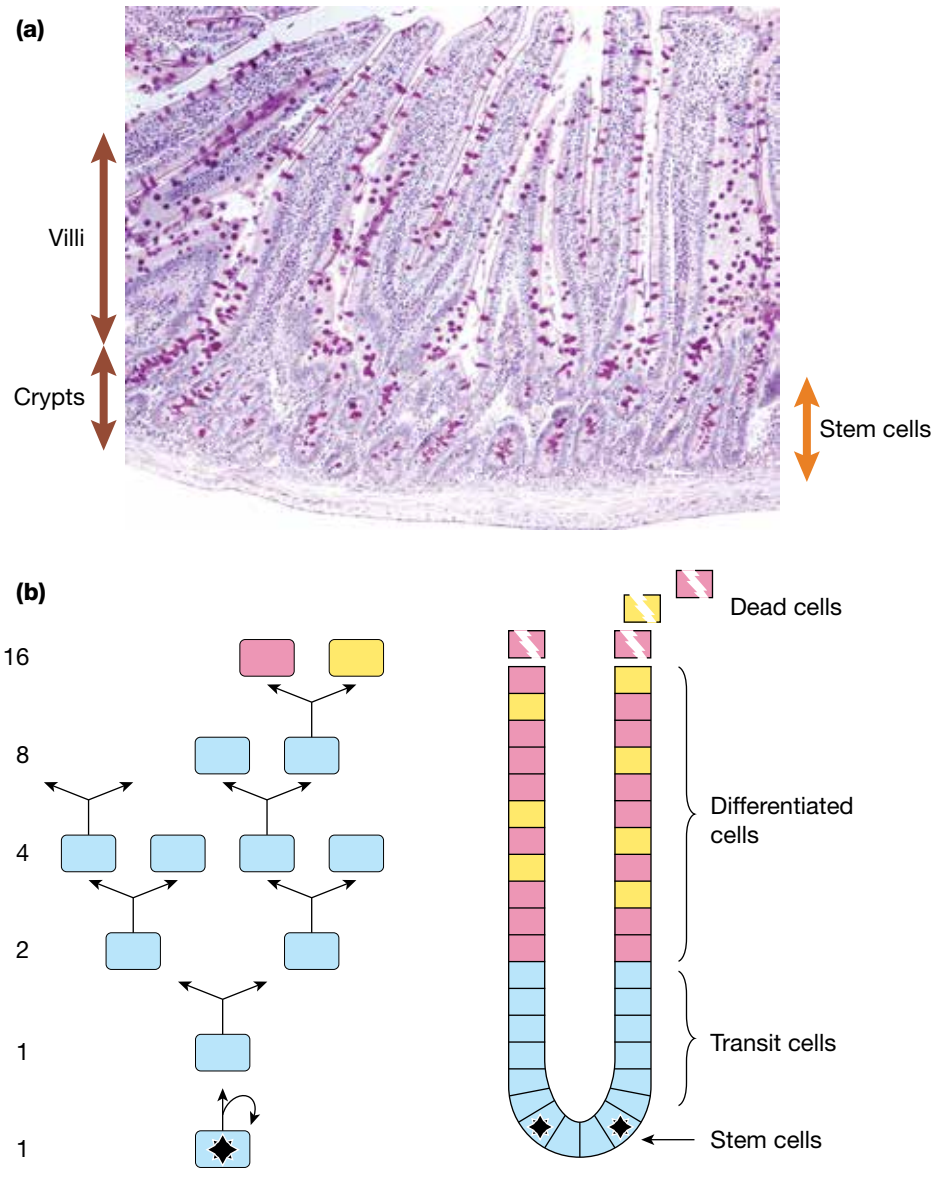


FIGURE 9.18 **(a)** Longitudinal section through the small intestine showing the upward projecting villi with the downward projecting crypts. Intestinal stem cells that are responsible for the regeneration of the intestinal lining are located in these crypts. **(b)** Diagram showing the progression of the cells produced by the intestinal stem cells. Note that of the two cells produced by a stem cell, one will differentiate into a cell on the villus and the other replaces the stem cell.

Haematopoietic stem cells

Haematopoietic stem cells, located in the bone marrow, divide to give rise to cells that subsequently differentiate into the various types of blood cells, including red blood cells, white blood cells of various kinds and platelets (refer to figure 4.17, p. 151). Bone marrow is a spongy tissue found in the core of most bones, including the ribs, hips and spine. Most blood cells are short lived and must be constantly replaced.

NOBEL LAUREATE IN PHYSIOLOGY OR MEDICINE

Dr Elizabeth H Blackburn

Dr Elizabeth Blackburn received her Nobel Prize from His Majesty King Carl XVI Gustaf of Sweden in Stockholm in December 2009 (figure 9.19) for her work on telomeres (figure 9.20) and telomerase. Telomeres are found at the ends of all eukaryotic chromosomes and comprise repetitive DNA strands that get shorter each time a cell divides. This shortening of the telomeres eventually leads to the death of a cell. However, telomerase is an enzyme that prevents shortening in some cells and so extends the life of those cells.

FIGURE 9.19 Dr Elizabeth Blackburn receiving her Nobel Prize from His Majesty King Carl XVI Gustaf of Sweden at the Stockholm Concert Hall, 10 December 2009

Elizabeth Blackburn was born in Tasmania in 1948, one of seven children. After moving to Melbourne, she completed secondary school at the University High School. This was followed by Honours (1971) and Masters degrees (1972) in Biochemistry from the University of Melbourne. Elizabeth then travelled to Cambridge University in England where she was admitted as a PhD student in the Medical Research Council's Laboratory of Molecular Biology. After completing her PhD, Dr Blackburn did postdoctoral training at Yale in the USA, and then worked in the Department of Molecular Biology at the University of California, Berkeley. In 1990, she moved to the Department of Microbiology and Immunology at the University of California, San Francisco (UCSF) (figure 9.21). She is currently the Morris Herzstein Professor of Biology and Physiology at UCSF and a non-resident fellow of the Salk Institute.

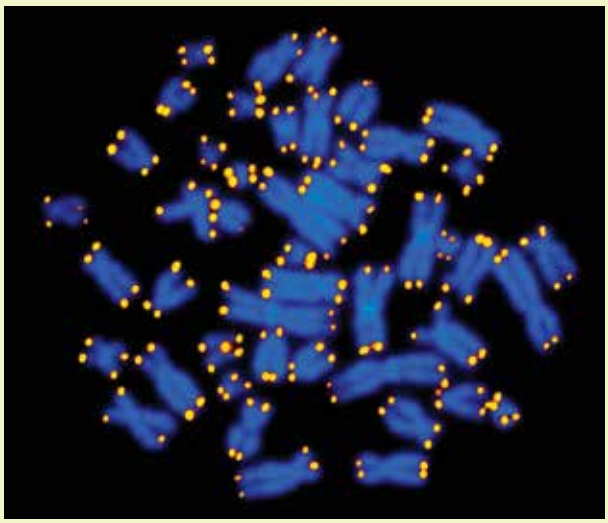


FIGURE 9.20 Mitotic chromosomes (blue) with telomeres (yellow) at the tips of each chromatid

FIGURE 9.21 Dr Elizabeth Blackburn in her lab at the University of California, San Francisco

Dr Blackburn has received many notable awards and honours. They include California Scientist of the Year (1999), American Cancer Society Medal of Honor (2000), L'Oreal–UNESCO Award for Women in Science (2008) and, of course, a Nobel Prize (2009). In 2007, Dr Blackburn was listed by *Time* magazine as one of the '100 most influential people in the world.'

FIGURE 9.22 If a starfish is cut into two, each half can regenerate into a whole.

Cell cycle in other animals

Planaria, phylum Platyhelminthes, are flatworms that live in water. They are one of the few animals that can reproduce asexually by regeneration. The parent breaks into two or more pieces and each piece grows into a new planarian. The new parts are produced by mitosis of cells and each new planarian is an exact copy of the parent.

If a starfish loses some of its 'arms', new ones are regenerated by mitosis (see figure 9.23).

FIGURE 9.23 If a starfish loses some of its 'arms', they regrow. Here you can see six new 'arms' on a damaged starfish.

KEY IDEAS

- The cell cycle is important for the growth, repair and maintenance of eukaryotes.
- In some organisms, the cell cycle plays a role in producing cells involved in reproduction.
- Actively dividing human tissues include the epidermis of the skin, the epithelium of the gut and the bone marrow.
- Stem cells carry out the cell divisions that are responsible for tissue regeneration.

QUICK CHECK

7 Identify where you would find the following.
- **a** Skin stem cells
- **b** A red blood cell precursor
- **c** Keratinocytes
- **d** Haematopoietic stem cells

8 Identify whether each of the following statements is true or false.
- **a** All human cells regularly undergo cell division.
- **b** Haematopoietic stem cells are responsible for skin regeneration.
- **c** The intestinal crypts are where intestinal stem cells are located.
- **d** Tissues composed of short-lived cells would be expected to show a high rate of cell division.

FIGURE 9.24 Psoriasis on the skin of a person's back. This condition is a result of the overproduction of skin cells.

When the cell cycle goes wrong

As identified earlier in this chapter, the cell cycle in various tissues is normally regulated so that, in a mature organism, the rate of production of new cells balances the rate of loss of cells.

If the rate of cell production exceeds that of cell loss, a build up of cells results. This may be seen in the skin condition **psoriasis** (see figure 9.24). Psoriasis is a chronic autoimmune condition in which skin cells are overproduced, resulting in raised patches of red inflamed skin, often covered in a crust of small silvery scales.

More serious consequences of errors in the regulation of the cell cycle in a tissue are cancers.

Cancer: control of cell cycle gone awry

Cancers may result from a breakdown of the normal regulation of the cell cycle, when the cell cycle becomes uncontrolled. In cancerous tissue, cells reproduce at a rate far in excess of the normal regulated rate of the cell cycle and produce masses of cells called tumours. Some tumours are malignant, such as **melanomas** that are cancers derived from the pigment-producing cells, or melanocytes, of the skin epidermis. In malignant tumours individual cells can break free from the primary tumour and migrate throughout the body, establishing sites of secondary cancers.

ODD FACT

The most common cancer diagnosed in Australians aged 15 to 29 years are melanomas, which account for just over 25 per cent of cancers diagnosed in this age group. Most deaths from skin cancers are due to melanomas because of their tendency to spread (metastasise) to other parts of the body.

A clue to what goes wrong in cancer comes from studying cells growing in culture in a Petri dish in a laboratory. In culture, normal (non-cancerous) cell numbers increase through regulated cell divisions and form a single, orderly layer attached to the base of plastic dishes. These cells do not crowd; they are said to show contact inhibition. In addition, normal non-cancerous cells typically undergo a limited number of cell cycles.

In contrast, cancerous cells in culture continue to divide in an unregulated manner. These cells show no contact inhibition, become crowded and form masses of cells in disorganised multiple layers. In addition, the number of cell cycles that cancerous cells can undergo is unlimited.

What causes the breakdown in the control of the cell cycle in cancerous cells? In normal cells, the rate of cell division is regulated so that, in a mature organism, cell production matches cell loss. In addition, checkpoints exist in normal cells to ensure that the DNA that is to be transmitted to daughter cells is complete and error free (refer to pp. 400–1). In cancerous cells, however, the genes that normally control the progress of a cell through the cell cycle are changed by mutation. These various mutations mean that the cell cycle occurs in an unregulated manner and that checkpoints are overridden. No error detection or error correction takes place. Cancerous cells continue to divide even in the presence of significant DNA damage. When this happens, abnormal cells with errors in their DNA continue through the cell cycle, passing these errors onto their daughter cells, and these cells in turn will pass the errors onto their daughter cells.

As mentioned on page 400 the 'security guard' that operates the G2 checkpoint is a protein called p53. The normal p53 protein binds to DNA and this sets up a sequence of events that stops cells from continuing through the cell cycle and enables checks to be carried out. However, when a mutation of the controlling gene occurs, the abnormal p53 protein cannot bind to DNA so that the cell cycle cannot be stopped. As a result, cells can divide in an uncontrolled manner and form tumours.

KEY IDEAS

- The cell cycle is normally regulated so that, in a mature organism, the rate of production of new cells balances the rate of loss of cells.
- Cancers may result from the breakdown of the normal control of the cell cycle.
- Cancerous cells are characterised by unregulated rates of cell division.

QUICK CHECK

9 Identify whether each of the following statements is true or false.
- **a** Cancerous cells divide at rates in excess of the normal regulated rate.
- **b** Cell production and cell loss are kept in balance by genes that regulate the cell cycle.
- **c** Normal non-cancerous cells in culture show contact inhibition.

Cell cycle in plants

In vascular plants, only the cells in meristematic tissues can complete cell cycles and divide to produce identical daughter cells. The cells in permanent plant tissues cannot divide (refer to chapter 4, p. 180). Meristematic tissue is present in several locations including root tips (see figure 9.25) and stems.

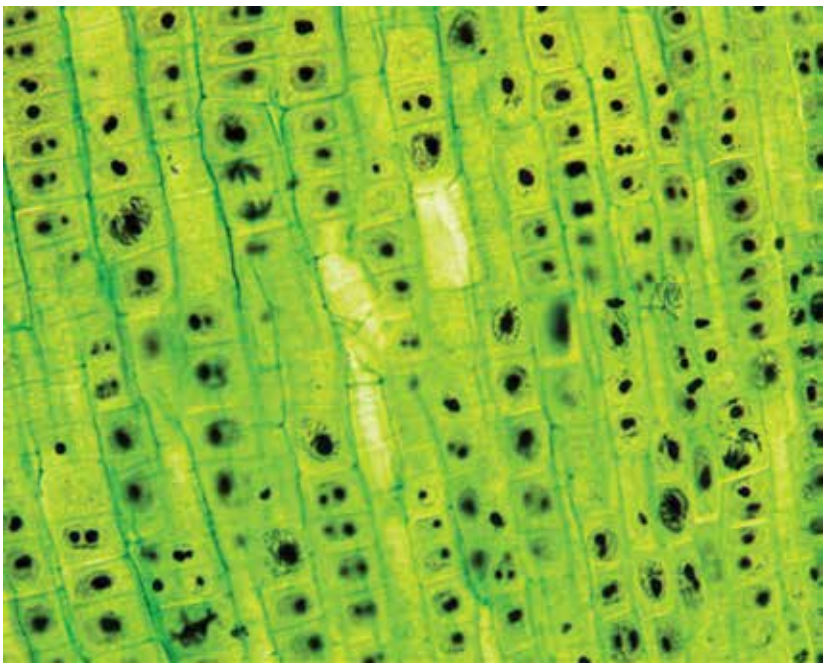


FIGURE 9.25 Light microscope image of a longitudinal section through the meristematic tissue of a root tip. This is a region of active cell division and many rows of cells can be seen. Examine this image and see if you can identify some cells that are in the mitosis stage of the cell cycle.

Other examples of the cell cycle in plants include those discussed below.

Epicormic shoots after a bushfire

Bushfires are common in many areas of Australia. Although trees may appear to be burnt to a point that one might think they are dead, a picture such as the one in figure 9.26 (taken just 6 weeks after the area was devastated by bushfire) shows this is not the case. It is clear from the photograph that the fire has completely destroyed the undergrowth of grasses, shrubs and

FIGURE 9.26 The new shoots from the trunk of a burnt eucalypt tree develop as a result of mitosis in buds present beneath the bark. The buds do not develop unless the canopy is destroyed, as has happened in this case.

herbs. Fire-blackened trees with their scorched dead canopy of leaves are in the background, while in the foreground the burnt trunks of rough-barked eucalypt trees are visible. One tree is already showing signs of regrowth; it is a thick-barked eucalypt whose thick outer layer of protective bark has insulated the underlying living tissues from the effects of the fire.

The trunk of a eucalypt does not usually show growing shoots. However, if the normal leaf canopy is destroyed, as happened in this fire, buds that are present beneath the bark grow and reproduce new green leafy shoots, known as **epicormic shoots**. The growth of epicormic shoots involves the production of new cells. The buds below the bark contain tissue called **meristem**, which is made of cells that are able to reproduce to give rise to new cells. These new cells are identical to each other and to the parent cell.

New liverworts from cells in a cup

Liverworts, class Hepatica, are small plants that have a flat, fleshy, leaf-like structure from which **rhizoids** extend into the soil. The name *liverwort* is derived from the shape of the organism — rather like that of a liver — and the Anglo-Saxon word for herb — wort. As you might predict from the name, it was once thought that this plant might be useful in the treatment of liver diseases. In addition to reproducing sexually, liverworts reproduce asexually by means of fragmentation of parts of the plant. Also, liverworts produce gemmae, small multicellular bodies produced in special cuplike structures called gemma cups (see figure 9.27). When rain falls, the gemmae are splashed out of the cup. Gemmae are produced from cells of the parent plant by mitosis. When they grow into new plants they do so by mitosis. The new liverwort plants produced by growth of the gemmae are genetically identical to the parent plant from which they were derived.

FIGURE 9.27 A new plant develops from each of the small bodies that splash out of the gemma cups on a liverwort plant. The new plants are genetically identical to the parent plant.

Cell cycle in fungi

The cell cycle plays an important role in the reproduction of fungi.

The fungus or mould you see on bread or fruit grows by mitosis. A single cell, a fungal spore, lands on food and grows into a mass of threads called hyphae. Specialised stalks — each with a spore case at its tip — grow up from the mass of hyphae (see figure 9.28). Mitosis occurs within the spore case and thousands of black spores are formed. On maturing, the spore case splits open and the tiny, light spores are scattered. When conditions are favourable, each spore germinates and grows into a new hyphal mass.

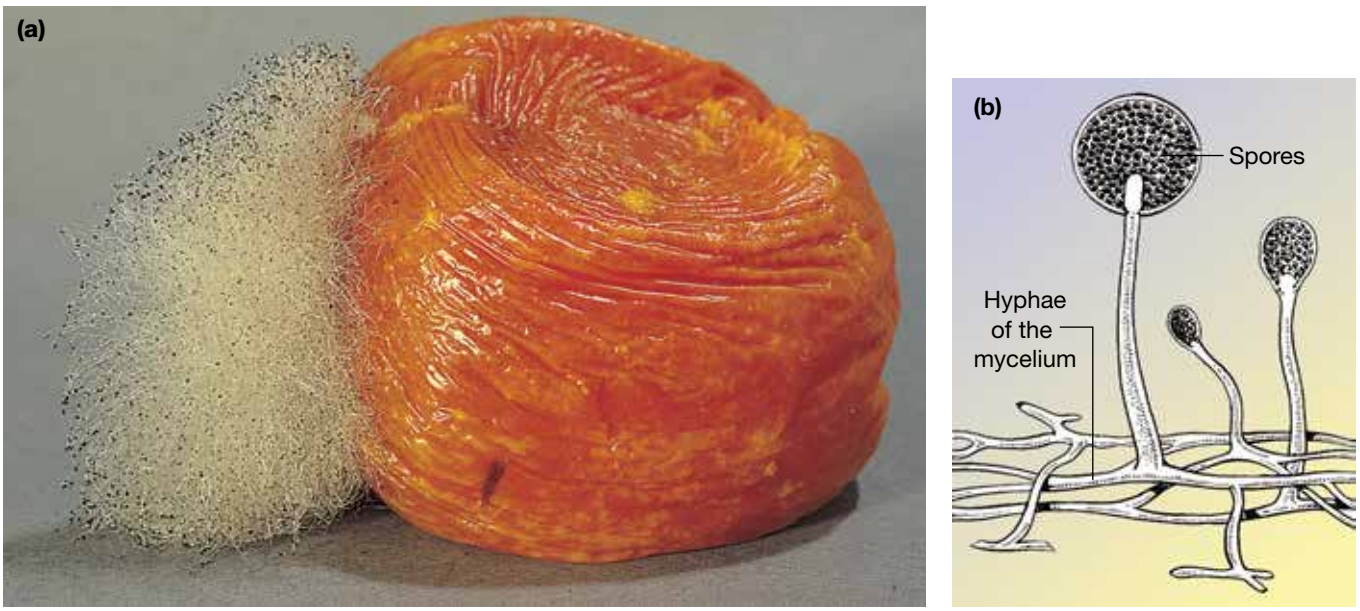


FIGURE 9.28 The fungus on a rotting tomato **(a)** comprises a mass of white threads or hyphae. Asexual reproduction occurs at the tips of some hyphae and **(b)** large numbers of black spores are formed, each genetically identical with the parent.

KEY IDEAS

- The meristematic tissue of plants contains cells that can complete the cell cycle and produce identical daughter cells.
- In vascular plants, meristematic tissue is present in root tips, shoots and stems.
- Cell division in epicormic shoots is important in the recovery of trees damaged by bushfire.
- Some cells produced by the cell cycle have a reproductive function, but offspring from this process are genetically identical.

QUICK CHECK

10 In which plant tissues would you expect to find dividing cells?

11 Consider the gemmae of liverworts. Would the next generation of plants that are derived from the gemmae of one liverwort be genetically identical or genetically dissimilar?

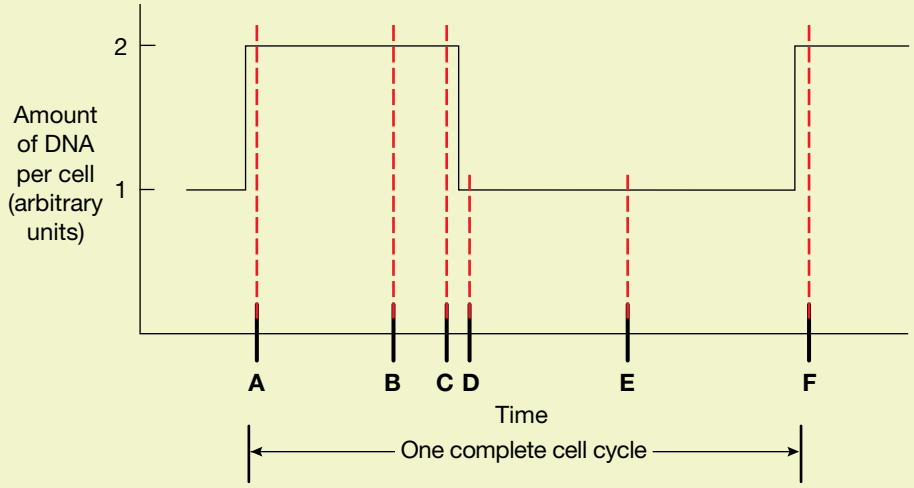
12 How do epicormic shoots contribute to the survival of fire-damaged trees in the Australian bush.

BIOCHALLENGE

1 A number of cells were monitored as they completed one cell cycle. The average amount of DNA per cell was measured and graphed over the time it took for the completion of one cycle. The graph obtained is shown on the right.

a The letters A to F in the graph represent different times in a cell cycle. What are the stages indicated?

b At the same time, sample cells were examined. The cells examined were as follows:



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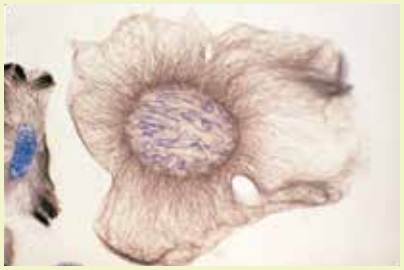

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3

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5

Match the cells 1, 2, 3, 4 and 5 with the appropriate points, A to F, in the cell cycle graph.

Chapter review

studyon
Unit 2
AOS 1
Topic 1
The cell cycle
Sit topic test

Key words

allograft
anaphase
autograft
binary fission
cell cycle
centrioles
centromere
chromatid
crypts
cytokinesis
dermis
dyad
epicormic shoots
epidermis
exponential growth
G1 checkpoint
G1 stage of interphase
G2 checkpoint
G2 stage of interphase
interphase
keratinocytes
kinetochore
M checkpoint
melanocytes
melanomas
meristem
metaphase
mitosis
prophase
psoriasis
rhizoids
S stage of interphase
spindle
spindle fibres
telophase

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map. You may use other words in drawing your map.

2 **Applying understanding** ➜ A cell containing 24 chromosomes reproduced by mitosis. A genetic accident occurred and one of the resulting cells had only 23 chromosomes.
- **a** How many chromosomes would you expect in the other cell produced? Explain why.
- **b** At what stage of cell reproduction do you think the genetic accident occurred?

3 **Interpreting and applying understanding of a new concept** ➜ Grafting is a technique used with some plants. In grafting, two pieces of living plant tissue are connected in such a way that they will unite and subsequently behave as one plant. For example, the shoot of one kind of plant can be grafted onto the root of another kind of plant (see figure 9.29). The shoot of a pear tree, *Pyrus communis*, was grafted onto the root of a quince tree, *Cydonia oblonga*, and then allowed to grow. The chromosome number of pear is 68 and the chromosome number of quince is 34.
- **a** After several years' growth, how many chromosomes would you expect in the leaves of the tree?
- **b** How many chromosomes would you expect in cells of a newly grown root? Explain.

4 **Analysing and evaluating information** ➜ Do you agree or disagree with each of the following claims about mitosis?
- **a** The nuclear envelope is visible throughout the process.
- **b** Mitosis would occur in the developing limb of a larval frog.
- **c** Mitosis in plants is significantly different from mitosis in animals.
- **d** Mitosis is accompanied by replication of cell organelles such as mitochondria and ribosomes.

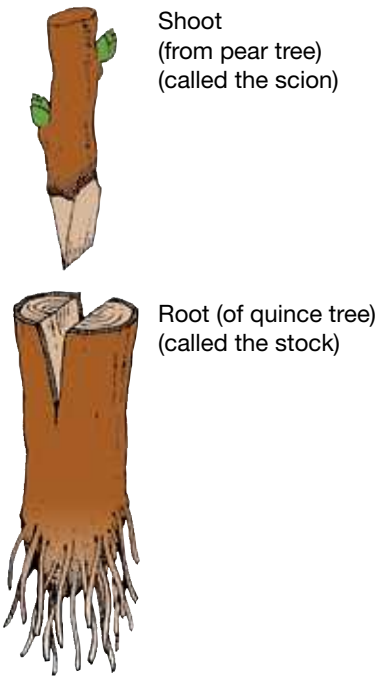

FIGURE 9.29 A slit is made in the bark of the stock and the bud graft with its own piece of bark is slipped inside. The graft is held in place with tape or twine and the wound covered with grease to exclude fungi and reduce evaporation.

5 **Analysing and interpreting information** ➜ Figure 9.30 shows a series of drawings, all of the same cell at some stage during mitosis.
- **a** Starting with cell A, place the drawings in the sequence that the stages would occur during mitosis.

b Draw what you would expect to see next in the sequence.

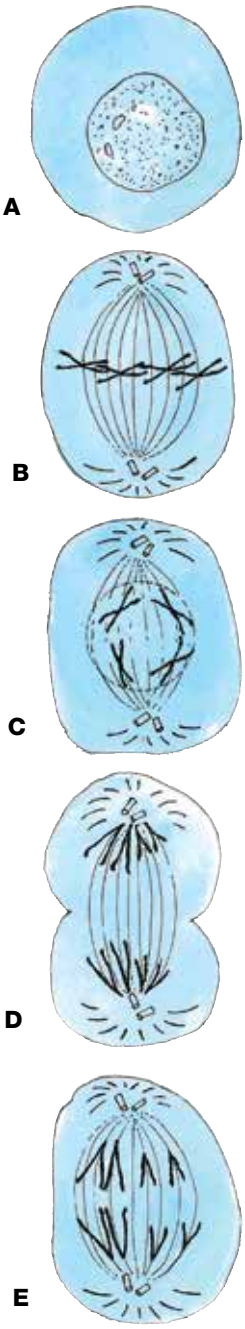

FIGURE 9.30

6 Applying understanding to new concepts ➜ Some drugs used in the treatment of some cancers act on microtubules. They act by interfering with the normal contraction and extension capabilities of microtubules. Explain the effect you would expect such drugs to have on mitosis and cell replication.

7 Applying knowledge ➜ Arrange the following events in animal cell replication in the correct order.

- **a** Alignment of chromosomes on the spindle equator
- **b** Attachment of microtubules to centromere region
- **c** Breakdown of nuclear envelope
- **d** Condensation of chromosomes
- **e** Decondensation of chromosomes
- **f** Duplication of centromere
- **g** Elongation of the spindle
- **h** Pinching of cell into two
- **i** Re-formation of nuclear envelope
- **j** Separation of centromeres
- **k** Separation of sister chromatids

8 Demonstrating skills of understanding and communication ➜ You are shown a video sequence of the entire cell cycle for one cell, but you are not told whether this cell is from an animal or a plant.

- **a** Is it possible to decide the identity of the cell as either animal or plant from the video?
- **b** If so, on what evidence would you base your decision? If not, give a reason for your choice.

9 Developing an explanation ➜ After a cell with 10 chromosomes completed the cell cycle, its daughter cells were examined. One daughter cell was found to contain 11 chromosomes and the other daughter cell had only 9 chromosomes. Suggest a possible explanation in biological terms for this observation.

10 Interpreting data and demonstrating understanding ➜ Cell A has four pairs of chromosomes with a total DNA content of 12 units. Cell A undergoes one cell cycle.

- **a** List, in order, the stages that cell A would proceed through, starting from the earliest.
- **b** At the end of this cell cycle, how many cells would be present: one, two or three?
- **c** How many units of DNA would be present in Cell A at the following point in the cell cycle?
  - i G2 stage of interphase
  - ii Anaphase of mitosis
  - iii G1 stage of interphase
- **d** How many units of DNA would be present in one daughter cell of cell A?
- **e** How many chromosomes would be present in this daughter cell?

11 Making predictions based on given information ➜ A particular gene mutation affects a protein that is a key part of the special attachment site, the kinetochore, that allows a chromatid to be linked to spindle fibres. This

mutation is present in cell B and it disables the function of the kinetochore.

a Would this mutation be expected to affect the progress of cell B through the cell cycle?

b If so, what effect would you predict? If not, give a reason for your decision.

12 **Applying skills of analysis and communication** ➜ Using a light microscope, you examine a longitudinal section of the meristematic tissue of a plant root. Consider each of the following statements in turn and identify whether or not you would expect to observe each in the particular cells you are viewing. Briefly explain your choice.

a The majority of the cells would be in one of the stages of mitosis.

b A cleavage furrow would be present in cells at telophase of mitosis.

c Sister chromatids at anaphase of mitosis would be moving away from the equator and towards opposite ends of the spindles.

d Double-stranded chromosomes would be visible in cells at the S stage of interphase.

13 **Demonstrating understanding** ➜ The cell cycle in eukaryotes is highly regulated so that cell production in a tissue occurs at a rate that balances cell loss.

a What is a possible outcome if a breakdown in the regulation of the cell cycle occurs?

b A disorder known as polycythemia vera is a result of the overactivity of the bone marrow, resulting in the production of too many red blood cells. This condition results in a thickening of the blood and the common treatment is the regular removal of a fixed amount of blood. The cause of polycythemia vera is a mutation in the **JAK2** gene. What is the probable function of the normal **JAK2** gene?

14 **Evaluating visual information** ➜ Figure 9.31 shows the winner of the 2012 Healthcare Cell Imaging Competition Microscopy Category; various fluorescent stains have been used to highlight different components of a cell that is progressing through the cell cycle.

a Suggest a possible identity for each of the following.

i The blue-stained structures

ii The green-stained structures

iii The red-stained structures

b At what stage of the cell cycle was this image taken?

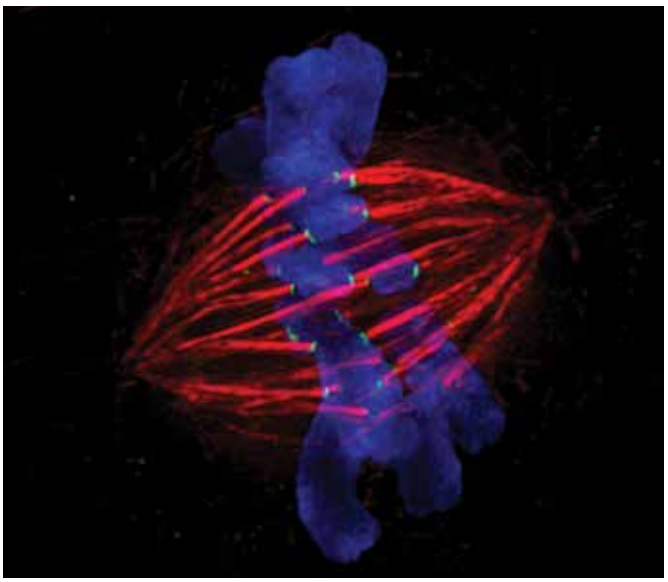

FIGURE 9.31 A cell stained for various components. This prize-winning image was displayed on the big screen at Times Square in New York City. (Image courtesy of Jane Stout, Research Associate, Walczak Laboratory, Indiana University)

CHAPTER

10 Asexual reproduction

FIGURE 10.1 Reproduction is one of the defining characteristics of living organisms, from the smallest microbes, such as *Mycoplasma pneumonia*, about 0.1 µm in diameter, to the largest multicellular eukaryote, the blue whale (*Balaenoptera musculus*). Reproduction comes in two modes, sexual and asexual. Here we see a microbe undergoing binary fission, a process of asexual reproduction. In this chapter we will explore the world of asexual reproduction in which single parents produce clones of themselves in the form of genetically identical offspring.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- understand the concepts of asexual reproduction
- understand that asexual reproduction has biological advantages but also disadvantages
- evaluate the emerging issues concerning cloning.

Jake's headache

In the winter of 2001, a young child was not well. Jake had been vomiting, was feverish, and told his parents that he had a headache and that his neck was hurting. Jake's parents initially thought that the boy was coming down with the flu. His parents became increasingly concerned, however, when the young boy became confused and disoriented. They rushed him to the Emergency Department of a public hospital.

The doctors who saw Jake at the hospital quickly assessed the boy and performed some simple tests that led them to suspect that Jake was suffering from **meningitis**. Meningitis is an inflammation of the protective membranes, known as **meninges**, that surround the brain and the spinal cord. A common cause of meningitis is an infection by *Neisseria meningitidis* bacteria. As a precaution, Jake was immediately treated with an antibiotic.

Meninges from *mēning* = membrane

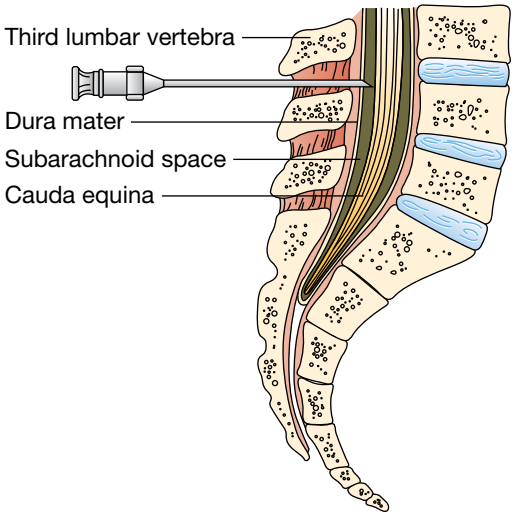

FIGURE 10.2 Simplified diagram showing the lumbar puncture procedure in which a needle is passed between the vertebrae in the lower back into the subarachnoid space. Note that the cerebrospinal fluid is located in the subarachnoid space. The outer boundary of this space is formed by the dura mater, one of the three membranes of the meninges. The cauda equina is a bundle of nerve fibres extending from the end of the spinal cord.

A sample of cerebrospinal fluid (CSF) was taken from Jake in a process known as a **lumbar puncture**. CSF is the fluid that bathes the brain and the spinal cord and it is located in the space between the middle and innermost layer of the meninges (the subarachnoid space).

To obtain a CSF sample, a needle is inserted between two of the lumbar vertebrae in the spinal column (see figure 10.2), either between L3 and L4 or between L4 and L5. The needle passes through two of the layers of the meninges until it reaches the subarachnoid space; a sample of CSF can be taken from this space. (An adult has about 120 to 150 mL of CSF.) The CSF sample from Jake was sent for testing. The CSF of a healthy person is a clear fluid with few, if any, white blood cells present (0 to 5 cells per microlitre). In contrast, the CSF sample from Jake was cloudy and contained high numbers of white blood cells, in excess of 100 cells per microlitre. Further testing showed the presence of bacteria that matched the shape and the biochemical characteristics of *Neisseria meningitidis*, the causative agent of bacterial meningitis.

Once it was confirmed that Jake had bacterial meningitis, he was given appropriate treatment. Happily, Jake recovered with no long-term ill effects and is now a healthy teenager.

ODD FACT

The spinal cord does not extend to the base of the spine. Typically, the spinal cord ends at about lumbar vertebrae L1 or L2. Nerve fibres leaving the end of the spinal cord at that point extend to the hips, legs, anus and bladder.

Meningococcal diseases

Neisseria meningitidis bacteria are natural residents of the mucus that lines the cells of the naso-pharynx (nose and throat) in about 10 per cent of young healthy adults. In a very few people, these bacteria penetrate the mucosal cells and gain entry to the body. These bacteria cause several diseases, including meningitis and **meningococcal sepsis**. The term, **meningococcal disease** (MCD) covers the range of diseases caused by *N. meningitidis*. Meningococcal disease affects mainly young children but it does occur, less commonly, in other age groups (see figure 10.3). Although these diseases are uncommon, they are very serious.

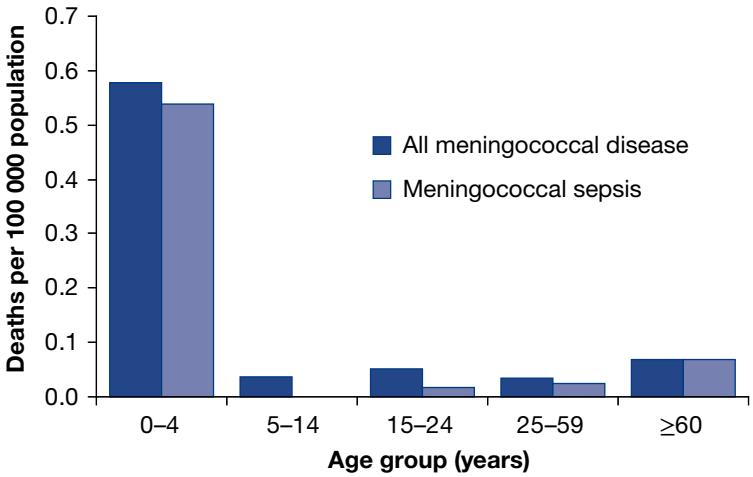

FIGURE 10.3 Graph showing the distribution of deaths from meningococcal disease by age group in the period from 2005 to 2007

The *N. meningitidis* bacteria can be spread from an infected carrier to a second person by air droplets from coughing or sneezing, and by close contact with saliva, as may occur from kissing or from sharing drinking vessels.

The *N. meningitidis* bacteria can undergo rapid cell divisions, with a **doubling time** of 40 minutes. This means that in about 6 hours one bacterial cell can undergo 8 cycles of cell division, producing more than 200 daughter cells. Within about 16 hours ongoing divisions of a single bacterial cell can produce more than one million daughter cells.

Meningitis

If *N. meningitidis* reaches the bloodstream, the bacteria can spread to other organs. Meningitis is the disease that results if the bacteria cross the blood–brain barrier and reach the CSF that bathes the brain and spinal cord. If the bacteria become established here, they undergo cell division and cause an inflammation of the protective membranes (meninges) that surround the brain and spinal cord. In some patients, the concentration of living bacteria, either single cells or clumps of cells, was found to be in the range of 10 000 to 100 000/mL of CSF.

ODD FACT

In 1887, the Austrian doctor Anton Weichselbaum (1845–1920) was the first person to identify the bacterium *Neisseria meningitidis* in the spinal fluid of patients with meningitis.

The outer surface of each *N. meningitidis* bacterium contains a complex lipopolysaccharide (lipid + polysaccharide), known as **endotoxin**. Endotoxin stimulates the human immune system and activates a range of undesirable and damaging inflammatory responses in human cells. The endotoxin on dead bacterial cells is also active in producing inflammation.

Meningococcal sepsis

The condition of meningococcal sepsis (also termed septicaemia) is the result of an *N. meningitidis* infection in the bloodstream. The bacteria start dividing in an uncontrolled manner, producing more and more bacterial cells. As the numbers of bacteria in the blood grow, an infected person is exposed to ever-increasing amounts of endotoxin. In one study, patients with severe sepsis had bacterial DNA loads of 10^6 to 10^8 DNA copies per millilitre of blood. Yes, that's one million to one hundred million bacterial cells, alive or dead, in every millilitre of their blood. The endotoxin from the massive numbers of living and dead bacteria in the blood causes a condition known as sepsis. This results in system-wide inflammatory changes and may develop into septic toxic shock that damages major organs including the heart, kidneys and liver. This can lead to multiple organ failure and, in some cases, death. (Later in this chapter, we will see how these cells are produced.)

ODD FACT

Many bacteria produce endotoxin. However, *N. meningitidis* produces far more than other bacteria, 100 to 1000 times more.

In some cases of meningococcal sepsis, the endotoxin causes septic shock that damages blood vessels and interferes with the blood supply to the limbs. In rare cases, the oxygen-starved tissues of the limbs die and decay. For the patient to have any chance of survival, amputation of part or all of the gangrenous limb or limbs is necessary.

Worldwide, 13 different strains of *N. meningitidis* occur. In Australia, as in other developed countries, the most common strains are C then B. In developing countries, the most common strain of *N. meningitidis* is strain A.

In Jake's case, *N. meningitidis* bacteria resulted in meningitis. In other persons, such as Charlotte Cleverley-Bisman (see figure 10.5), the *N. meningitidis* from her throat became established in her bloodstream and multiplied. The endotoxin from this bacterial load caused meningococcal sepsis that developed further into massive septic shock.

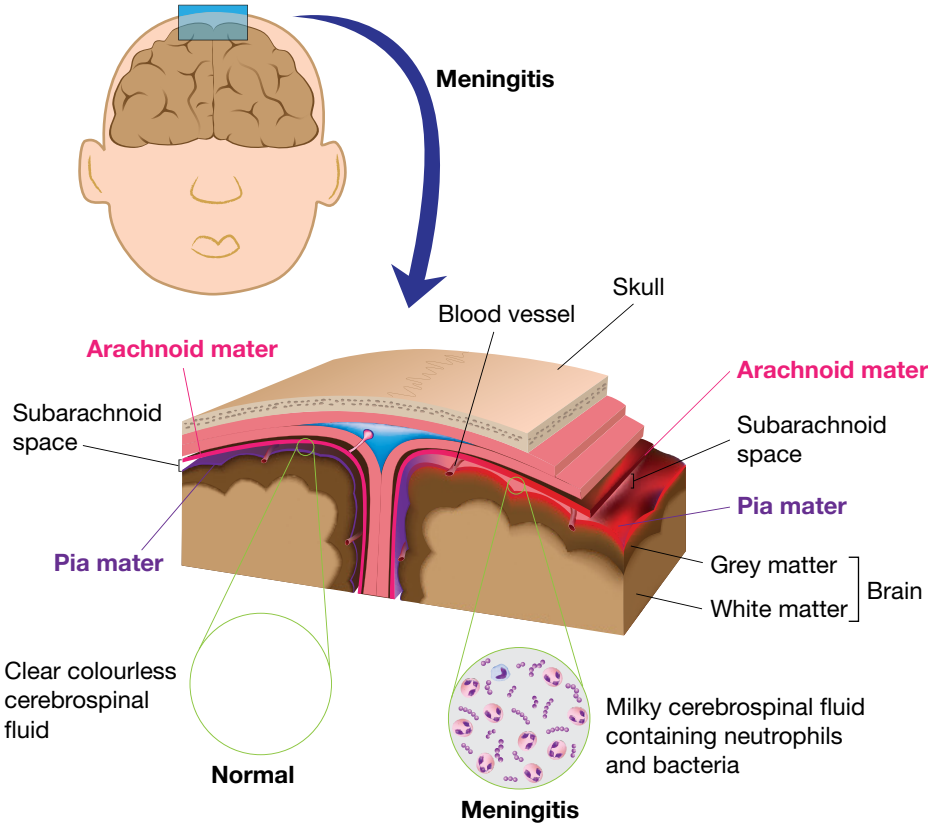

FIGURE 10.4 Meningitis is a result of a bacterial infection of the membranes (meninges) that cover the brain, most commonly caused by *Neisseria meningitidis*. A sample of the cerebrospinal fluid that bathes the brain and spinal cord can reveal the presence of the causative bacteria.

FIGURE 10.5 Charlotte Cleverley-Bisman — aged between 1 and 2 years — following her amputations. Charlotte became the face of the campaign that promotes meningococcal meningitis vaccination in New Zealand and raises awareness of the devastating diseases (meningitis and meningococcal sepsis) caused by *N. meningitidis* bacteria.

Preventive immunisation

The conjugate meningococcal C vaccine was introduced into the National Immunisation Program from 2003 to protect against meningococcal disease caused by *N. meningitidis,* strain C. Immunisation is free for children aged 12 months, and for children from 13 months up to and including 9 years who have not been fully vaccinated. (In the period from 2003 to 2006, a catch-up immunisation was offered to all children and young people aged from 1 to 19 years.) Since the introduction of this immunisation program, the incidence of meningococcal disease has decreased.

In June 2004, Charlotte Cleverley-Bisman (see figure 10.5), then 6 months old, was diagnosed with a meningococcal sepsis infection. The speed of onset of the disease was sickeningly fast; within hours of being taken to a medical centre near her home in New Zealand, little Charlotte's body became covered in swollen, purple areas and her extremities became black — a sign of dead gangrenous tissue. To survive this devastating disease, Charlotte had to undergo the amputation of parts of her four limbs. Charlotte became the 'face' of the campaign that promotes meningococcal meningitis vaccination, launched in New Zealand 1 month after she contracted the disease.

The threatening and serious effects of an infection by *N. meningitidis* bacteria are due to the fact that these bacteria can undergo complete cell divisions within about 40 minutes. (In contrast, a mammalian cell takes about 24 hours for a complete cell cycle (refer to chapter 9, p. 394)). This rapid production of two daughter cells from a single parental cell is just one example of asexual reproduction. Let's now look at this type of reproduction.

Reproduction without sex

Asexual reproduction is a form of reproduction in which one parental organism produces offspring that are genetically identical to each other and to the parent. The daughter cells are **clones**, and asexual reproduction is an example of natural cloning. Another definition of asexual reproduction is that it is a mode of reproduction that produces offspring without the involvement of gametes.

Asexual reproduction occurs in prokaryotes (bacteria and archaea) and in eukaryotes (animals, plants and fungi). The outcome is identical in both prokaryotes and eukaryotes, namely two identical daughter cells, but the process differs in these two groups. In prokaryotes, asexual reproduction involves **binary fission**, while in eukaryotes, asexual reproduction involves **mitosis**.

Table 10.1 compares asexual with sexual reproduction and highlights some key differences between the two modes of reproduction.

TABLE 10.1 Some differences between asexual and sexual reproduction

Feature	Asexual reproduction	Sexual reproduction
number of parents or parental contributions	one	two
processes involved	binary fission (prokaryotes) cell replication involving mitosis (eukaryotes)	gamete production involving meiosis (eukaryotes)
fertilisation	absent	fusion of gametes required
offspring	no genetic variability; offspring are clones of single parent	offspring differ from parents and from each other
rate of offspring reproduction	faster	slower

Sexual reproduction will be explored in detail in chapter 11.

ODD FACT

The prefix 'a' in asexual means 'not'. Other comparable words include asymmetrical, atypical and acentric. What does each of these mean?

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Examples of asexual reproduction Concept summary and practice questions

Seahorses are the only animals where the male gives birth. The female releases her eggs into a brood pouch on the male where they are fertilised and incubated before he later gives birth.

Asexual reproduction: advantages

One advantage of asexual reproduction is that population growth can occur very rapidly. Producing offspring by asexual reproduction is a faster process than by sexual reproduction. Only a single parental organism is required. For various animals, there is no need to spend time looking for a mate and no need for courtship displays; for vascular plants, there is no need to produce pollen and rely on a vector, such as the wind or an insect, to transfer this pollen to another plant for fertilisation.

We have already seen how the cell division of the *Neisseria meningitidis* bacteria can rapidly produce massive numbers of bacteria in the CSF and in the blood of persons with meningococcal diseases.

In addition, in multicellular species that reproduce sexually, the population necessarily consists of two sexes, male and female, but only the females can give birth to offspring. In contrast, in asexually reproducing species, every member of a population can give birth to offspring. This means that, all other things being equal, asexually reproducing organisms can reproduce at twice the rate of sexually reproducing organisms.

If a population suffers a sudden reduction in size as a result of a natural disaster, those species that can reproduce asexually can rebuild their numbers more rapidly than other species that must rely on sexual reproduction.

Another advantage of asexual reproduction is that if a new habitat becomes available for colonisation, those species that reproduce asexually can more quickly exploit the resources of space and energy in this new habitat.

In favourable conditions, asexual reproduction is an advantage because organisms with a successful genetic make-up (genotype) can spread quickly because offspring are exact replicas of the parent. If a parent has already survived in particular conditions, it is highly probable that its offspring will also survive. Such parents can pass their successful genotypes to their offspring, and this will continue, generation after generation. In asexual reproduction, the parental genotype is passed on unaltered to the offspring because this mode of reproduction does *not* involve the processes of genetic shuffling that occurs in sexual reproduction.

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Biological advantages of asexual reproduction
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Asexual reproduction: disadvantages

The principal disadvantage of asexual reproduction is that it does not create any **genetic variation** in a population because the offspring of each parent are genetically identical clones of that parent. In a population that reproduces asexually no new genotypes are produced. The only genotypes are those that are already present in the population. While conditions are favourable and unchanging, this does not matter, but this feature becomes a clear disadvantage if conditions change and become unfavourable.

In an environment subject to change, the existing genotypes in the population may not be suited to the new conditions. Likewise, the outbreak of a disease could affect all members of an asexually reproducing population. If one member of the population is susceptible to the disease, all will be susceptible.

In summary, asexual reproduction appears to be advantageous when rapid population growth is important or in unchanging stable environments. Sexual reproduction is advantageous where the genetic variation in offspring enables adaptation to unstable and changing environments.

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Biological disadvantages of asexual reproduction
Concept summary and practice questions

The best of both worlds

Some species have the ability to use both the asexual and the sexual modes of reproduction depending on circumstances (see figure 10.6). These species include various insects (such as aphids), some crustaceans (such as fairy shrimp), algae (such as *Volvox* sp., see figure 10.7), almost all fungal species and many plants.

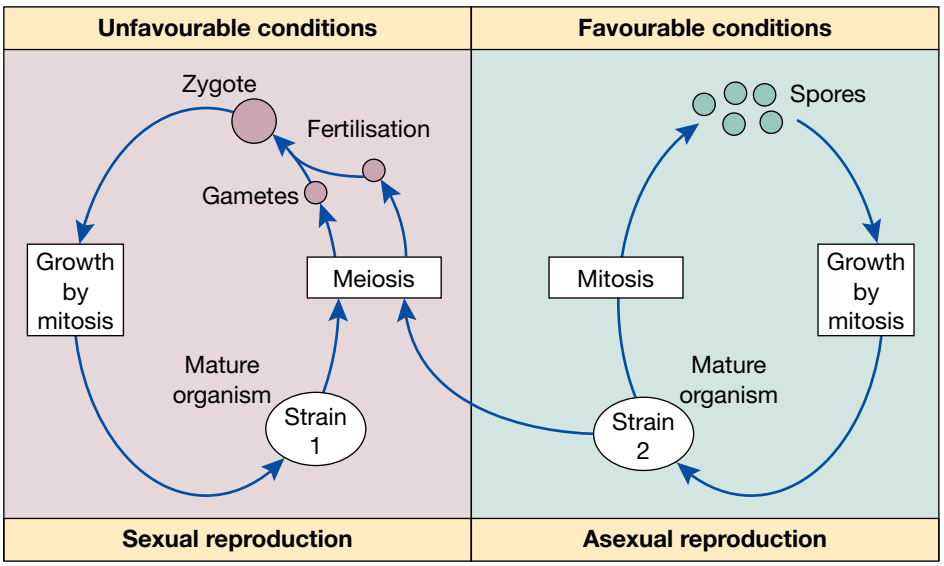

FIGURE 10.6 Some species use both asexual and sexual reproduction depending on circumstances. In preparation for known seasonal changes, such as the onset of winter, these species may switch from asexual to sexual reproduction. Typically, sexual reproduction involves different mating types or strains.

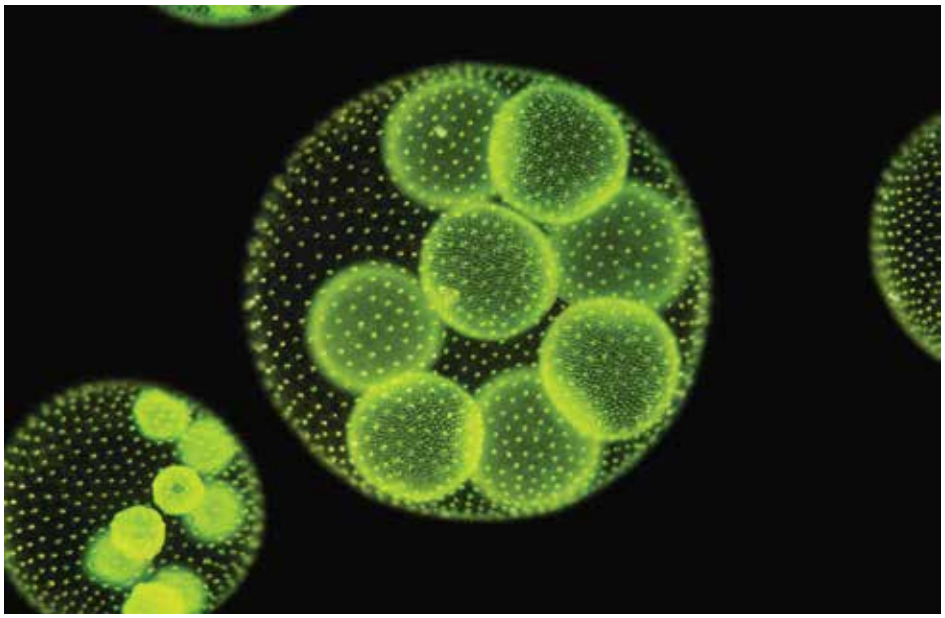

FIGURE 10.7 The freshwater alga *Volvox* sp. is found in temporary ponds and is an example of a colonial organism. *Volvox* can reproduce both sexually and asexually. Daughter colonies produced by asexual reproduction in summer are visible inside the spherical parent colonies. The daughter colonies are released into the water when the parent disintegrates. Because daughter colonies are produced asexually, all the daughter colonies within one parent colony are genetically identical to each other and to the parent colony.

The switch from asexual to sexual reproduction may occur in advance of a seasonal change to less favourable and more unstable conditions. For example:

- *Volvox carteri* is found in shallow pools that form during the spring rains but that dry out during the late summer. When the pools first form, this *Volvox* uses the asexual mode of reproduction to produce offspring that are clones of the single parent. However, not long before the ponds dry out, *Volvox* switches to sexual reproduction that involves genetic contributions (egg and sperm) from two parents. Sexual reproduction produces dormant zygotes that can survive through both the hot dry conditions of the summer and the cold conditions of winter. When the spring rains return and the ponds re-form, these zygotes emerge from their dormant state and give rise to a new generation of *Volvox carteri* that reproduce asexually until the ponds start to dry out again. And so the cycle continues.
- Aphids (see figure 10.8) reproduce asexually when conditions are favourable in terms of temperature and availability of food. When conditions become unfavourable, however, aphids switch to sexual reproduction as the temperatures fall and as the day lengths become shorter.

FIGURE 10.8 Aphids are insects typically found feeding on the sap of plants. Aphids use the asexual mode of reproduction during favourable conditions. When conditions become unfavourable, they switch to sexual reproduction. Note that these aphids are wingless. Remarkably, when aphids need to disperse, such as when their host plant becomes too crowded or when their food supplies are exhausted, they produce wings.

The advantage of sexual reproduction over asexual reproduction is that the offspring resulting from sexual reproduction are genetically variable. This variability equips a population to adapt better to changing conditions, because some of the new gene combinations created by sexual reproduction are likely to contribute to survival of some offspring.

However, when environmental conditions are favourable and resources are in plentiful supply, these species use asexual reproduction. Because the rate of offspring production by asexual reproduction is faster than by sexual reproduction, asexual reproduction can lead to a more rapid increase in population size. However, as noted above the disadvantage of asexual reproduction is that all the offspring of one parental organism are genetically identical to each other and to their single parent because they are the result of mitosis. This genetic uniformity means that, for example, if one offspring is susceptible to an infectious agent, all the offspring will be susceptible, or, if one cannot tolerate drought, all will be drought intolerant. **Genetic uniformity reduces the chance of a population adapting to new environmental conditions.**

KEY IDEAS

- Reproduction is an essential characteristic of all living organisms.
- Two modes of reproduction exist: asexual and sexual.
- Asexual reproduction involves a single parental organism that produces offspring which are genetically identical to each other and to the parent.
- Asexual reproduction is faster, requires less energy and can led to rapid population growth in favourable and stable circumstances.
- Asexual reproduction has the disadvantage that it cannot produce any new genotypes to enable adaptation to changing environments.
- Some species can reproduce asexually or sexually depending on circumstances.

QUICK CHECK

1 How many parents are required for asexual reproduction?
2 What is the doubling time of the *N. meningitidis* bacteria?
3 How many new genetic combinations can be produced by asexual reproduction?
4 Name the mode of reproduction that:
   a produces clones of the parent
   b can increase more rapidly under favourable conditions
   c does not involve fertilisation
   d produces offspring that are genetically variable
   e involves mitosis.

Examples of asexual reproduction

Examples of asexual reproduction in which a single parent produces identical offspring include:

- binary fission in prokaryotic microbes
- splitting in single-celled eukaryotic organisms
- spore formation in fungi
- natural cloning in animals, for example
  - budding in sponges and corals
  - 'virgin birth' in insects
- vegetative reproduction in plants, as in runners, cuttings, rhizomes and suckers.

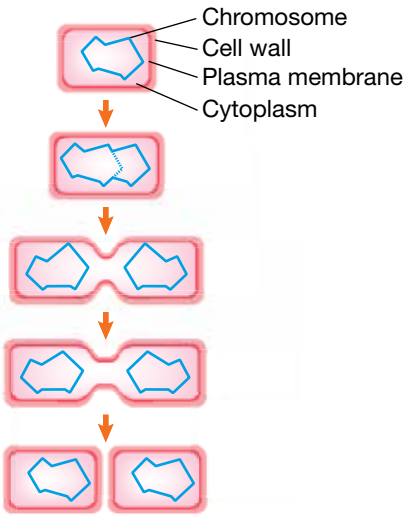

FIGURE 10.9 Binary fission in a bacterial cell. Replication of the circular DNA molecule is followed by cell lengthening and then its division into two. Why is this process an example of asexual reproduction?

Prokaryotes: binary fission

Microbes such as bacteria are unicellular prokaryotic cells. Multiplication of bacterial cells occurs by an asexual process of reproduction known as binary fission (*binary* = two; *fission* = splitting). The binary fission of a bacterial cell involves:

- replication of the circular molecule of DNA of the bacterial cell
- attachment of the two DNA molecules to the plasma membrane
- lengthening of the cell
- division of the cell into two via a constriction across the middle of the cell, so that each new cell contains one circular molecule of DNA (see figure 10.9).

The process of asexual reproduction by binary fission in bacteria is simpler and faster than asexual reproduction in eukaryotic organisms. Asexual reproduction in eukaryotes involves the more complex process of mitosis (refer to chapter 9) followed by division of the cytoplasm (cytokinesis). This process typically takes many hours to complete. Binary fission in some bacteria can be completed in about 20 minutes at room temperature. This means that, if resources are available, one bacterial cell, through successive binary fissions over an 8-hour period, could produce 16 million descendants! This is an example of exponential growth and it reminds us why a bacterial infection, if not treated, can have serious outcomes.

Figure 10.10 shows a cell of the bacterial species *Escherichia coli* dividing by binary fission.

FIGURE 10.10 Transmission electron microscope image of a bacterial cell dividing by binary fission

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Binary fission
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Eukaryotes: asexual reproduction

Among the eukaryotic organisms — animals, plants, fungi and protists — many different forms of asexual reproduction occur. Let's look at some examples.

Let's split into two!

Some eukaryotic unicellular organisms, such as *Amoeba* (figure 10.11), *Euglena* and *Paramecium*, live in freshwater ponds and are less than pinhead-size. These unicellular organisms can reproduce asexually by splitting into two (see figure 10.12). Just to confuse matters, this process is also known as binary fission. However, the process of binary fission in these unicellular eukaryotes is different from that which occurs in bacteria. In eukaryotes, the formation of new cells by binary division involves the process of mitosis.

ODD FACT

In prokaryotes the genetic material, DNA, is a naked circular molecule. In eukaryotes DNA is combined with proteins, extensively folded and organised into chromosomes.

ODD FACT

Amoebae can also undergo **multiple fission**. Mitosis occurs repeatedly and many nuclei form within a single cell. Each nucleus becomes enclosed within a small amount of cytoplasm and forms a **spore**. Spores can later develop into new amoebae.

FIGURE 10.11 Phase contrast microscope image of an *Amoeba*

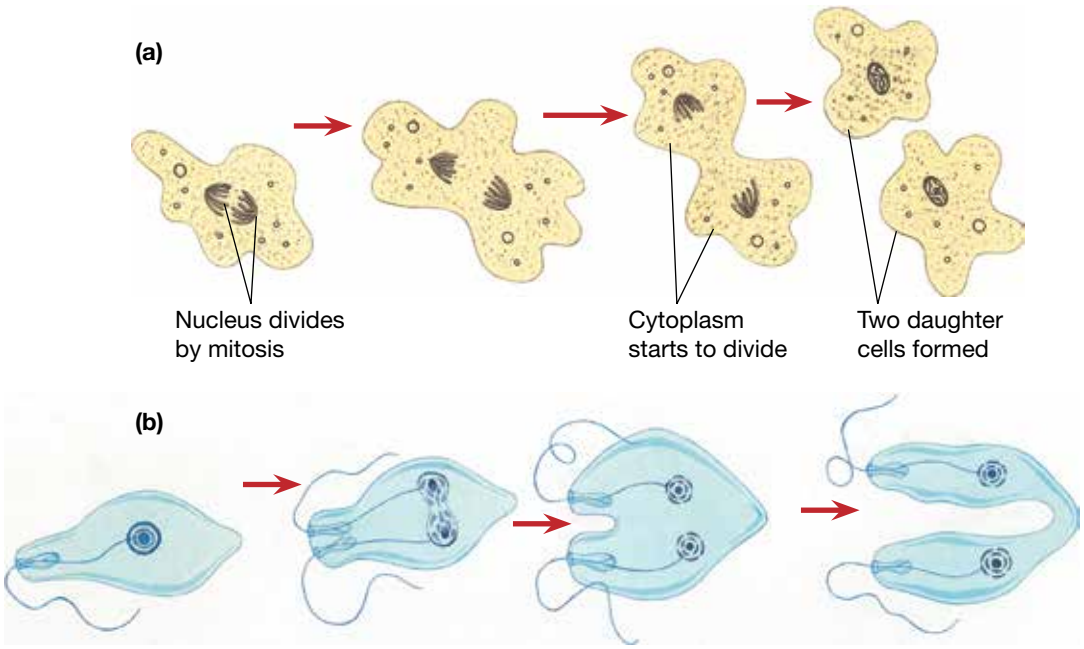


FIGURE 10.12 Binary fission or splitting in simple eukaryotes **(a)** Splitting into two in *Amoeba* sp., a unicellular organism. The cytoplasm divides after the chromosomes have replicated and separated during mitosis. Will the daughter cells be identical to or different from each other? **(b)** Splitting into two along a longitudinal axis, a process known as longitudinal binary fission, occurs in *Paramecium* sp., another unicellular eukaryote.

ODD FACT

Coral polyps can also reproduce asexually. Some bud, others grow new polyps from fragments that break off from a parent polyp and some divide longitudinally to form two new polyps, genetically identical to each other.

Simple multicellular animals, such as flatworms, anemones and coral polyps, can also reproduce asexually by splitting into two (see figure 10.13). Each of the parts then grows into a complete animal. This kind of splitting does not occur in other multicellular organisms because their structure is more complex, being built of many different tissues and organs.

FIGURE 10.13 An anemone (*Anthopleura elegantissima*) in the process of reproducing by splitting in two. Note the narrowing (centre of image) that marks the point where it will split.

Budding to make more

Sponges are common in many marine habitats. Each sponge is made of thousands of cells but has no specialised organs or nervous system. Sponges are able to reproduce asexually from small groups of cells formed by mitosis that bud or break away from the main organism and are carried by currents to other locations where they settle and develop into new sponges. The small group of cells settles on some substrate; the cells reproduce by mitosis and develop into a new sponge. Other simple animals, such as *Hydra*, also undergo **budding** (see figure 10.14).

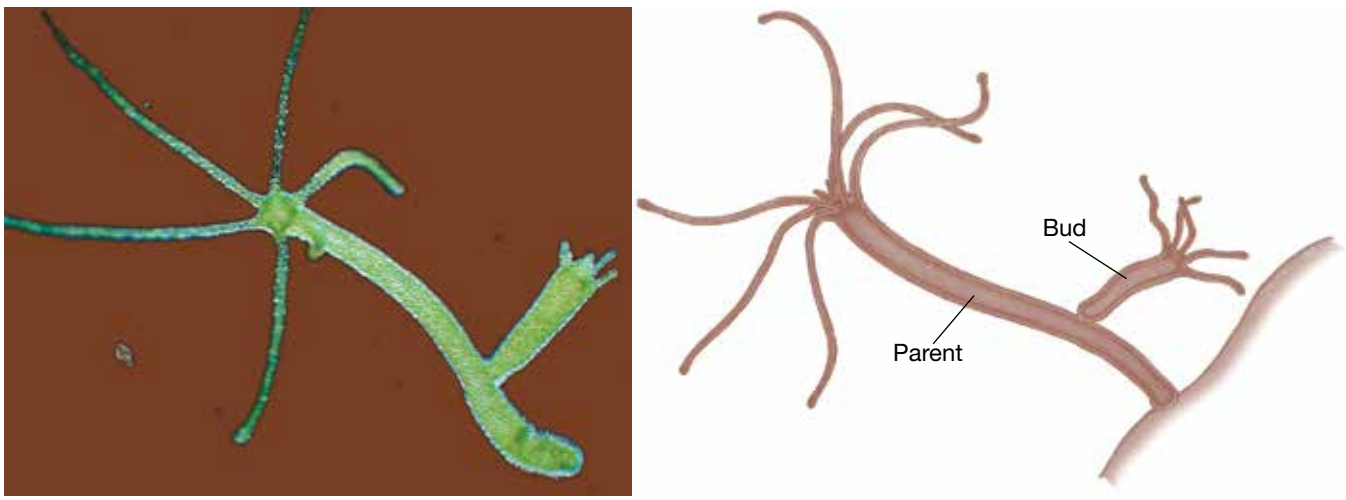


FIGURE 10.14 Asexual reproduction involving budding from one parent occurs in *Hydra*.

Parthenogenesis

An unusual form of asexual reproduction in animals is **parthenogenesis** (*parthenos* = virgin; *genesis* = birth), which is also called virgin birth. Parthenogenesis is defined as reproduction without fertilisation, and almost always involves the development of an unfertilised egg. Offspring are produced from unfertilised eggs — no sperm is necessary. These eggs are produced by mitosis and develop into offspring identical to the female parent. This type of reproduction is seen in aphids when conditions are favourable (see figure 10.15). In contrast to other insects that typically lay eggs, aphids give birth to live young.

Parthenogenesis is seen in many invertebrate animals. It is rare in vertebrate species, but has been reported in several reptile species, such as whiptail lizards (see figure 10.16), and in some shark species.

FIGURE 10.15 Adult female aphid giving birth. The numerous offspring have developed from unfertilised eggs. What is the name of this kind of reproduction?

FIGURE 10.16 *Aspidoscelis tesselata* is one of the many species of whiptail lizard that reproduce by parthenogenesis. Populations of this obligate parthenogen are all female.

Populations that reproduce using parthenogenesis are typically all-female. Parthenogenesis can be **obligate**, meaning that this is the only way in which a species can reproduce. This is the case for about one-third of the 50 plus species of whiptail lizard of the genus *Aspidoscelis*. These obligate unisexual lizard species consist only of females. Other species that show a complete absence of male contribution to reproduction are other reptiles including some snakes, rock lizards (*Lacerta* spp.) and Australian geckos (*Heteronotia* spp.).

In other species, parthenogenesis can be **facultative**, meaning that it is a reproductive strategy that is only used when required, such as when no males are around. When males re-appear, the species return to sexual reproduction. Facultative parthenogenesis has been reported to occur in komodo dragons (*Varanus komodoensis)*. Offspring produced by female komodo dragons through parthenogenesis are always male. (We will explore this surprising fact in chapter 11.)

ODD FACT

The komodo dragon is the largest living species of lizard. Dragons can reach lengths of up to 3 m and have a body mass of up to 70 kg.

Spore formation in fungi

Spore formation is an important process in the asexual reproduction of some fungi (and also some algae). These spores produced are true asexual spores produced by mitosis. After dispersal, the spores develop into new organisms that are genetically identical to each other and to the parent.

The bread mould (*Rhizopus stolonifer*) provides an example of asexual spore formation in a fungal species (see figure 10.17). Spores are formed by mitosis in aerial structures called sporangia. When released from a **sporangium**, the spores are carried away by air currents. If a spore lands on a moist location, such as a slice of bread, the spores germinate and form a branching structure and, soon after, new sporangia containing spores develop. And so the cycle is completed.

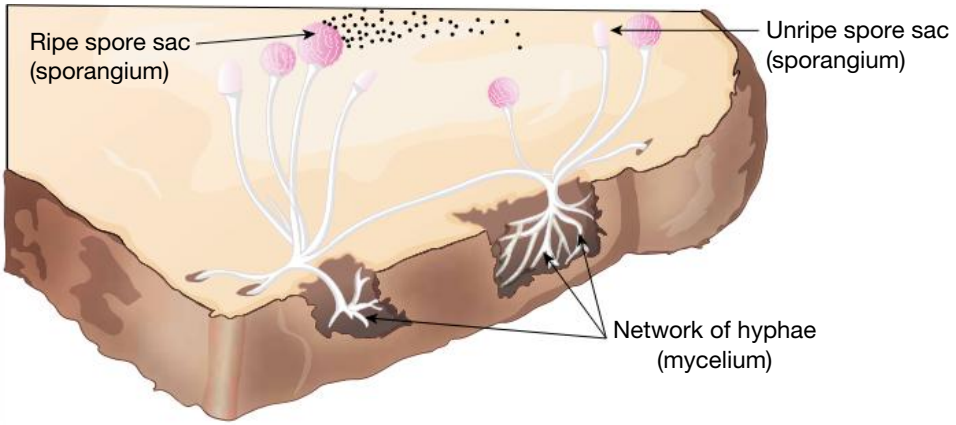


FIGURE 10.17 The bread mould fungus (*Rhizopus stolonifer*) is a common fungus. It reproduces asexually through spores that are windblown. Once a spore lands on a suitable substrate, it germinates and produces the fungal network, or **mycelium**. Note the 'stalks' that raise the sporangia above the substrate surface. Why is this important?

Plants such as mosses and ferns also produce spores as part of their life cycles. However, because the spores are produced by meiosis, not mitosis, the spores produced by one moss or one fern are not genetically identical to the plant that produced them, or to each other. Each spore then develops into a new plant, called a gametophyte, by a process of mitosis.

Asexual reproduction in plants

Asexual reproduction is common in plants. In plants, asexual reproduction is also called **vegetative reproduction**.

Runners

Over 10 years, one strawberry plant (*Fragaria ananassa*) grew into the strawberry patch in figure 10.18. How did one small plant grow into such a large patch? Strawberry plants have **runners**, special stems that grow over the ground. The runner grows away from the parent plant and, at alternate nodes on the runner, new buds give rise to roots, leaves, flowers and fruit (see figure 10.19).

Another example of a plant that spreads by runners — this time in water — is the water hyacinth (*Eichhornia crassipes*) (see figure 10.20). This is a declared noxious weed that infests wetlands, lakes and rivers in Australia.

A variation of 'runners' occurs in blackberry plants (*Rubus* spp.) that propagate when their long stems (canes) bend over and make contact with the ground. Shoots and roots grow from the point where the tips of the stems make contact with the ground.

FIGURE 10.18 In 10 years, one strawberry plant grew by asexual reproduction into this strawberry patch.

FIGURE 10.19 The strawberry (*Fragaria ananassa*) has runners, special stems that grow over the ground.

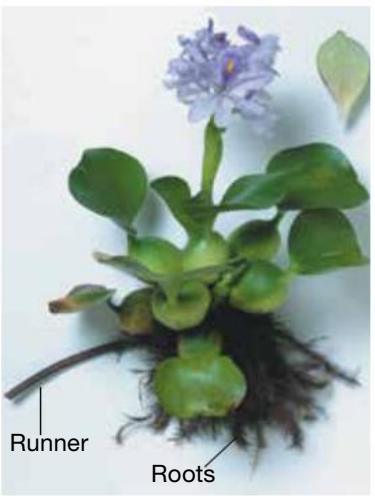


FIGURE 10.20 The water hyacinth

As well as runners, other means of asexual reproduction in plants include:

- **cuttings**
- **rhizomes** (underground stems)
- **tubers** (swollen underground stems)
- **bulbs** (underground structures with short stems and many closely packed, fleshy leaves).

Some of these structures are shown in figure 10.21.

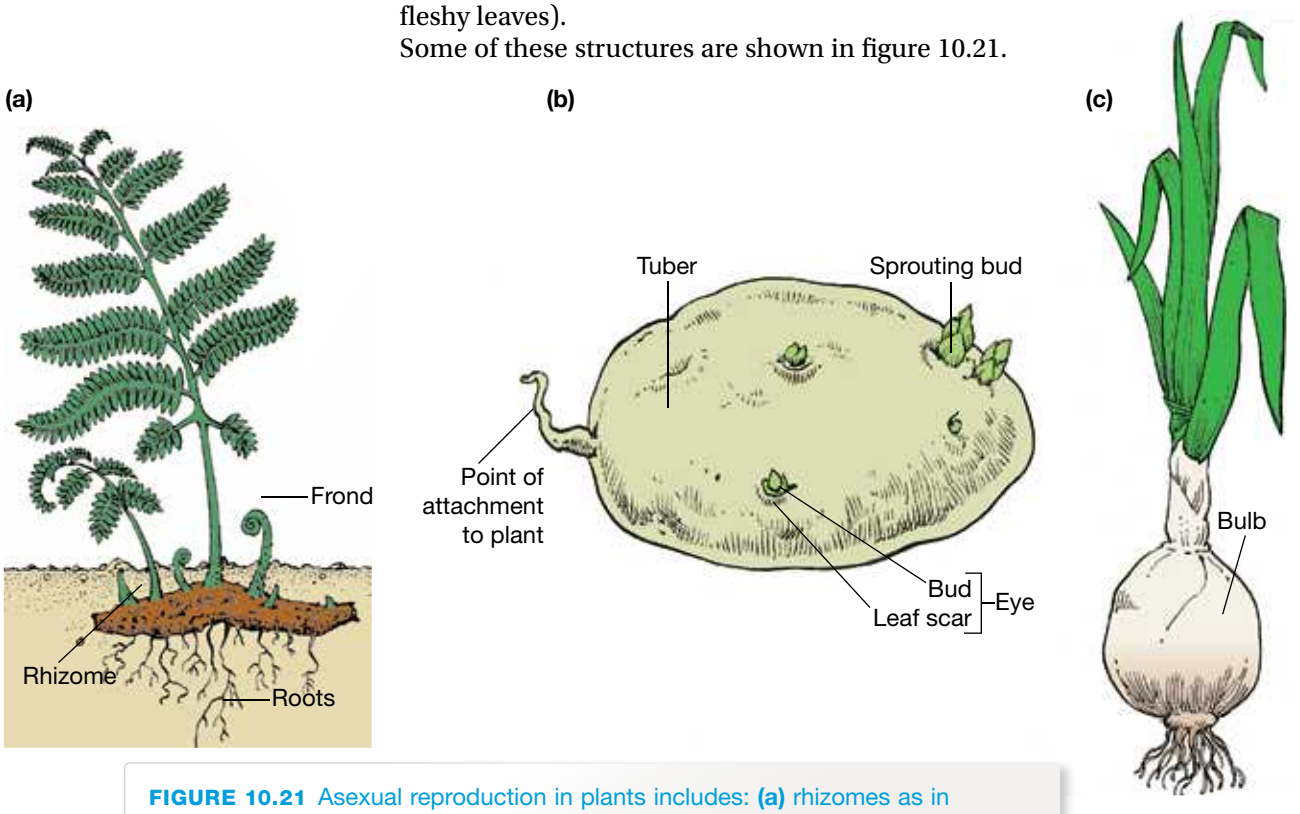


FIGURE 10.21 Asexual reproduction in plants includes: **(a)** rhizomes as in bracken and some grasses; **(b)** tubers as in potatoes; and **(c)** bulbs as in onions. In each case, the new plants are genetically identical to the parent plant.

Cuttings

With some plants, it is possible to clone them by taking cuttings of shoots, roots or leaves and planting them.

Rhizomes

Some plants propagate through underground stems or rhizomes (see figure 10.21a). Buds and roots sprout from nodes along a rhizome and produce new daughter plants. Rhizomes can be distinguished from plant roots by the presence of buds, nodes and often tiny scale-like leaves. Plants that propagate by rhizomes include garden plants, such as irises; grasses, such as kikuyu grass (*Pennisetum clandestinum*) and couch grass (*Cynodon dactylon*); the austral bracken, an Australian fern (*Pteridium esculentum*) (see figure 10.22); and many reeds. Rhizomes are typically thick in structure because they have a food reserve, mainly in the form of starch.

FIGURE 10.22 Austral bracken reproduces asexually from underground stems (rhizomes) when buds from the rhizome develop into new fronds. After a bushfire, austral bracken quickly becomes re-established in a burnt area. Can you suggest why?

ODD FACT

Most ferns are delicate and need moist, shady conditions to reproduce by sexual means. In contrast, austral bracken propagates asexually by rhizomes and thrives in exposed areas.

Suckers

Suckers are new shoots that arise from an underground root at some distance from a parent plant. Blackberry suckers can appear more than 2 m from the parent plant.

Plantlets without sex

The fern *Asplenium bulbiferum*, which is native to Australia and New Zealand, can reproduce asexually. Figure 10.23 shows the small **plantlets** that arise from the fern frond. A similar process also occurs in the plant *Bryophyllum* sp. (see figure 10.24). In both cases, **meristematic tissue** is the source of the cells that grow into plantlets. When they reach a particular size, the plantlets drop from the parent plant and take root.

ODD FACT

In New Zealand, *Asplenium bulbiferum* is commonly known as hen and chickens fern. In Australia, the common name of the same fern is mother spleenwort.

FIGURE 10.23 Asexual reproduction in the fern *Asplenium bulbiferum*. Note the new plantlets on the fern fronds.

FIGURE 10.24 New plants form by asexual reproduction on the leaf margin of *Bryophyllum* sp.

KEY IDEAS

- Asexual reproduction occurs by binary fission in prokaryotes.
- Asexual reproduction in all eukaryotes occurs through mitosis.
- Unicellular eukaryotes reproduce by binary fission that involves mitosis.
- Simple multicellular animals reproduce asexually through budding.
- Parthenogenesis is the development of offspring from unfertilised eggs.
- Certain fungi produce spores as part of their cycle of asexual reproduction.
- Various types of asexual reproduction occur in plants including runners, rhizomes and tubers.

QUICK CHECK

5 What is the key difference between binary fission in a microbe and the binary fission that occurs in an amoeba?
6 Starting with one bacterial cell, how many cells would be expected from six cycles of binary fission?
7 Identify two ways in which a plant might reproduce asexually.
8 What is the key cellular process that is involved in all cases of asexual reproduction in eukaryotic organisms?
9 You are told that a population consists of obligate parthenogens. State two additional correct statements that you could make about this population.

Technology: asexual reproduction

Reproductive technologies such as cloning involve methods of asexual reproduction in which the genetic information of new organisms comes from one 'parent' cell only. For many years, whole plants have been cloned by traditional methods, such as cuttings, but the horticultural industry **now uses the technique of plant tissue culture to clone plants in large numbers**.

Cloning in horticultural practice

Using the technology of plant tissue culture in the laboratory, many identical copies, or clones, of a plant can be produced starting from a small amount of tissue from one plant. This technique is used with ornamental plants, such as orchids and carnations, and Australian native plants, such as bottlebrush (*Callistemon* spp.), the flannel flower (*Actinotus helianthi*) and various eucalypts (*Eucalyptus* spp.). Tissue culturing can also be used with endangered or very rare plants, such as the Wollemi pine (*Wollemia nobilis*) since only a few specimens exist in the wild.

Figure 10.25a shows flannel flowers in tissue culture in a laboratory and figure 10.25b shows mass plantings of flannel flowers propagated by tissue culture.

Tissue culture cloning of plants has several advantages:

- Slow-growing plants can be produced in large numbers.
- Plants can be cultured all year round in controlled conditions of temperature and day length, rather than relying on seasonal growth.
- Virus-free tissue can be used to produce a large number of plants that do not carry the virus. (Viruses are responsible for many plant diseases that can affect commercial crops.)
- Cultured plants can be transported from country to country. The sterile conditions in which they are cultured ensures that the plants are pest free, so that lengthy quarantine periods are avoided.

How does tissue culture work? Tissue culture starts with a small piece of a healthy plant such as a piece of leaf or bud or stem. The plant that supplies the tissue is selected because it has particular desirable characteristics, such as flower colour or disease resistance or timber quality.

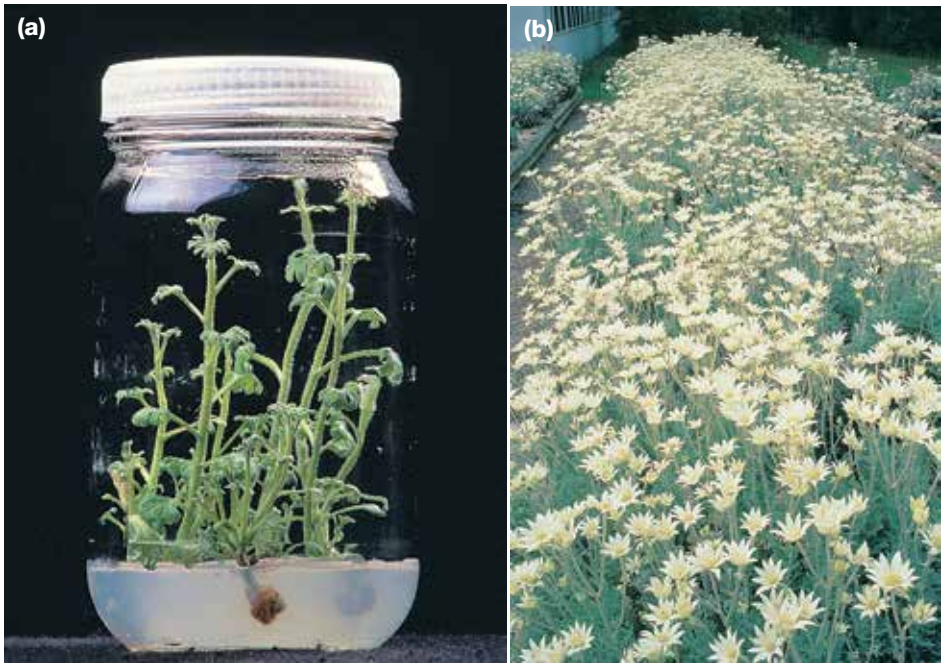


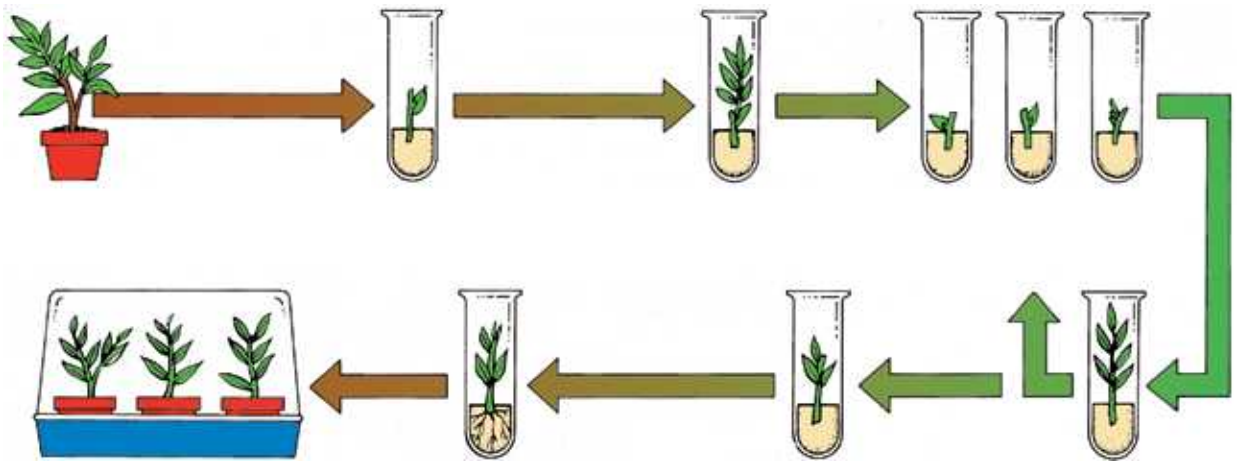
FIGURE 10.25 **(a)** Flannel flowers in tissue culture **(b)** Large-scale bed plantings of flowers propagated by tissue culture

Pieces of a plant to be cultured must contain meristematic tissue because this is the only plant tissue that is capable of cell division by mitosis. The pieces of tissue are sterilised and placed in sterile test tubes containing a culture medium. The culture medium is a mixture of agar (jelly) and essential nutrients (see figure 10.25a). The pieces are treated with cytokinin, a plant hormone that stimulates shoot formation by mitosis.

The tubes are incubated at controlled temperature and day length. After a few weeks, new shoots appear. Each of these shoots is cut into several pieces and each piece is placed into a fresh culture tube. Again, treatment with cytokinin stimulates these pieces to produce more shoots. This process is called **subculturing** and it can be repeated several times. (If you began your tissue culture with one piece of tissue, after 1 month you could cut the tissue produced by tissue culture into five pieces and grow these in culture. A month later, you could repeat this process, giving you a total of 25 tissue cultures.) The process of subculturing multiplies the output from the original tissue selected.

After the shoots have been subcultured a number of times, the hormone auxin is added to stimulate root production. Once roots develop, the small plants are complete with roots, stems and shoots. These small plants are removed from culture and planted in sterile compost and sand.

FIGURE 10.26 Tissue culture procedure. Here many *Eucalyptus* plants are produced from a parent plant selected for its genetically determined timber quality. Will the plants produced by tissue culture be expected to have this quality when they mature?



The success of tissue culturing of plants depends on the fact that asexual reproduction produces genetically identical clones of the parent, whether the parent is a whole organism or a tissue sample or even a single cell. This exact copying is a result of the precision of cell division by mitosis.

Artificial cloning of mammals

Reproduction in mammals in their natural setting is sexual, involving fertilisation of an egg by a sperm, and one fertilisation event typically produces a single offspring.

Artificial cloning of mammals is a recent development and several techniques have been used:

- cloning using **embryo splitting**
- cloning using **somatic cell nuclear transfer**.

Embryo splitting to make identical copies

Cloning by embryo splitting occurs when the cells of an early embryo are artificially separated, typically into two cell masses. This process mimics the natural process of embryo splitting that produces identical twins or triplets. Embryo-splitting technology has been used for stockbreeding for many years. It has become a relatively simple technique, but is limited to twinning. Typically, the embryos to be split are produced through in-vitro fertilisation (IVF), for example, the in-vitro fertilisation of a cow's egg by bull sperm. The parents are chosen because of desirable inherited commercial characteristics that they exhibit, such as high milk yield or high milk fat content in dairy cattle, or muscle formation or fat distribution in beef cattle. Using a very fine glass needle, **an embryo at an early stage of development is divided into two smaller embryos**. The small embryos from the splitting of one embryo are identical, as will be the adults that develop from them. Each small embryo is then implanted into the uterus of a surrogate female parent where embryonic development continues. Figure 10.27 shows an outline of this process.

The two embryos from the splitting of a single embryo can be termed demi-embryos.

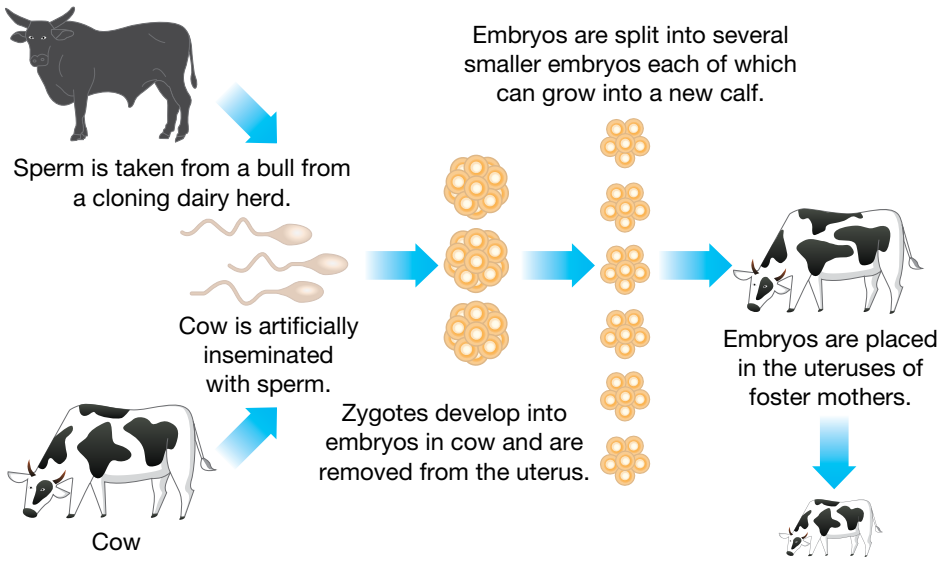


FIGURE 10.27 An outline of the process of embryo splitting to clone dairy cattle. The cow may first be treated with hormones to cause the release of several eggs (superovulation). Does the surrogate mother make any genetic contribution to the embryo?

Embryo splitting has been used for some years in the livestock industry. In cattle, for example, embryo splitting enables the genetic output from several matings of a top bull and a prize cow to be doubled. Instead of just one calf from each such mating, two calves can be produced. This process depends on the use of surrogate mothers.

The two offspring from the splitting of one embryo are *not* genetically identical copies of either the cow that produced the egg or the bull that provided the sperm

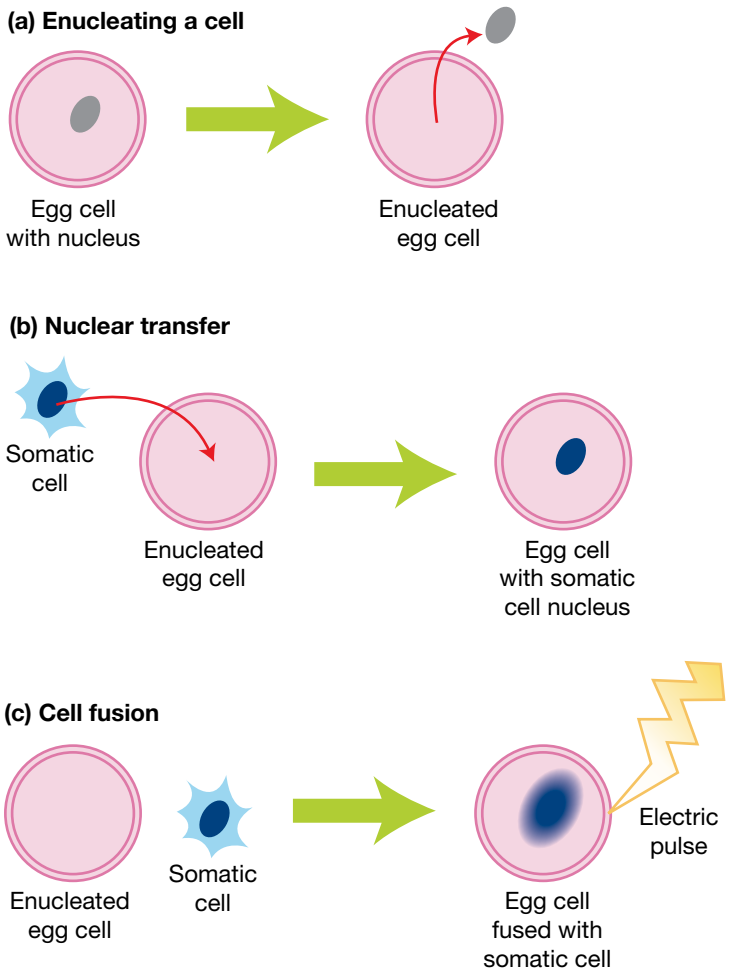


FIGURE 10.28 **(a)** Producing an enucleated cell **(b)** Nuclear transfer between two cells **(c)** Cell fusion. Fusion of two cells is commonly done using a short electric pulse.

used to produce the embryo that was split. The two offspring are genetically identical to each other and are identical copies of the *fertilised* egg from which the embryo came.

The eggs produced by one cow are not genetically identical to each other, nor are the sperm from one bull. This is because these gametes are produced by meiosis, not mitosis. As we will see in chapter 12, the process of meiosis juggles and re-assorts the genes of eggs and sperm. This means that the offspring from the splitting of embryos derived from different fertilised eggs from the same mating will be genetically different.

Cloning using somatic cell nuclear transfer

Some possibilities exist to manipulate cells and their nuclei. It is possible, for example, to:

- remove the nucleus from a cell (when this occurs the cell is said to be enucleated) (see figure 10.28a)
- transfer the nucleus from one cell to an **enucleated cell** to form a re-designed nucleated cell (see figure 10.28b)
- fuse a somatic cell with an enucleated cell (see figure 10.28c).

The birth of two sheep, Megan and Morag (see figure 10.29), in 1995 marked a significant scientific milestone. These two sheep were the first mammals ever to be cloned using nuclear transfer technology. Each of these **sheep developed from an unfertilised enucleated egg cell that was fused with an embryonic cell that contained its nucleus.** In each case, the embryonic cell used came from the culture of one embryonic cell line; as a result, Megan and Morag were identical twins.

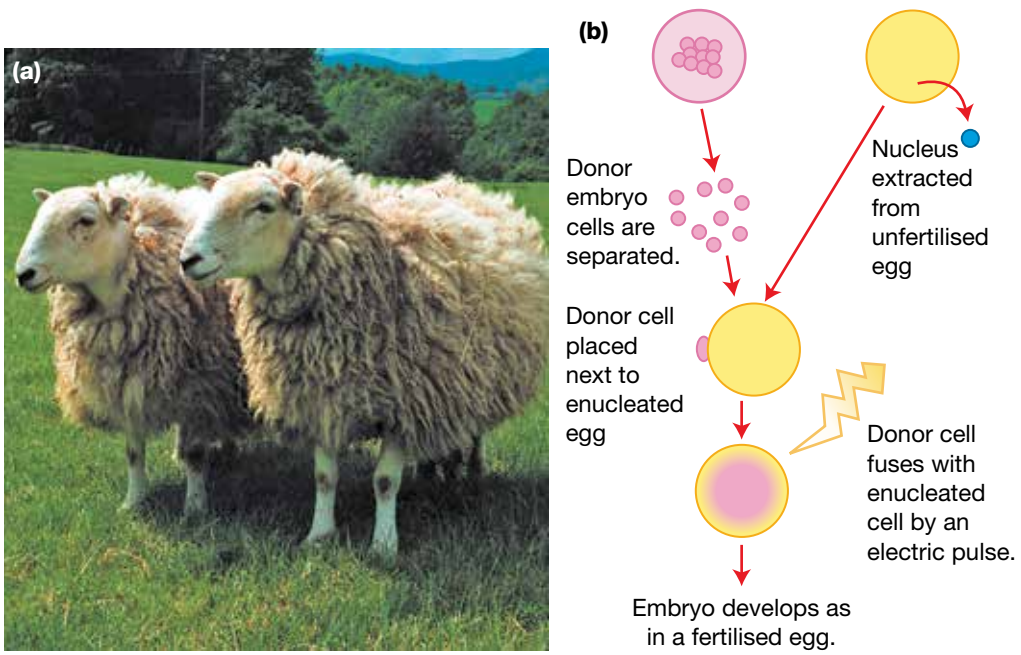


FIGURE 10.29 **(a)** Megan and Morag, two Welsh mountain ewes, born in August 1995 **(b)** Megan and Morag were not born as a result of a normal mating between a ram and a ewe, but were created using nuclear transfer cloning. What cells were involved in their production?

FIGURE 10.30 Dolly and her first lamb, Bonnie. Bonnie was born in April 1998 after a natural mating of Dolly with a Welsh mountain ram.

. . . and then came Dolly!

The scientific world was stunned after the announcement in February 1997 of the existence of Dolly, a Finn–Dorset female lamb born the previous year at the Roslin Institute in Scotland (see figure 10.30). The scientists who created Dolly were Ian Wilmut, Keith Campbell and their colleagues from the Roslin Institute that is part of the University of Edinburgh in Scotland.

Why was Dolly the lamb famous? Read what Ian Wilmut wrote about Dolly:

> Dolly seems a very ordinary sheep . . . yet, as all the world acknowledged, . . . she might reasonably claim to be the most extraordinary creature ever to be born . . .
>
> Dolly has one startling attribute that is forever unassailable: *she was the first animal of any kind to be created from a cultured, differentiated cell taken from an adult.* Thus she confutes once and for all the notion — virtual dogma for 100 years — that once cells are committed to the tasks of adulthood, they cannot again be totipotent.
>
> (*Source:* I Wilmut, K Campbell and C Tudge, *The Second Creation: Dolly and the Age of Biological Control*, Harvard University Press, Cambridge, Mass., 2000)

While cloning via nuclear transfer had occurred successfully in the past, those earlier cases involved embryonic or fetal cells, never adult somatic cells. The use of **adult somatic cells**, such as skin cells, to construct new organisms represents remarkable human intervention in the evolutionary processes. Through this means, cells from sterile animals or from animals past their reproductive period, or even stored cells from dead animals, can provide all the genetic information of new organisms. In nature, the normal evolutionary processes would not allow these events to occur.

Totipotent refers to a cell that is able to give rise to all different cell types.

How was Dolly created?

The artificial cloning of mammals involves:

- obtaining the nucleus from a somatic (body) cell of an adult animal — this is the 'donor' nucleus
- removing the nucleus from an unfertilised egg cell, typically of the same species — this is the enucleated egg cell
- transferring the donor nucleus into the enucleated egg cell
- culturing the egg cell with its donor nucleus until it starts embryonic development
- transferring the developing embryo into the uterus of a surrogate animal where it completes development.

The genetic information in the cloned animal comes from the nucleus of the adult body cell and so the genotype of the cloned animal is determined by the donor nucleus, not by the egg into which the nucleus is transferred.

The procedure in the case of Dolly is shown in figure 10.31. An unfertilised egg from a Scottish Blackface ewe had its nucleus removed. A cell was taken from the culture of mammary cells derived from the udder (mammary gland) of a Finn–Dorset ewe. Using a short electric pulse, the cultured mammary cell was fused with the enucleated egg cell to form a single cell. This reconstructed cell was cultured for a short time and was then implanted into the uterus of a surrogate Blackface ewe where the embryo developed. At 5 pm on 5 July 1996, this surrogate Scottish Blackface ewe gave birth to Dolly, a Finn–Dorset lamb, the first mammal to be produced by cloning using an adult somatic cell.

ODD FACT

Dolly was named in fun after Dolly Parton, because she was derived from an udder (mammary gland) cell.

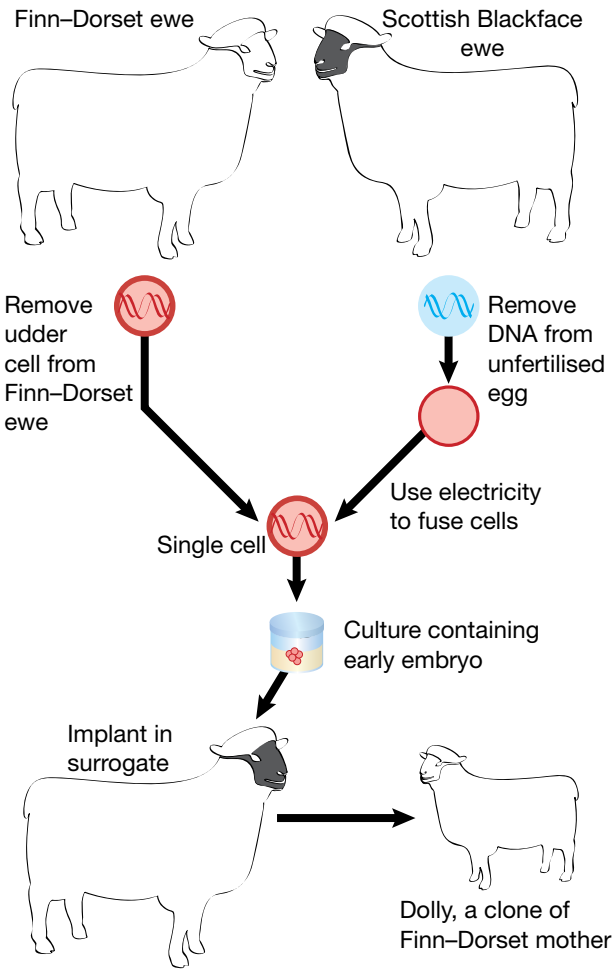


FIGURE 10.31 Technique of animal cloning by somatic nuclear transfer

After Dolly — what next?

Who are Matilda, Suzi and Mayzi, cc and Snuppy?

- Matilda the sheep was the first lamb to be cloned in Australia and was born in April 2000 (see figure 10.32a).
- Mayzi and Suzi (see figure 10.32b) were Australia's first calves to be artificially cloned from the skin cells of a cow fetus. Mayzi and Suzi are identical twins but were born two weeks apart in April 2000. Why were they not born on the same day?
- cc (short for carbon copy) was the first cat to be artificially cloned using a cumulus cell from an adult female cat, Rainbow, as announced by a group of US scientists in February 2002 (see figure 10.32c).
- Snuppy, the Afghan hound, was the first dog to be artificially cloned from an ear cell of a 3-year-old Afghan hound, as announced by a group of South Korean scientists in August 2005 (see figure 10.32d). Snuppy is short for ***S****eoul* ***N****ational* ***U****niversity pu****ppy***.

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Cloning: the downside

The success rate in initiating development of the egg cell after transfer of the donor nucleus is low. For example, in the case of an artificially cloned calf, known as Second Chance, 189 implantations were made into surrogate cows before a pregnancy was achieved. This case, however, was remarkable because the adult cell that provided the donor nucleus came from a 21-year-old Brahman bull called First Chance. This was an extremely old adult cell to use as the starting point for cloning. Because of testicular disease, First Chance had been castrated so that he was sterile when one of his body cells was successfully cloned.

ODD FACT

At the time of birth of the cloned calf Second Chance, the bull First Chance that provided the donor nucleus from one of his somatic cells was dead.

FIGURE 10.32 A picture gallery of mammalian clones since Dolly: **(a)** Matilda, the first lamb to be cloned in Australia, was born by caesarean section at the Turretfield Research Centre of the South Australian Research and Development Institute (SARDI). She is pictured here with Dr Teija Peura, one of the scientists responsible for the achievement. **(b)** Suzi, one of two genetically identical Holstein calf clones derived from the skin cell of one cow fetus. **(c)** cc, shown on the right at 1 year old, was the world's first cat produced by somatic cell cloning, using a cumulus cell from Rainbow (left). **(d)** Snuppy, the world's first dog produced by somatic cell cloning, is shown with the Afghan dog that supplied the ear cell (left) and his surrogate mother, a Labrador (right).

ODD FACT

One estimate is that the 'ends' (telomeres) of human chromosomes progressively shorten by tens or hundreds of base pairs per year.

ODD FACT

Dolly's stuffed remains are now on display in the Royal Museum in Edinburgh.

The kitten cc, produced by somatic cell cloning, was the only one of 87 embryos implanted into surrogate mothers that survived to term. To get Snuppy, 123 dog embryos were surgically implanted into surrogate females and, of these, only three survived for a significant period, with one dying before birth, one dying soon after birth, and the sole survivor being Snuppy. Dolly was the only live birth from a series of 277 cloned embryos. Clearly, somatic cell cloning is presently far from routine, with fewer than 1 per cent of the cloned embryos surviving beyond birth. Of the clones that survive beyond birth, many have abnormalities that can cause death early in life. One institution reported in 2003 that, for every healthy lamb clone born, about five had abnormalities. Abnormalities reported include impaired immune system function and the 'large offspring syndrome' in which clones have abnormally large organs.

There is evidence that, each time a mammalian cell divides, the specialised 'ends' of their chromosomes lose some DNA base pairs and become shorter. These 'ends', which are known as **telomeres**, do not carry structural genes. Some scientists suggest that the shortening of the chromosome ends is

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associated with ageing. Will ageing be more rapid in a cloned animal that originates from an adult cell that already has shortened chromosome 'ends' than in a normal organism? The death of Dolly in February 2003 suggested that this may be the case. Six-year-old Dolly was put to sleep because of a deteriorating lung disease and arthritis, unusual conditions for a sheep of Dolly's age and one that was housed indoors, since sheep can live for about 12 years. Matilda, the cloned lamb (see figure 10.32a) that was born in March 2000, died less than 3 years later. However, this question remains unanswered.

Attitudes to cloning

Public attitudes to animal cloning are mixed. Some people support the concept because they believe that it will benefit people by providing a source of tissues for transplantation or other products. Other people oppose the concept for various reasons, such as their belief that cloning is interfering with nature.

When people are questioned about the cloning of human beings, there is a very high level of opposition to it. Some governments, including Australia's, have banned experiments directed to producing human clones, and leaders of some religious groups have opposed human cloning. The *Prohibition of Human Cloning Act 2002*, passed by the Australian Parliament in December 2002, bans human cloning. This Act took effect on 16 January 2003 and was amended in 2006.

ODD FACT

Under the *Prohibition of Human Cloning for Reproduction and the Regulation of Human Embryo Research Amendment Act 2006* (Cwlth), the maximum penalty for offences relating to human cloning is 15 years imprisonment.

KEY IDEAS

- Artificial cloning of plants involves subdividing cultured plant tissue.
- Cloning of plants produces organisms that are genetically identical to each other and to the original cultured plant tissue.
- Artificial cloning of mammals is a new technology of asexual reproduction.
- Two types of artificial cloning techniques are embryo splitting and nuclear transfer.
- Embryo splitting involves the artificial separation of embryo cells in vitro.
- Nuclear transfer involves the transfer of a nucleus from an adult somatic cell to an egg cell that has had its own nucleus removed.
- Legislation of the Australian Parliament prohibits human cloning.

QUICK CHECK

10 Identify whether each of the following statements is true or false.
- **a** Cloning mammals involves fusing an intact egg cell with an intact somatic cell.
- **b** The genotype of a cloned mammal is determined by the egg cell.
- **c** An enucleated cell is one that has had its nucleus removed.
- **d** Dolly was produced by a process of embryo splitting.
- **e** Megan and Morag were produced by a process of cloning using nuclear transfer.
- **f** Cloning of mammals uses a different technique from that used in cloning plants.

BIOCHALLENGE

1 Figure 10.33 shows five calves: Lily, Daffodil, Crocus, Forsythia and Rose. These calves are genetically identical and are the same age. These calves were produced through the use of a particular reproductive technology.

FIGURE 10.33 Five genetically identical calves — or more correctly, heifers

a Consider the possible reproductive technology that produced these five calves:
   i Could the five calves be the products of cloning by embryo splitting, where the embryos developed from several fertilised eggs from the mating of the same cow and bull? Give a reason for your decision.
   ii Could the five calves be the products of cloning by nuclear transfer using adult somatic cells of one particular animal? Give a reason for your decision.

b Assume that the calves are indeed the products of cloning by nuclear transfer, was a cow or a bull the source of the adult somatic cells used for cloning? Give a reason for your decision.

c Are surrogate animals required in either or both of the procedures referred to in question 1a and b. Briefly explain.

2 Examine figure 10.34. Flatworms have a remarkable power of regeneration. If cut into several pieces, each piece has the ability to regenerate the missing parts of the body.

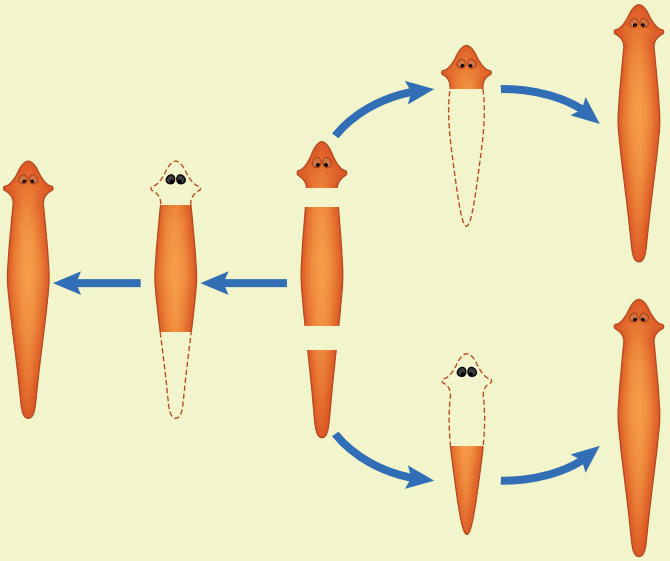

FIGURE 10.34 Regeneration in flatworms

a What cellular process is essential for and underpins this regeneration?

b The degree of regeneration in flatworms is extreme. Other animals can carry out more limited regeneration. Give an example of an animal that can regenerate one part of its body that is lost.

Chapter review

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Key words

adult somatic cells
asexual reproduction
binary fission
budding
bulbs
clone
cuttings
doubling time
embryo splitting
endotoxin
enucleated cell
facultative parthenogenesis
genetic variation
lumbar puncture
meninges
meningitis
meningococcal disease
meningococcal sepsis
meristematic tissue
mitosis
multiple fission
mycelium
obligate parthenogenesis
parthenogenesis
plant tissue culture
plantlets
rhizomes
runners
somatic cell nuclear transfer
sporangium
spore
subculturing
suckers
telomeres
totipotent
tubers
vegetative reproduction

Questions

1 **Making connections** ➜ Use at least eight chapter key words to draw a concept map. You may use other words in drawing your map.

2 **Solving problems** ➜ Refer to figure 10.10, which shows binary fission in the bacterial species *E. coli*.

Assume that the time for binary fission in these bacteria is an average of 20 minutes at 15 °C.

Starting with 10 bacteria, about how many bacteria would be present at the end of two hours of binary fission?

The rate of binary fission doubles (or halves) for each rise (or fall) of 10 degrees in temperature. Assume that, at 25 °C, binary fission becomes twice as fast and is completed in 10 minutes. Assume that, at 5 °C, binary fission is slowed and requires 40 minutes for completion.

a At 25 °C, starting with 10 bacterial cells, how many bacterial cells would be present after 2 hours?
b At 5 °C, starting with 10 bacterial cells, how many bacterial cells would be present after 2 hours?
c By what process do these bacteria reproduce?

3 **Demonstrating understanding and communication** ➜ Give an explanation in biological terms for each of the following observations.

a Cooked meats should be stored in a refrigerator, rather than at room temperature.
b After a bushfire, one of the first plants to re-appear is the austral bracken (*Pteridium esculentum*).
c An amoeba can be considered to be immortal (unless it is eaten by a predator).
d Populations of some species of whiptail lizard are entirely female.
e Some species can reproduce without fertilisation.
f An infection of *Neisseria meningitidis* bacteria in the blood can cause a person to go into septic shock within hours after the first symptoms appear.

4 **Demonstrating knowledge** ➜ Give an example of an organism in which you would expect to find or see the following.

a Sporangia
b Longitudinal binary fission
c Tubers
d A switch from asexual to sexual reproduction

5 **Demonstrating knowledge and understanding** ➜ Figure 10.35 shows part of a lily (*Canna* sp.) pulled from the ground. The dark purple vertical part is a stem that is almost all above the ground, while the remainder of the structure is below ground.

FIGURE 10.35 Part of a lily (*Canna* sp.) pulled from the ground

a What is this below-ground structure?
b List the evidence that you used to make your decision.
c What function does this structure serve?

6 Applying understanding and evaluating alternatives ➜ The occurrence of facultative parthenogenesis in some reptile populations was unexpected, for example, in the komodo dragon.
a What is facultative parthenogenesis?
b How does it differ from obligate parthenogenesis?
c Identify an example of a reptile that is an obligate parthenogen.
d A female komodo dragon in a zoo has not had recent contact with any males. She produces some eggs and a live baby dragon hatches from one of the eggs. One person said that this birth could be explained as due to sperm that was stored in the female's reproductive tract. Another person said that the birth is a case of parthenogenesis. What data would be needed to decide whether or not the baby dragon was a true 'virgin birth'?

7 Demonstrating knowledge and understanding ➜ A means of reproduction used by some plants is the formation of underground bulbs. Bulbs are formed by parent plants during a growing season and, at the end of that time, the parent plants typically die back.

Examine figure 10.36 that shows the typical structure of a bulb. The apical bud will give rise to leaves and a flower; the lateral buds will produce shoots.

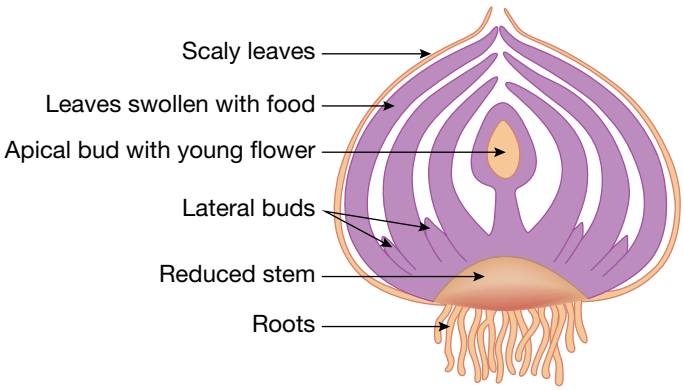

FIGURE 10.36 Typical structure of a bulb

a What parts of the new plant are present in a bulb?
b What mode of reproduction does bulb formation exemplify?
c What role do the leaves within a bulb serve?
d What cellular process will transform the embryonic plant within the bulb into a mature plant?
e Give the name of a bulb that might be part of a meal — raw or cooked.

8 Discussion question ➜ Cloning of mammals using the technique of somatic cell nuclear transfer has a very low success rate. One study has identified the success rate as between 0.1 and 3.0 per cent.
a Consider the various steps involved in this technique, and identify at what points the technique could fail.
b Use the success rate given above to identify the maximum number of successful live births expected if 1000 nuclear transfers were carried out. What is the minimum number?
c What were the success rates for the following cloned mammals?
i Snuppy, the dog
ii Dolly, the sheep
iii Second Chance, the bull
iv cc, the cat
d Some people see somatic cell nuclear transfer as a means of contributing to the conservation of endangered mammalian species. Their view is that tissues in cryogenic storage from long-dead mammals of an endangered species may hold valuable genes. Using these cells to clone an endangered mammal might enable the genes to be brought back into the current population. Other persons reject this concept and say that preserving endangered species requires preserving them in their habitats. Discuss these alternatives with your classmates.

CHAPTER

11 Sexual reproduction

FIGURE 11.1 Sexual reproduction is a prominent feature of the living world. These three puppies from a litter of Siberian huskies show the classical outcome of sexual reproduction — the production of offspring that differ from each other and from their two parents. Note the different coloured face marking — black, chocolate and fawn. In this chapter, we will explore aspects of sexual reproduction, including the process of meiosis that is responsible for creating the genetic variation in offspring produced through sexual reproduction by the same parents.

KEY KNOWLEDGE

The contents of this chapter are designed to enable students to:

- recognise that genetic variation exists in offspring resulting from sexual reproduction
- gain knowledge of the process of meiosis that generates haploid gametes
- identify how meiosis produces the genetic variability in offspring of the same parents.

Changes in family size

A ship called *Bee* arrived in the port of Geelong on 18 April 1857 after a 4-month journey from England. Among the 459 passengers, mainly assisted migrants, was a young married couple, James and Sarah Minter.

Earlier in England, in May 1852, James, then 22, and Sarah, then 17, married. At first they lived in the south Yorkshire town of Barnsley where James worked as a handloom linen weaver. Their first child was born in June 1853 but died from pneumonia about a year later. Within a month of the death of their first baby, Sarah was again pregnant. Their second child was born in May 1855 but died 9 months later in March 1856. Five months later, Sarah was again pregnant and during that pregnancy, she and her husband emigrated to Australia.

Soon after arriving on the *Bee* at the port of Geelong, Sarah gave birth to her third child in May 1857. The couple then moved to Ballarat where their fourth child was born in April 1859. Their fifth and sixth children were born near Maldon in April 1861 and in April 1863, but the sixth baby died aged 10 months. The family — the couple and three surviving children — then moved to Sandhurst (now Bendigo) where they lived at first in a tent on land off Sheepwash Road and later in a house at the same location. Their next five children (seventh to eleventh) were born in Sandhurst with birth dates as follows: January 1865, May 1867, April 1869, April 1871 and February 1873. Apart from the eleventh baby, which was stillborn, these babies survived beyond infancy. James and Sarah's twelfth baby, Emma, was born on 24 April 1874 at Sandhurst. Two days after the birth of this baby, Sarah, aged 40, died from childbirth (puerperal) fever. She was buried at White Hills Cemetery in Bendigo on 26 April 1874. Seven days later, baby Emma died and was buried in the same plot.

In terms of family size, intervals between births and infant mortality, this story of settlers living in country regions of Australia at that time is not unusual. An example of the change in average family size is shown in figure 11.2 with formal photographs for (a) a nineteenth-century family and (b) a twenty-first-century family.

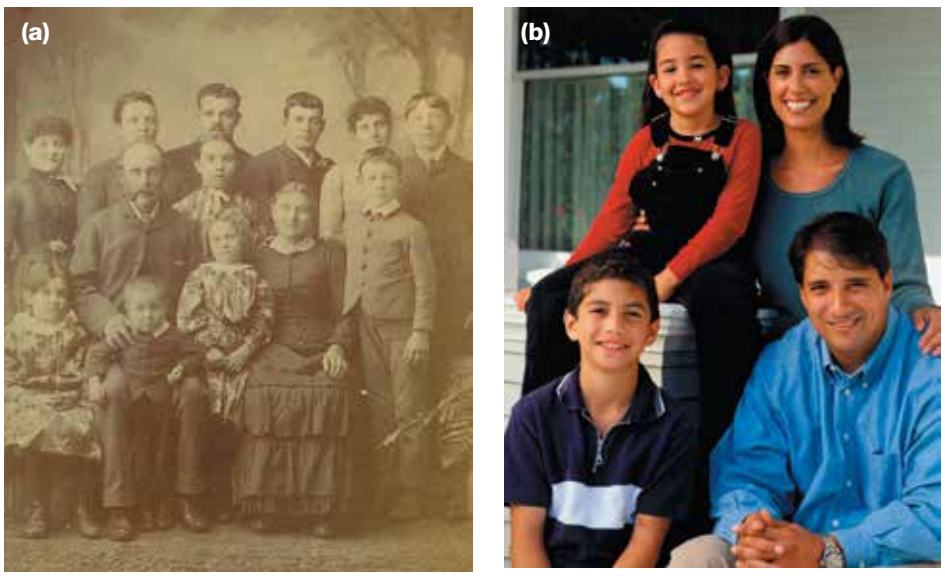

FIGURE 11.2 Changing average family sizes. Formal family portraits taken **(a)** in the mid to late 1880s and **(b)** around 2005. The late nineteenth-century portrait shows two parents and their 11 surviving children. Contrast this with the twenty-first-century portrait that shows two parents with their two children.

The interval between successive births for Sarah Minter was usually about 24 months. The shortest interval was 14 months between the stillbirth (eleventh) and the twelfth baby, Emma. This occurred because breastfeeding did not take place after the stillbirth. Breastfeeding prevents a woman from becoming pregnant by changing her hormone production to hormones concerned with

ODD FACT

One study has shown that if women breastfeed their babies five times per day for a total of at least 65 minutes, their ovarian activity is suppressed so that they are infertile.

the production and release of milk and suppressing those hormones concerned with ovulation. If no breastfeeding occurs, or after a breastfed baby is weaned, hormone production changes to that for a normal ovarian cycle and fertility is restored.

In the period from 1860 into the twentieth century and then into the twenty-first century, a decline in the average family size has occurred in Australia. Figure 11.3 shows crude birth rates, expressed as the annual number of births per 1000 population, for that period. These birth rates signal that family sizes were much larger in 1860 than in 2000.

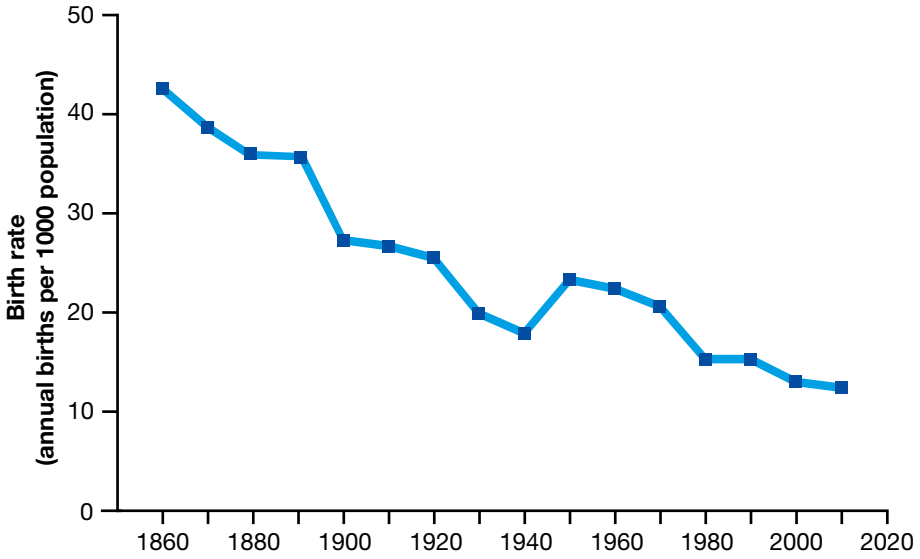

FIGURE 11.3 Trends in the crude birth rate (annual births per 1000 population) in Australia for given years in the period 1860–2010 (using data from ABS Cat. 3105.65.001, table 42). What factors have contributed to the overall decline in birth rates?

ODD FACT

In 2011 in Australia, the median age for women at their first marriage was 28 years, while that for men was 29.7 years. In 2010, the median age of women giving birth to their first baby was 28 years.

Likewise, the decline in average household size from 1911 to 2011 also signals a reduction in average family size. In 1911, the average household size was 4.5 persons; in 1961, the average household size had declined to 3.6, and in 2011 it was 2.6. (*Source:* www.aifs.gov.au/institute/info/charts/households/index.html#havsize.)

Factors contributing to the decrease in birth rate include the approval in 1961 of the oral contraceptive pill for use in Australia, and the later average age of marrying and starting families. The oral contraceptive pill was not the first contraceptive. The diaphragm was introduced into Australia in the 1920s. Earlier contraceptive practices identified in the 1904 report of the *Royal Commission into the Decline in Birth Rate in New South Wales* were the use of douches, sponges, condoms, pessaries and withdrawal.

Human reproduction, as for that of familiar animals and plants around us, involves the genetic contribution of two parents to each of their offspring. This is the process of sexual reproduction.

ODD FACT

In Australia in the mid-eighteenth century, the infant mortality rate was 125 deaths per 1000 births. In 2014, the rate was 4.4 deaths per 1000 live births.

Sexual reproduction

One of the characteristics of all living organisms is their ability to reproduce according to genetic instructions within the organisms themselves. In chapter 10, we explored the world of asexual reproduction, as seen in prokaryotes and some eukaryotes. Now, let us explore aspects of the world of sexual reproduction, with a focus on animals, in particular mammals.

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Unit 2
AOS 1
Topic 3
Concept 1

Gamete production
Concept summary and practice questions

Two parental contributions

Sexual reproduction involves genetic contributions, in the form of **gametes**, from two parental sources to their offspring. In animals, gametes are the **eggs** produced by female parents and the **sperm** produced by male parents. Gametes are produced in specialised reproductive organs, known as **gonads**. In females, the gonads are the **ovaries** (see figure 11.4) and in males, the gonads are the **testes** (see figure 11.5). The cells in the gonads that give rise to the gametes are termed **germ cells**.

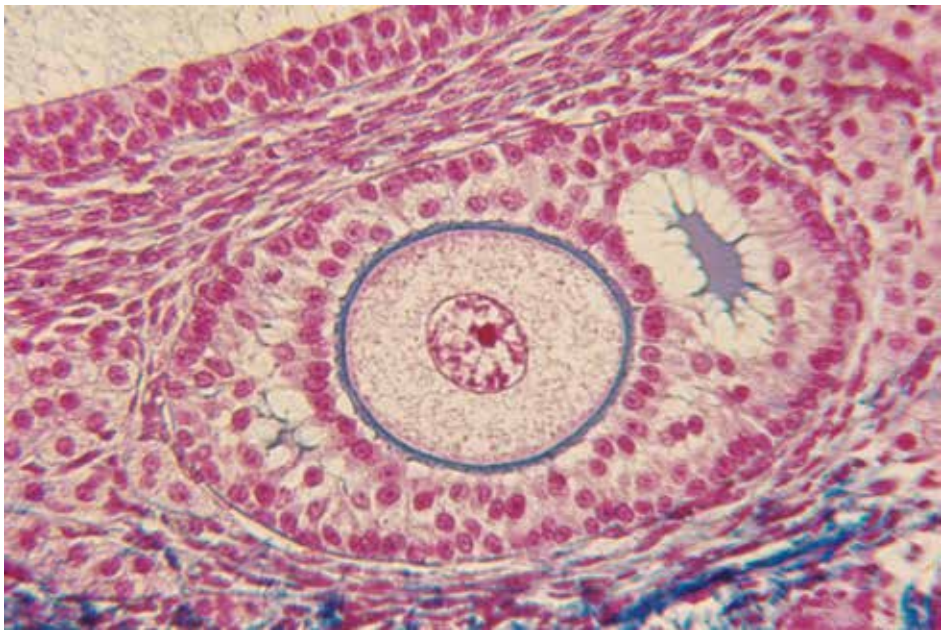

FIGURE 11.4 Photomicrograph of a section through a human ovary, showing a prominent egg cell (oocyte) enclosed within a follicle (with a blue border). The empty structure to the right of the egg-containing follicle is a follicle that has previously discharged its egg. It now forms a structure known as a corpus luteum (*corpus* = body; *luteum* = yellow).

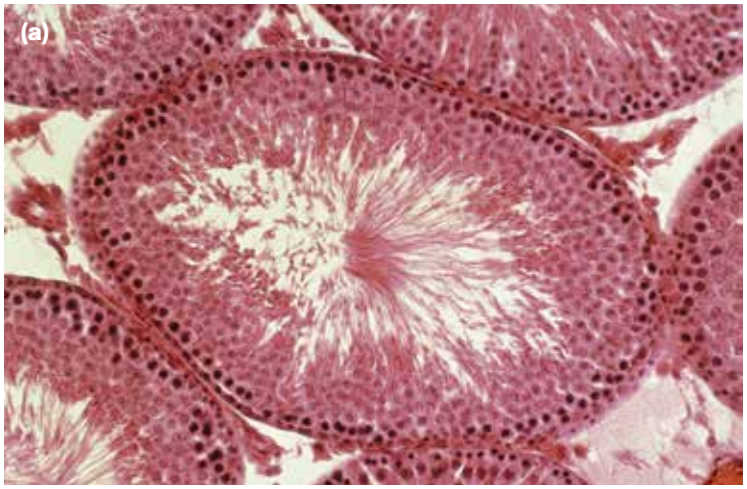

FIGURE 11.5 **(a)** Photomicrograph of a section through a mammalian testis. The mature sperm are located most centrally inside the tubules of the testis. **(b)** Diagram of a longitudinal section through a mammalian testis showing the folded tubules in which sperm are formed **(c)** Diagram of a cross-section through a tubule showing the primary spermatocytes that undergo reduction division (meiosis) to form sperm

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Interactivity
The reproductive system
int-3032

Typically, in people and in familiar animals, such as domestic pets and farm animals, two different sexes — females and males — produce the different gametes, with males producing sperm and females producing eggs. However, this is not the case in many other kinds of animal (see pp. 454–6) and it is rarely the case in flowering plants.

Just which sex are you?

ODD FACT

In general, hermaphrodites cross-fertilise. However, isolated virgin individual organisms of some species can self-fertilise.

In some animal species, a single organism has both egg-producing and sperm-producing organs. These organisms are termed **hermaphrodites** (see figure 11.6) and include the garden snail (*Helix aspersa*) (see figure 11.7) and the common earthworm (*Lumbricus terrestris*).

The common earthworm has about 100 body segments, with ovaries in segment 13 and testes in segments 10 and 11 (counting from the head). Sperm released through pores in segment 15 are exchanged between a mating pair of earthworms. They store the sperm in sacs in segments 9 and 10 prior to using them to fertilise their eggs, which are then released through pores in segment 14.

FIGURE 11.6 Some animals can change their sex during their lifetime. They are called sequential hermaphrodites.

When both sperm-producing and egg-producing organs are present in one organism, such as occurs in snails and earthworms, this is called **simultaneous (synchronous) hermaphrodism**. In contrast, some fish species found around coral reefs change sex and are known as **sequential hermaphrodites**.These fish start life as one sex and can transform to the other sex under certain conditions. Examples of sequential hermaphrodite organisms include various species of anemonefish (*Amphiprion* spp.) that live in groups of several males with one dominant female. If the dominant female fish dies or is removed, one large male fish then changes to become a functioning female.

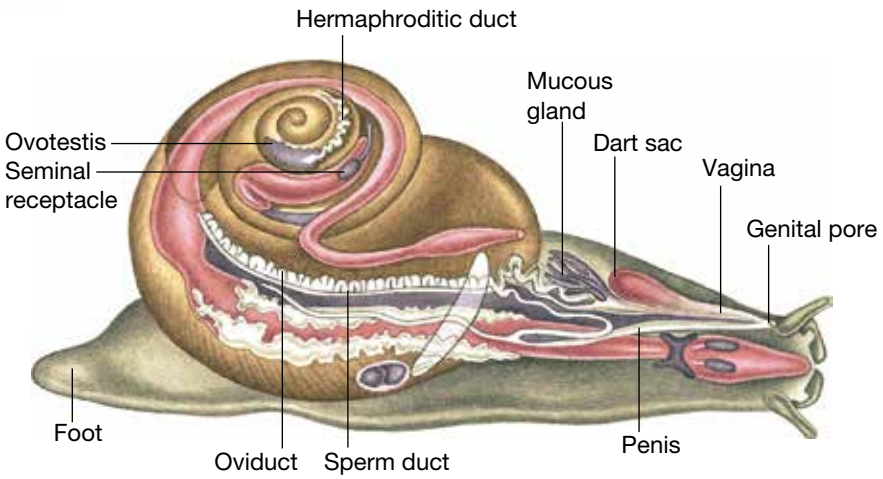

FIGURE 11.7 Internal anatomy of the garden snail. Note the presence of an organ labelled 'ovotestis' that produces both eggs and sperm.

Chromosome number stays constant

Chromosomes are the carriers of genetic information. Each eukaryotic species has a characteristic number of chromosomes in its body or **somatic cells**. This number is called the **diploid number** and is denoted by the symbol $2n$. For the human species, the number of chromosomes in somatic cells is 46, so, for a person, we can write: $2n = 46$. Each other species has its own characteristic diploid number. The chromosomes in a diploid cell exist as matching or **homologous** pairs. So, in a diploid cell ($2n = 12$), there are 6 matching or homologous pairs of chromosomes.

Chromosomes are examined in more detail in chapter 14.

studyon
Unit 2
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Concept summary and practice questions

In sexual reproduction, each parent makes an essentially equal genetic contribution to each of its offspring in the form of a gamete, that is, an egg and a sperm. If, in the case of people, these gametes each contained 46 chromosomes, this would mean that an offspring would have a total of 46 + 46 = 92 chromosomes. Over successive generations, this chromosome number would increase further. However, this doubling of the number of chromosomes does *not* occur across generations. **Each generation of human beings has a constant 46 chromosomes in their somatic cells**. In consequence, this means that each normal human gamete must have just 23 chromosomes, so that an offspring receives 23 + 23 = 46 chromosomes in total from its parents (see figure 11.8).

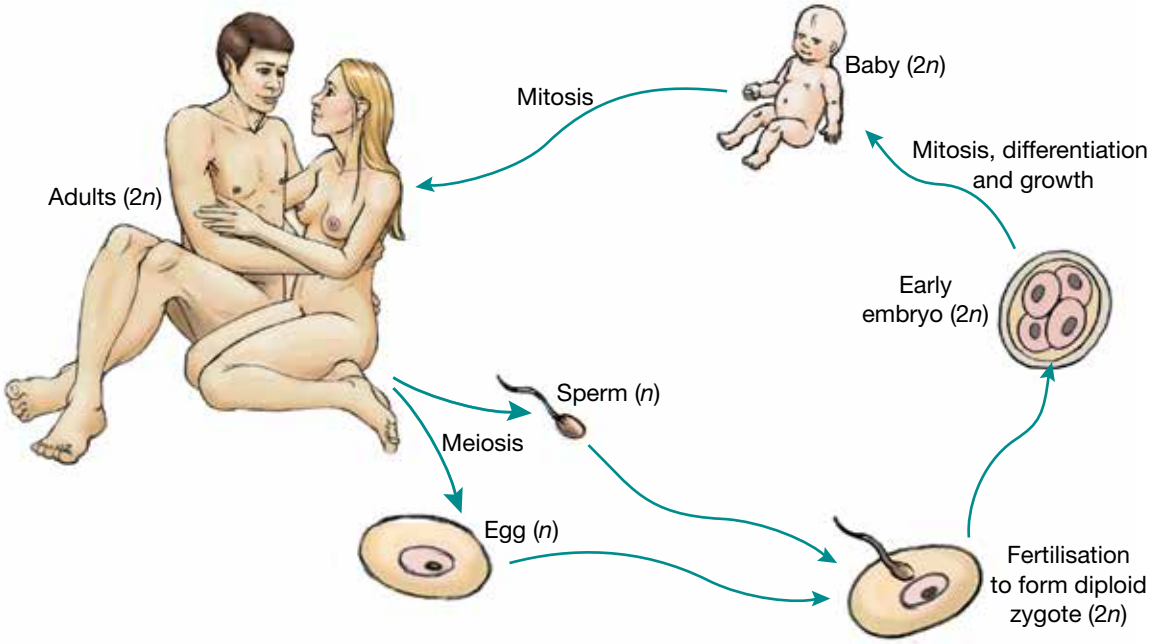

FIGURE 11.8 The life cycle of the human species. In sexual reproduction, offspring result from the fusion of two parental contributions (one egg and one sperm). Note, that apart from the gametes that are haploid (n = 23), the life cycle is otherwise diploid ($2n$ = 46).

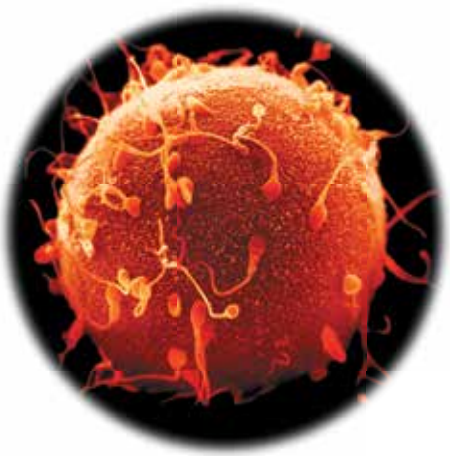

FIGURE 11.9 An egg cell with sperm cells adhering. Only one sperm will succeed in fertilising the egg. Both egg and sperm carry a haploid set of chromosomes.

So, while all normal somatic cells of people have 46 chromosomes, their gametes (either eggs or sperm) have just 23 chromosomes. This is called the **haploid number** and is denoted by the symbol, n. So, for people, n = 23. It is reasonable to conclude, then, that the process of gamete formation in a person involves a **reduction division** in which a starting cell with 46 chromosomes gives rise to gametes, either egg or sperm, that have only 23 chromosomes. This reduction division is a process called **meiosis**. The **fertilisation** of an egg by a sperm restores the diploid number (see figure 11.9).

We will see in the following section that meiosis is a non-conservative division in which the chromosome number is halved and, as we will see later, the genetic information on the chromosomes is juggled.

A key feature of sexual reproduction is that offspring produced through this mode of reproduction differ genetically from each other and also differ from their parents. In contrast, as we saw in chapter 10, asexual reproduction involves a cellular process called mitosis that is conservative, so it faithfully reproduces an exact copy of the genetic information of the single parent cell in the two daughter cells.

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Interactivity
Mitosis and meiosis
int-3028

KEY IDEAS

- In animals, offspring resulting from sexual reproduction receive two genetic contributions, one via an egg and the other via a sperm.
- Somatic (body) cells possess a diploid number of chromosomes.
- Mature gametes contain the haploid number of chromosomes.
- Eggs and sperm are gametes that are produced in the ovary and testis respectively.
- The chromosome number is restored to diploid when an egg is fertilised by a sperm.
- Meiosis is the process that produces haploid gametes from diploid germ cells.

QUICK CHECK

1 What is the diploid number of the human species?
2 Identify whether each of the following statements is true or false.
  a The diploid number refers to the number of chromosomes in somatic cells.
  b A hermaphrodite has both egg-producing and sperm-producing organs.
  c Meiosis is a conservative process of nuclear division.
  d Offspring produced by sexual reproduction are genetically different from each other.
3 What is the name of each of the following?
  a A male gamete
  b The female reproductive organ
  c The product of fusion of an egg and a sperm

Meiosis: the halving and mixing machine

Meiosis is the process that produces gametes with the haploid number of chromosomes, that is, half the number present in somatic cells. After fertilisation, when the nucleus of a sperm fuses with that of an egg, the diploid number of chromosomes is restored (see figure 11.10).

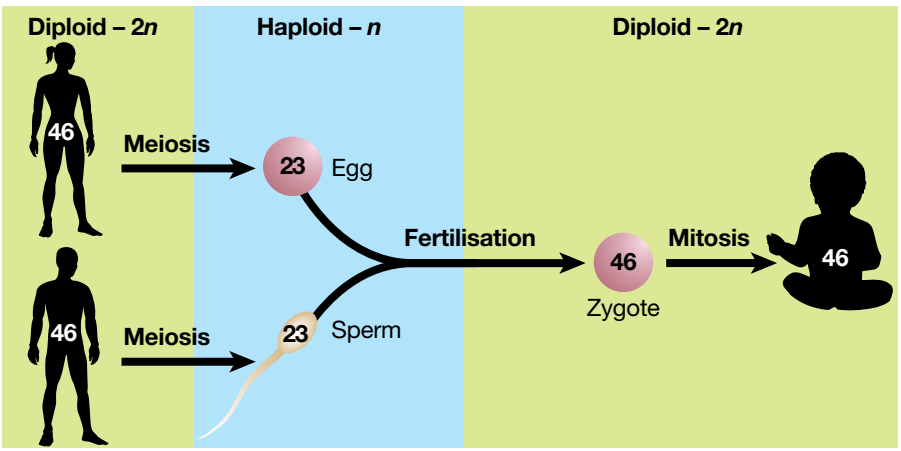


FIGURE 11.10 Diploid animals produce haploid gametes that fuse at fertilisation to produce a diploid zygote.

First let us consider meiosis from the point of view of input and output only. What are some of the observations that have been made?

The *first observation* is that, if a cell containing $2n$ chromosomes undergoes meiosis, four cells are produced each containing n, or half the number of chromosomes present in the original cell (see figure 11.11).

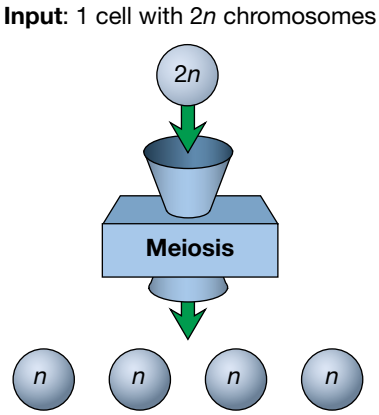


FIGURE 11.11 Meiosis halves the chromosome number. The four cells produced indicate that two cell divisions have occurred.

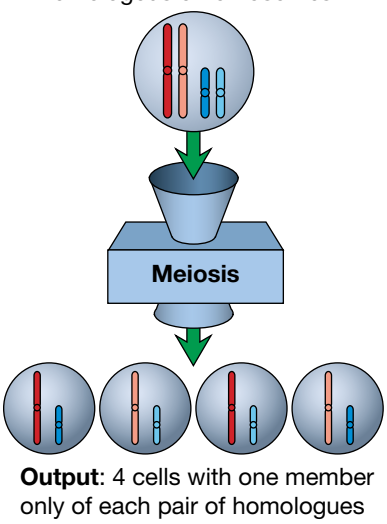


FIGURE 11.12 The halving is precise — one member of each pair of chromosomes appears in the cell products.

This halving applies for all organisms in which meiosis occurs. Somatic cells of the brushtail possum (*Trichosurus vulpecula*) contain 20 chromosomes. Since meiosis results in halving the number of chromosomes, the gametes of this animal would contain 10 chromosomes.

The diploid number of *Eucalyptus* species is 22. Gametes produced by a *Eucalyptus* tree would contain half this number: 11 chromosomes.

The diploid number of the human species is 46. So, human gametes each contain 23 chromosomes.

The *second observation* is that each gamete produced by meiosis contains only one member of each pair of chromosomes (see figure 11.12).

From this observation we can conclude that the halving of the number of chromosomes is very precise. The members of each pair of chromosomes separate or disjoin into different gametes. In addition, the separation of the members of each pair of homologous (matching) chromosomes is independent of the separation of the members of another pair. This means that it is equally likely that, in another gamete, the long red chromosome would be present with the short blue chromosome.

The *third observation* is that during meiosis, exchanges of segments between matching chromosomes occur. This results in the creation of some new genetic combinations that differ from those in the starting cell (see figure 11.13). This process of exchange between matching chromosomes is called **crossing over**.

In summary, the key outcomes of meiosis are as follows:

- Meiosis halves the chromosome number, reducing it from diploid to haploid; as a result, each gamete contains just one member of each matching pair of chromosomes.
- Meiosis produces random combinations of the members of the different matching chromosome pairs. As a result, in a large number of gametes, any member of one matching pair of chromosomes can be found with any member of another matching pair.
- Meiosis involves exchanges of part of one chromosome with the corresponding part of its matching partner, a process termed crossing over. As a result, meiosis produces gametes containing chromosomes with new genetic combinations that differ from each other and from those in the precursor cell.

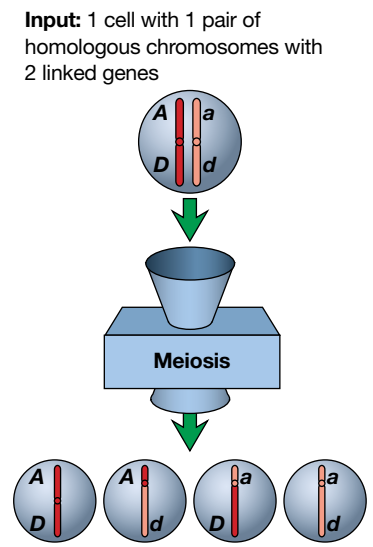
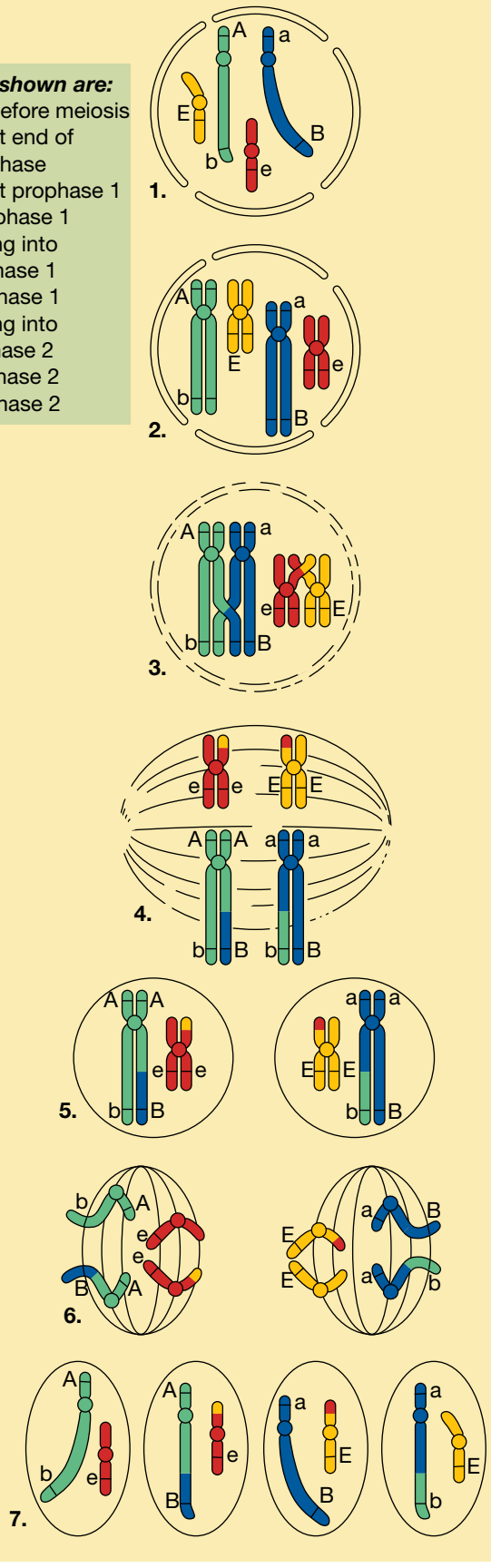


FIGURE 11.13 During meiosis, exchanges of segments between matching chromosomes can occur in a process known as crossing over.

Figure 11.14 shows various stages of meiosis, how this process halves the number of chromosomes and how crossing over changes the particular genetic information that the chromosomes carry. Cell 1 in this figure shows the diploid cell that will undergo meiosis. This cell will first pass through an **interphase** stage during which the DNA of its chromosomes is replicated and checkpoints are passed. Cell 3 shows a cell during **prophase** 1 of meiosis. Its chromosomes are visibly double stranded, with each chromosome consisting of two sister chromatids joined at their centromeres. During this stage, the matching chromosomes pair (**synapse**) and crossing over occurs, with a mutual exchange of segments between matching chromosomes. By the end of prophase 1, the nuclear envelope has broken down.

Stages shown are:
1 Cell before meiosis
2 Cell at end of interphase
3 Cell at prophase 1
4 Metaphase 1 moving into anaphase 1
5 Telophase 1 moving into prophase 2
6 Anaphase 2
7 Telophase 2



1. Starting point: cell with two pairs of single-stranded homologous chromosomes ($2n = 4$).

2. By the end of interphase, the chromosomes have replicated and now appear double-stranded.

3. The homologous chromosomes align and pair closely or synapse. One or more exchanges or crossovers occur between a matching segment of one chromosome with a strand in its paired homologue. Crossing over produces new combinations of genetic instructions. The chromosomes then line up across the equator of the cell. Different arrangements are possible.

4. The homologous chromosomes separate (disjoin) from each other when their centromeres are pulled to opposite poles. The disjunction of each homologous pair is independent of any others. (For example, if the 'red' chromosome goes to the left-hand side, this in no way influences which of the longer chromosomes will go to the right-hand side.)

5. The resulting two products each have two double-stranded chromosomes, one long and one short.

6. The strands of each replicated chromosome then disjoin so that the single-stranded chromosomes move in opposite directions. The separation of the single-stranded copies of each chromosome is independent of that of other chromosomes.

7. End point: typically, four cells result from meiosis with each end product containing the haploid number of chromosomes. Having started from one cell ($2n = 4$), the process has produced four cells, each with $n = 2$. Note the variation between end products resulting from crossing over and independent disjunction of homologous pairs.

FIGURE 11.14 Stages in the process of meiosis, from the starting diploid cell ($2n = 4$) to the final haploid gametes ($n = 2$)

Just as in mitosis, the microtubules of the spindle are responsible for the arrangement and the movement of the chromosomes during the **metaphase** and **anaphase** stages of meiosis.

Note that two cells present at **telophase** 1 of meiosis are not genetically identical to each other. The two events in meiosis that create the genetic diversity of gametes are:

- crossing over, that is the mutual exchange of chromosomal segments between members of homologous pairs of chromosomes during prophase 1 of meiosis
- independent assortment of nonmatching (**nonhomologous**) chromosomes at anaphase.

The division of a diploid germ cell by meiosis typically produces four cells that are haploid and are genetically varied. In male mammals, the products of meiosis of one diploid germ cell in the testis are four functional sperm. In female mammals, however, the meiotic division of one diploid germ cell in the ovary produces just one functional egg. The other products are small polar bodies (see figure 11.15).

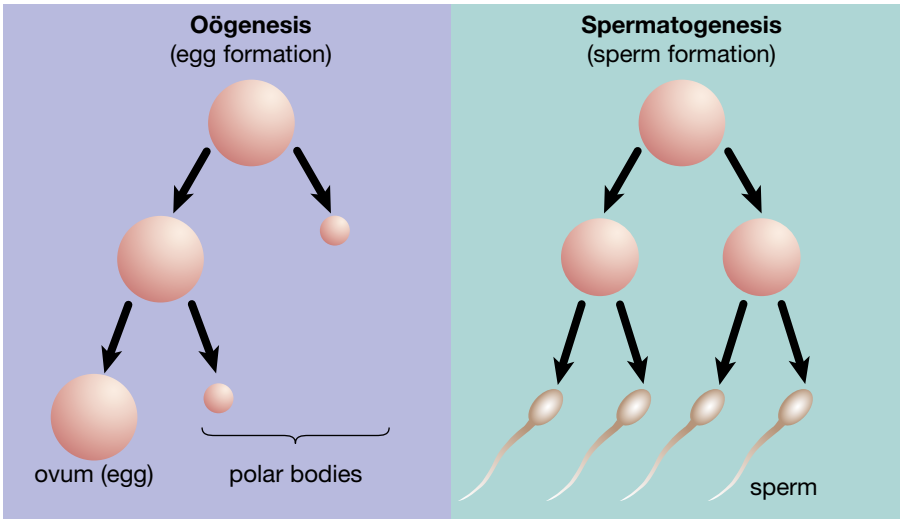


FIGURE 11.15 The formation of eggs and sperm by meiosis. Note that only one egg is formed but four sperm are produced from each starting cell.

Meiosis: source of variability in offspring

The biological significance of meiosis is that it produces genetic variability among the offspring produced by sexual reproduction involving gametes from two parents. No two offspring are the same!

A litter of pups may consist of an odd mixture of colours and patterns (see figure 11.16 and refer to figure 11.1). A litter of piglets shows the variation that is generated by meiosis (see figure 11.17). Siblings (brothers and sisters) in a human family can show differences in hair colour, eye colour, blood types and other traits. Inherited differences between offspring can be traced back to the process of meiosis and to the genetic variation that it produces in gametes.

FIGURE 11.16 Pups from two parents show variation in colour and pattern.

FIGURE 11.17 This litter of piglets shows genetic variation in coat colour that is the result of meiosis. These piglets differ genetically from each other and from their two parents because they are products of sexual reproduction.

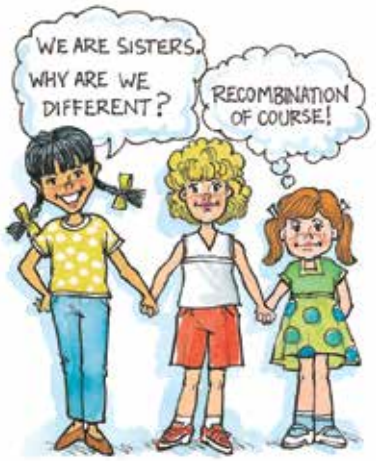


FIGURE 11.18

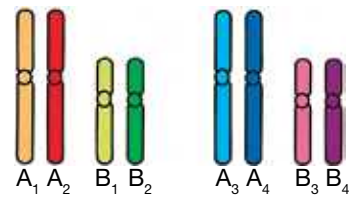


FIGURE 11.19 Matching chromosomes in an organism. The matching pairs are colour coded.

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Unit 2 AOS 1 Topic 3 Concept 3

Meiosis II
Concept summary and practice questions

Table 11.1 shows a brief summary of some similarities and differences between the processes of mitosis and meiosis in animals.

TABLE 11.1 Similarities and differences between mitosis and meiosis in animals

Feature	Meiosis	Mitosis
location	occurs only in germ cells of either ovary or testis	occurs in body cells
function	production of gametes, eggs and sperm	growth, by an increase in cell number, and repair
DNA replication in interphase	yes	yes
number of divisions	two	one
pairing of matching chromosomes (synapsis)	yes	no
crossing over occurs	yes	no
end result	four haploid gametes, none being identical to each other	two daughter cells, identical to each other and to the single parent cell

Recombination produces variation

Gametes carry unique genetic combinations because of:

1. crossing over between homologous (matching) chromosomes
2. independent disjoining (separation) of nonmatching chromosomes during meiosis.

This re-assortment of genetic material from both crossing over and disjoining that produces new genetic combinations is known as **recombination** and is a major cause of variation in offspring of the same parents (see figure 11.18).

We can get some idea of the variation produced by sexual reproduction if we consider organisms with just two pairs of chromosomes ($2n = 4$) (see figure 11.19). Ignoring crossing over, the female parent can produce gametes with four different combinations of chromosomes: A_1B_1 and A_1B_2 and A_2B_1 and A_2B_2. Likewise, the male parent can produce four combinations: A_3B_3, A_3B_4, A_4B_3 and A_3B_3. Consequently, the chance that two offspring receive the same chromosomal combinations from their two parents is $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$. The probability that two offspring receive different chromosomal combinations from their parents is $\frac{15}{16}$.

Table 11.2 shows how the variation in sexually reproducing species increases with increasing numbers of chromosomes, even without the added impact of crossing over. Notice that as the number of chromosomes increases the chance that two offspring will receive the same complement of chromosomes from their parents becomes infinitesimal. For organisms with a diploid number of 20 ($2n = 20$) that chance decreases to just one in more than one million. Given that the diploid number in the human species is 46, the chance that offspring from the same parent will receive the same chromosomes from their parents is less than one in about 70 million. So, unless you have an identical twin, the process of meiosis has made you a genetically unique individual.

If we were to take crossing over into consideration, the chance of two offspring inheriting the same chromosomes from their parents becomes impossibly small even with a small number of chromosomes. Figure 11.20 shows how crossing over further recombines the homologous chromosomes transmitted by the parents. The chromosomes at the left-hand side show the two chromosomes as passed on by a person's female parent and male parent. Note that crossing over recombines the homologous chromosomes so that the output cells or gametes will carry a different combination of genetic information from the input germ cell.

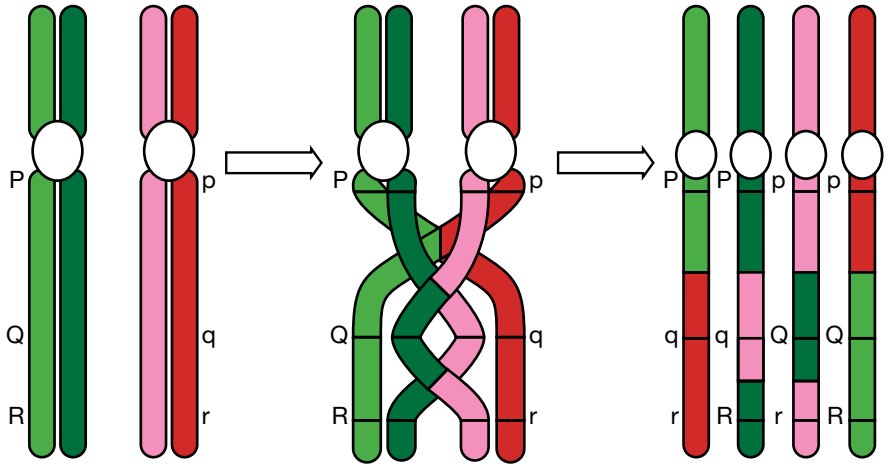

FIGURE 11.20 Diagram showing one pair of homologous replicated chromosomes (left) at the interphase of meiosis. Note the genetic information that they carry. On the right it can be seen how this genetic information is recombined as a result of the exchange of segments when crossing over occurs during prophase 1 of meiosis.

The process of meiosis also generates a similar genetic diversity in all other eukaryotic organisms that reproduce sexually. Meiosis is the major contributor to genetic biodiversity in populations on planet Earth.

TABLE 11.2 Probabilities of two offspring receiving identical or dissimilar chromosomal combinations from parents. What happens as 2*n* increases? (If crossing over is included, the chances of identical combinations are much, much lower.)

Diploid number of chromosomes	Chance of receiving identical chromosomal combinations	Chance of receiving different chromosomal combinations
$2n = 4$	1/16	15/16
6	1/64	63/64
8	1/256	255/256
10	1/1024	1023/1024

study on
Unit 2
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Nondisjunction in meiosis
Concept summary and practice questions

When meiosis goes wrong

Occasionally, a pair of chromosomes fails to disjoin or separate at anaphase so that either two copies of a chromosome, rather than the usual one, are present in a gamete or a copy of one chromosome is missing. This event is termed **nondisjunction**, and it is an unpredictable error. Nondisjunction can occur at either step 4 or 6 of meiosis (refer to figure 11.14). This issue will be further discussed in chapter 14.

Advantages and disadvantages of sexual reproduction

The advantage of sexual reproduction comes from the genetic diversity that it creates in offspring. In contrast to a population generated by asexual reproduction that is composed of genetically identical organisms, a population of organisms produced by sexual reproduction contains a remarkable level of genetic diversity. The presence of this variation within its gene pool means that such a population is better equipped to survive in changing, unstable environmental conditions, to cope with an outbreak of a new viral or bacterial disease, or to survive a natural disaster.

Disadvantages of sexual reproduction (relative to asexual reproduction) include the commitment of energy required to find, attract and secure a mate — a process that for some species may involve elaborate courtship displays, or contests between males for mating rights. However, the sexual mode of reproduction dominates the world of eukaryotic organisms, indicating that its advantages outweigh its combined disadvantages. In the next section, we will explore some of these energy costs of sexual reproduction.

study on
Unit 2
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Topic 3
Concept 5
Biological advantages of sexual reproduction
Concept summary and practice questions

KEY IDEAS

- Meiosis is the process that produces haploid gametes from a diploid germ cell.
- Genetic variation in gametes results from crossing over and from independent assortment of nonmatching chromosomes.
- Crossing over and independent assortment contribute to the recombination of genetic information in gametes.
- The major advantage of sexual reproduction arises from the genetic diversity that it produces in populations of sexually reproducing organisms.
- Nondisjunction errors can occur during meiosis.
- Apart from persons with an identical twin, every human individual is genetically unique.

QUICK CHECK

4 Identify whether each of the following statements is true or false.
- **a** Meiosis in one organism would be expected to generate four different kinds of gamete.
- **b** Crossing over is a major contributor to the recombination of genetic information in gametes.
- **c** The major advantage of sexual reproduction is the genetic diversity that it creates.
- **d** DNA replication does not occur in meiosis.
- **e** In meiosis, independent assortment of nonmatching (nonhomologous) chromosomes occurs twice.

5 The mating of two animals with a diploid number of $2n = 20$ produces a litter of 10 offspring. Is it reasonable to assume that at least two of these offspring will be genetically identical? Briefly explain.

Getting gametes together

ODD FACT

Tapeworms that live in the gut of an animal are hermaphrodites that self-fertilise.

In sexual reproduction, two parental contributions (egg and sperm/pollen) fuse to produce a zygote that then develops into an animal or a plant. Even in the case of hermaphrodite animals, the gametes typically come from two separate animals, rather than self-fertilisation occurring.

Some animals release their gametes into the external environment so that fertilisation occurs outside the body of females. This situation is termed **external fertilisation**. This has the energy cost of producing large numbers of gametes in order to increase the chance of fertilisation.

In other species of animal, males deliver sperm directly into the reproductive tract of females so that fertilisation of eggs occurs inside the body of females. This situation is termed **internal fertilisation**. This process has the energy cost of finding, attracting and securing a female mate.

ODD FACT

Mass release of gametes by coral polyps (or spawning) on the Great Barrier Reef occurs every year after the full moon in October and November. For coral polyps on the Ningaloo Reef off the Western Australian coast, this mass spawning occurs after the full moon in March.

External fertilisation in animals

When animals use external fertilisation, they produce very large numbers of gametes. These large numbers increase the chance of fertilisation but also mean much gamete wastage. Aquatic species that live in large bodies of water and depend on external fertilisation produce very large numbers of gametes. Oysters, for example, each produce about 500 million eggs in a single season.

Because sperm need a watery environment to swim to an egg, external fertilisation is limited to animals that either live in aquatic environments or reproduce in a watery environment. External fertilisation occurs in aquatic invertebrates such as coral polyps, bony fish and amphibians (frogs and toads).

External fertilisation can be a chancy process. Some species that use external fertilisation have developed strategies to increase the chance that eggs and sperm will meet and that fertilisation will occur.

All together now

Figure 11.21a shows the release of eggs by a colony of coral polyps, the animals that build coral reefs. All the polyps in one region release their eggs and sperm into the sea in a synchronised manner, creating a 'soup' of gametes (see figure 11.21b). The high concentration of gametes during spawning increases the likelihood of eggs and sperm colliding and fertilisation occurring.

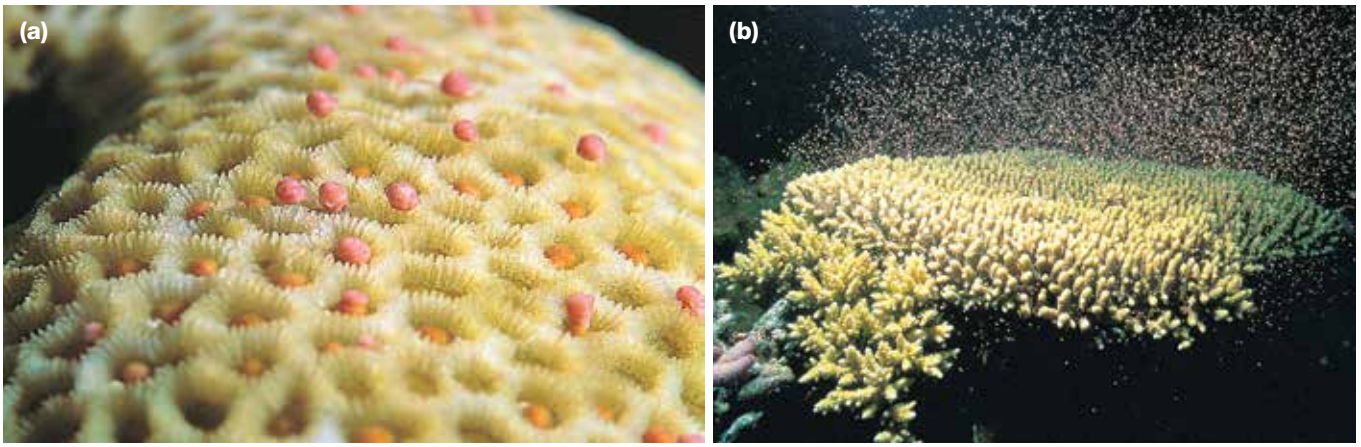

FIGURE 11.21 **(a)** Close-up of the release of gametes by a group of colonial animals known as coral polyps **(b)** Mass spawning of eggs and sperm bundles by coral polyps occurs at the same time (synchronously) each year. What benefit results from this synchrony?

Just checking you out

Fish depend on external fertilisation. If a female fish releases her eggs independently of the release of sperm by a male fish of the same species, then the chance of fertilisation of her eggs is extremely low or even nil.

Behaviours such as courtships before spawning can lead to an improved chance of fertilisation. Through a courtship display, a female can recognise that a male is a member of her species and, if she is ready to release her eggs, this occurs in close proximity to a male. In turn, he will release sperm nearby so that the likelihood of fertilisation is increased. Again, courtship has an energy cost.

ODD FACT

In one Australian frog species, fertilised eggs are swallowed by females and develop in their stomachs. They are regurgitated later as tiny froglets. In another Australian frog species, after fertilisation the eggs are transferred into moist pouches on the hips of the male of the species where embryonic development occurs.

Hang on there

Frogs and toads have external fertilisation. The chance of fertilisation is increased by a behavioural adaptation of males. When a female frog is ready to lay eggs she goes into a nearby pond or pool. A male tightly clasps her and remains on her back until she releases her eggs (see figure 11.22). As the female releases her eggs, the male is stimulated to release sperm over the eggs, fertilising them. The fertilised eggs then undergo embryonic development and give rise to larvae, known as tadpoles, that later metamorphose to frogs.

FIGURE 11.22 Ornate burrowing frogs (*Limnodynastes ornatus*). The male is clasping the female tightly and when the female releases her eggs into the water, the male releases sperm over the eggs. The eggs are suspended on a raft of bubbles.

Internal fertilisation in animals

The watery environment in which aquatic animals live enables external fertilisation because it provides an environment in which eggs are protected from drying out and in which gametes can move to meet. However, **with internal fertilisation, the chance of gametes meeting is greater** and hence the chance of fertilisation is increased. So, it is not surprising that internal fertilisation occurs in some aquatic organisms.

Marine animals

Octopuses have internal fertilisation. In the male octopus, one of his eight arms is shorter than the other arms. This arm is specialised for the direct transfer of a parcel of sperm to a female. Figure 11.23 shows a male octopus that has mounted a female and inserted his specialised arm into her mantle cavity where he will deposit a package of sperm.

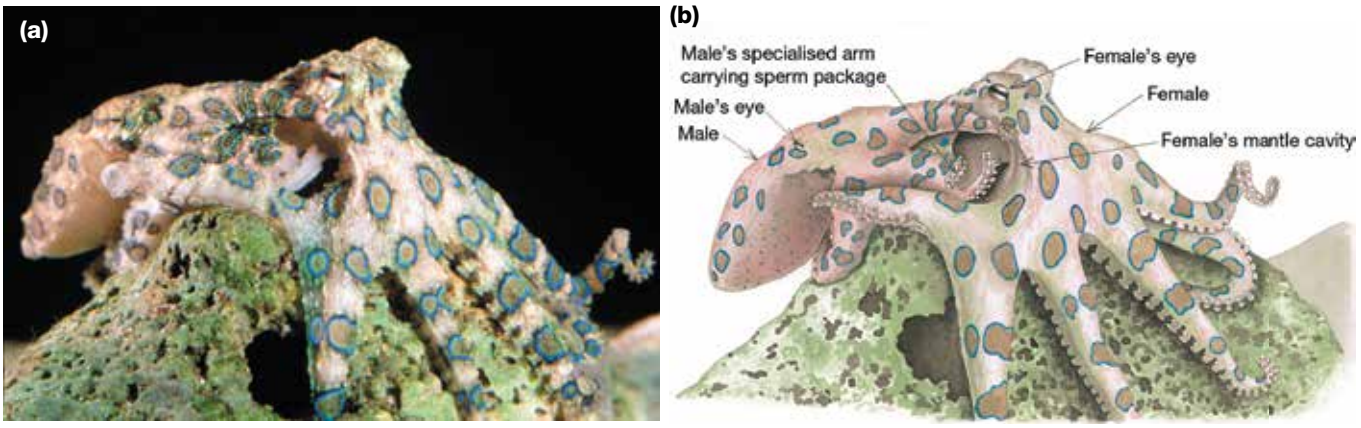

FIGURE 11.23 **(a)** Smaller male blue-ring octopus (*Hapalochlaena lunulata*) transferring a sperm package into the mantle cavity of a larger female **(b)** Diagram showing the smaller male blue-ring octopus (at left) inserting his specialised arm carrying a sperm package into the mantle cavity of the larger female octopus (at right)

In sharks, the male of the species has claspers that are appendages of his pectoral fins (see figure 11.24). The male shark inserts his claspers into the vagina of a female and forces his sperm inside her carried by water pressure that he generates.

FIGURE 11.24 Ventral (belly) view of a male shark showing its two claspers. Claspers are a modification of the shark's pelvic fins. During mating, the male shark uses one of his claspers to deposit sperm in the genital duct of a female shark via her cloaca.

Terrestrial animals

Except for amphibians, such as frogs and toads that return to water to get their gametes together, other terrestrial animals have internal fertilisation. We will briefly explore internal fertilisation in some terrestrial animals.

Insects. **Internal fertilisation occurs in insects.** Complex genital structures at the end of the abdomen of a male insect enable him to couple with a female and transfer sperm packages into her reproductive tract. Some insects, such as dragonflies, mate on the wing but most insects keep their feet (all 12 in a mating couple) on the ground (see figure 11.25).

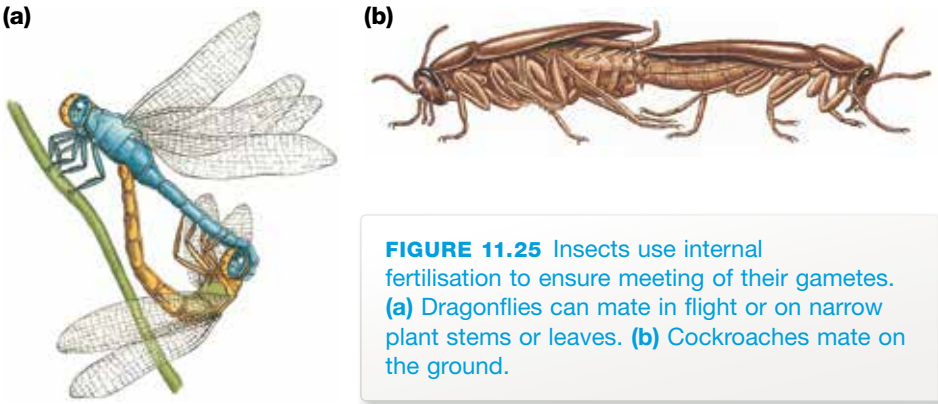

FIGURE 11.25 Insects use internal fertilisation to ensure meeting of their gametes. **(a)** Dragonflies can mate in flight or on narrow plant stems or leaves. **(b)** Cockroaches mate on the ground.

Reptiles. Ancestral reptiles were the first vertebrates to evolve a male copulatory organ, the penis (see figure 11.26). The presence of a penis enabled reptiles to transfer sperm directly into the reproductive tract of a female. Apart from sharks, reptiles were the first vertebrates that did not need to release their gametes into water for fertilisation to occur. Internal fertilisation freed the ancestral terrestrial reptiles and their descendants from the need to return to water for reproduction.

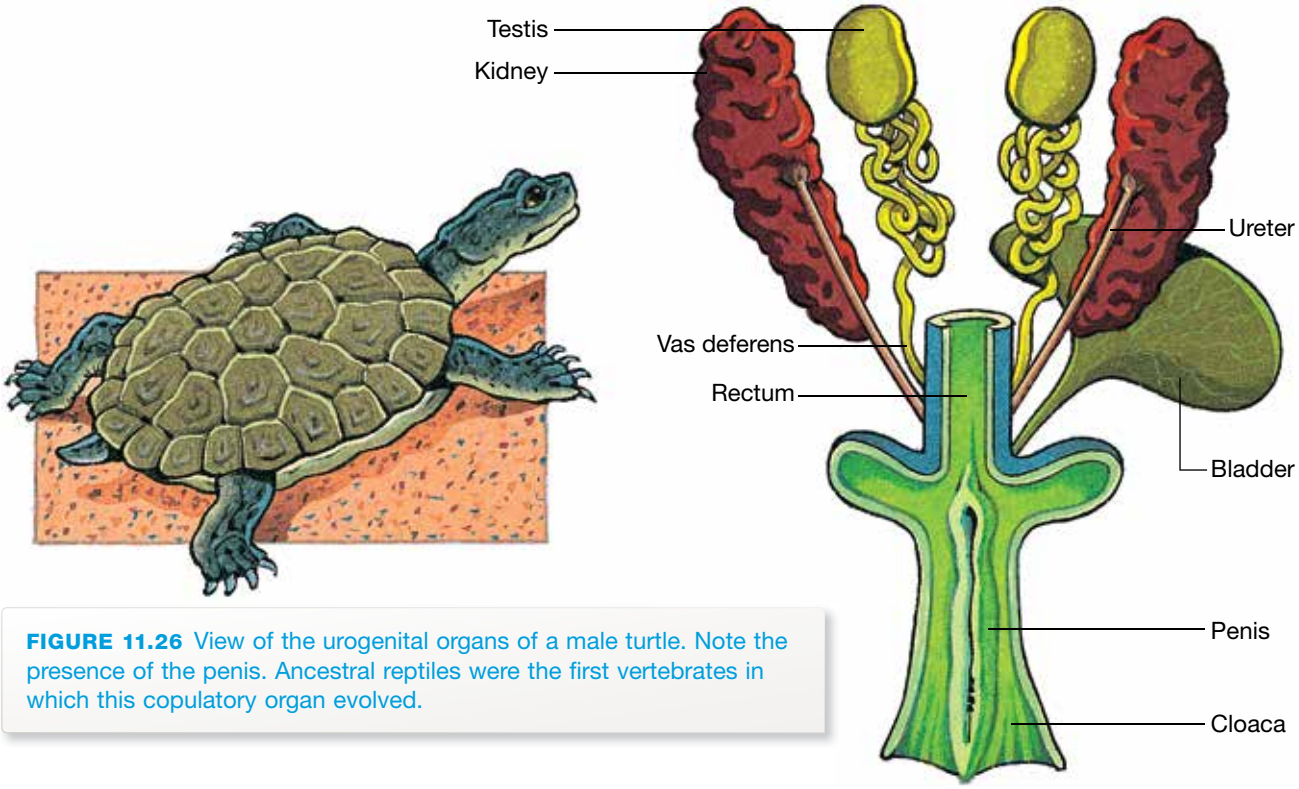

FIGURE 11.26 View of the urogenital organs of a male turtle. Note the presence of the penis. Ancestral reptiles were the first vertebrates in which this copulatory organ evolved.

For internal fertilisation, female animals produce a small number of eggs (or even a single egg) in each reproductive cycle. Less gamete wastage occurs and the chance of fertilisation for a given egg is quite high.

Another important evolutionary change in ancestral reptiles was the appearance of an egg with a protective outer shell, a series of internal membranes and a food supply for the developing embryo. This type of egg is a self-contained aquatic environment in which embryonic development occurs even when the egg is laid on land and is called an amniotic egg (see figure 11.27).

Birds. Birds also have internal fertilisation but male birds lack a penis. Instead, sperm transfer takes place through close contact of the urogenital

FIGURE 11.27 Amniotic eggs of reptiles, in this case those of a snake, enable reptiles to reproduce on dry land without the dependence on the presence of free water (as exists for amphibians). Developing reptilian embryos are enclosed in self-contained leathery eggs that are impermeable to water. Having completed development, a snake is hatching from the egg.

openings (cloacae) of male and female birds. Like their reptilian ancestors, birds produce eggs in which their embryos develop (see figure 11.28). The production of a shell amniot occurs as the fertilised egg passes through the genital tract of a female bird to the cloaca from where the egg is laid.

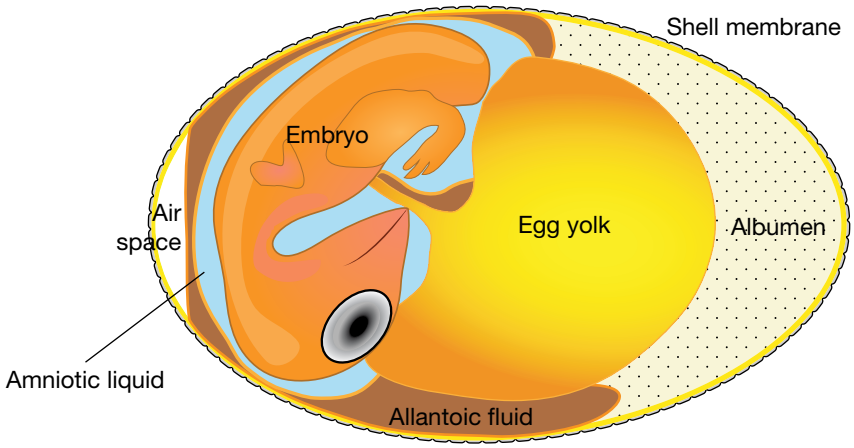

FIGURE 11.28 Simplified diagram showing a bird developing within an amniotic egg — a self-contained apartment. Note the watertight outer hard eggshell, the yolk and the albumen (egg white) that are sources of nutrients, the fluid within the amnion that prevents the embryo from drying out and the allantois, a sac in which waste products are stored as insoluble uric acid.

Mammals. Mammals have internal fertilisation.

- In monotreme mammals, such as the platypus and the echidna, the fertilised egg becomes enclosed within a shell and embryonic development occurs within the shelled egg (see figure 11.29).
- Female marsupials and placental mammals retain the fertilised eggs in their bodies and embryonic development proceeds within the uterus. Young marsupials are born at a very undeveloped stage. Young placental mammals are born at a much more developed stage.

FIGURE 11.29 Platypus egg

KEY IDEAS

- Compared with asexual reproduction, sexual reproduction has a higher energy cost.
- In animals, fertilisation may be internal or external.
- Some species that use external fertilisation have developed strategies to increase the chance of fertilisation occurring.
- With internal fertilisation, there is a greater chance of gametes meeting and fertilisation occurring.
- The emergence of the amniotic egg allowed the first reptiles to colonise dry land.

QUICK CHECK

6 Briefly explain why external fertilisation is far more common in aquatic animals than in terrestrial animals.

7 Identify two energy costs of sexual reproduction that are not present in asexual reproduction.

8 Identify one example of each of the following.
- **a** A marine animal that uses external fertilisation
- **b** A marine animal that uses internal fertilisation
- **c** A terrestrial animal that uses external fertilisation.

BIOLOGIST AT WORK

Jan West and the test-tube puppies

Jan West, a Senior Lecturer at Deakin University, tells the story of her test-tube puppies.

There are two breeds of corgi — the Pembroke Welsh corgi made famous by Queen Elizabeth II and the lesser known Cardigan Welsh corgi, which was bred to drive cattle across the hills of Wales. Cardigan Welsh corgis are now an endangered breed in Britain, their country of origin, and numbers are also declining in Australia. The small gene pool available locally makes breeding challenging because genetic diversity must be maintained to ensure healthy dogs.

How can the gene pool be increased? Dogs can be imported from other countries or frozen semen can be imported from suitable stud dogs. Frozen semen has several advantages; it increases the breeding life of males and, as animals do not move between countries, no quarantine is needed.

Meet the female Cardigan corgi Gem, born in England and imported to Australia in early 2010 with the long-term goal of increasing the Cardigan corgi gene pool in Australia. On arrival, Gem spent 30 days at the Spotswood quarantine station in Melbourne.

In 2011, Gem produced a litter of eight puppies conceived using frozen semen. The first step was a series of progesterone tests to identify when ovulation had occurred in Gem. Once this was known, a new technique, called transcervical insemination (TCI), was used by reproductive specialist Dr Stuart Mason to implant thawed semen in Gem's uterus. In TCI, a thin catheter fitted with a tiny camera is inserted into the reproductive tract, passing through the cervix into the uterus where the eggs are located. Semen is placed in the uterus where, within 6 to 12 hours, viable sperm can fertilise the eggs. In Gem's case, a total of eight eggs were fertilised. Previously the procedure to place semen in the uterus involved surgery. The advantage of TCI is that no surgery is required.

Just over a week after fertilisation, mitotic divisions increased the cell numbers, with each embryo consisting of a hollow ball of cells about 2 mm in diameter. Three weeks after fertilisation, the embryos, floating in amniotic fluid, were 7 mm long, and the first signs of eyes and ears were evident. An ultrasound showed sacs of amniotic fluid enclosing the developing puppies and, at this stage, development of the internal organs was complete (see figure 11.30). Five weeks after fertilisation, the first signs of the pups' sex were detected, predicting a litter of four males and four females. By 6 to 7 weeks, the developing pups reached about 90 mm in length and had whiskers, toes and toenails. The pups then started growing body hair and the shafts of their bones formed.

FIGURE 11.30 Colour Doppler ultrasound carried out at Monash Veterinary Clinic at week 4 of Gem's pregnancy. The coloured structure is the heart of one of the pups. Colours indicate the direction and speed of blood flow, with red-yellow identifying blood flow towards top of image and blue identifying flow towards bottom of image. The other smudges are caused by movement of Gem, the mother.

Between weeks 8 and 9, the finishing touches were put on the pups' footpads and their coats of various colours: red and white, black and white with brindle points, and brindle and white. Finally, after 61 days (a couple of days shorter than the normal gestation of 63 days because of the transcervical implantation), the puppies were born on 3 December 2011.

At birth, the puppies' eyelids and ear canals were closed (see figure 11.31a). About 12 days later these opened and their pink noses turned black. Puppies have a well-developed sense of smell and a strong 'suck' reflex. Their suckling stimulates the mother's pituitary gland to release oxytocin, the hormone that triggers her mammary glands to release milk. Milk is high in calories and nutrients and the pups doubled their birth weight in their first week. Figure 11.31b shows some of the pups aged 2 months, well on the path of developing into healthy adult Cardigan Welsh corgis.

FIGURE 11.31 **(a)** Three of Gem's litter of eight pups, one day after birth. Note the pink noses and closed eyes of these pups at this age. **(b)** Gem and three of her pups, aged 2 months. Note the colour of their noses.

BIOCHALLENGE

1 Figure 11.32 shows some of the variation in the gametes resulting from meiosis. Just three of many possible sets of gametes from the division by meiosis of one germ cell are shown.

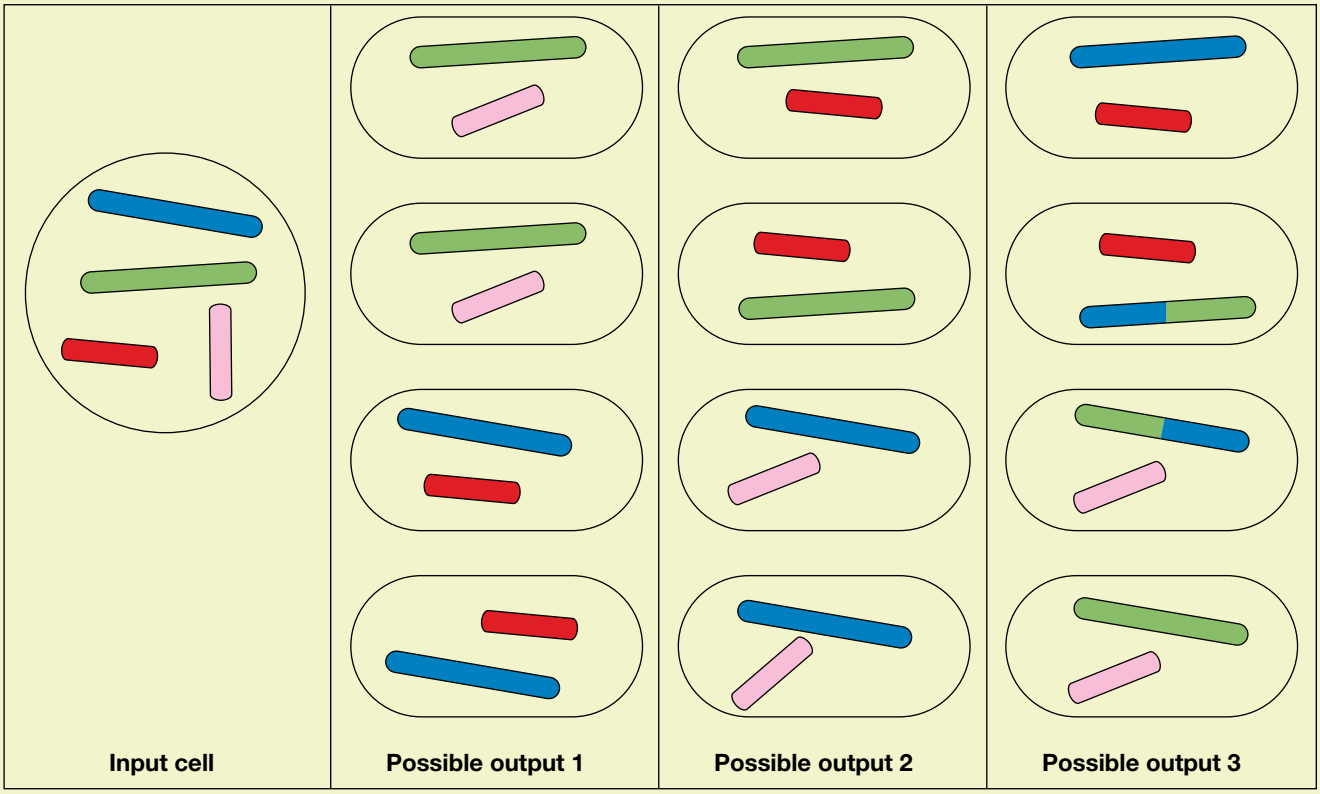

FIGURE 11.32 Variations in outputs of meiosis. Notice that, even with the same starting input, the outputs of meiosis can differ each time.

In this diagram, the input germ cell is diploid ($2n = 4$), with two pairs of homologous (matching) chromosomes: one long pair (one blue and one green) and a short pair (one red and one pink).

Your challenge is to replicate this table, starting with the same input cell, but producing three more possible outcomes.

2 Figure 11.33 shows a stage of meiosis.

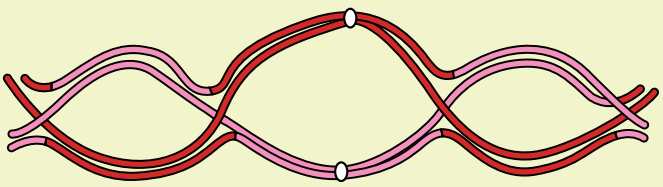

FIGURE 11.33

a Identify what this structure is.
b Where is this happening?
c When does this happen?
d Draw the chromosomes in the four gametes that would result from meiosis.

Chapter review

Key words

anaphase
chromosome
crossing over
diploid number
egg
external fertilisation
fertilisation
gametes
germ cells
gonads
haploid number
hermaphrodite
homologous
internal fertilisation
interphase
meiosis
metaphase
nondisjunction
nonhomologous
ovaries
prophase
recombination
reduction division
sequential hermaphrodite
sexual reproduction
simultaneous (synchronous) hermaphrodite
somatic cell
sperm
synapse
telophase
testes

Questions

1 **Making connections** ➜ Use at least eight chapter key words to draw a concept map. You may use other words in drawing your map.

2 **Communicating understanding** ➜ For each of the following questions, identify two correct answers from the choices given.
- **a** Which animals have internal fertilisation: crocodiles, frogs, koalas, cats?
- **b** Which animals depend on the availability of water for breeding: cane toads, goannas, seagulls?
- **c** Which animals produce shelled eggs: platypus, frogs, kangaroos, turtles, toads, penguins?

3 **Applying your knowledge and understanding** ➜ Figure 11.34 shows various stages during the process of meiosis. Examine the figure.
- **a** List the stages in order from the beginning to the end of meiosis.
- **b** What is the diploid number of this cell?

4 **Making valid predictions based on your knowledge** ➜ Plesiosaurs are extinct reptiles that lived in the sea. What prediction, if any, can be made about their manner of reproduction?

5 **Applying your knowledge** ➜ Consider the following statements about internal fertilisation and identify them as true or false.
- **a** Internal fertilisation occurs in all terrestrial animals.
- **b** Internal fertilisation occurs in all marine animals.
- **c** Internal fertilisation does not occur in hermaphrodite animals.

6 **Applying your knowledge** ➜ Identify the structure that assists sperm transfer to the female in internal fertilisation in the following species.
- **a** Tortoises
- **b** Sharks
- **c** Dogs
- **d** Octopuses

7 **Communicating understanding** ➜ Refer to figure 11.14 on page 449 that shows the stages of meiosis.
- **a** How many nuclear divisions occur during meiosis?
- **b** A student commented: 'One of the divisions in meiosis is just like mitosis!'
  Indicate whether you agree or disagree with this student, giving a brief reason for your choice.

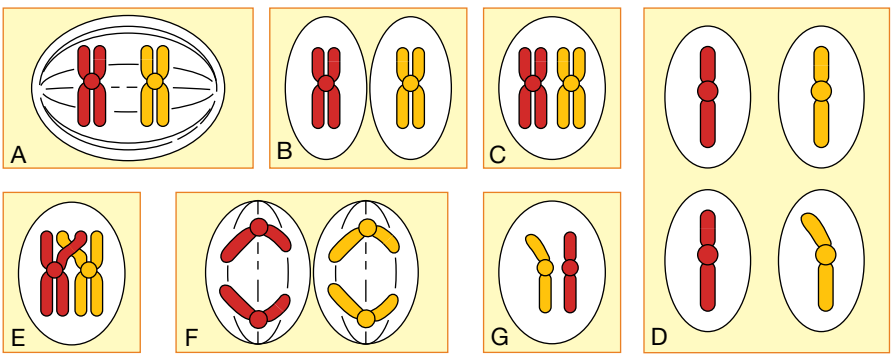

FIGURE 11.34

8 Applying your understanding three ➜ A particular organism produces normal sperm with three chromosomes.

- **a** What is the haploid number of this organism?
- **b** What is the diploid number of this organism?
- **c** How many matching pairs of chromosomes would be expected to be present in a somatic cell of this organism?
- **d** How many matching pairs of chromosomes would be expected in an egg cell of this organism.
- **e** Sketch a possible image of the chromosomes in a somatic cell of this organism.
- **f** Without including crossing over, and using your diagram from part (e) above, identify how many different kinds of gametes (in terms of different chromosome combinations) this organism could produce.
- **g** Would this number increase or decrease if you included crossing over? Briefly explain.

9 Applying your knowledge and understanding ➜ Horses (*Equus caballus*) have a diploid number of 64, while the diploid number in the closely related donkeys (*Equus asinus*) is 62. Mules (see figure 11.35) are the sterile offspring of the mating of a male donkey (jack) with a female horse (mare).

FIGURE 11.35 A mule

- **a** How many chromosomes would be expected to be present in each of the following?
  - i A normal egg of a horse
  - ii A normal sperm of a donkey
  - iii A somatic cell of a mule

  As indicated above, mules are sterile and cannot reproduce.
- **b** In light of your knowledge of meiosis, suggest a possible reason for the inability of mules to produce functional gametes.

10 Communicating understanding ➜ If two brothers obtain half their genes from their mother and half from their father, why are they not identical?

11 Applying your knowledge ➜ External fertilisation in a marine environment frees a sexually reproducing organism from having to find, court and secure a potential mate.

- **a** What is the energy downside to this type of external fertilisation?
- **b** List four different ways in which gametes can be made to meet.

12 Applying your knowledge and understanding ➜ For each of the following stages of meiosis, identify the amount of DNA in one cell. Assume that the amount of DNA in the diploid germ cell before it starts to undergo meiosis is 2X.

- **a** Metaphase 1 of meiosis
- **b** Telophase 1 of meiosis
- **c** Prophase 1 of meiosis
- **d** Telophase 2 of meiosis

CHAPTER

12 Cell growth and differentiation

FIGURE 12.1 This baby was once a single fertilised egg, or zygote, that underwent a remarkable developmental journey involving growth in cell numbers, cell migration and cell differentiation. By the time of its birth, a baby is a complex organism composed of billions of cells, organised into tissues, organs and systems. In this chapter we will explore some of the processes involved in this transformation, including the role of stem cells.

KEY KNOWLEDGE

The contents of this chapter are designed to enable students to:

- develop understanding of the function of stem cells in antenatal (pre-birth) human development
- gain knowledge of the different types of stem cells
- become aware of the potential use of stem cells in medical treatment of certain disorders
- recognise how disruption of the cell cycle can result in developmental abnormalities and cancers.

studyon

Unit 2 AOS 1 Topic 4 Concept 3

Human prenatal development
Concept summary and practice questions

Antenatal human development

In the transition from a single-celled zygote to a newborn baby, remarkable changes will take place:

- Many mitotic cell divisions occur that, by the time of birth, will increase the total number of cells to many billions. Estimates of the number of cells in a newborn vary; however, a reliable indication that this figure must be in the billions comes from one study that identified, at birth, the number of cells in *just the forebrain* as 38 billion. (*Source:* GB Samuelsen et al., 'The changing number of cells in the human fetal forebrain and its subdivisions: A stereological analysis', *Cereb. Cortex,* vol. 13, pp. 115–122, 2003.)
- A process of cell differentiation occurs, which will produce an estimated 200-plus different cell types.
- A process of organisation of these differentiated cells of various types into tissue organs and systems occurs.

Antenatal or pre-birth development in humans involves a number of stages. The starting point is a single-celled zygote formed by **fertilisation** of an egg by a sperm; then follows the development of an embryo and finally a fetus.

Figure 12.2 shows a typical timeline of antenatal development. By convention, the standard historical method that is commonly used by doctors and hospitals to identify the duration of a pregnancy starts from the time of a woman's last menstrual period. Why? This is a known event, in contrast to the time of fertilisation, which is usually less well-defined (except of course in cases of in-vitro fertilisation (IVF)). Week and month numbers in this figure, such as the sixth week of pregnancy, give the so-called **gestational** or **menstrual age** of a pregnancy. However, when talking about events in **embryonic** or **fetal development** in the sections below, the times given will refer to the days or weeks *since* fertilisation, and are based on direct observations. So, 5 days after fertilisation corresponds to the third week of a pregnancy as measured in gestational age.

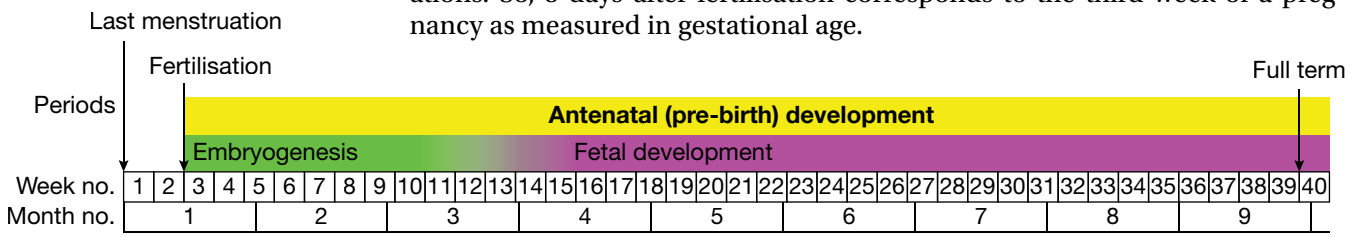

FIGURE 12.2 Diagram showing the typical course of a normal human pregnancy. The weeks of a pregnancy are, by convention, counted from the time of the last period because this is a known point in time.

ODD FACT

The use of the date of a woman's last menstrual period as a starting point to measure the duration of a pregnancy means that this start date is actually 2 weeks *before* **ovulation** — the release from the woman's ovary of the egg that was fertilised, thus producing the pregnancy.

Egg to zygote

After a female reaches puberty, as part of each menstrual cycle about 20 of the immature eggs in her ovary begin their development into a mature haploid egg cell or oocyte. The immature eggs that start this development are each enclosed in a fluid-filled sac called a **follicle** (see figure 12.3). This process begins in response to a hormonal signal from the pituitary gland that secretes **follicle-stimulating hormone** (FSH). Normally, only one of these eggs will complete the developmental process and will be released from the follicle and leave the ovary. Can you suggest what might be a possible outcome if two eggs simultaneously complete development and are released?

The mature egg is released from a follicle and out of the ovary, then normally passes into the fallopian tube. Figure 12.4 shows a striking image of a human egg being released from a follicle and from the ovary.

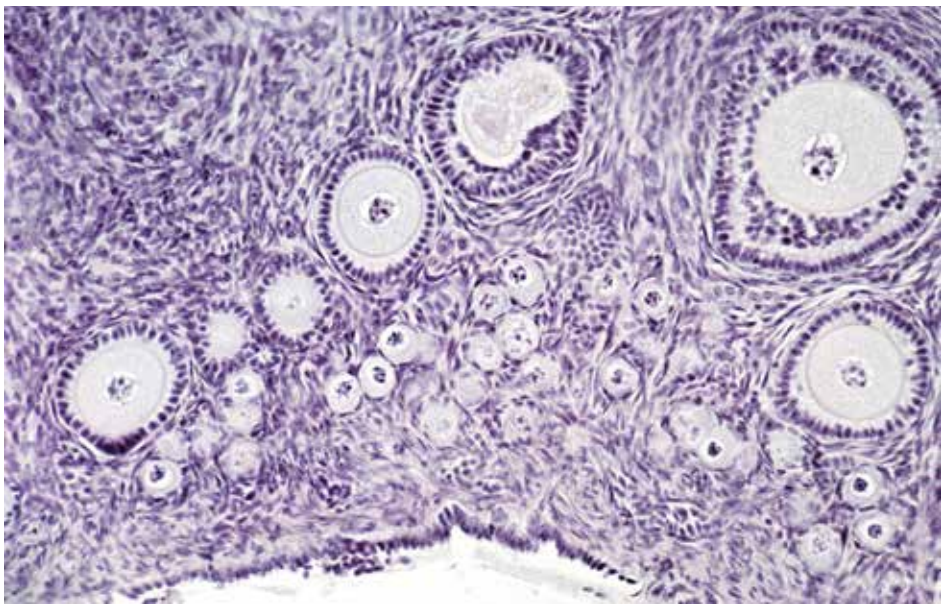

FIGURE 12.3 Photomicrograph (50X magnification) of a cross-section of a mammalian ovary showing egg cells (oocytes) at various stages of development within the ovarian follicles.

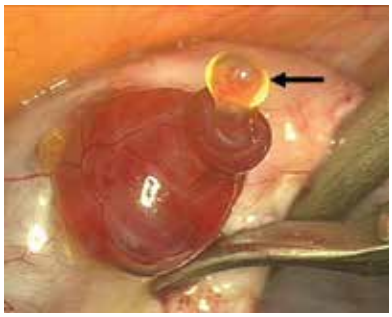

FIGURE 12.4 Moment of ovulation in a human ovary. The egg within a jelly-like substance (yellow and arrowed) emerges from a follicle (red) that protrudes from the surface of the ovary. The silver object is a surgical instrument.

ODD FACT

As well as its plasma membrane, a mature egg (oocyte) is coated in a thick layer of carbohydrate, known as the *zona pellucida* (= transparent girdle). Outside this are several layers of cells that form a ring called the *corona radiata* (= radiating crown).

After releasing an egg cell, the follicle that remains develops into a structure known as the **corpus luteum**. The corpus luteum releases the hormone **estrogen**. Release of estrogen causes the lining of the uterus to thicken. (Refer to figure 11.4, which shows a corpus luteum developing alongside a follicle that contains a maturing egg cell.)

After release from a follicle, the oocyte moves into the fallopian tube where it remains capable of being fertilised for a period of up to 12 hours. For fertilisation to occur, one sperm must first penetrate the various layers that surround the egg (see Odd fact) and then enter the cytoplasm of the egg cell. When a sperm penetrates the egg, the egg rapidly completes the second division of meiosis, forming a second polar body and a mature oocyte (refer to figure 11.15). The haploid sperm nucleus then fuses with the haploid nucleus of the egg to create a single diploid cell known as a **zygote** (see figure 12.5). The DNA of the chromosomes of the zygote, half from the mother and half from the father, creates a new genome that contains all the genetic information needed to form a unique human being.

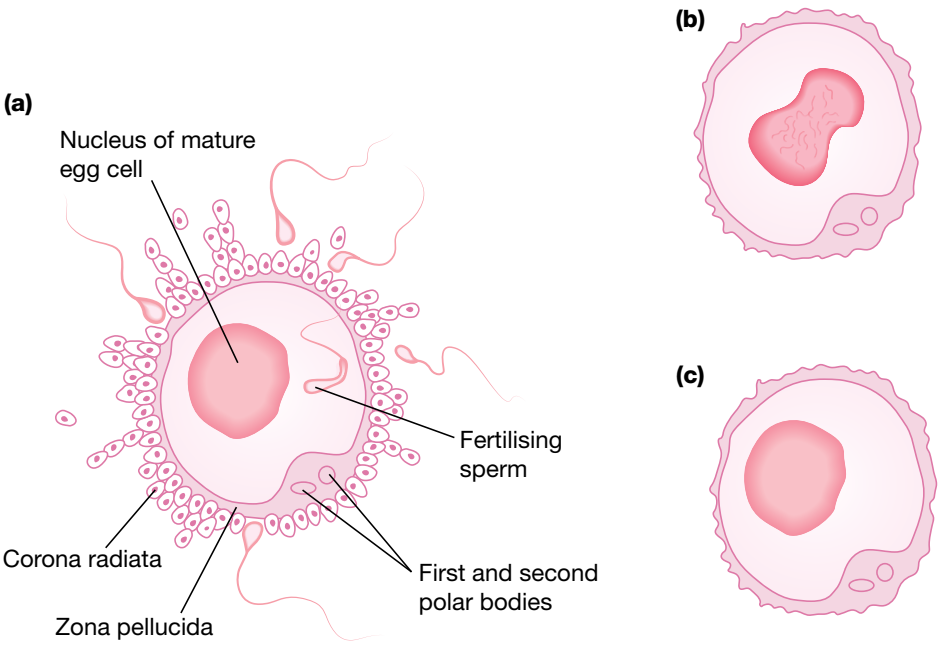

FIGURE 12.5 Process of fertilisation **(a)** A single sperm moves into the cytoplasm of the egg cell that then quickly completes the second division of meiosis, forming a second polar body and a mature oocyte. **(b)** Combination of the paternal chromosomes of the sperm ($n = 23$) and the maternal chromosomes of the egg ($n = 23$) **(c)** Formation of a diploid single-celled zygote ($2n = 46$) marks the completion of fertilisation.

ODD FACT

Sperm cells in the female reproductive tract remain viable for 48 to 72 hours and so can fertilise an egg up to the end of that time.

The human embryo: two cells to blastocyst

A human **embryo** may be defined as the entity that is produced by the first mitotic division of the zygote produced after completion of the fertilisation of a human egg by a human sperm, and this stage continues up to the eighth week of development.

So the embryonic period starts when the zygote undergoes the first cell division by mitosis to form a two-celled entity. Over a period of several days, as the embryo moves along the fallopian tube, it undergoes further mitotic divisions to produce four cells, then eight cells, then 16 cells, and so on. These cells initially form a solid mass. However, by about the fifth day of embryonic development, the embryo is no longer a solid mass of cells. It now consists of a hollow fluid-filled structure, called a **blastocyst**, with an inner mass of cells surrounded by an outer layer of cells (see figure 12.6). **The inner cell mass of the blastocyst will form the tissues of the embryo, while the cells of the outer layer will become the embryonic contribution to the placenta**. The blastocyst has now reached the uterus where it attaches to the uterine wall. By about day 9 of embryonic development, the process of implantation of the embryo in the uterine wall is complete.

blastocyst from *blastos* = sprout and *cystos* = cavity

ODD FACT

Most pregnancy tests are designed to detect the presence of the hormone human chorionic gonadotrophin (hCG) in urine or blood. hCG is secreted by cells of a fertilised egg, but it cannot be detected until *after* implantation, that is, about 9 days after fertilisation.

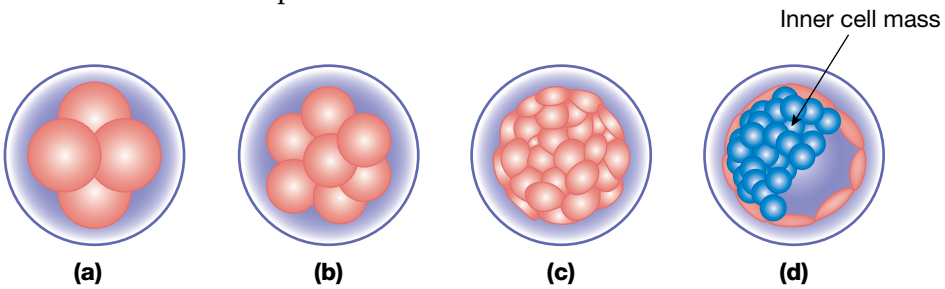

FIGURE 12.6 **(a)** and **(b)** Embryos at very early stages of development **(c)** Embryo composed of a solid mass of cells **(d)** Early blastocyst showing the inner cell mass that will give rise to the embryonic tissues and an outer ring of cells that will later become part of the placenta

The human embryo: formation of three germ layers

The final event associated with embryonic development is a process known as **gastrulation**. Gastrulation is the name given to the complex cell migrations that re-organise the inner cell mass of the embryo blastocyst into a three-layered structure. The cell migrations and the re-organisation produce three distinct layers of cells known as the primary **germ layers**:

1. **ectoderm**
2. **mesoderm**
3. **endoderm**.

These primary germ layers are composed of **stem cells** that can give rise to or **differentiate** into the various cell types that form the mature organism. The three germ layers are the embryonic source of all the different kinds (about 200-plus) of body cells. Table 12.1 identifies some of the possible differentiated cell types that can arise from embryonic stem cells in the three primary germ layers of an embryo.

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Critical periods for organ development

The embryonic period is relatively short — about 9 weeks after fertilisation — but it is a critical period. In a following section (see p. 468), we will explore some of the critical events during embryogenesis. The embryonic period from week 3 to week 9 is the period during which the organ system and structures of the human body are established. Not surprisingly, it is also the period during which the most serious birth abnormalities can arise, for example, through

ODD FACT

By 1960, thalidomide was marketed as a completely safe drug in 46 countries, including Australia, and its level of sales were close to those of aspirin.

exposure to damaging chemicals, known as **teratogens** (*teratos* = monster) or teratogenic agents. A well-known teratogen is **thalidomide**, which in the past was taken by women to treat morning sickness during pregnancy. Ingestion of thalidomide by women during the first trimester (3 months) of their pregnancies resulted in the birth of babies with severe physical abnormalities. Thalidomide was available from the late 1950s but was banned in most countries by 1962, when the link was established between the use of the drug and serious congenital malformations, particularly of the limbs, which were either completely missing or severely shortened (see figure 12.7).

TABLE 12.1 Some of the differentiated cell types that can arise from embryonic stem cells in the three primary germ layers

Primary germ layer	Differentiated cells/tissues/organs
ectoderm	skin melanocytes brain, spinal cord and nerves pituitary gland adrenal medulla sense organs: eyes sense organs: inner ears
mesoderm	heart and blood vessels adrenal cortex smooth, skeletal and cardiac muscle part of urogenital system bone marrow blood cells bone and cartilage lymphatic tissue
endoderm	larynx, trachea and lungs lining of respiratory tract lining of gastrointestinal tract liver pancreas thymus thyroid gland urinary bladder and urethra

During very early embryonic development, exposure to a teratogen can cause the death of an embryo. Exposure later in the embryonic period can result in major malformations that may either lead to a spontaneous loss of a pregnancy or to the appearance at birth of severe **congenital malformations** or **birth defects** (such as those experienced through exposure to thalidomide, discussed above). Exposure to teratogens during fetal development may be expected to give rise to less serious congenital malformations.

The critical periods for organ development are shown in figure 12.8. From these data, you can see that the embryonic period is the most critical time for organ development.

FIGURE 12.7 Thalidomide is a teratogenic agent that can result in the birth of babies with severe malformations of the limbs.

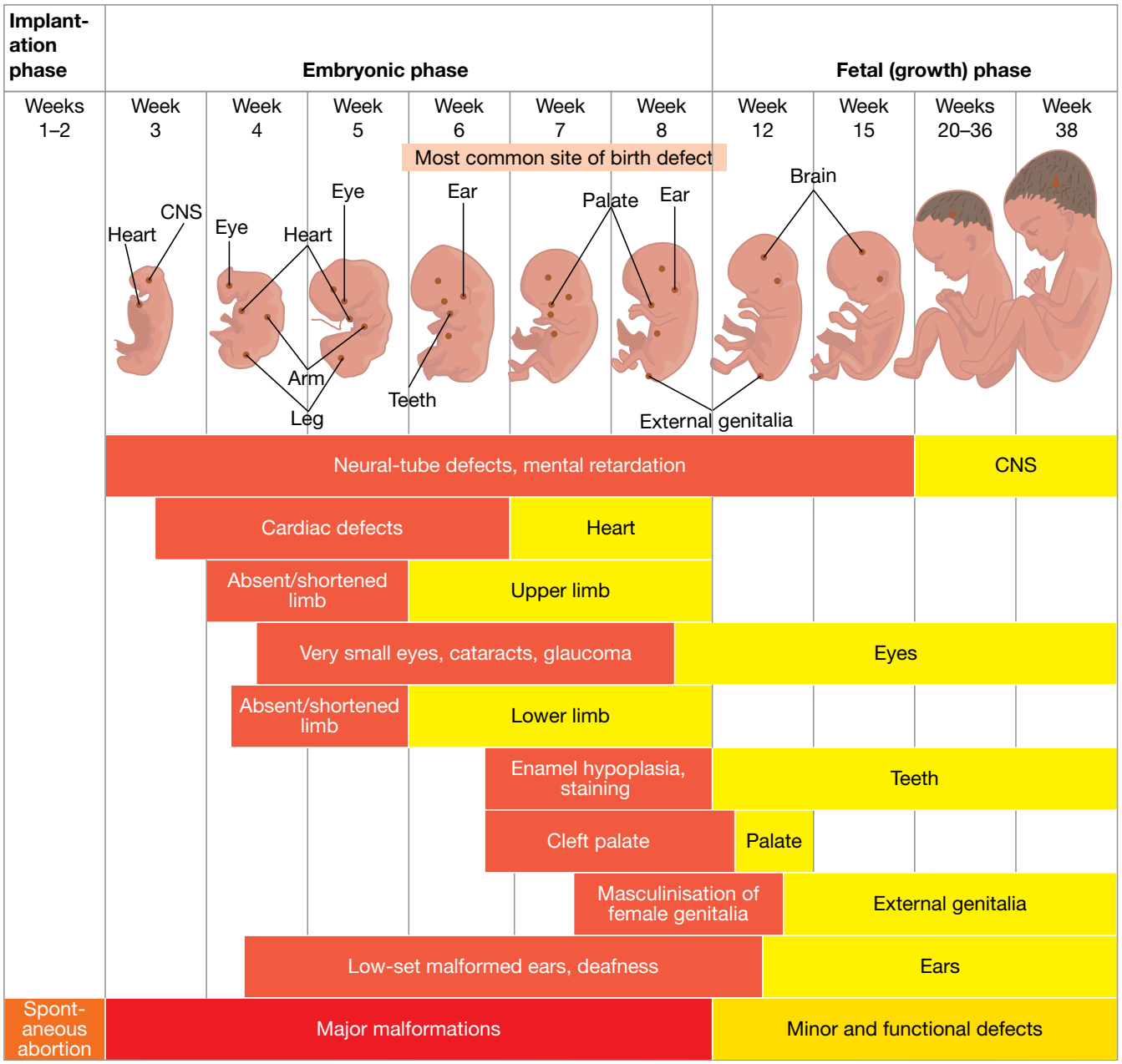

FIGURE 12.8 The critical periods for organ development. Note that the major defects occur in the embryonic phase.

The human fetus

Nine weeks after fertilisation is regarded as the point at which the fetal stage of development is reached. In general, a **fetus** is characterised by the presence of all the major body organs, although they are not fully developed. Organ systems that were formed during embryonic development will develop further in the fetus, and, in some cases, even after birth, for example, the circulatory system, the respiratory system and the nervous system.

Fetal development is the period during which the major growth in size of the fetus and the mass of its organs occurs (see figure 12.9). Table 12.2 shows the change in average fetal length and weight at various times from the start of the fetal period (nine weeks after fertilisation) to full term (birth). Over a period of about 30 weeks, the mass of the fetus increases more than 400-fold (see figure 12.9).

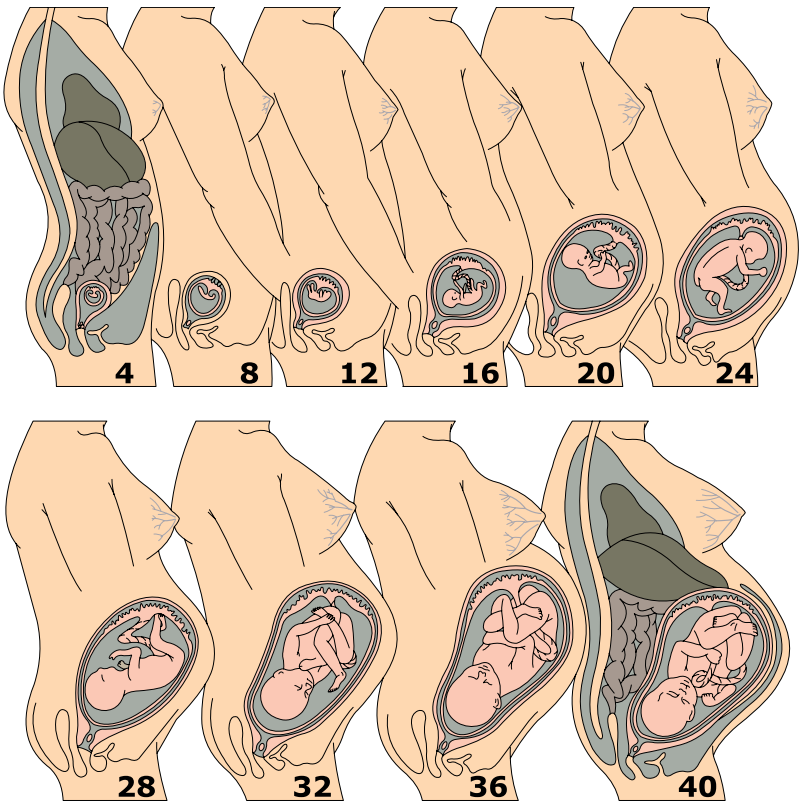

FIGURE 12.9 Relative change in size from late embryonic stage, through fetal development to full term

TABLE 12.2 Approximate fetal lengths and weights over the period of fetal development. Up to 16 weeks, lengths are given as crown–rump lengths. From and including 22 weeks, lengths are given as crown–heel lengths.

Weeks after fertilisation	Length	Mass
9	3 cm	8 g
10	5 cm	14 g
16	14 cm	190 g
22	30 cm	600 g
28	40 cm	1320 g
34	47 cm	2600 g
40	51–52 cm	3685 g

KEY IDEAS

- Antenatal development involves the formation of a zygote, followed by periods of embryonic and fetal development.
- The increase in cell numbers during the periods of both embryonic and fetal development is a result of cell division by mitosis.
- Key events in embryonic development include blastocyst formation, which produces the inner cell mass that gives rise to all the tissues of the embryo, and gastrulation, which organises the migration of embryonic cells into the three primary germ layers.
- Cells from the primary germ layers give rise to or differentiate into a variety of different cell types.
- Fetal development commences at about week 9 after fertilisation and is a period of major growth as well as continued development of organ systems.
- Severe congenital malformations can result from exposure to certain chemicals (teratogens) during critical periods of organ development, in particular during the embryonic stage of development.

QUICK CHECK

1 What is the length of the period of embryonic development in humans?
2 What event initiates the completion of the second meiotic division in a human egg?
3 Which is longer: the period of embryonic development or the period of fetal development?
4 What is a teratogen?
5 Identify whether each of the following statements is either true or false.
   a Fertilisation occurs in a woman's ovary.
   b A zygote is the single diploid cell resulting from the fertilisation of an egg by a sperm.
   c A zygote divides by meiosis to produce an increase in cells.
   d Gastrulation involves cell migrations to form a three-layered embryo.
   e The three primary germ layers are ectoderm, mesoderm and endoderm.

Key events: embryonic development

The embryonic period, from zygote formation to the end of about the eighth week of development, is the time during which key developmental events occur, as follows:

- organisation of cells into the three primary germ layers from which all the structures and organs of the body will develop
- formation of a head–tail axis and a front-to-back (ventral-to-dorsal) axis of the embryo
- cell differentiation and beginning of formation of the brain, spinal cord and nerve cells, heart, sense organs such as eyes, lungs, kidneys, digestive tract, and arms and legs.

Key cells involved in the establishment of the organ systems are the embryonic stem cells.

Stem cells in action

Stem cells are undifferentiated or unspecialised cells that have the ability to differentiate into organ- or tissue-specific cells with specialised functions, such as nerve cells, blood cells, bone cells, heart cells, skin cells and so on. These terminal cells with specialised functions, such as a liver cell or a muscle cell, are differentiated and, once differentiated, cannot normally revert to an undifferentiated state. A second feature of stem cells is that they are capable of dividing and renewing themselves over long periods. Figure 12.10 shows mouse stem cells that have been stained to show the presence of one of the proteins (Oct4) that are essential to keep the stem cells in an undifferentiated state.

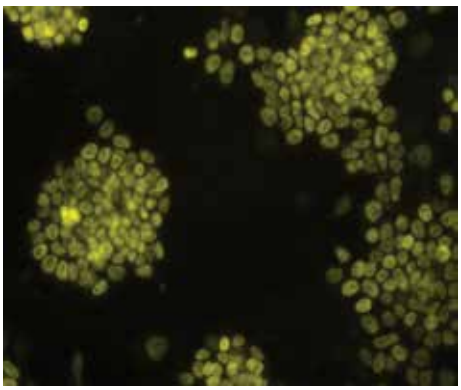

FIGURE 12.10 Mouse stem cells. The yellow colouring shows the presence of a protein, known as Oct4, which is essential to keep these stem cells in an undifferentiated state.

Some stem cells in your body are constantly dividing to replace tissues. Examples of these are the stem cells in the basal layer of your skin (refer to figure 9.17), and stem cells in the crypts of your intestine (refer to figure 9.18). Each of these stem cells divides to produce a specialised differentiated cell and a replacement stem cell (see figure 12.11). This is how stem cells self-renew.

Different kinds of stem cell occur and they can be distinguished in terms of their potency to produce different cell types. Descriptions of stem cell potencies include:

- totipotent
- pluripotent
- multipotent
- oligopotent
- unipotent.

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Unit 2 AOS 1 Topic 4 Concept 1

Stem cell differentiation
Concept summary and practice questions

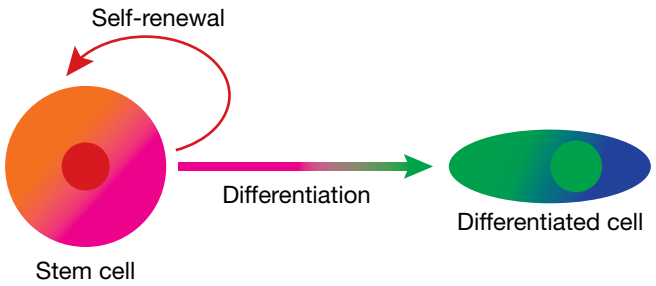

FIGURE 12.11 The division of a stem cell by mitosis gives rise to two daughter cells, one of which differentiates to become a specific cell type and the other that replaces or renews the original stem cell. Why is this self-renewal important?

The fertilised egg is said to be **totipotent** (*totus* = entire) because such a cell has the potential to give rise to all cell types. Other totipotent cells include embryonic cells of a two-, four- or eight-cell embryo.

The embryonic stem cells from the inner cell mass of the embryonic blastocyst are **pluripotent** (*plures* = several, many), as are the cells of the primary germ layers — ectoderm, mesoderm and endoderm. These cells can differentiate into many cell types.

Multipotent cells have the ability to differentiate into a closely related family of cells; for example, a multipotent blood stem cell can develop into a red blood cell or a white blood cell or platelets (all specialised cells).

Oligopotent cells have the ability to differentiate into a few cells, for example, adult (somatic) lymphoid or myeloid stem cells.

Unipotent stem cells have the ability to produce only cells of their own type, but because they can self-renew they are termed stem cells. Examples include adult (somatic) muscle stem cells.

ODD FACT

Scientists have discovered that proteins produced by three key genes maintain pluripotent stem cells in their undifferentiated state. These proteins, known as Oct4, Sox2 and Klf4, repress or silence the genes needed for embryonic development. When production of these proteins stops, the stem cells start to differentiate and are no longer stem cells.

Sources of stem cells

Stem cells can be obtained from the following sources:

- **Embryonic stem cells** (ESCs) may be obtained from the inner cell mass of an early embryo at a stage known as a blastocyst (see figure 12.12), that is, the clump of cells adhered to the inside surface of a blastocyst (see figure 12.13a). A single cell is isolated from the inner cell mass of a blastocyst and is grown in culture, dividing by mitosis to produce a culture of stem cells. These ESCs are obtained from extra embryos created as part of IVF procedures and they are in excess of requirements. Taking these cells from the inner mass of a blastocyst destroys an embryo and this procedure has raised ethical issues (see below).

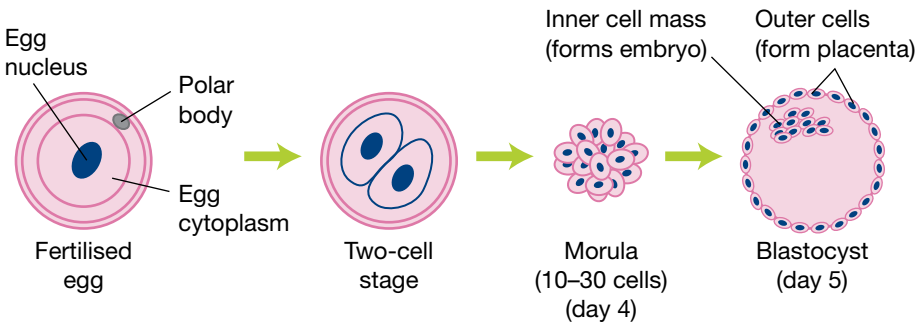

FIGURE 12.12 The development of a fertilised cell to a blastocyst stage. To see some real cells, use the **Embryos** weblink for this chapter in your eBookPLUS.

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- **Parthenotes** are another potential source of embryonic stem cells. These are derived from unfertilised human eggs that are artificially stimulated to begin development. Such an egg, of course, may start development but it is not capable of developing into a human being.
- **Adult stem cells** (more accurately called **somatic stem cells**) can be obtained from various sources throughout the body such as bone marrow, skin, the liver, the brain, adipose tissue and blood. In addition, another source of stem cells is cord blood that can be harvested from the umbilical cord of a baby after birth (see figure 12.13b). Samples of some of these tissues are more accessible than others, such as blood, bone marrow that can be harvested by drilling into bones — typically the iliac crest or the femur, and adipose tissue, which can be obtained by liposuction.

  Somatic stem cells are multipotent. This means that they can give rise to particular cell types such as different kinds of blood cells or skin cells. Cord blood, for example, contains mainly stem cells that give rise to various blood cells.

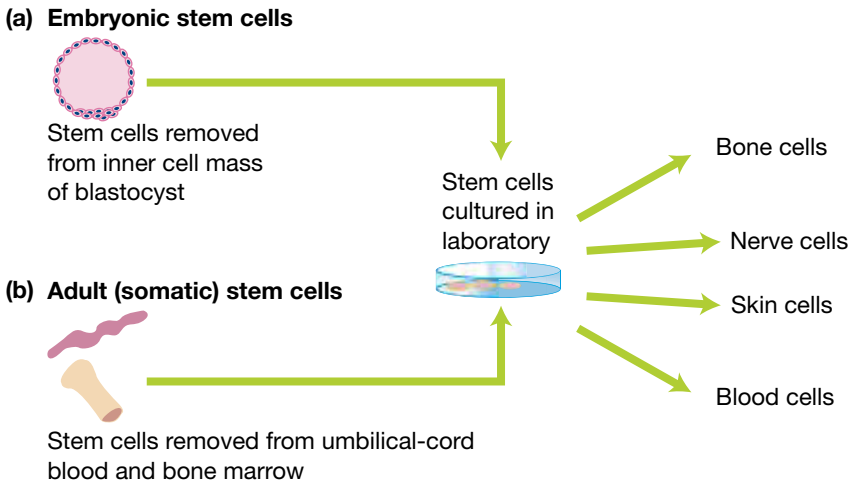

FIGURE 12.13 Stem cell lines can be created from various sources. **(a)** One source of stem cells is embryonic stem cells from the inner cell mass of a blastocyst. **(b)** Somatic stem cells can be extracted from bone marrow and from umbilical cord blood. *Somatic stem cells* is the preferred term for *adult stem cells*. Can you suggest why?

ODD FACT

One advantage of somatic stem cells is that, if used for the person from whom they were taken, there is no risk of rejection.

- **Induced pluripotent stem cells** (iPSCs) — research by Shinya Yamamaka in Japan in 2006 led to the discovery that some specialised adult somatic (skin) cells could be genetically reprogrammed to return to an undifferentiated embryonic state. This reprogramming was achieved by the addition to these cells of four specific embryonic genes, which encode proteins that are known to keep stem cells in an undifferentiated state. One of these genes is the **OCT4** gene that encodes the Oct4 protein (refer to figure 12.10). The creation of iPSCs does not involve the ethical issues related to the embryo deaths that necessarily accompany embryonic cell stem cells derived from blastocysts.

  The ability to produce iPSCs is supporting new lines of research into disease and drug development. For example, iPSCs can be made from skin samples of patients with Parkinson's disease, and these cells show signs of that disease. This means that aspects of the disease can be studied in detail in cell cultures in the laboratory, allowing the effectiveness of new drugs to be explored using these iPSCs.

  Cell-based therapies using iPSCs are not practical at present. The current procedure for reprogramming of somatic cells involves genetic modification, which can sometimes cause cells to produce tumours.

ODD FACT

Shinya Yamamaka was the co-recipient of the Nobel Prize for Physiology or Medicine in 2012 for 'the discovery that mature cells can be reprogrammed to become pluripotent'.

Stem cells in regenerative medicine

As people age, a number of degenerative disorders appear more commonly, such as Parkinsonism or Parkinson's disease. This particular disorder results from the death of certain brain cells that normally produce a chemical (dopamine) that controls muscle movements. People with Parkinsonism show impairment of their motor movements, balance and speech. Early treatment for Parkinsonism involved administering dopamine to affected persons. This treatment gave only short-term improvement.

Is there a way in which the lost dopamine-producing cells can be replaced? Experimental work is now proceeding on the potential use of stem cells to replace the lost cells in the brain.

Because stem cells have the unique ability to regenerate damaged tissue, research is being carried out on the potential use of stem cells in the treatment of Parkinson's disease and on some other human disorders or conditions. Potential uses of stem cells for these purposes are called **cell-based therapies**, and the field of research is termed **regenerative medicine**.

In addition to Parkinson's disease, other conditions that are potential targets for cell-based therapies include:

- type 1 diabetes, a condition in which the insulin-producing cells of the pancreas are destroyed by people's own immune system so that they cannot control their blood glucose levels and require the administration of insulin
- heart disease where sectors of heart muscle have died as a result of a heart attack (myocardial infarction) (refer to chapter 6)
- spinal cord injuries as a result of accident or trauma where the interruptions to the passage of nerve signals along the spinal cord have resulted in quadriplegia.

Cell-based therapies also have the potential to restore normal function in conditions such as macular degeneration of the retina, burns, and various forms of arthritis. However, the field of regenerative medicine is still experimental. The present challenges are to improve the culturing of stem cells under laboratory conditions to increase their numbers, and to increase the understanding of how stem cells differentiate into specific cell types. Once these challenges are overcome and the use of stem cells can be shown to be predictable, reliable and to do no harm, the use of specific differentiated cell types from stem cells in the treatment of certain diseases and injuries would be expected to become routine. However, at present, for most diseases, conditions and injuries, safe and effective treatments using cell-based therapies are yet to be realised.

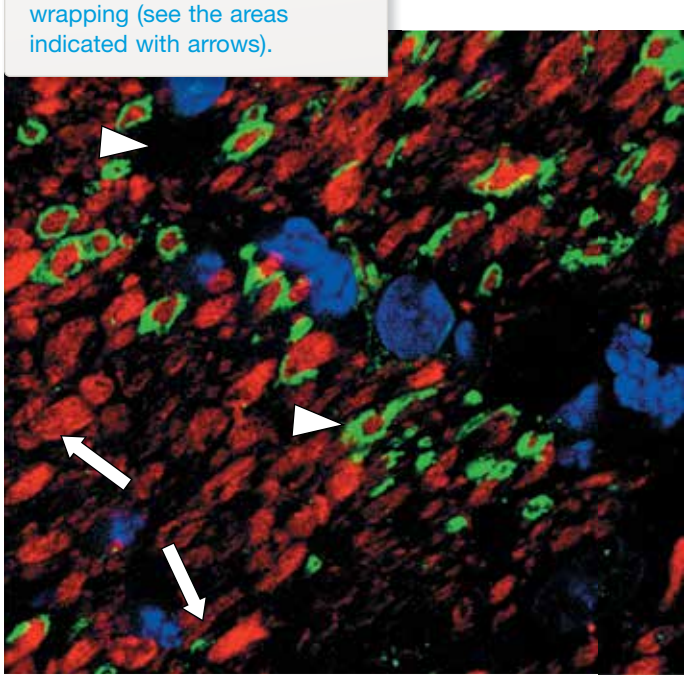

FIGURE 12.14 Injured spinal cord of mouse following injection of human stem cells. These stem cells developed into myelin-producing cells that form a wrapping (green) around nerve cells (red) (see the areas marked by arrowheads). Other nerve cells remained without a myelin wrapping (see the areas indicated with arrows).

Research in the field of regenerative medicine is ongoing. Scientists at the University of California reported that, following the injection of human stem cells from nerve tissue into the spinal cords of paralysed mice, the test group of mice displayed better mobility than the non-injected controls after just nine days and, after four months, the test group of mice could walk. The stem cells migrated up the spinal cord and developed into different kinds of cells including those cells that form insulating layers of myelin around nerve cells. Figure 12.14 shows the growth of myelin around nerve cells in the damaged region of a mouse spinal cord following injection of stem cells.

Scientists at the Walter and Eliza Hall Institute of Medical Research in Melbourne identified a cell line within mouse breast tissue that included multipotent

stem cells. Remarkably, they found that just one of these cells introduced to fat tissue in the laboratory could produce a branching mammary gland (see figure 12.15a). These stem cells were able to give rise to the various cell types present in mammary glands (see figure 12.15b).

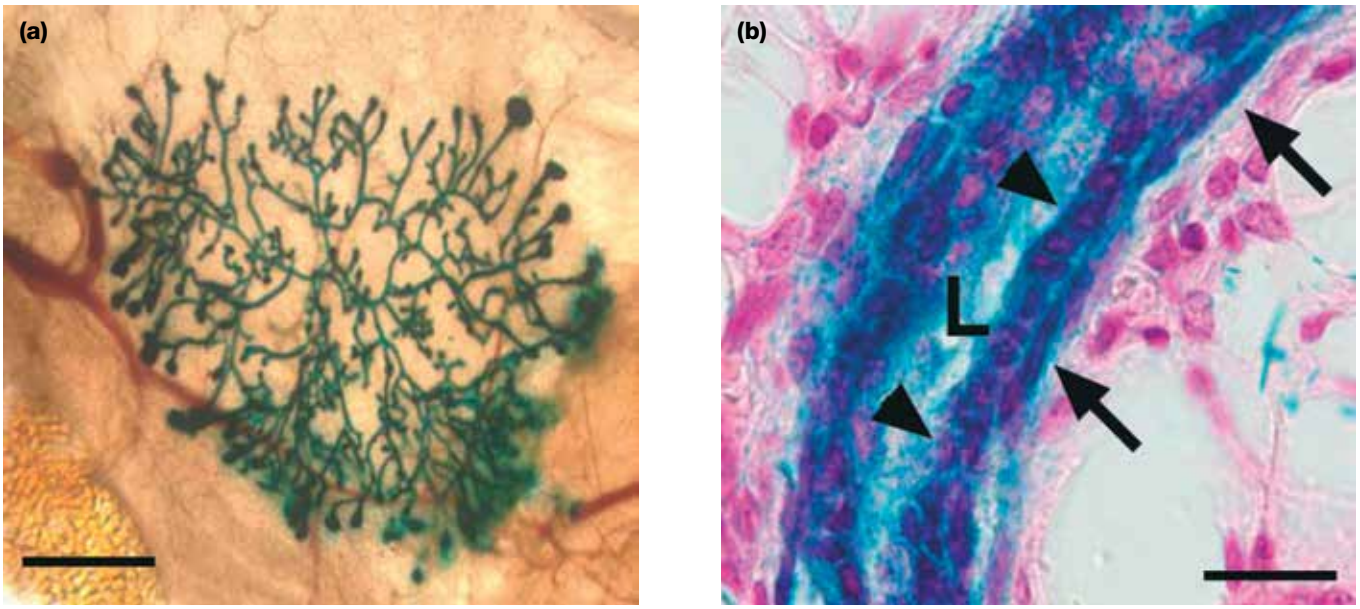

FIGURE 12.15 **(a)** Branching mammary gland produced from a single mouse breast stem cell **(b)** Section through mammary tissue produced from stem cell with different cell types shown by arrows (L = lumen)

Therapeutic cloning

The purpose of **therapeutic cloning** is to produce stem cells for use in treatment.

Therapeutic cloning involves the creation of an embryo, through the technique of somatic nuclear transfer, for the purpose of obtaining stem cells from that embryo. These stem cells are intended for use in treating a patient who has a degenerative disease. The cell that provides the nucleus in therapeutic cloning is a healthy cell from the patient who is to receive treatment. As a result, the embryo that is created is a genetic match to the patient and these cells do not cause an immune response. Figure 12.16 shows the process of therapeutic cloning.

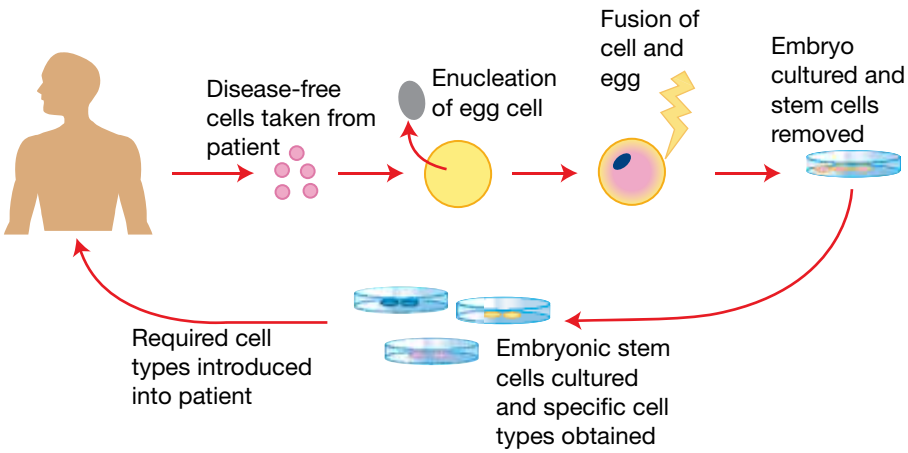

FIGURE 12.16 Therapeutic cloning involves the creation of an embryo that is genetically identical to a patient. The patient's cell is fused with an enucleated egg cell and develops into an early embryo. Stem cells are then taken from the inner cell mass of the early embryo (blastocyst) and grown in culture as pluripotent stem cells. Would these cultured cells be expected to cause an immune response if injected into the patient? Why?

The use of early embryos as a source of stem cells **raises ethical issues** because establishing an embryonic stem cell line destroys an embryo. Likewise, ethical issues arise for therapeutic cloning because this procedure involves the artificial creation of an embryo solely for the purpose of obtaining stem cells, a process that then destroys the embryo.

In December 2002, the *Research Involving Human Embryos Act 2002* was passed in the Australian Parliament. This Act established a framework that regulated the use of 'excess' embryos. Provisions of this Act included the statement that 'embryos cannot be created solely for research purposes'. Under the provisions of this Act, therapeutic cloning was not permitted in Australia. However, in December 2006, the legislation was amended with Parliament lifting the ban of the cloning of human embryos for stem cell research and allowing therapeutic cloning to be undertaken.

KEY IDEAS

- Stem cells are undifferentiated or unspecialised cells that have the ability to differentiate into organ- or tissue-specific cells with specialised functions and to self renew.
- Stem cells include embryonic stem cells and somatic (adult) stem cells.
- Stem cells from different sources differ in their potency or ability to produce differentiated cells of various types.
- Therapeutic cloning is the creation, through the technique of somatic nuclear transfer, of an embryo for the purpose of obtaining stem cells from that embryo.
- Regenerative medicine is still at an experimental stage but it raises promises for the treatment of degenerative conditions and severe trauma injuries.

QUICK CHECK

6 What is the difference between the members of the following pairs?
- **a** Totipotent and pluripotent
- **b** Undifferentiated and differentiated
- **c** Embryonic stem cell and somatic (adult) stem cell

7 Identify one source of embryonic stem cells.
8 List two sources that could be used to obtain somatic (adult) stem cells.
9 What is a parthenote?

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Abnormal embryonic development

Abnormalities arising during antenatal development are described as congenital malformations or birth defects. One estimate is that about three percent of babies are born with a congenital abnormality. Some of these cause the death of a baby soon after birth, while others leave the child with a lifelong defective function, either physical or physiological. Some congenital malformations can be treated by surgery, such as cleft lip and palate, or by other forms of treatment.

Congenital defects arise in several ways and may be due to:

1. *genetic factors*. Genetic factors include single gene defects and chromosomal abnormalities
   - Single-gene defects are usually inherited, for example, phenylketonuria and cystic fibrosis, which most commonly appear in newborns of unaffected parents who are heterozygous carriers of the allele involved.

     In other cases, the single gene defect may be the result of a mutation in one of the gametes involved in fertilisation. For example, a form of

dwarfism, known as achondroplasia, is a dominant trait, with about 80 per cent of cases being due to such a mutation.

- Chromosomal abnormalities, such as the presence of an extra copy of a chromosome so that instead of the normal two copies of an autosome, three copies are present — a condition termed trisomy. Examples of these chromosomal abnormalities surviving to birth are found in Down syndrome ($2n$ = 47, +21), Edward syndrome ($2n$ = 47, +18), and Patau syndrome ($2n$ = 47, +13).

  These chromosomal abnormalities arise as a result of the disruption of the normal cell cycle, either during gamete formation by meiosis, or during the early cell divisions of the embryo by mitosis. If the DNA is damaged in cells undergoing mitosis, cell division is held up at the G1 checkpoint to prevent replication of damaged. DNA cell division is normally held up at another checkpoint to ensure that homologous chromosomes are attached to the correct spindle fibres. This means that, normally, cell division continues only when DNA is not faulty and when homologous chromosomes are attached to the correct spindle fibres so that at anaphase they disjoin to opposite poles of the spindle. In chromosomal abnormalities, the normal operation of this second checkpoint breaks down so that two copies of a chromosome move to the same pole of the spindle.

  Research has shown that the risk of an egg with a chromosomal abnormality is much higher in older women than in younger women (see figure 12.17). This suggests that the operation of checkpoints is more at risk of malfunctioning in older women that in younger women.

In some cases, interactions may occur between genetic factors and environmental factors.

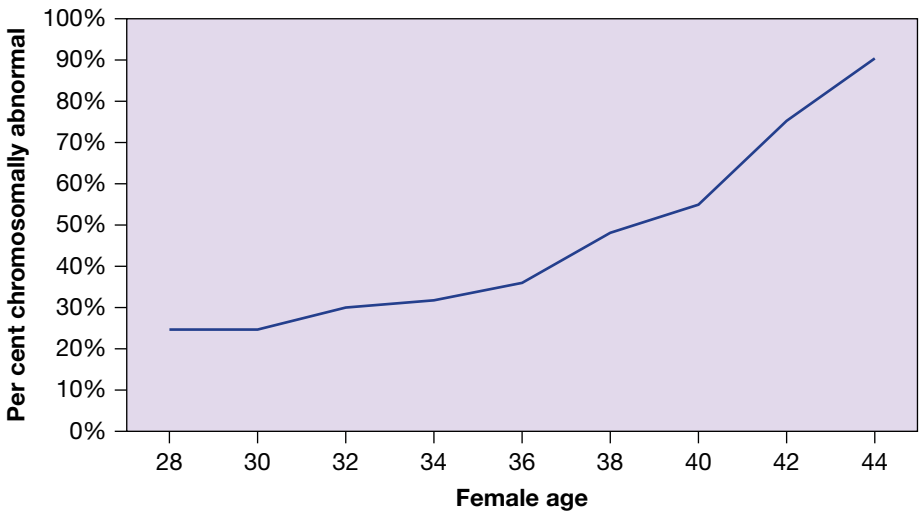

FIGURE 12.17 Graph showing the increase in production of chromosomally abnormal eggs with increasing maternal age

2. *environmental factors*. Environmental factors that can result in a birth defect are known as teratogens, for example, chemicals in the pregnant woman's bloodstream that reach the developing embryo, such as thalidomide (refer to p. 467).

   Other known teratogens include physical agents such as radiation, hyperthermia (resulting from use of hot tubs, saunas); viral infections, such as rubella (German measles); drugs and chemicals such as alcohol and

FIGURE 12.18 Kazumitsu Hannaga, a congenital Minamata disease patient, at Meisui-en Hospital, Minamata, 1991. The hospital opened in 1972 to care for Minamata victims.

cocaine; and seafood with a high mercury content. Factors such as maternal diabetes, smoking or malnutrition can also contribute to the development of birth abnormalities. A dietary deficiency may result in a birth defect, for example, a deficiency of vitamin A; in experiments using pigs exposed to a vitamin A-deficient diet, offspring were born with the absence of one or both eyes, and with cleft palates.

One tragic example of the action of a teratogen is the methylmercury poisoning that occurred in Minamata Bay, Japan for several decades as a result of unchecked industrial pollution. As well as affecting adults who ate fish with high levels of methyl mercury, pregnant women gave birth to babies with severe congenital abnormalities (see figure 12.18).

The earlier in the stages of development that exposure to a teratogen occurs, the more serious its effects will be. In some cases, spontaneous miscarriage may occur even before a woman is aware that she is pregnant.

3. *unknown factors.* In some cases, the cause of a birth abnormality may be unknown.

Cancer and the cell cycle

In the healthy body, some cells can divide to produce new cells and this process usually occurs in an orderly and carefully controlled manner. This normal process enables the body to grow during childhood and adolescence, and to replace damaged, dead or lost cells during adulthood.

In contrast, **cancer** is a disease in which cells divide in an uncontrolled manner, forming an abnormal mass of cells (see figure 12.19). Cancer cells are out of control because of mutations in their genes that result in a breakdown of the normal regulation of the cell cycle. So cancer is a disease that results from the loss of control of the cell cycle.

ODD FACT

The first teratogen that was not a chemical was identified in 1941 by an Australian physician, Norman Gregg. He recognised the link between the rubella virus infection of mothers during the first two months of their pregnancies and the occurrence of eye defects in their newborn babies.

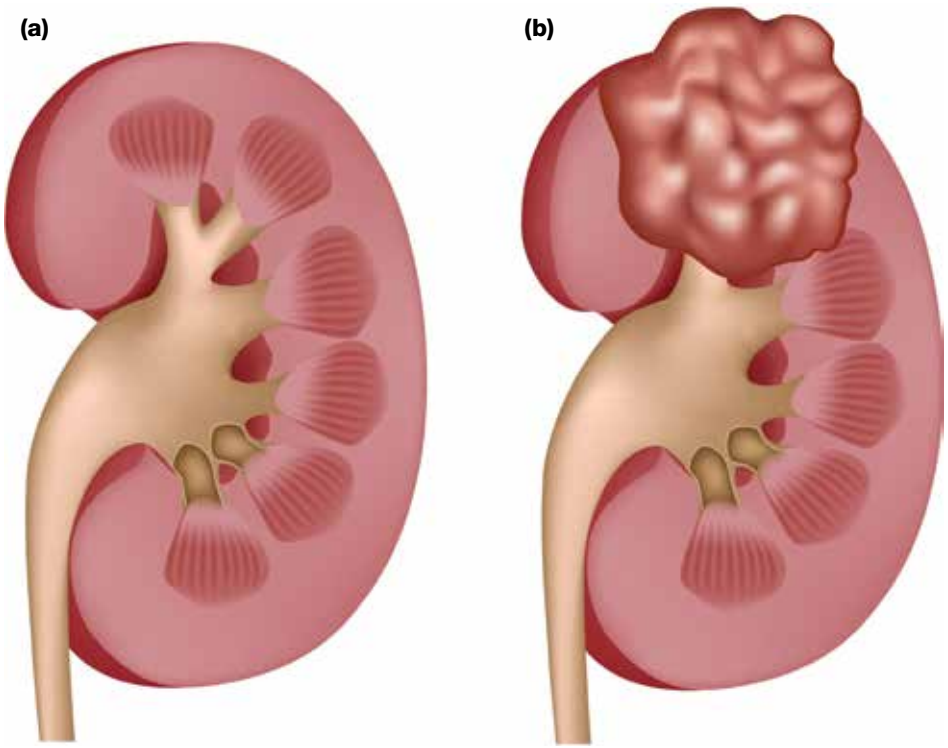

FIGURE 12.19 Section through human kidney: **(a)** normal kidney and **(b)** kidney with cancer growing

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Normal control or regulation of the cell cycle involves several mechanisms including:

- Checkpoints, such as the G1 checkpoint, ensure that the replication of chromosomal DNA is error-free. If errors such as lesions, breaks or other damage are found, the progress of the cell cycle is delayed to allow the DNA to be repaired.
- Proteins, known as cyclins, ensure that chromosomes are attached to the correct spindle fibres so that an equal distribution of chromosomes to daughter cells occurs.
- Normal cells display so-called '**contact inhibition**', which means they will stop dividing if they begin to overgrow adjacent cells.
- Chemical signals convey information to cells about when to divide faster and when to slow down or stop dividing. Two kinds of genes are involved in this signalling: (1) **oncogenes** that signal cells to continue dividing and (2) **tumour suppressor genes** that signal cells to stop dividing. Mutations of these genes would be expected to disrupt the control of the cell cycle.
- If cells are chromosomally abnormal or are damaged, they receive a signal to self-destruct in a process known as **programmed cell death** or apoptosis.

In cancer cells, however, these various controls of the cell division cycle are lost and the cells do not respond to signals to stop dividing. Instead, cancer cells divide in an uncontrolled manner, forming tumours that damage the surrounding healthy tissues. Cancer cells do not show 'contact inhibition' but will overgrow existing cells. While some tumours are benign, others are malignant because cells from these tumours can enter the bloodstream or lymphatics and spread to other regions of the body — a process known as **metastasis** (see figure 12.20).

Many cancers have a genetic component. Some cancers are inherited, for example, retinoblastoma, a cancer of the eye. In other cases, the presence of a particular gene can increase the risk of occurrence of a cancer (see table 12.3). The **BRCA1** and **BRCA2** genes are rare, but between 45 and 90 per cent of women with one of those genes develop breast cancer. These genes also increase the risk of ovarian cancer. The **BRCA2** gene in men increases their risk of developing breast or prostate cancer. However, it should be noted that these genes are involved in only a small percentage of cancers of a particular organ; for example, less than 3 per cent of breast cancers are caused by a faulty gene.

TABLE 12.3 Some genes that are associated with an increased risk of developing cancer in a specific tissue

Genes that increase risk	Associated cancer
APC, MYH	bowel cancer
BRCA1, BRCA2	breast and ovarian cancer
VHL, TCS1, TCS2	kidney cancer
FAMMM, CDKN2A	melanoma

ODD FACT

Cancer Research UK suggests that around 4 out of 100 cancers (4%) are linked to alcohol. It increases the risk of mouth cancer, liver cancer, breast cancer, bowel cancer and throat cancer.

The majority of cancers result from the action of environmental factors, such as exposure to ultraviolet (UV) radiation, carcinogenic chemicals in cigarette smoke, viruses and diet. Tobacco use in combination with excessive alcohol consumption is a risk factor in the development of oral cancer (cancer of the mouth). These environmental factors cause gene mutations and so can be called **mutagens**.

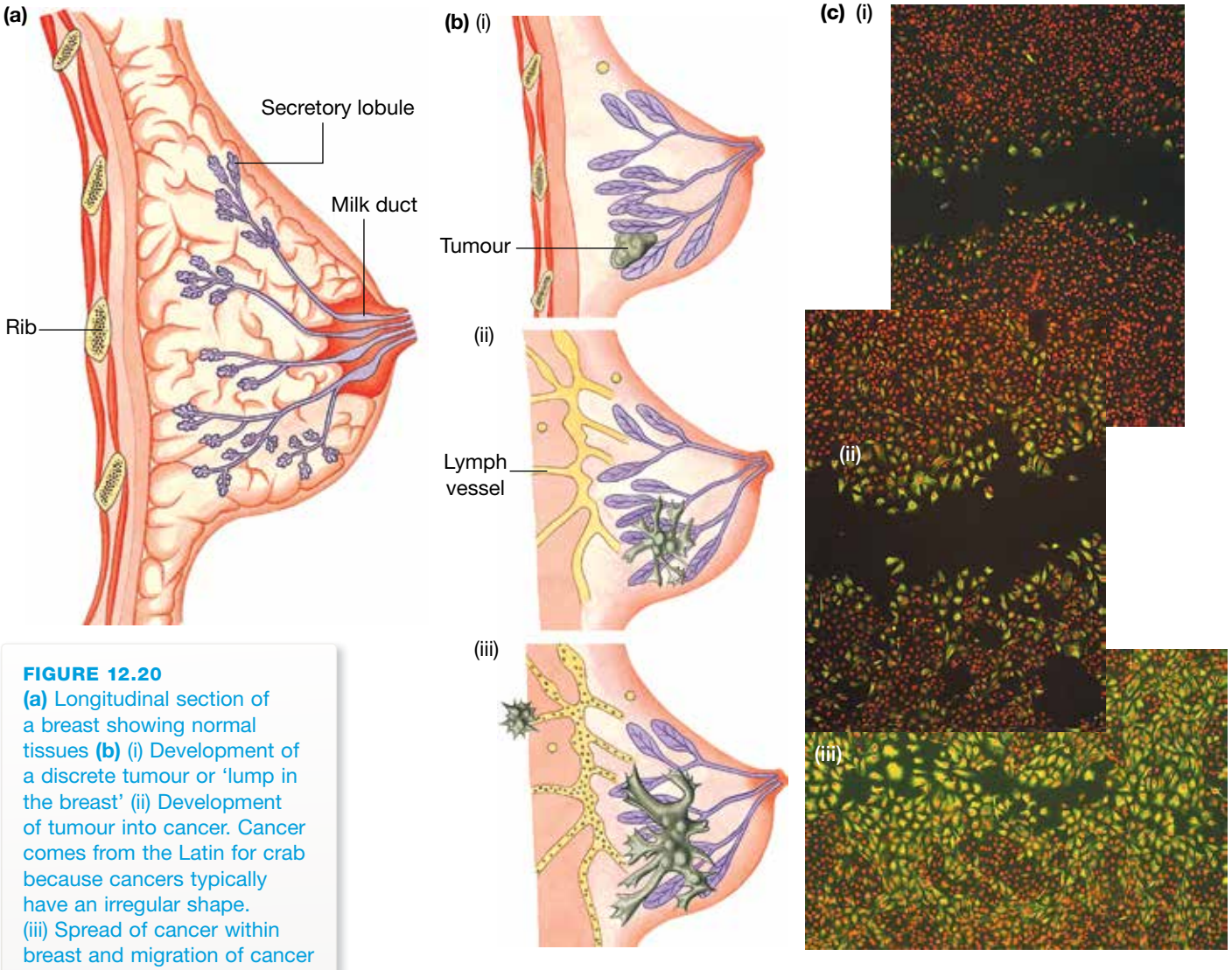

FIGURE 12.20
(a) Longitudinal section of a breast showing normal tissues **(b)** (i) Development of a discrete tumour or 'lump in the breast' (ii) Development of tumour into cancer. Cancer comes from the Latin for crab because cancers typically have an irregular shape. (iii) Spread of cancer within breast and migration of cancer cells from the breast through lymph vessels and blood vessel to new sites where secondary cancers develop, the process of metastasis. **(c)** Spread of breast cancer cell *in vitro*, that is, in a cell culture in the laboratory. Migrating cancer cells show the presence of a specific protein, vimentin, that stains green and is not present in normal cells. Note how the cancer cells (green) migrate and multiply filling the space and crowding out the normal cells (red). (Image courtesy of Professor Leigh Ackland)

KEY IDEAS

- **Abnormalities arising during antenatal development are described as congenital defects.**
- **Congenital defects may be due to genetic or environmental factors or be of unknown origin.**
- **Teratogens are physical, chemical or biological agents that can cause birth defects.**
- **Cancer is a disease that results from the loss of normal control of the cell cycle, resulting in an uncontrolled growth of cells.**

QUICK CHECK

10 Identify two of the control mechanisms that are in place in normal cells to prevent uncontrolled growth by cell division.
11 What was the teratogen that caused Minamata disease?
12 What is a mutagen?
13 Give two examples of environmental agents that are believed to act as mutagens.

BIOCHALLENGE

Cell growth and cell differentiation

1 The following statement appeared in an article by IR Fox et al., 'Use of differentiated pluripotent stem cells in replacement therapy for treating disease', which was published in the journal *Science* on 22 August 2014.

> Unlimited populations of differentiated PSCs [pluripotent stem cells] should facilitate blood therapies and hematopoietic stem cell transplantation, as well as the treatment of heart, pancreas, liver, muscle, and neurologic disorders. However, successful cell transplantation will require optimizing the best cell type and site for engraftment, overcoming limitations to cell migration and tissue integration, and possibly needing to control immunologic reactivity.

Consider this statement and answer the following questions.

- **a** What challenges must be overcome before the use of PSCs can become a routine clinical practice?
- **b** What is meant by the phrase 'overcoming immunologic reactivity'?
- **c** If this article was about the use of induced pluripotent stem cells (iPSCs), would immunologic reactivity be a challenge? Explain your response.

2 Fetal stem cells were used to treat a boy with the genetic disorder, Ataxia Telangiectasia (A-T), a rare neurodegenerative disease that produces significant disability including poor coordination, a weakened immune system and a breakdown in the DNA repair mechanism so that an affected person's risk of cancer is increased.

Four years after the treatment with these stem cells, the boy developed abnormal growths in his brain and spinal cord. This rare event was believed to have been a result of the boy's weakened immune system. Fortunately these tumours were benign and were able to be surgically removed.

- **a** When the tumours were removed, it was found that they were a result of the treatment, not an independent event that occurred in the boy. How might this have been determined?
- **b** Person A commented: 'The use of stem cell therapy should be stopped. No further research should be done'.

Person B commented: 'More research is needed with a focus on the safety of stem cell therapy, finding out what can potentially go wrong and developing safeguards to reduce any risks'.

With which person do you agree, and why?

3 One form of stem cell therapy that has been in use for decades is the use of stem cells (see figure 12.21) from bone marrow transplants for treatment of disorders of the blood and the immune system, as well as the acquired loss of bone marrow function. Advanced techniques are in practice for collecting blood stem cells and their use is well established clinically. In contrast, other stem cell therapies are still experimental.

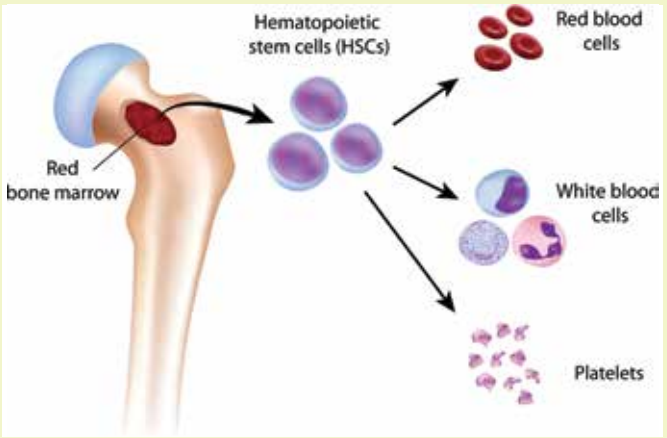

FIGURE 12.21

- **a** What is the difference between a *clinical* procedure and an *experimental* procedure?
- **b** Suggest why stem cells from bone marrow have been used for treatment of blood and immune disorders for decades while stem-cell therapies for other conditions are still experimental.

Chapter review

Key words

adult stem cell
antenatal
birth defect
blastocyst
cancer
cell-based therapy
congenital malformation
contact inhibition
corpus luteum
differentiation
ectoderm
embryo
embryonic development
embryonic stem cell
endoderm
estrogen
fertilisation
fetal development
fetus
follicle
follicle-stimulating hormone
gastrulation
germ layer
gestational age
induced pluripotent stem cell
inner cell mass
menstrual age
mesoderm
metastasis
multipotent
mutagen
oligipotent
oncogene
ovulation
parthenote
pluripotent
programmed cell death
regenerative medicine
somatic (adult) stem cell
stem cell
teratogen
thalidomide
therapeutic cloning
totipotent
tumour suppressor gene
unipotent
zygote

Questions

1 **Making connections** ➜ Use at least eight chapter key words to draw a concept map. You may use other words to draw your map.

2 **Demonstrating knowledge** ➜ Stem cell therapy is a treatment that uses stem cells, or cells that come from stem cells, to replace or to repair damage to a patient's cells or tissues. The stem cells might be put into the blood, or transplanted into the damaged tissue directly, or even recruited from the patient's own tissues for self-repair.
- **a** What differentiated cells might come from stem cells in the case of pluripotent stem cells?
- **b** What differentiated cells might come from unipotent stem cells?
- **c** Outline one procedure by which a patient's own cells might be recruited for self-repair.
- **d** Which, if any of these procedures, would not entail the problem of immunological reactivity?

3 **Interpreting graphical data** ➜ Refer to figure 12.8 on page 468.
- **a** Which organ is most susceptible to damage over the most extended period of antenatal life?
- **b** Which organs would be susceptible to damage by teratogens in the embryonic period only?
- **c** What level of damage (major, minor or nil) would you predict from exposure to a teratogen as follows?
  - i To ears in weeks 10 to 12
  - ii To limbs in weeks 4 and 5
  - iii To palate in weeks 5 and 6
  - iv To an embryo in week 2
- **d** A newborn has a cleft lip and a cleft palate. Over what period might exposure to a teratogen have occurred to produce this birth defect?

4 **Making comparisons** ➜ What is the difference between the members of the following pairs?
- **a** Embryonic stem cells and somatic stem cells
- **b** Parthenote and fertilised egg
- **c** Totipotent and multipotent
- **d** Induced pluripotent stem cell and pluripotent stem cells

5 **Applying your understanding** ➜ In 2012, researchers at Harvard University's School of Public Health and Boston University's Slone School of Epidemiology compared the birth outcomes of 4524 pregnant women who had been prescribed anti-nausea medication ondansetron during the first trimester to those of 5859 women who had not sought medical treatment for morning sickness. They found that women who had taken ondansetron as a morning sickness treatment were 2.37 times more likely to deliver babies with a cleft palate. (*Source:* http://montco.legalexaminer.com/2015/04/09/causes-cleft-lip-palate)
- **a** What tentative conclusion might be drawn from this observation?
- **b** What further research, if any, might be done to provide further evidence in support of your conclusion?

6 Interpreting data ➜ Figure 12.22 shows the number of scientific publications in the domain of stem cell research in the period from 1996 to 2012. (ESC: embryonic stem cells; hESCs: human embryonic stem cells; iPSCs: induced pluripotent stem cells)

- **a** Explain why global research publications on iPSCs appear much later than research publication on hECSs.
- **b** What area of stem cell research dominates the publications?
- **c** By what approximate factor has the number of research publication on iPSCs increased in the period from 2008 to 2012?
- **d** In what year did the total number of publications on stem cells of all types first exceed 10 000?

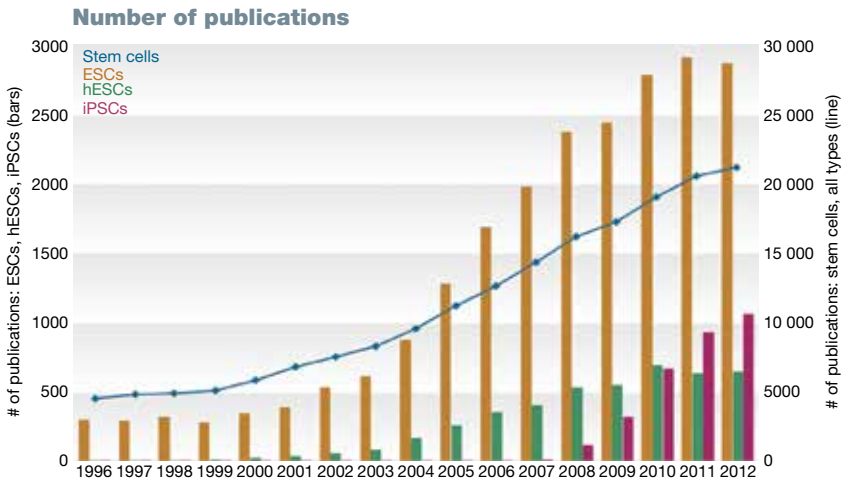

FIGURE 12.22

7 Analysing information ➜ Figure 12.23 shows the distribution of causes of congenital malformations.

- **a** Give one example of each of the environmental factors listed in this chapter.
- **b** Two types of genetic causes exist. What are they?

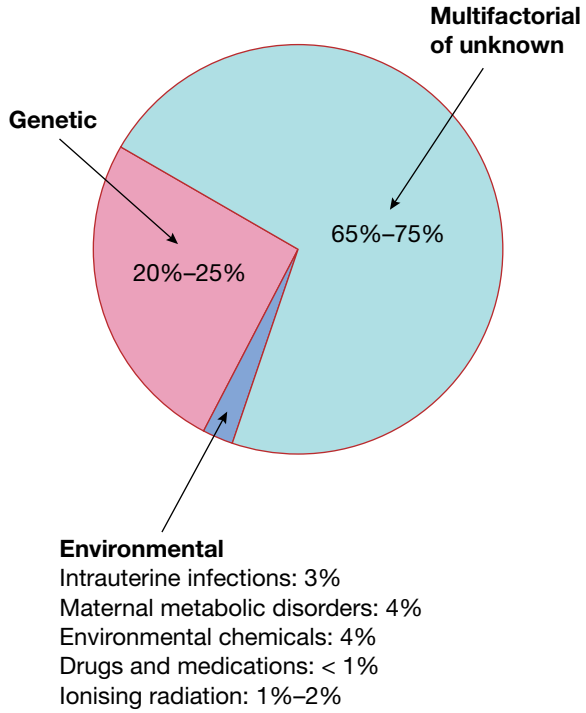

FIGURE 12.23

8 Demonstrating understanding ➜ Outline the events that can initiate the conversion of a normal cell to a cancer cell.

CHAPTER

13 Genomes, genes and alleles

FIGURE 13.1 The completion of the sequencing of the platypus genome was announced on the front cover of the science journal *Nature* of 8 May 2008; this is just one of the several thousand genomes that have been sequenced. In this chapter we will explore the Human Genome Project, identify how the field of genomics provides data that are being mined to produce new insights in many areas, including evolutionary relationships and the improved diagnosis and treatment of inherited human diseases.

KEY KNOWLEDGE

This chapter is intended to enable students to:

- recognise that the genome of an organism is the total base sequence of its genetic material, DNA
- gain knowledge of the Human Genome Project
- give examples of the actual and potential uses of genomics research
- gain knowledge and understanding of the concept of genes and the history of their elucidation
- identify the difference between genes and their alleles.

What is a genome?

In the journal *Science* in 1910 (vol. 32, p. 120) Thomas Hunt Morgan (1866–1945), an American geneticist, published the first experimental evidence that genes are located on chromosomes. Morgan put into place the first piece of a giant jigsaw by showing the gene for white eye colour in the fruit fly (*Drosophila melanogaster*) is located on its X chromosome. At that time, no one knew just what a gene was, but locating genes on chromosomes showed that they were physical entities.

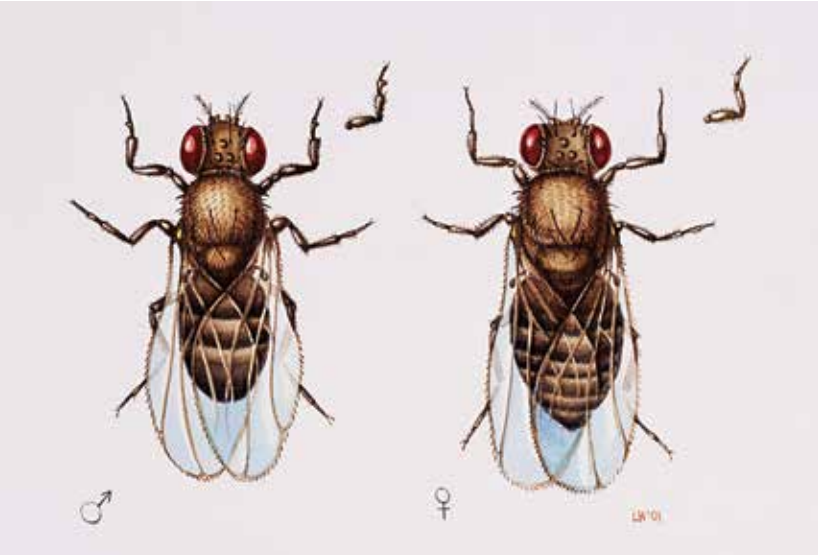

FIGURE 13.2 This image shows a male (left) and female (right) fruit fly.

Morgan would have been amazed to know that just 90 years later the genetic jigsaw of his fruit flies was complete. In the 24 March 2000 issue of the same *Science* journal the base sequence of the entire DNA of the *Drosophila* chromosomes was published. This base sequence is expressed using just four letters: A, T, C and G. The base sequence contains the complete set of genetic instructions of the fruit fly (see figure 13.2) and is called its **genome**.

The genome of an organism is its complete set of genetic instructions, encoded in DNA. For humans, the haploid genome consists of the DNA of the haploid set (22) of autosomes plus the sex chromosomes. The human genome has been variously described as 'the book of life', 'humanity in chemical language' and the 'instructions to make a human'.

Similarly, the genomes of other eukaryotes (animals, plants, fungi and protists) are the DNA of the haploid sets of their chromosomes. When we refer to the genome of a eukaryotic organism, such as the chimp genome or the rice genome, we are speaking about the nuclear DNA. We can also talk about the genomes of those cell organelles that contain DNA, such as the mitochondrial genome or the chloroplast genome.

The genomes of prokaryotes (bacteria and archaea) comprise the DNA of their single circular chromosome that carries the genetic instructions of each species. The genomes of viruses consist of their entire genetic instructions encoded in one DNA molecule, or, in the case of **retroviruses**, in one RNA molecule.

The field of study of genomes is called **genomics**. **Each genome is the sum total of an organism's DNA and is expressed as the base sequence of the haploid set of chromosomes.**

ODD FACT

In October 2004, a scientific description of the human genome was published in which the number of protein-coding genes was identified as being in the range of 20 000 to 25 000, down from an expected 35 000 genes. The figure generally accepted is 'about 21 000 genes'.

The Human Genome Project

Start counting! One, two, three . . . one million . . . three billion. To reach that three billion counting at one number per second would take about 95 years. Three billion is the approximate number of bases in the total DNA of a haploid set of human chromosomes, the human genome. Every human egg and sperm cell has a copy of the haploid genome and every nucleated somatic cell in the human body has a copy of the diploid human genome.

The international cooperative and publicly funded research project known as the **Human Genome Project (HGP)** began in 1990 (see figure 13.3). Its aim was to sequence the human genome, to store the sequence in accessible

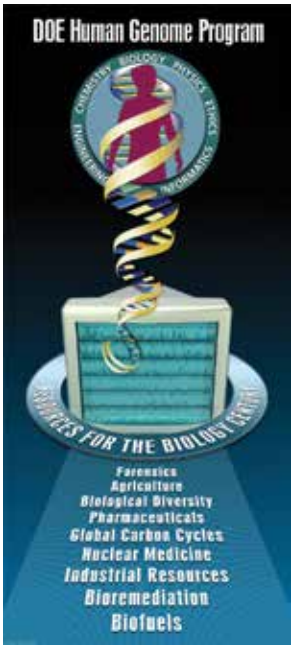

FIGURE 13.3 The HGP began in 1990. This image shows the logo for this project and identifies many areas that were seen as benefitting from the results of the project.

databases and to map all the human genes. **When a genome is sequenced, it means that the precise order or sequence of bases in the DNA of the genome has been identified**, with the error rate in the final sequence being less than one base in every 10 000 bases. Research groups in several countries, principally the United States, United Kingdom, France, Germany and Japan, undertook the sequencing of individual human chromosomes. The HGP was 'big science' that could only be undertaken by involving many scientists from different laboratories around the world, working cooperatively.

In December 1999, chromosome 22 became the first human chromosome to be sequenced and it was found to have just 51 million bases and carry 431 genes. Six months later, in May 2000, chromosome 21 was also sequenced and its 48 million bases were found to contain 225 genes, far fewer than expected. In contrast chromosome 1, the largest human chromosome, has almost 250 million bases with at least 2100 genes.

In June 2000 the first working draft of the human genome was announced (see figure 13.4). In February 2001, a draft sequence that covered more than 90 per cent of the human genome was published in the journal *Nature*. The HGP formally ended in April 2003 when the final version of the human genome sequence was completed.

In revealing the sequence of the entire genetic instructions that make us human, the HGP stands as one of the greatest scientific explorations ever carried out. In announcing the first draft of the human genome in June 2000, US President Clinton described this achievement as being 'the most important and most wondrous map ever produced by humankind'.

FIGURE 13.4 In June 2000, Francis Collins, of the US National Institutes of Health (NIH) and leader of the Human Genome Project (right), and Craig Venter, founder of the private company Celera Genomics (left), stood alongside US President Clinton to jointly announce the mapping of the human genome. British Prime Minister Blair was also involved in this announcement through a satellite link.

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What does a genome look like?

The first human genome sequence was completed using DNA from anonymous donors from diverse populations. Since then, complete sequences of the genomes of hundreds of persons have been completed and published, including that of James Watson, the co-discoverer of the double helical structure of DNA. **Sequencing is the process of identifying the order of the bases in DNA**. Technological advances, such as the development of new generation **DNA sequencers**, have made the process of sequencing genomes both quicker and cheaper (see figure 13.5). To complete a full human genome sequence in 2015 costs a few thousand dollars — a lot cheaper than the billions of dollars, and much faster than the 13 years, required to produce the first human genome.

FIGURE 13.5 A new generation high-speed DNA sequencer that rapidly reads the sequence of DNA input to this system

Benefits resulting from the HGP include positive impacts on medicine and other areas of human biology:

- *Diagnosis.* Data from the HGP are being used to provide improved and more accurate diagnoses of inherited disorders due to single genes. In 2013, researchers identified a mutated gene, **CALR**, that is present in 40 per cent of people with certain chronic blood cancers. This discovery will enable such people to be diagnosed more quickly and accurately.
- *Treatment.* Data from the HGP are being used to identify the products of genes and infer how mutant alleles produce the undesirable effects of inherited disorders. Such understanding will generate new treatments for inherited disorders as well as improve accuracy of diagnosis.
- *Prevention.* Data from the HGP are identifying genetic factors that predispose some people to disabling conditions, such as strokes and cancers. This knowledge is expected to identify people at risk and develop treatments to reduce the incidence of these conditions. It is of interest to note that in a recent survey of nearly 7000 people, 98 per cent of them stated that they would want to be told if a researcher found that their genomes contained an indicator of a serious treatable or a serious preventable disease (see Biochallenge, p. 518).
- *Human biology.* Data from the HGP provide better understanding of the genetic control of normal human development; for example, the Deciphering Developmental Disorders (DDD) project, a 5-year research project that began in 2011 in the United Kingdom, is collecting genomic

data from a large sample of children with multiple malformations or with significantly delayed physical or mental development. The researchers will use this genomic information to identify any genetic bases for these conditions with the intention of achieving improvements in the diagnosis and the care of such children. In December 2014, researchers on the DDD project announced the identification of the first 12 genes found to cause these rare but serious developmental disorders.

- *Human evolution.* Mitochondrial DNA sequence data are providing new insights into aspects of human evolution and the prehistoric migrations of human groups. The sequencing in December 2013 of the genome of a Neanderthal female (*Homo neanderthalensis*) provided the first genomic information about a first cousin to modern humans (*Homo sapiens*).

While the HGP has officially ended, ongoing research continues including deciphering the functions of the various parts of the human genome, identifying how and when genes function and how they are controlled. Because of the enormous amount of data involved, computers are needed for the storage, retrieval and analysis of genomic data.

Many projects have built on the HGP database, such as the DDD project mentioned previously. Other projects include:

- *the 1000 Genomes Project.* This project aims to sequence the genomes of at least a thousand people from around the world in order to develop a new map of the human genome that will highlight biomedically relevant DNA variations. These variations may be in protein-coding genes, but they may also be in regions of the genome that include gene promoters and enhancers which control whether genes are switched on or off and, if switched on, the level of gene activity.
- *the Cancer Genome Anatomy Project.* This project (see figure 13.6) aims to determine the patterns of gene expression of normal, precancer and cancer cells, including the identification of genomic changes seen in various tumours as compared with normal cells. This information is leading to improvements in the early detection, diagnosis and treatment of patients with cancer.
- *the International HapMap Project.* The aim of this project is to develop a haplotype map of the human genome that will identify the common patterns of human DNA sequence variation and to identify genes affecting health, disease and responses to drugs.
- *the Encyclopedia of DNA Elements (ENCODE) Project.* This project involves many hundreds of scientists worldwide working collaboratively. Its aims are to identify of all the biochemically active DNA of the human genome. To date, scientists have identified biochemical functions for about 80 per cent of the genome.

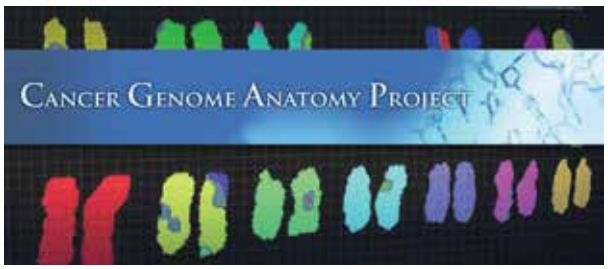

FIGURE 13.6 The Cancer Genome Anatomy Project (CGAP) is an online resource that holds data on gene expression in normal, precancer and cancer cells, and is available to researchers worldwide.

Apart from large-scale studies, genomic information can be used at an individual level where, along with a person's family history and information about their lifestyle, the risk for a particular disease can be estimated. In addition, people differ in their responses to various pharmaceutical drugs. As genomic information becomes more widely available, this is expected to lead to decisions about aspects of medical care becoming more personalised, for example, about which drugs to prescribe and what dosages to administer.

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What does the HGP tell us?

Every person — apart from identical twins — has a unique genome, but the genomes of all members of the human species *Homo sapiens* share many similarities. It is estimated that the genomes of two unrelated people will on average have about three million differences. Sounds like a lot, but it is not as

this means they differ by only one base pair in a thousand, or 0.1 per cent. Put another way, the genomes of two unrelated people are 99.9 per cent the same (see figure 13.7).

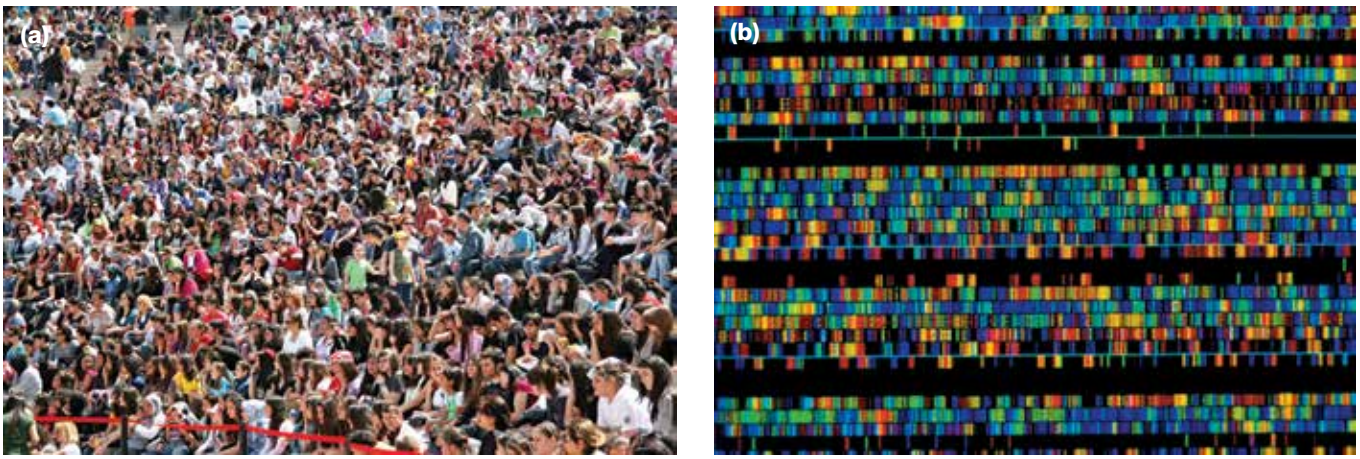

FIGURE 13.7 **(a)** Each person in this group has a unique genome but, as humans, their genomes are 99.9 per cent similar. How many of the 3 billion bases in the human genome are represented by a difference of 0.1 per cent? **(b)** A colour-coded computer rendering of the base sequence of a fragment of DNA of the human genome. It is *not* possible to fit the complete 3 billion bases on a single screen display. How many different colours are needed to represent the bases involved?

Many of the differences between the genomes of different people are single-base differences in the DNA sequences of their genomes (see figure 13.8). When a particular variant appears in at least 1 per cent of the population, it is called a **single nucleotide polymorphism** (SNP, pronounced 'snip'). When SNPs occur in a protein-coding region of DNA, they can alter the function of the protein and result in an inherited disorder. However, most SNPs occur in the noncoding region of the DNA.

FIGURE 13.8 Matching parts of the DNA sequence in the genome of two people. There is just a single difference (shown arrowed) in one of the DNA strands (and of course in the complementary strand). Differences of this type between genomes are known as SNPs.

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Other differences that exist between people's genomes include the number of repeats of short DNA sequences, typically 3 to 5 nucleotides long, known as **short tandem repeats (STRs)** — this difference has important forensic applications.

The HGP revealed various facts about the human genome, for example:

- *How big?* About 3 000 000 000 bp (3 billion base pairs) organised as a DNA double helix of the chromosomes. The full print-out of the 3 billion plus base sequence of the entire human genome fills 116 volumes, each with about 1000 pages and printed in very small type. The base sequence of chromosome 1, the largest human chromosome, fills nine volumes, while the base sequences of the smallest chromosomes, 21 and 22, and the Y chromosome fill just two volumes each. Figure 13.9 shows these volumes at the Wellcome Collection in London.

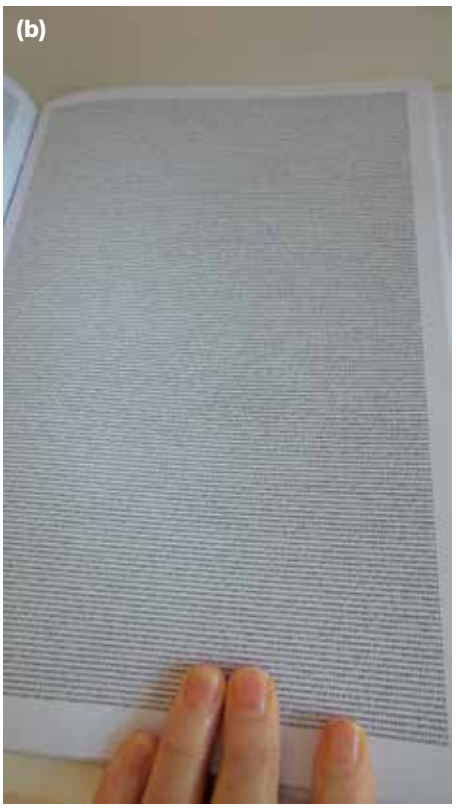

FIGURE 13.9 **(a)** The print-out of the HGP in the Wellcome Collection's 'Medicine Now' exhibition contains 116 volumes, which have the complete set of genetic instructions to make a human being. In what language are these books written? **(b)** One page from the chromosome 6 volume. Note the very small typeface.

- *How many genes?* There are about 21 000 genes located on the DNA of the 22 nonhomologous autosomes and the X and Y sex chromosomes. Possible genes are identified by computer scans of a chromosomal DNA sequence that looks for a start signal (TAC) followed by a long sequence before a stop signal is reached. Such sequences are called **open reading frames** (ORFs) and indicate possible genes.
- *What do these genes do?* The majority of the genes on a chromosome are **protein-coding genes** that are transcribed into messenger RNA (mRNA) molecules; these in turn are translated into polypeptide chains. Surprisingly, these protein-coding genes constitute less than 2 per cent of the total genome! In addition, there are genes that are transcribed into other kinds of RNA, including **ribosomal RNA (rRNA)**, which forms part of the ribosomes, and **transfer RNA (tRNA)**, which is involved in the synthesis of proteins in a cell. Together, these two kinds of gene make up just a small percentage of the human genome. This means that the bulk of the human genome is **noncoding DNA**.
- *What are the functions of the noncoding DNA?* The function of much of the noncoding DNA is not known. However, some of the DNA sequences in the genome are regulatory elements, including so-called **promoters** and **enhancers** that govern when a gene is active and its level of expression. Other noncoding DNA is present in the telomeres at the chromosomal ends and these are important in maintaining chromosome structure. Yet other noncoding DNA comprises multiple repeats of short DNA sequences.

ODD FACT

Noncoding DNA was formerly called **'junk' DNA**. Far from being junk, this DNA plays an important role in cells.

Sequencing of other genomes

By the end of 2014, the complete genomes of more than 15 000 different species had been sequenced, either completely or as permanent drafts. Scientific journals regularly include papers on the complete sequencing of the genome of various species; for example, in 2008 the completion of the platypus genome was announced (refer to figure 13.1).

eBook*plus*

Weblink
The Human Genome Project

Table 13.1 lists a few key species whose genomes have been sequenced. In addition, the genomes of the mitochondria of several species, including the human mitochondrial genome (16 568 bp), have been sequenced, as have the chloroplast genomes of several plant species. GOLD (**G**enomics **O**n**L**ine **D**atabase) identifies all genomes that have been completely sequenced as well as those for which the sequence is incomplete.

TABLE 13.1 Dates of complete sequencing of genomes of a virus and species from the three domains (Bacteria, Archaea and Eukarya)

Organism	Date published	Size of genome (base pairs, bp)	Estimated number of coding genes	Comment
virus phiX174	Apr. 1993	5 386	11	first genome sequenced
Haemophilus influenza (bacterium)	July 1995	1 830 000	1 850	first bacterium
Saccharomyces cerevisiae (brewer's yeast)	Apr. 1996	12 069 000	6 294	first eukaryote and first fungus
Methanococcus janaschii (archaean found at hydrothermal vents)	Aug. 1998	1 700 000	1 738	first archaean
Caenorhabditis elegans (nematode worm)	Dec. 1998	97 000 000	19 099	first animal
Arabidopsis thaliana (thale cress)	Dec. 2000	115 000 000	25 498	first plant
Equus caballus (horse)	Nov. 2009	2 689 000	20 322	thoroughbred
Yersinia pestis	Aug. 2011	4 553		cause of Black Death plague
Brassica rapa (Chinese cabbage)	Aug. 2011	485 000		
Anolis carolinensis (green anole lizard)	Aug. 2011	2 200 000	16 533	see figure 13.10a
Anopheles gambiae (mosquito)	2002	278 268 413	12 843	main vector of malaria in sub-Saharan Africa
Gallus gallus (chicken)	2004	1 072 544 763	15 508	
Canis familiaris (dog)	2005	2 392 715 236	19 856	
Felis catus (domestic cat)	2007	2 365 745 914	19 493	
Oryctolagus cuniculus (rabbit)	Nov. 2009	2 604 023 284	19 293	
Pongo pygmaeus (orangutan)	2011	3 109 347 532	20 424	one of the five great apes
Macropus eugeni (tammar wallaby)	Aug. 2011	2 549 429 531	15 290	see box, pp. 493–4
Sarcophilus harrisii (Tasmanian devil)	Feb. 2011	2 931 556 433	18 788	
Escherichia coli 0111 (bacterium)	2011	5 766 081	5 407	10 000th genome in GOLD database
Falco peregrines (Peregrine falcon)	2013	1 200 000 000	16 263	a top predator in some ecosystems
Panthera tigris (Amur (Siberian) tiger)	Sep. 2013	~2 440 000 000	20 226	first entire genome of the endangered Amur tiger (see figure 13.10b)
Phascolarctos cinereus (koala)	Apr. 2013	~3 000 000 000	approx 15 000	

FIGURE 13.10 **(a)** Green anole lizard **(b)** Amur (Siberian) tiger

FIGURE 13.11 Logo of the Open Tiger Genome Project

Many research groups around the world continue to collaborate on identifying the genomes of key species. Among these are the Koala Genome Consortium, a joint initiative of the Australian Museum and the Queensland University of Technology. Another group is the Open Tiger Genome Project (see figure 13.11), which has many collaborators, including major institutions in Korea.

Comparative genomics

The availability of the complete genome sequences for an increasing number of species has created a new field of study known as **comparative genomics**. Comparing the genomes of various species will elucidate how various features have evolved and how the genomes of closely related species differ.

In August 2005, the sequencing of the genome of the chimpanzee (*Pan troglodytes*) (see figure 13.12) was completed. Comparisons between the chimp genome and the human genome can identify the genes that control the distinctive features of primates, such as high brain-to-body-mass ratios, and the genes that are unique to the human species.

ODD FACT

The bacterium *Carsonella ruddii* has the smallest number of genes of any living organism — just 182 genes — and a genome of just 160 000 base pairs. *C. ruddi* lives as an endoparasite in the cells of a sap-eating insect.

FIGURE 13.12 Of all living species, the chimpanzee is most closely related to humans through evolution.

Comparative genomics provides data to assist research into medicine, ecology and biodiversity. It is also a powerful tool in exploring evolution; for example, comparative genomics can provide evidence of the occurrence of processes, such as **gene duplication**, where a second copy of a gene appears in a genome, and **horizontal gene transfer**, where a new gene is acquired by one species as a result of the transfer of DNA from a second species.

Comparative genomics also reveals which genes are conserved in different species. Figure 13.13 shows a map of the B2 cat chromosome alongside human chromosome 6. The genes that are conserved in the two species are indicated by the dotted lines. These conserved genes have key functions so that natural selection favours their retention during evolution.

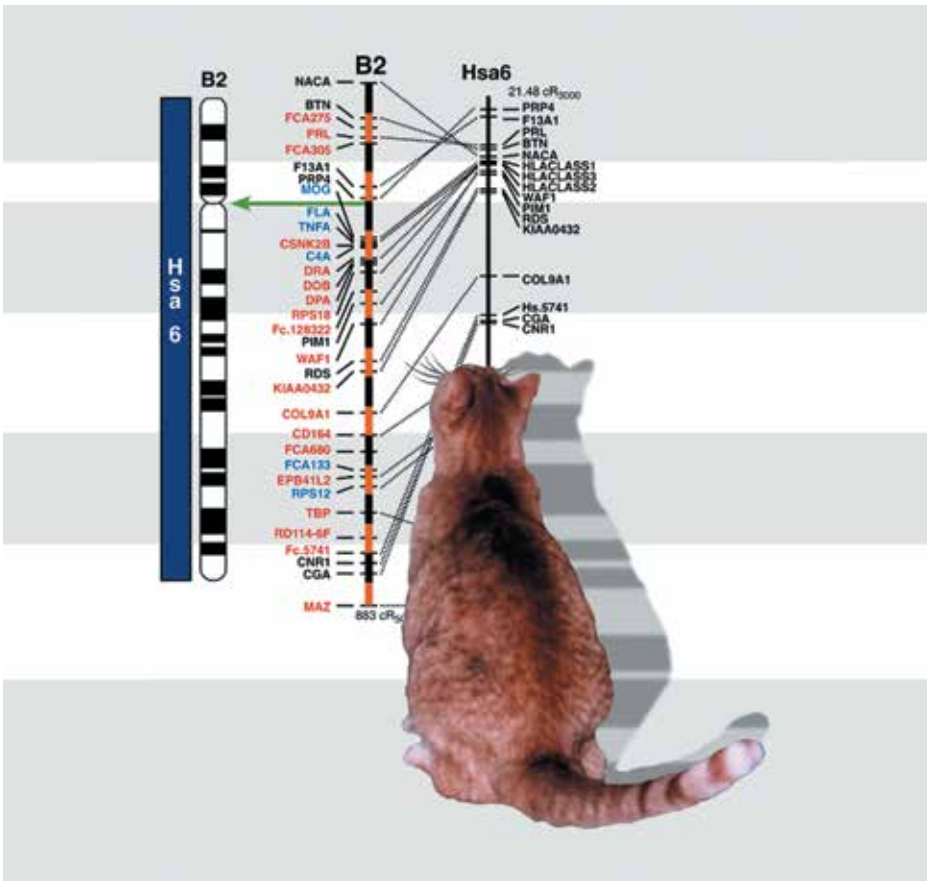

FIGURE 13.13 Comparison of cat and human chromosomes at the gene loci level

Comparative genomics has become a powerful tool in exploring the degree of evolutionary relationships between different species and enabling a more precise identification of their degree of relatedness. For example, the genomes of the big cats (lions, tigers, leopards) are being compared to identify regions of similarity and regions of difference that provide clues to their evolutionary history. In addition, knowledge emerging from comparative genomics may provide clues to improved strategies for conservation of endangered and rare species.

New fields of research are emerging

The field of genomics involves far more than producing a sequence of nucleotides or base pairs for different species. From genome sequences, researchers are producing maps that identify the order of genes and their relative positions on the chromosomes.

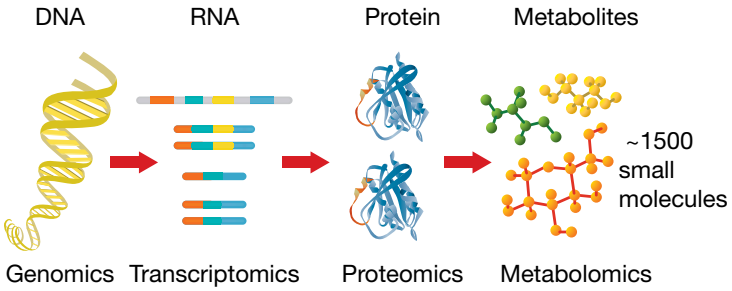

FIGURE 13.14 The emerging '-omics' fields of research

Genomics is raising questions about the how, where and when of gene action. Exploring these questions is generating new fields of research including (see figure 13.14):

- **transcriptomics**, which seeks to identify all the mRNA transcripts produced by each cell type
- **proteomics**, which seeks to identify all the different proteins produced by each cell type
- **metabolomics**, which seeks to identify all the metabolites present in each cell type.

Another recent field to emerge is that of **microbiomics**. The **microbiome** is composed of the total collection of genes (genomes) of the several thousand different kinds of microbe that colonise the human body, including the gut, throat and skin. The US National Institutes of Health has sponsored the Human Microbiome Project. This project is sampling and sequencing, not individual microbes but the microbial communities living at different sites on and in the bodies of 300 healthy young adults. This project will enable researchers to identify differences in the microbiomes of persons as they change from good health to a state of disease. In addition, the microbiome is being investigated in various chronic conditions, such as the microbiome of the lung in persons with chronic lung conditions and the microbiome of the gut in persons with an inflammatory condition of the gut known as Crohn's disease.

In the next section, we will briefly examine DNA and its constituent bases. It is these bases that form the genome of an organism.

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BIOLOGIST AT WORK

Dr Sue Forrest — molecular geneticist

Dr Sue Forrest is a molecular geneticist and the CEO of the Australian Genome Research Facility, a major national research facility with nodes in Brisbane, Melbourne, Adelaide, Perth and Sydney. In her previous position she spent a total of 13 years at the Murdoch Children's Research Institute at the Royal Children's Hospital in Parkville. There she headed the Gene Discovery Group for 5 years, developing methodologies for the discovery of the genes responsible for common human diseases and, prior to that, ran the DNA Diagnostic laboratory for 8 years.

'My interest in genetics developed right from my first introduction to this fascinating area in first year Biology as part of my Bachelor of Science at Melbourne University. Following completion of my Honours degree, majoring in Biochemistry and Genetics, I headed overseas to study for my DPhil at Oxford University where I was fortunate to work with Professor Kay Davies. We cloned the gene dystrophin in 1987. This gene, when mutated, results in Duchenne muscular dystrophy and was one of the first disease-causing genes to be cloned in the late 1980s.

'A fantastic event in genetic history occurred in 2003 when the sequence of the human genome was announced as completed. The first major outcome was that there were only about 21 000 genes in the human genome, compared with the 100 000 originally predicted, requiring new ideas about gene structure and function to be developed. Since the Human Genome Project was instigated, there is far more information about genes and their sequences on the internet and much of the research is now done as 'computer cloning' rather than actual laboratory bench work! The challenge now is to determine the functions of the genes in the human genome and how they are regulated.

'During this finalisation of the Human Genome Project in 2001, I was offered the position of Scientific Director of the Australian Genome Research Facility (AGRF) followed by Director/CEO in 2003. AGRF is partly funded by the federal government to provide access to state-of-the-art genetic tools and technologies that can be used by researchers across the whole biological spectrum. Thus, moving to this position dramatically opened my eyes to the vast array of molecular biology and genetic research in all different species, from microbes through to animals, that was occurring within Australia and around the world.

(continued)

'Australia did not play a major role in the sequencing of the human genome, but through a unique collaboration between the US National Institutes of Health and the Australian Genome Research Facility, funded by the state government of Victoria, the genetic sequence of the tammar wallaby was determined. The project took 3½ years and the results were published in 2011. This sequence has assisted with defining which regions of the genome share sequences between human and wallaby, thereby indicating that they are likely to have a significant function. Such sequences could be involved in regulating gene expression as an example. Also, much biological research has been done in Australia on the tammar wallaby demonstrating novel properties of lactation, development and reproduction that will be unravelled using the genetic sequence.

'What next? In the last few years, the technology available for sequencing DNA has become faster and cheaper. The ability to sequence a human genome for $1000 is just about here! The challenge now is to understand the ethical, legal and social issues that surround the availability of human genetic information. It is an exciting time in genetics and I certainly would never have predicted in the early 1980s that, 30 years later, I could be reading my own genome sequence!'

FIGURE 13.15 Dr Sue Forrest, Director of the Australian Genome Research Facility, and a tammar wallaby named 'Wriggles'

KEY IDEAS

- A genome is the complete set of genetic instructions for an organism.
- The haploid human genome consists of the base sequence of the DNA of the 22 autosomes plus the sex chromosomes.
- The Human Genome Project (HGP) produced the first working draft of the complete human genome.
- The genomes of members of the human species have a high level of similarity.
- Many benefits and new fields of research have flowed from the HGP.

QUICK CHECK

1 Identify whether each of the following statements is true or false.
   - **a** A complete genome can be expressed using just four letters.
   - **b** The human genome (haploid) contains about 3 million base pairs.
   - **c** The first human chromosome to be sequenced was the number-21 chromosome.
   - **d** The genomes of unrelated persons would be expected to show a high degree of difference.
   - **e** The first eukaryotic organism to be fully sequenced was a nematode worm.

2 Briefly identify two benefits of the HGP.

3 What is meant by the following terms?
   - **a** Comparative genomics
   - **b** Proteomics
   - **c** Microbiome?

FIGURE 13.16 Part of the sequence of bases in the DNA that makes up the genome of an organism. Would this image look significantly different if this organism were a plant rather than an animal?

DNA and its bases

As we have seen in the previous section, genomics is concerned with the sum total of DNA in the haploid set of chromosomes of an organism.

Genomes are the complete sequence of bases present in the DNA of an organism. A genome can be shown in several ways: as a long sequence using just four letters — A, T, C and G — to denote the four bases in DNA (see figure 13.16), or expressed as a series of coloured bands, using just four different colours to denote the four bases — typically, green for **adenine (A)**, red for **thymine (T)**, yellow for **cytosine (C)** and blue for **guanine (G)** (refer to figure 13.7b).

Nucleotides: building blocks of DNA

Complex structures are built from one or more building blocks (sub-units) that are organised in a regular manner: insect eyes are built from ommatidia, walls are built of bricks, fences are built of palings. The genetic material DNA is a complex molecule built of many basic building blocks called **nucleotides**. (Other complex molecules that are made of basic building blocks include proteins that are built of amino acids.)

The nucleotide sub-units in DNA are assembled head-to-tail forming a chain. Four different kinds of nucleotides are found in DNA and they are normally distinguished by the letters A, C, G and T.

Each nucleotide has a sugar (**deoxyribose**) part, a phosphate part and an N-containing base. The sugar and the phosphate parts are the same in all four nucleotides. However, the different nucleotides vary in the bases they contain.

Note that the letters A, T, C and G that are used to label the four different kinds of nucleotides come from the names of the bases they contain. Figure 13.17 shows various representations of the four nucleotides.

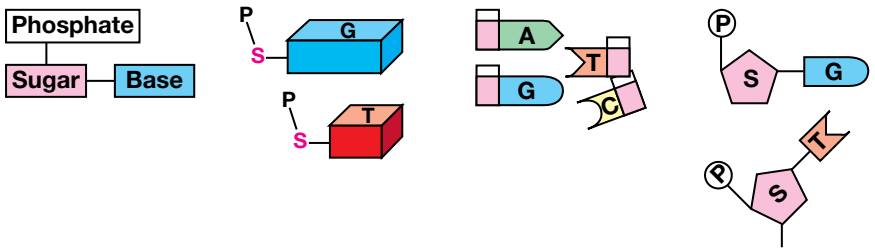

FIGURE 13.17 Four different representations of the nucleotides that are the sub-units of DNA. Can you identify the phosphate, the sugar and the base in each nucleotide?

ODD FACT

Two of the bases, cytosine and thymine, belong to the class of chemical compounds called pyrimidines. The other two, adenine and guanine, are larger and belong to the class of chemical compounds called purines.

When many nucleotides join to form a chain, a bond forms between the sugar of one nucleotide and the phosphate group of the next nucleotide, and so on (see figure 13.18). So, one chain of nucleotides runs from 'head-to-tail', with a phosphate group at the 'head' end (also known as the 5′ [5 prime] end) and a sugar molecule at the 'tail' end (also known as the 3′ [3 prime] end).

So **DNA is built from nucleotides joined to form a chain**. However, the question remained: how is a typical DNA molecule arranged in three-dimensional space? For example, does it consist of one nucleotide chain coiled into a ball? Does it contain more than one nucleotide chain?

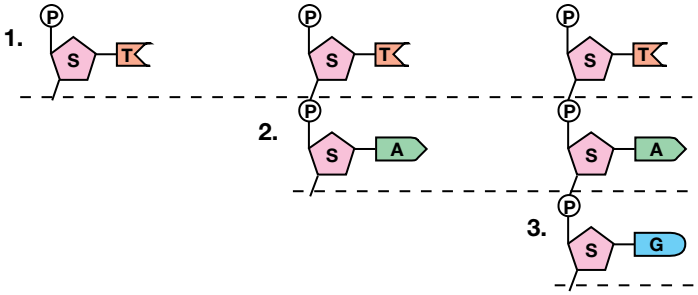

FIGURE 13.18 Joining nucleotides to form a DNA chain

ODD FACT

DNA was first isolated from nuclei of cells from pus on bandages by the young Swiss postgraduate student Miescher. At that time in 1869, he was working in a laboratory located in a castle in Tubingen, Germany, and gave the name nuclein to the compound he isolated. DNA was the only known nucleic acid for many years but, in the 1930s, a second kind was found in the cell cytosol — this was given the name **RNA (ribonucleic acid)**.

Early analysis of DNA

The relative proportions of the different nucleotides in DNA from various organisms can be identified. Table 13.2 shows a summary of experimental results obtained by various scientists in the late 1940s and early 1950s.

TABLE 13.2 Approximate values for the total amounts of the four kinds of nucleotides in DNA samples from different organisms. What predictions would you make about DNA from calf liver cells?

	Nucleotides			
Source of DNA	A	T	C	G
calf thymus	1.7	1.6	1.0	1.0
yeast cells	1.8	1.9	1.0	1.0
tubercle bacteria	1.1	1.0	2.6	2.6
herring sperm	1.1	1.1	0.9	0.9

These figures indicate a possible pattern. It appears that in DNA **the proportions of A and T are about equal and also that the proportions of C and G are about equal.** This idea, known as **Chargaff's rule**, was an important observation that later contributed to understanding the 3D structure of DNA.

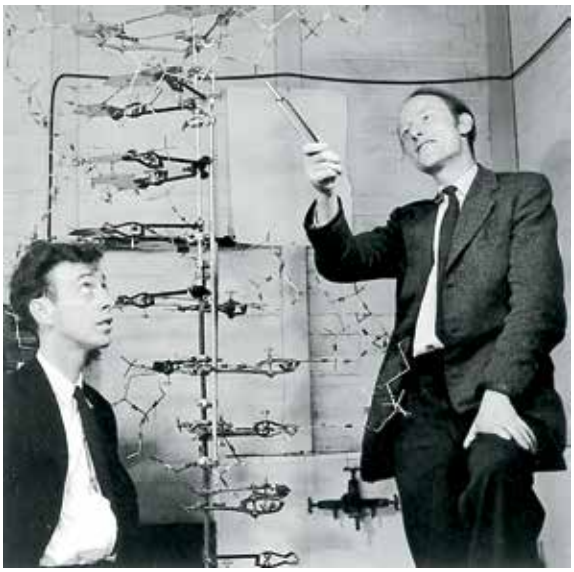

FIGURE 13.19 James Watson and Francis Crick identified the double helix structure of DNA.

DNA forms a double helix

In 1953, James Watson (1928–) and Francis Crick (1916–2004) (see figure 13.19) announced that they had identified the 3D structure of DNA as being two nucleotide chains arranged to form a **double helix**. Their work built on the work of other scientists, in particular, the pioneering X-ray crystallography work of Rosalind Franklin (1920–58) and Maurice Wilkins (1916–2004).

The key features of the double helix model of DNA (see figure 13.20) are:

- Each DNA molecule consists of two nucleotide chains.
- The chains run in opposite directions and are said to be 'anti-parallel'.
- The sugar–phosphate backbones of the two chains are on the outside of the DNA double helix and they coil around each other in a regular manner to form a molecule with a constant diameter.
- The nucleotide bases (A, T, C and G) are arranged so that they point to the inside of the DNA molecule.
- The bases in one chain pair with the bases in the second chain in a very specific way; there is pairing only between A and T and between C and G.
  Weak **hydrogen bonds** form between the **base pairs**.

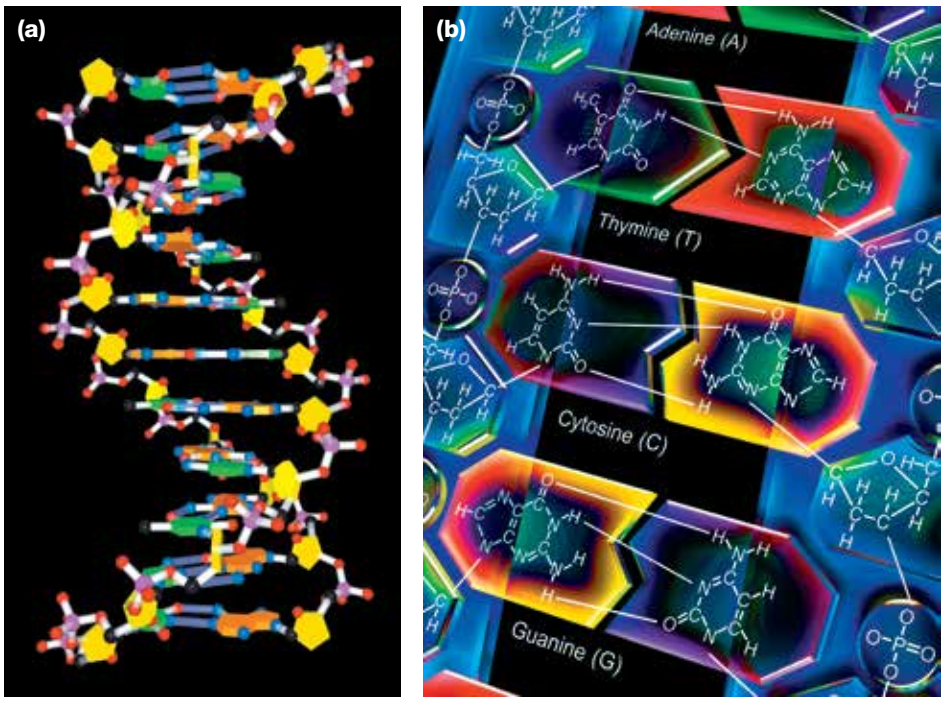

FIGURE 13.20 Two representations of DNA **(a)** Double helix (side view) showing the sugar–phosphate backbones on the outside of the DNA, with the sugars (deoxyribose) shown in yellow and the phosphates in pink. The inner 'rungs' are formed by base pairing of A with T and C with G. **(b)** Pairing of the nucleotide bases of the inner rungs of the DNA double helix. Here we see the complementary pairing between A and T and between C and G. Notice that the size of an A–T pair is the same as the size of a C–G pair. This observation was an important clue in solving the structure of DNA.

The base pairs between the two strands, namely, A with T and C with G, are said to be **complementary base pairs** (see figure 13.21). This complementary double helix structure for DNA fits with the known properties of the genetic material including the facts that DNA:

- can act as a template for its own replication
- contains genetic instructions
- can undergo change or mutation.

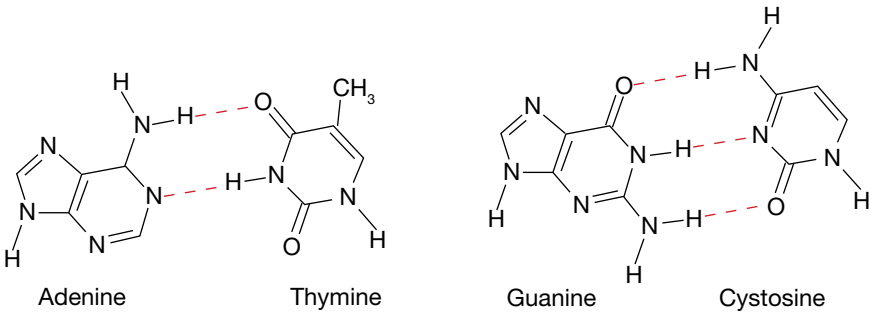

FIGURE 13.21 Chemical formulae for the complementary bases in DNA. Note the two hydrogen bonds in the A–T pair and the three hydrogen bonds in the C–G pair (shown in red).

ODD FACT

In 1962 the Nobel Prize was awarded jointly to Watson, Crick and Wilkins for their work in discovering the structure of DNA. The other person who played a decisive role in this discovery was Rosalind Franklin. She died of cancer in 1958 at the age of 37. The rules governing the Nobel Prize do not permit an award to be made to a person after death.

The box on pages 499–500 contains excerpts from James Watson's personal account of the discovery of the DNA double helix (*The Double Helix*, Atheneum, New York, 1968). Reading these excerpts may help you understand how scientists work and realise that they spend time thinking about problems and assessing alternative ideas, not just doing experiments.

A double helical DNA molecule contains complementary base pairs: A–T, T–A, C–G and G–C. If the order along one DNA chain is known, the sequence of bases in the second chain can be inferred. So, if one DNA chain has the **base sequence** G G T A C G T A . . . , the sequence in the complementary chain must be C C A T G C A T . . .

Double helical DNA consists of two nucleotide chains held together by weak hydrogen bonds between the complementary nucleotides. These bonds are easily broken with a low input of energy. If a solution of DNA is heated to 90 °C for 2 minutes, each double helical DNA molecule separates (a process called **dissociation**) to form two single chains of DNA (see figure 13.22). This heating does not break the strong sugar–phosphate bonds that join nucleotides

into one chain. If this solution is then allowed to cool, the complementary regions of the chains pair, the hydrogen bonds re-form and the DNA returns to a double-stranded helix form (**re-association**) (see figure 13.22). Pairing between complementary DNA chains or parts of chains from different sources is referred to as **hybridisation**.

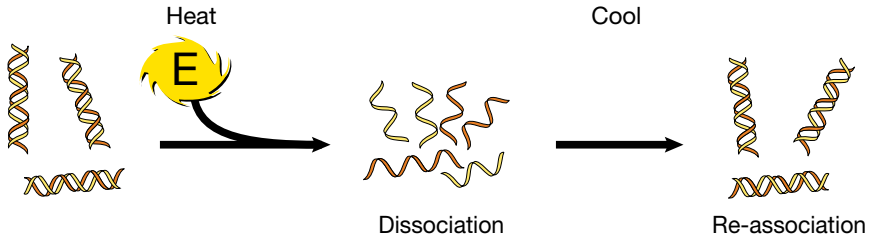

FIGURE 13.22 The double helix structure of DNA can undergo a reversible change. What is this change?

How is DNA packed into a chromosome?

The total length of DNA in a diploid human cell is more than 2 m. Yet, a human cell is typically only about 30 micrometres (μm) in diameter. It seems strange, if not impossible, that this amount of DNA could fit into one cell, let alone just the nucleus of a cell.

The width of a DNA double helix is about 2 nanometres (or just 0.002 μm). The DNA double helix becomes tightly coiled around proteins known as **histones** and these coils become further coiled into super coils called **nucleosomes** (see figure 13.23). Further coiling enables the DNA to be organised into chromosomes.

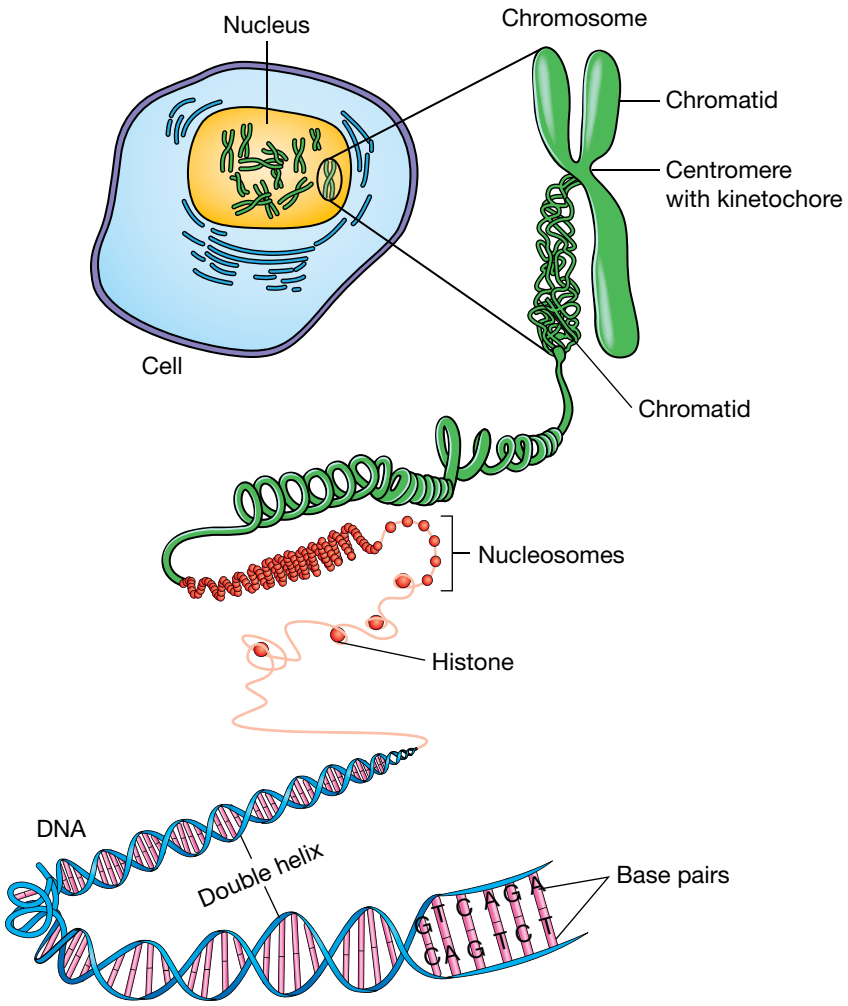

FIGURE 13.23 Coiling and super-coiling of DNA

FINDING THE DOUBLE HELIX

In the 1950s, in addition to James Watson and Francis Crick from Cambridge University, other scientists were trying to discover the structure of DNA. These included Rosalind (Rosy) Franklin and Maurice Wilkins, also at Cambridge, who identified the X-ray diffusion patterns of crystalline DNA, and Linus Pauling in the United States.

Possibly three chains?

Watson wrote:

> **Superficially, the X-ray data were compatible with two, three, or four strands.**

At first, Watson and Crick tried a three-chain model, with the sugar–phosphate backbones at the inside of the model. Watson wrote:

> **. . . we decided upon models in which the sugar–phosphate backbone was in the centre of the molecule. Only in that way would it be possible to obtain a structure regular enough to give the crystalline diffraction patterns observed by Rosy and Maurice.**
>
> **Our first few minutes with the models, though, were not joyous . . . After tea, however, a shape began to emerge which brought back our spirits. Three chains twisted about each other . . . Admittedly, a few of the atomic contacts were still too close for comfort, but, after all, the fiddling had just begun.**

Eventually, Watson and Crick realised that this three-chain model had major faults. Watson wrote:

> **A fresh start would be necessary to get the problem rolling again.**

Chargaff's rule provides a clue

A new avenue of exploration was raised by the ratio of the four bases in DNA:

> **The moment was thus appropriate to think seriously about some curious regularities in DNA chemistry . . . the number of adenine (A) molecules was very similar to the number of thymine (T) molecules, while the number of guanine (G) molecules was very close to the number of cytosine (C) molecules.**
>
> **Back in my rooms I lit the coal fire . . . With my fingers too cold to write legibly I huddled next to the fireplace, daydreaming about how several DNA chains could fold together in a pretty and hopefully scientific way.**

At that time, Linus Pauling, an American scientist, developed his model for the structure of DNA. He sent the details of his model through his son Peter to Watson and Crick, who at first were disappointed to think that they had been beaten to the answer. Watson commented:

> **. . . my stomach sank in apprehension . . . Seeing that neither Francis nor I could bear any further suspense, he [Peter] quickly told us that the model was a three-chain helix with the sugar–phosphate backbone in the centre. This sounded so suspiciously like our aborted effort of last year . . .**

In fact, Pauling's model was incorrect. The critical breakthrough came when Rosalind Franklin prepared X-ray diffraction patterns of a different form of DNA (the B-form) (see figure 13.24). Watson wrote:

> **The instant I saw the picture my mouth fell open and my pulse began to race. The pattern was unbelievably simpler than those obtained previously. Moreover, the black cross of reflections which dominated the picture could arise only from a helical structure . . .**

FIGURE 13.24 Evidence for the double helix came from this X-ray pattern of the B-form of DNA prepared by Rosalind Franklin. The regular pattern indicated that DNA formed a helix.

(continued)

He later recalled:

> **Then as the train jerked towards Cambridge, I tried to decide between the two- and three-chain models . . . Thus by the time I had cycled back to college and climbed over the back gate, I had decided to build two-chain models. Francis would have to agree. Even though he was a physicist, he knew that important biological objects come in pairs.**

Fitting two chains together

Over the next months, Watson and Crick tried to build a two-chain model, but they were still working with the incorrect idea that the sugar–phosphate backbones were in the centre of the molecule and the bases on the outside. Watson said:

> **. . . for a day and a half I tried to find a suitable two-chain model with the backbone in the centre . . . Though I kept insisting that we should keep the backbone in the centre, I knew none of my reasons held water.**
>
> **But the real stumbling block was the bases. As long as they were outside, we did not have to consider them. If they were pushed inside, the frightful problem existed of how to pack together two or more chains with irregular sequences of bases.**

Slowly, the correct model started to evolve:

> **The next morning, however, as I took apart a particularly repulsive backbone-centred molecule, I decided that no harm could come from spending a few days building backbone-out models. This meant temporarily ignoring the bases . . . There was no difficulty in twisting an externally situated backbone into a shape compatible with the X-ray evidence.**

The sugar–phosphate backbones were arranged on the outside of the model; they posed no further problem, but the nagging problem of what to do with the bases still remained:

> **I went ahead spending most evenings at the films, vaguely dreaming that at any moment the answer would suddenly hit me . . . Even during good films I found it almost impossible to forget the bases. Thus, unless some very special trick existed, randomly twisting two polynucleotide chains around one another should result in a mess.**

Another clue was recognised:

> **Thus, conceivably the crux of the matter was a rule governing hydrogen bonding between bases.**

Watson first considered the pairing of identical bases, that is, A with A, T with T, and so on:

> **I thus started wondering whether each DNA molecule consisted of two chains with identical base sequences held together by hydrogen bonds between pairs of identical bases.**
>
> **For over two hours I happily lay awake with pairs of adenine residues whirling in front of my eyes. Only for brief moments did fear shoot through me that an idea this good could be wrong.**

However, the answer was very close. Watson wrote:

> **. . . so I spent the rest of the afternoon cutting accurate representations of the bases out of stiff cardboard . . . the following morning, I quickly cleared away the papers from my desk top so that I would have a large, flat surface on which to form pairs of bases held together by hydrogen bonds . . . Suddenly I became aware that an adenine–thymine pair held together by two hydrogen bonds was identical in shape to a guanine–cytosine pair held together by at least two hydrogen bonds. All the hydrogen bonds seemed to form naturally; no fudging was required . . .**

The DNA double helix structure was at last identified.

The pairing between the bases in DNA involves hydrogen bonding between complementary bases, not identical bases. This model with A–T and C–G pairs between the chains made sense in terms of Chargaff's rule that the number of As was about equal to those of T, and that the number of Gs was about the same as those of C. This model also gave a clue as to how DNA could be replicated:

> **Chargaff's rules then suddenly stood out as a consequence of a double-helical structure for DNA . . . Given the base sequence of one chain, that of its partner was automatically determined. Conceptually, it was thus very easy to visualise how a single chain could be a template for the synthesis of a chain with the complementary sequence.**

Watson and Crick announced their double-helix model in the short article that briefly outlines a discovery that ranks as one of the major discoveries of the twentieth century:

JD Watson and FHC Crick, 'Molecular structure of nucleic acids — a structure for deoxyribose nucleic acid', *Nature*, vol. 171, pp. 737–8, 1953.

Use the **Francis Crick** weblink in your eBookPLUS to read what Francis Crick thought.

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KEY IDEAS

- DNA is a macromolecule built of nucleotide subunits.
- Each nucleotide contains a sugar (deoxyribose), a phosphate group and a base.
- Nucleotides differ only in their bases, which may be one of four different bases.
- DNA normally exists as a double helix, with the two chains stabilised by weak hydrogen bonds.
- In a DNA double helix, each base along one chain pairs with its complementary base in the other chain.
- Double helical DNA can be reversibly dissociated into two single DNA chains by heating and the chains then re-associate on cooling.
- Chargaff's rule states that in double helical DNA the proportions of A and T are equal as are the proportions of C and G.

QUICK CHECK

4 Identify whether each of the following statements is true or false.
- **a** DNA is composed of four different nucleotides.
- **b** Nucleotides differ in their sugar component.
- **c** Treating double helical DNA at 90 °C causes irreversible denaturation of the molecule.
- **d** Complementary base pairing occurs between bases in the two chains of a DNA double helix.

5 Consider part of a DNA chain that has the nucleotide sequence . . . T T A G G A C . . . Which of the following is part of the complementary strand?
- **a** . . . C C G A A G T . . .
- **b** . . . T T A G G A C . . .
- **c** . . . A A T C C T G . . .

6 The relative proportion of the G base in DNA from human gut cells was found to be 1.4 and that of T was 0.9. What other valid conclusions may be drawn?

Solving the puzzle: the nature of genes

DNA (deoxyribonucleic acid) is now widely known to be the raw material of genes. The term DNA now appears in newspapers: 'DNA found at the crime scene . . .' People talk about attributes as 'being in their DNA'. However, the nature of genes as segments of DNA with particular functions was not known to your grandparents.

The story of genes begins in a monastery garden in 1856 where the patterns of inheritance of 'factors' was identified. The term 'gene' was first used to refer to these factors in 1909. However, the chemical nature of genes was not experimentally demonstrated until the 1920s, and it was not until the 1940s that their chemical nature was shown to be DNA. The structure of DNA, that underpins key properties of genes, such as their ability to self-replicate and to mutate, was not elucidated until 1953.

Let's look briefly at the emergence of genes, firstly as Mendel's factors and finally as specific segments of double helical DNA controlling a specific function.

Factors in the monastery garden

In the summer of 1856, visitors to the monastery of St Thomas in the town of Brno, in what is now the Czech Republic, would have seen monks at work and prayer. Visitors may have noticed one monk examining flowers on pea plants in the vegetable garden near the monastery kitchen.

Figure 13.25 shows the typical structure of a pea flower. Under normal conditions, pea plants are self-fertilising, that is, pollen from one flower fertilises the ovules of the same flower. However, this monk was carrying out a procedure to prevent self-fertilisation. Using forceps, he carefully removed the stamens from flower buds on one pea plant and dusted pollen that he had collected from another pea plant onto the stigma of the first plant. In doing this, he was **artificially crossing the pea plants** (see figure 13.26).

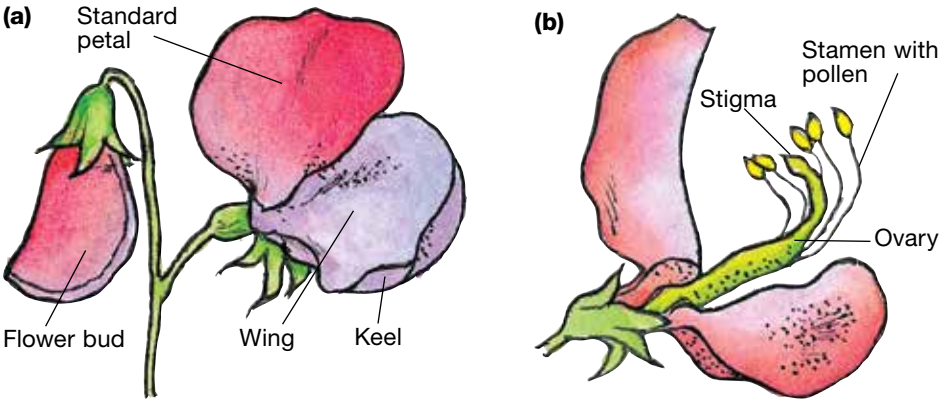


FIGURE 13.25 Structure of the flower of a pea plant **(a)** Pea flower and bud — the five petals include the keel made of two fused petals at the base of a pea flower, a large standard and two wing petals. **(b)** Flower opened to show reproductive structures. The male structures are the stamens, which produce pollen (sperm). Only five of the ten stamens are shown. The stigma is part of the female structure and leads to the ovary, which contains ovules (eggs).

Later, the monk wrote about his procedure for an artificial cross as follows: 'For this purpose, the bud is opened before it is perfectly developed, the keel is removed and each stamen carefully extracted by means of forceps, after which the stigma can once be dusted over with the foreign pollen.'

At another time, this monk could be seen in another section of the vegetable garden where he recorded the characteristics of mature pea plants in his notebook. Later, with others assisting him, the monk sat at a table where he shelled peas, sorted them into groups of different colours and shapes and counted the numbers in the various groups.

Who was this quiet monk? He was Gregor Mendel (1822–1884) (see figure 13.27a). Growing up on a farm, the young Mendel would have noticed variation in the offspring of farm animals. Years later in the monastery, Mendel turned his attention to edible pea plants (*Pisum sativum*) and examined the **inheritance of variation in seven different traits of this species** (see figure 13.28). He also used other plant species, such as beans, and experimented with bees.

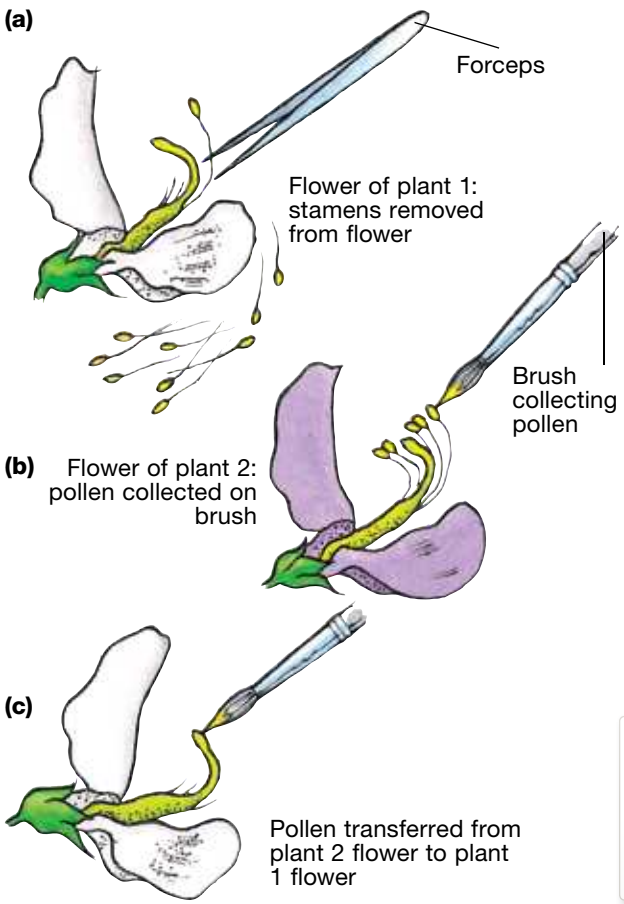


FIGURE 13.26 Process of artificial crosses of pea flowers from different plants **(a)** Unripe stamens are removed from the flower of plant 1. **(b)** Ripe pollen is collected on a brush from plant 2. **(c)** The ripe pollen is brushed onto the stigma of the flower of plant 1.

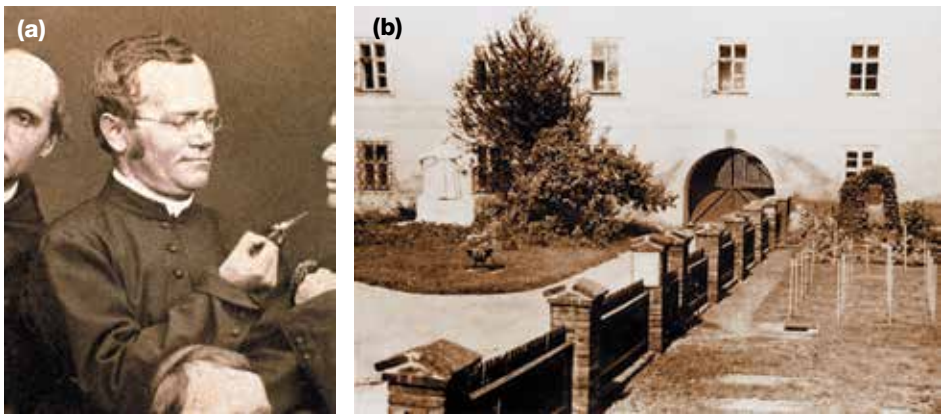


FIGURE 13.27 **(a)** Gregor Mendel
(b) The monastery gardens in which he carried out his plant-breeding experiments. Mendel stopped his genetic experiments in 1871 after being elected Abbot in 1868. He died of Bright's disease.

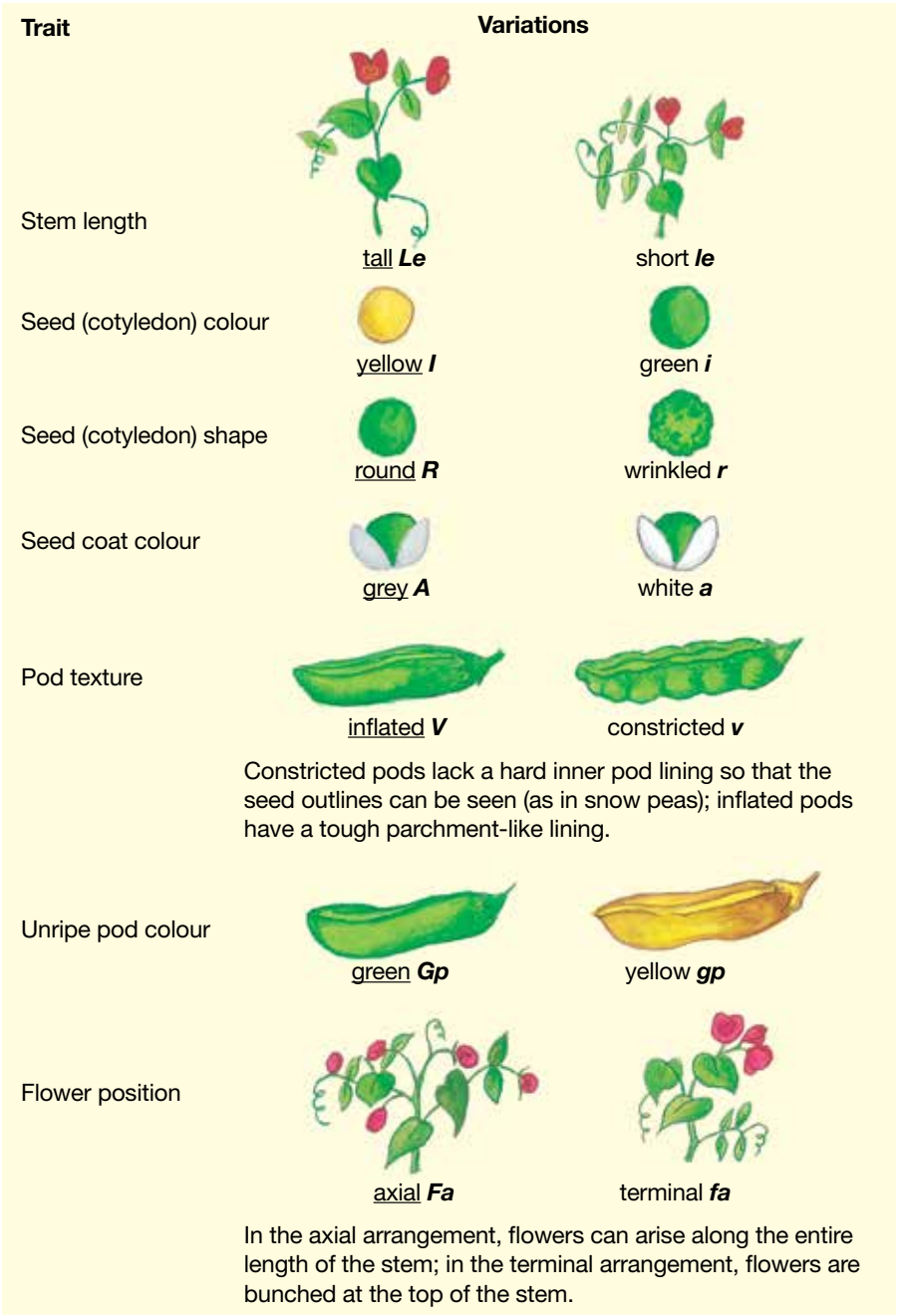


FIGURE 13.28 Variations in pea plants used by Mendel in his experiments. Dominant traits are underlined. Which peas can be readily eaten, pods and all? (Modern allele symbols are shown.)

ODD FACT

Tall pea plants grow to a height of about 2 m, while short pea plants grow to less than half a metre.

ODD FACT

Over an 8-year period, Mendel grew over 30 000 pea plants.

Why Mendel did it

What inspired Mendel to carry out his experiments is not known as many of his personal papers were burned by the abbot who succeeded him. Fortunately, Mendel's official papers and the notebooks that held the records of his experimental results were safely stored in the monastery archives.

Just one first-hand account of Mendel exists and it is that of a horticulturalist named Eichling who visited Mendel at the Brno monastery in 1878. Recalling this visit years later in 1942, Eichling wrote that Mendel gave him lunch and showed him the monastery garden. Mendel told Eichling that he had 'reshaped [the green peas] in height as well as in type of fruit'. In response to Eichling's question of how he had done that, Mendel answered: 'It is just a little trick, but there is a long story connected with it which would take too long to tell'.

How Mendel did it

For 8 years from 1856 to 1864, Mendel carefully carried out breeding experiments with varieties of pea plants. **Features of his experimental crosses that led to his success** included the following:

- *One trait at a time*. Mendel initially examined variation in only one trait at a time. He set up crosses between plants that differed in just one trait, such as pod colour. Such crosses are termed **monohybrid** crosses. After he had recognised the pattern of inheritance of single traits, Mendel studied crosses of plants differing in two traits. Such crosses are termed **dihybrid** crosses. In contrast, other plant breeders tried to study variation in many traits at once and were confounded by all the variation that they observed in the offspring.
- *Known history of parents*. For his starting point (the P generation), Mendel used plants that were known to be pure breeding.
- *Recording parentage*. Unlike other plant breeders, Mendel kept careful records of the parents of every offspring.
- *Counting offspring*. Unlike other plant breeders, Mendel counted the appearance and numbers of different kinds of offspring produced in each generation. He also repeated his experimental crosses, obtaining large numbers of offspring so that average ratios could be determined.

Oodles of peas

Mendel's choice of pea plants for his breeding experiments meant that he was able to obtain relatively large numbers of offspring from even a single cross. Every pea in a pod on a pea plant is a single offspring and each pea 'baby' will grow into a mature plant (see figure 13.29).

In all, Mendel produced thousands of offspring from his pea plant crosses over eight years. **Large numbers of offspring allow regularities to be recognised and valid averages to be identified**. If only small numbers of offspring are obtained, regularities may not be seen and averages may be biased by chance events. Numbers do matter! For example, imagine that you have four coins and that one of them is double-headed. Would you be absolutely confident that you could identify the double-headed coin on the basis of the result of tossing each coin just once? What about ten tosses? Likewise, when Mendel was examining various outcomes from his crosses, such as green pods or yellow pods, he obtained large numbers because he wanted to 'ascertain their statistical relations'.

Mendel's model of inheritance

Mendel developed a model to explain the patterns of inheritance of the pea variations and to enable predictions to be made about the outcome of crosses (see figure 13.30). **Mendel's model was built on several assumptions**:

1. Each trait was controlled by a pair of inherited factors. For example, the trait 'seed colour' was assumed to be controlled by a pair of factors, with one producing 'yellow' and the other producing 'green'.

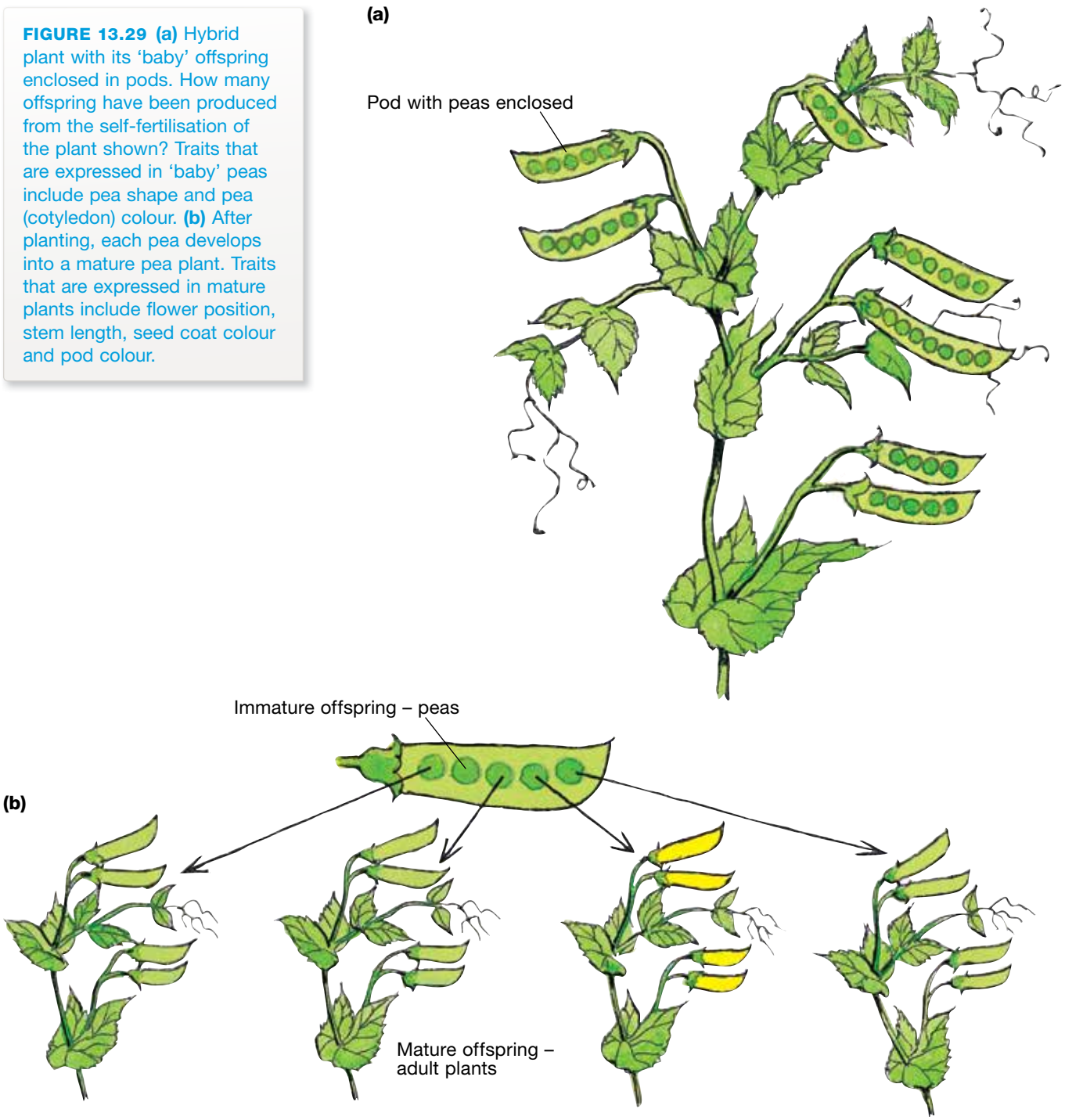


FIGURE 13.29 **(a)** Hybrid plant with its 'baby' offspring enclosed in pods. How many offspring have been produced from the self-fertilisation of the plant shown? Traits that are expressed in 'baby' peas include pea shape and pea (cotyledon) colour. **(b)** After planting, each pea develops into a mature pea plant. Traits that are expressed in mature plants include flower position, stem length, seed coat colour and pod colour.

2. For each trait, individual plants had two factors that could be identical or different. Plants with two identical factors (such as 'long' and 'long') were referred to as pure breeding, while plants with different factors (such as 'long' and 'short') were called hybrids.
3. Each factor was a discrete particle that retained its identity across generations. This idea challenged the commonly held view that inheritance was a blending process in which factors lost their identity (see figure 13.31).
4. The character that was expressed in the F1 hybrid plants was **dominant**, while the hidden character in the hybrid was **recessive**. For example, green pod colour is dominant and yellow pod colour is recessive.

FIGURE 13.30 Mendel demonstrated the existence of inherited factors that retained their identity across generations.

5. During gamete formation, the members of each pair of factors separated to different gametes, with one factor per gamete. This is the principle of segregation of alleles or Mendel's first law.
6. In separating, members of one pair of factors behaved independently of members of other pairs of factors. This is the principle of independent assortment or Mendel's second law.
7. The results of a particular cross were the same, regardless of which plant was used as the male parent and which as the female parent.

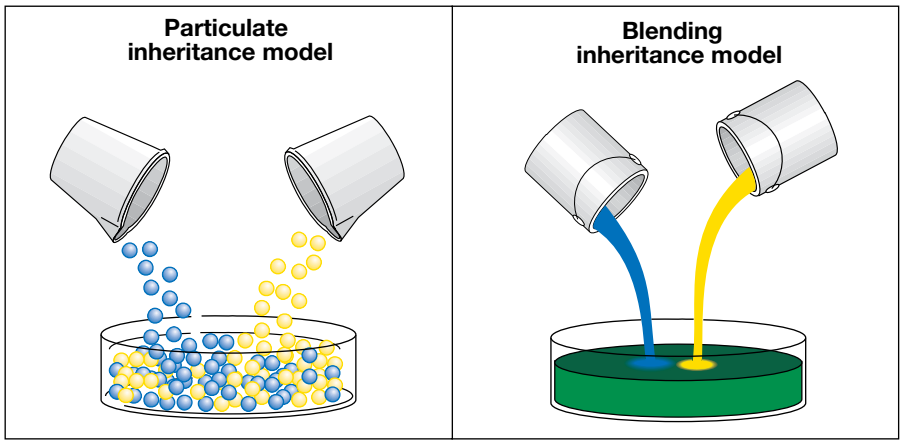


FIGURE 13.31 Two models of inheritance — particulate and blending. In which model do the factors lose their identity? Which model did Mendel assume applied to his factors?

Response to Mendel's results

Mendel's results and his model of inheritance were first reported at a meeting of a local scientific society in Brno in 1865 and were published in its journal in 1866. More than one hundred copies of this journal were distributed, including two copies that were sent to London. In addition, Mendel sent reprints of his paper to several scientists, including Carl Nägeli, one of the leading European biologists of that time.

Mendel's results were, however, ignored. Why? The scientific community failed to recognise the significance of Mendel's findings, perhaps because he was not a professional plant breeder or biologist. Nägeli published a book on heredity in 1884 that made no reference to Mendel. In that book, Nägeli commented on the appearance of a long-haired kitten in the litter from two cross-bred short-haired cats, but could not account for this observation. Nägeli did not realise that a monk from the monastery in Brno could easily have explained the occurrence of this long-haired kitten!

In the years following the publication of Charles Darwin's *On the Origin of Species* in 1859, it is claimed that the attention of scientists moved to evolution and to the differences *between* species. As a result, there was a decline in interest in the work of plant and animal breeders who were concerned with differences *within* species. In this climate, few biologists would have been interested in the plant-breeding experiments of an obscure monk in a monastery in Brno. Mendel's explanatory model was ignored for more than 30 years.

Mendel's model was rediscovered in 1900 by three biologists working independently. The biologists were de Vries (1848–1935), a Dutch plant breeder; Correns (1864–1935), an Austrian botanist; and Tschermak (1871–1962), a German botanist. After its rediscovery, biologists in Europe and America demonstrated that Mendel's model applied to inheritance in many plants and

ODD FACT

Mendel was disappointed that his work was not recognised and is reported to have stated: 'Meine Zeit wird schon kommen' ('My time is sure to come'). That recognition did not come until 1900, more than 30 years after Mendel's work was published and 12 years after his death.

ODD FACT

The first report of a human condition behaving as a Mendelian dominant characteristic was published in 1905. This condition is abnormally short fingers or brachydactyly.

animals. By the end of the first decade of the twentieth century, Mendelian principles had been found to apply to many organisms, including:

- nettles (*Urtica pilulifera*) — serrated leaf margin dominant to entire
- wheat (*Triticum* sp.) — late ripening dominant to early ripening
- stocks (*Matthiola* sp.) — coloured dominant to white
- mice (*Mus musculus*) — coloured coat dominant to albino
- rabbits (*Oryctolagus cuniculus*) — short fur dominant to Angora (long) fur
- cattle (*Bos taurus*) — polled (hornless) dominant to horned
- poultry (*Gallus gallus*) — brown eggs dominant to white eggs
- sheep (*Ovis aries*) — white wool dominant to black.

The Mendelian model of inheritance was soon universally accepted as the basis of inheritance in plant and animal species.

Identifying Mendel's factors

Early in the twentieth century, a **gene** was simply 'something' that was inferred to be present in a gamete and 'something' that acted in an unknown way to produce a particular phenotype. However, nothing was known about the nature of genes or how genes acted to produce particular phenotypes.

The writings of biologists show that the nature of genes (or factors) was a mystery:

> Beyond their existence in the gamete and their mode of transmission we make no suggestion as to the nature of these factors.
>
> —Punnett, 1911

> . . . the material is termed for convenience a factor or a gene, terms which do not imply any knowledge as to the nature of the substance causing characters to appear . . .
>
> —Cutler, 1923

A commonly held, but incorrect, view at that time was that genes were probably made of protein. However, over the first half of the twentieth century, several experiments revealed what genes were made of.

Two biologists played important roles in elucidating (1) that genes were made of a chemical substance and (2) that the chemical substance of genes was DNA. They were Frederick Griffith and Oswald Avery.

The clue from Griffith's transformed bacteria

Imagine a substance that can change mild-mannered and harmless organisms into disease-causing killer organisms. In 1928, a British biologist, Frederick Griffith (1877–1941), extracted such a substance. Just as pea plants show variations, pneumococci bacteria also show variations (see table 13.3).

TABLE 13.3 Kinds of pneumococci bacteria

Strain	Distinctive feature	Disease-causing or not
'smooth' type	external capsule present outside cell wall	cause pneumonia
'rough' type	external capsule absent	harmless

Griffith carried out experiments using two kinds of pneumococci bacteria (see figure 13.32). He found that:

- injection of living smooth type into mice caused them to die from pneumonia
- injection of living rough type left the mice healthy.

Griffith also killed smooth bacteria by heating and extracted the contents of these dead cells. When mice received an injection of this material, they remained healthy. These results supported the conclusion that pneumonia was caused by living smooth pneumococci bacteria.

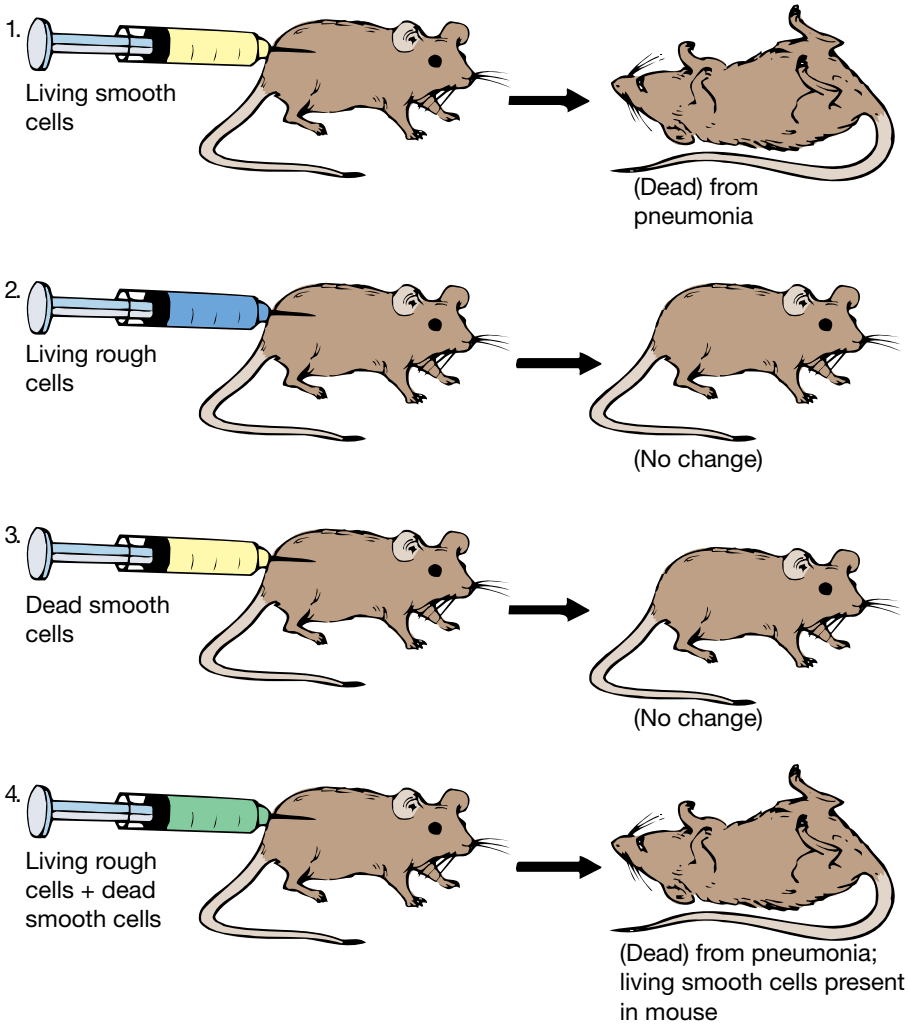


FIGURE 13.32 Griffith's experiments. The dead bacterial cells were obtained by killing the bacteria by heating. Living smooth bacterial cells were found in the dead mice in experiment 4. Where did these living smooth cells come from?

FIGURE 13.33 Griffith was the first to demonstrate the chemical nature of DNA.

Griffith then mixed the contents from dead smooth cells with living rough cells. He injected mice with these treated rough cells and found that they died from pneumonia. When the dead mice were examined, living smooth cells were found, even though no living smooth cells had been injected. How had this happened?

The deadly smooth bacteria found in the mice had formerly been harmless rough bacteria. The harmless rough bacteria had been changed or transformed by 'something' in the contents of the smooth cells. This change agent caused the harmless rough bacteria to produce an external capsule and become the deadly smooth type of bacteria. This 'something' became known as the **transforming factor**. It was concluded that the transforming substance was equivalent to the substance of the genetic material itself.

Griffith's experiments demonstrated that genetic material was a chemical substance (see figure 13.33). But, what was it?

Avery's answer to the puzzle

In 1943, Oswald Avery (1877–1955) and his co-workers identified the chemical nature of the transforming factor. Avery (see figure 13.34) obtained extracts of dead, smooth pneumococci bacteria and treated this material with various enzymes that could destroy lipids, proteins and carbohydrates. He found that the extracts could still transform harmless rough bacteria to deadly smooth bacteria (see table 13.4). However, when the extracts were treated with enzymes that destroy deoxyribonucleic acid (DNA), the extract could no longer transform

FIGURE 13.34 Oswald Avery. What was his contribution to the understanding of genes? His key research was published in the 1944 article 'Studies on the chemical nature of the substance inducing transformation of pneumococcal types', *Journal of Experimental Medicine*, vol. 79, p. 137. (Image courtesy of Rockfeller University Archives)

other bacteria. These experiments gave the first clue to the identity of the genetic material and supported the conclusion that genes were made of the chemical compound DNA.

TABLE 13.4 Outcomes of treatments of transforming factor from dead smooth pneumococci bacteria with various agents. Which treatment destroyed the transforming factor?

Treatment	Result
protein-destroying enzymes	ability to transform rough to smooth remained
lipid-destroying enzymes	ability to transform rough to smooth remained
carbohydrate-destroying enzymes	ability to transform rough to smooth remained
DNA-destroying enzymes	transformation ability destroyed

Later, Avery extracted the contents from smooth bacteria, separated and purified the various components until he had a highly purified sample of the transforming factor. When this was identified, it was found to be DNA.

The momentous discovery of Avery and his co-workers was not accepted immediately by the entire scientific community. Some biologists doubted the validity of Avery's conclusion. Even books published some years after Avery announced his discovery include cautious statements about the identity of genetic material, such as:

> . . . the present experiments 'strongly suggest' rather than prove that genes are pure DNA . . .
>
> —1957

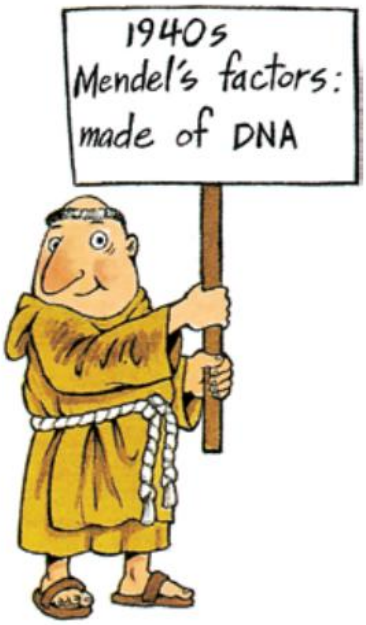
New scientific discoveries are not always rapidly accepted by the entire scientific community. If scientists hold strongly competing alternative views, they may not readily accept new findings that disagree with their views.

It is now universally accepted that genes are made of the chemical compound DNA. DNA belongs to the class of chemical substances called **nucleic acids**. Figure 13.35 shows one bacterial cell (centre) that has been treated to release its genetic material — strands of the nucleic acid DNA.

FIGURE 13.35 Threads of genetic material from the bacterium *Escherichia coli*. What is this material?

ODD FACT

Another clue to the fact that genes were physical entities came from the work of HJ Muller who showed that X-rays could cause changes (mutations).



The impact of Avery's experimental discovery that genes were made of the chemical substance deoxyribonucleic acid (DNA) was far reaching. Contrast the definitions of a gene taken from textbooks published before Avery's discovery with later definitions. A gene was variously defined as:

- a name for the thing in a germ cell that makes the germ cell develop a particular characteristic, such as tallness as opposed to dwarfness (1911)
- the hypothetical unit in a germ cell that determines the production of a particular characteristic in the individual derived from that germ cell (1921)
- a hypothetical unit in the chromatin of a cell that has a specific influence on certain characteristics (1934)
- a segment of a DNA molecule that can copy itself and pass on to other generations the directions it contains (1966)
- a locatable region of genomic sequence, corresponding to a unit of inheritance, that is associated with regulatory regions, transcribed regions and/or other functional sequence regions (2011).

KEY IDEAS

- Mendel carried out carefully controlled experiments in which he focused on the inheritance of variations in one characteristic at a time.
- Mendel developed a model of inheritance that built on a set of assumptions that explained observed results and allowed predictions to be made.
- Mendel's model of inheritance was ignored by the scientific community but was rediscovered in 1900 independently by three biologists.
- After its rediscovery, Mendel's model was soon found to apply to many other species.
- Griffith's discovery of the transforming factor in bacteria provided evidence that the genetic material was a chemical substance.
- Avery's experiments provided the evidence that the genetic material was composed of DNA.

QUICK CHECK

7 Identify whether each of the following statements is true or false.
   - **a** Mendel's model assumed that parental characters behaved as discrete entities or particles that did not blend.
   - **b** Pea plants normally undergo cross-fertilisation.
   - **c** Mendel's model of inheritance applies only to plants.
   - **d** The first human condition shown to behave in accord with Mendel's model was brachydactyly (abnormally short fingers).

8 List two assumptions of Mendel's explanatory model for inheritance.

9 What impact did Mendel's model have on the scientific community at the time it was first reported?

10 What was the significance of Griffith's discovery of a transforming factor?

11 What contribution did Avery make to the debate about the nature of genes?

Looking at genes

Genes are the basic units of heredity that transmit information in the form of discrete sequences of bases in DNA to the next generation. Let's look at genes by asking a series of questions.

How many genes?

Earlier in this chapter we saw that the total number of protein-coding genes in the human genome is about 21 000. (The most recent estimate is 20 678 protein-coding genes.)

What is the function of genes?

Many genes are protein-coding genes. The coded information present in the base sequence of these genes is translated (expressed) as a polypeptide chain or protein. Each protein-coding gene controls a specific characteristic or trait; for example, Mendel experimented with seven genes, each of which control different traits in pea plants (refer to figure 13.28).

In addition to these protein-coding genes, other genes present in the human genome are expressed only as RNA, such as ribosomal RNA (rRNA) and transfer RNA (tRNA). Because these genes do *not* code for proteins they are denoted as **ncRNA genes** (where the 'nc' means non-coding for protein).

How are genes named?

Genes can be named after the functions they control, such as 'the gene controlling Rhesus blood type'. For convenience, genes are given shorter identifiers. Just as a young boy named Benjamin James McDonald is called Ben, so scientists have developed a shorthand scheme for naming genes. In this scheme, genes are usually given a name consisting of a group of up to five characters (capital letters or numbers), with the first character always being a letter.

Examples of human genes include the **ABO** gene that controls ABO blood type, the **BRCA1** gene that controls DNA repair and is related to increased risk of various forms of cancer and the **CFTR** gene that controls the chloride ion channel protein in the plasma membrane.

Where are genes located in cells?

Almost all human genes are present in the DNA of the cell nucleus (see figure 13.36). Genes are transmitted to the next generation in gametes — eggs and sperm — that are produced by the process of meiosis (refer to chapter 11), so that each gamete contains the haploid human genome. (In chapter 14, we will explore the location of genes more precisely on chromosomes.)

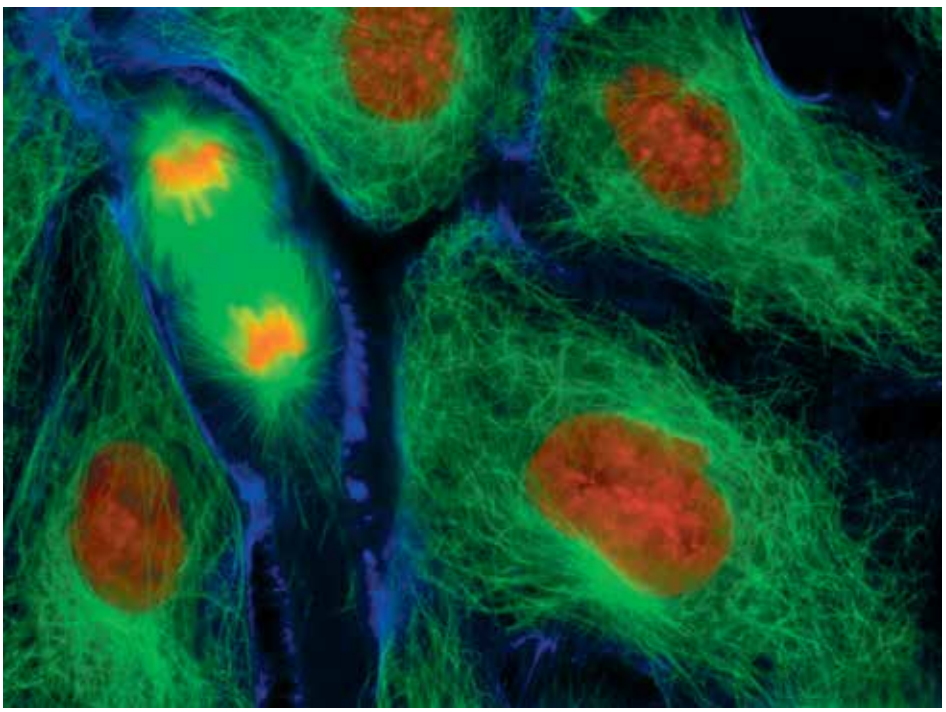


FIGURE 13.36
Photomicrograph of animal cells prepared with a stain (orange) that is selective for DNA. This image shows that the genetic material, DNA, is effectively confined to the cell nuclei. This means that genes are located within the nuclei. The cell in the upper right-hand side looks different. Can you identify what is happening in this cell?

ODD FACT

Of the 37 genes carried on mtDNA, 28 are located on one strand, known as the H strand, and 9 are located on the complementary strand, known as the L strand. The H(eavy) strand has many more G bases than the L(ight) strand, which is rich in Cs.

In addition to the genes in the nuclear DNA, a small number of genes are present in the DNA of mitochondria (mtDNA). The mtDNA consists of 16 568 base pairs (see figure 13.37). This DNA includes 13 protein-coding genes that are involved in cellular respiration — not surprising, since key steps of cellular respiration occur in the mitochondria. In addition, mtDNA contains 24 ncRNA genes that code for both rRNA and tRNA.

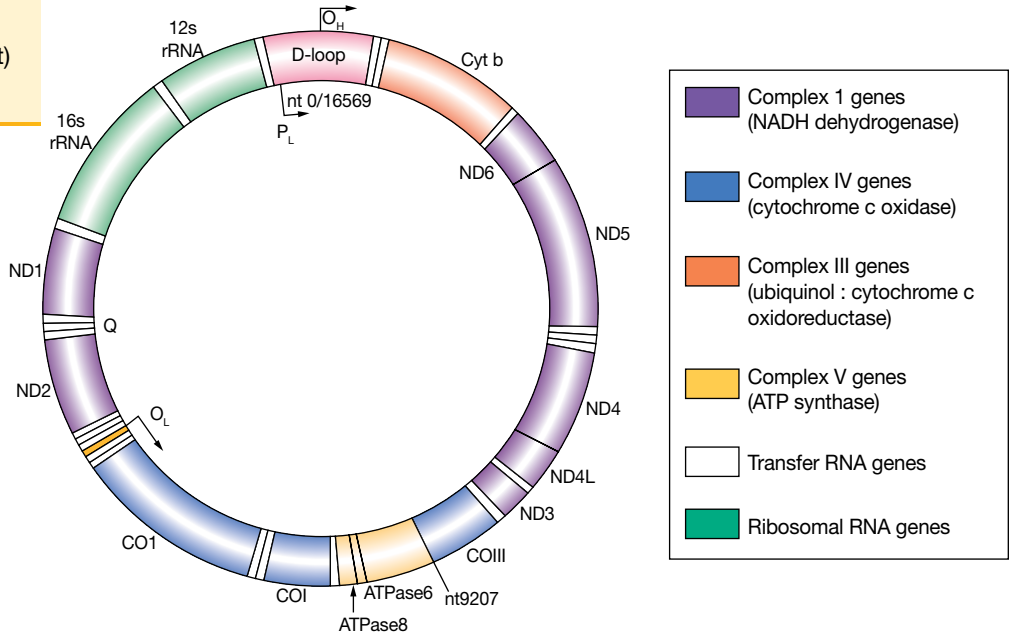


FIGURE 13.37 Map of the double-stranded circular molecule of human mitochondrial DNA (mtDNA) showing the various groups of genes coded for by the mtDNA

How do genes differ?

Every genetic instruction can be shown as a sequence of bases (written as As, Ts, Cs and Gs) in the nucleotides that form the DNA of the gene. The genetic material of all organisms is DNA and the structure of DNA is identical, regardless of whether it comes from wheat, jellyfish, wombats, bacteria, insects or people. In all organisms, genes are built of the same alphabet of four letters, namely the A, T, C and G of the bases in the nucleotide sub-units of DNA. So, the genetic instruction kit of the white shark and that of an oak tree and that of a person consists of thousands of different instructions, each consisting of DNA with different base sequences.

Each of the 21 000 or so protein-coding genes in the human genome carries a different genetic instruction. One gene may have the code for the instruction 'make the nail protein keratin', another gene may have the code for the instruction 'make the enzyme cytochrome oxidase', yet another gene may have the code for the instruction 'make the alpha chain of haemoglobin, the oxygen-carrying molecule of red blood cells'. These different genetic instructions differ in the base sequences of the genes concerned.

Table 13.5 shows the base sequence from segments of different genes from various organisms: a mallard duck (*Anas platyrhynchos*), a *Bacillus* bacterium, a corn plant (*Zea mays*) and a human being (*Homo sapiens*). Could you pick the human gene? Using logic only, it is not possible; the gene sequences share many similarities because the genetic language of all living organisms is written in the same language that is based on an 'alphabet' of four letters (A, T, C and G) that denote the bases in the nucleotide sub-units of DNA.

TABLE 13.5 Part of the sequences of different genes from various organisms. Numbers are placed above the sequences for ease of locating a particular nucleotide.

Organism P	1			10			20			30				40	
	ATG	GCT	ACC	AAG	ATA	TTA	GCC	CTC	CTT	GCG	CTC	CTT	TCC	CTT	TTA
Organism Q	1			10			20			30				40	
	ATG	AAG	TGT	AAT	GAA	TGT	AAC	AGG	GTT	CAA	TTA	AAA	GAG	GGA	AGC
Organism R	1			10			20			30				40	
	ATG	ACG	CTG	ACT	CAA	GCT	GAG	AAG	GCT	GCC	GTG	ATC	ACC	ATC	TGG
Organism S	1			10			20			30				40	
	ATG	AGG	CTC	TTG	TGG	TTG	CTT	TTC	ACC	ATT	GGG	TTC	TGC	TGG	GCT

P: corn plant Q: *Bacillus* bacterium R: duck S: human being

How much DNA is in a gene?

An average gene consists of about 3000 base pairs. Genes, however, vary markedly in size. The longest human gene is the **DMD** gene that encodes the muscle protein dystrophin and is 2 220 223 nucleotides long. An error in this gene is the cause of the inherited disorder Duchenne muscular dystrophy. Among the shortest human genes is a gene that encodes a histone protein and it consists of about 500 nucleotides.

KEY IDEAS

- The information in DNA is present as a sequence of bases.
- Different genes consist of DNA with different base sequences.
- Genes may be grouped into protein-coding genes and noncoding RNA genes.
- DNA is located almost exclusively in the nucleus.
- Genes average about 3000 nucleotides in length, but considerable variation about that average exists.

QUICK CHECK

12 Identify whether each of the following statements is true or false.
- **a** The **ABO** gene and the **CFTR** gene are both human genes and so could have identical base sequences.
- **b** The genetic material of plants differs from that of animals.
- **c** Noncoding RNA genes are expressed as RNA products, not as proteins.
- **d** The majority of genes in mtDNA are ncRNA genes.

13 If you saw the base sequence of part of a gene, could you identify if it came from a dog or from a flea? Briefly explain.

14 If the human **ABO** gene and the **CFTR** gene were compared:
- **a** in what way would they be similar
- **b** in what way would they differ?

Alleles: particular forms of a gene

A gene that controls one function can exist in different forms or variants that are called **alleles** of that gene. One gene can have several alleles and each is identified in terms of its specific action. The **ABO** gene has three different alleles. Alleles of one gene are commonly represented by variations of one letter of the alphabet (see table 13.6).

TABLE 13.6 Common alleles of selected genes, represented by variations of one letter of the alphabet

Gene and its function		Chromosomal location	Common alleles	
ABO	encodes A B H antigens	9	I^A	produces antigen A
			I^B	produces antigen B
			i	produces neither antigen
CFTR	encodes trans-membrane conductance regulator	7	***C***	normal secretions
			c	abnormal secretions (cystic fibrosis)
CBD	encodes green-sensitive pigment	X	***V***	produces green sensitive pigment
			v	lacks pigment (colour vision defect)
DMD	encodes muscle protein (dystrophin)	X	***M***	produces normal muscle protein
			m	produces abnormal muscle protein
EL1	encodes red blood cell membrane protein	1	***E***	elliptical red blood cells
			e	usual shape
F8	encodes factor VIII blood clotting protein	X	***H***	produces factor VIII
			h	no factor VIII (haemophilia)
HBB	encodes beta chains of haemoglobin	11	***T***	produces beta chains
			t	beta chains missing (thalassaemia)
LDLR	encodes low density lipoprotein receptor	19	***B***	abnormally high cholesterol level
			b	normal range
PHA	encodes phe hydroxylase enzyme	12	***P***	produces normal enzyme
			p	enzyme absent (PKU)
RHD	encodes Rhesus D antigen	1	***D***	Rhesus positive
			d	Rhesus negative
TYR	encodes tyrosinase enzyme	11	***A***	produces tyrosinase enzyme
			a	no enzyme (albinism) (see figure 13.38)

How many alleles?

In terms of the phenotypic expression of genes, the common situation for most genes is that they have two alleles, as indicated in table 13.6. This is not always the case, as can be seen for the **ABO** gene, which has three common alleles, I^A, I^B and *i*. When three or more alleles exist for a gene, the gene is said to have multiple alleles. Table 13.7 shows some examples of multiple alleles. Some chromosomal regions, known as short tandem repeats (STRs), are hyper-variable and each has multiple alleles, ranging from 10 to 40 different alleles for the various STRs.

FIGURE 13.38 An albino woman and her dark-skinned sister

TABLE 13.7 Multiple alleles of selected genes in various organisms. Not every allele is shown in each case, for example, there are more than 12 multiple alleles for the *Drosophila* eye colour gene in this table.

Gene function	Multiple alleles and their action	
controls human ABO blood type	I^A	antigen A present
	I^B	antigen B present
	i	neither antigen present
controls white spotting in dogs	S	white spots absent
	s^i	Irish spotting (as in collies) (see figure 13.39a)
	s^p	piebald spotting (as in fox terriers) (see figure 13.39b)
	s^e	produces extreme spotting (as in Samoyeds and Maltese terriers)
controls pigment levels in cats	C	intense pigment (as in a black cat, see figure 13.40a)
	c^b	Burmese dilution (see figure 13.40b)
	c^s	Siamese dilution (see figure 13.40c)
controls colour intensity in rabbits	C	intense pigment (as in solid black)
	c^{ch}	Chinchilla colouring (white fur with black tips)
	c^h	Himalayan colouring (colour on ears, nose, feet and tail only)
	c	albino (white fur and pink eyes)
controls white markings in cattle	S	white band around middle (as in Galloways)
	s^h	Hereford type spotting
	s^c	solid colour with no spots (as in Belmont Reds)
	s	Friesian type spotting
controls eye colour in fruit fly (*Drosophila* sp.)	w^+	red eye
	w^a	apricot
	w^h	honey
	w^p	pearl
	w^i	ivory
	w	white

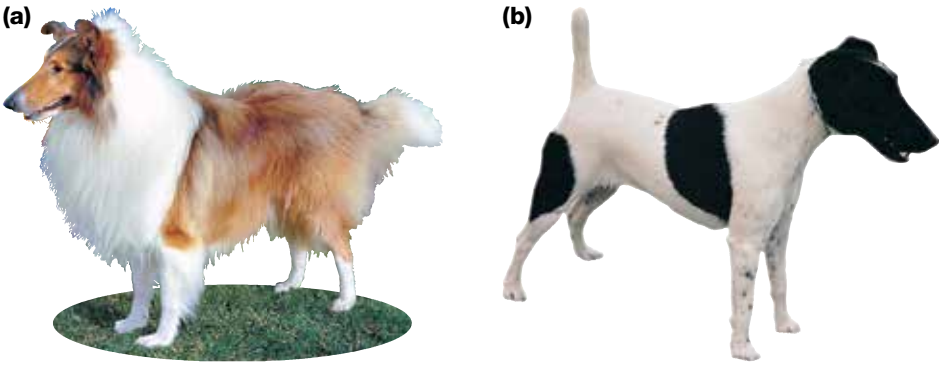


FIGURE 13.39 Dogs showing: **(a)** Irish spotting phenotype and **(b)** piebald spotting phenotype.

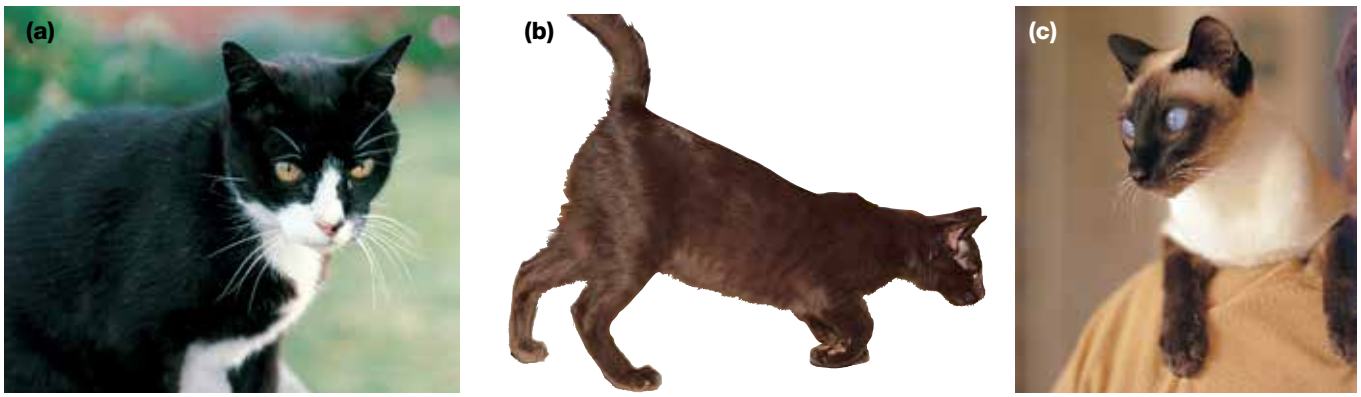


FIGURE 13.40 Cats showing: **(a)** intense black pigment; **(b)** Burmese dilution in which the black pigment is reduced to brown; and **(c)** Siamese pigment in which the pigment is further reduced and restricted to the ears, face, feet and tail. The order of dominance is $C > c^b = c^s$.

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Unit 2 AOS 2 Topic 1 Concept 1

Gene function
Concept summary and practice questions

Alleles of different genes may also be seen in plants. Figure 13.28 on page 503 shows the pea plants (*Pisum sativum*) that were the focus of Mendel's experiments. Note that the term 'trait' in this figure was appropriate in the time of Mendel but today the term used would be gene. Likewise, the 'variations' would today be referred to as alleles.

Table 13.8 identifies some alleles of genes in some other plant species. Note that the gene controls a general function, such as flower colour, but its alleles produce specific expressions of that function, such as purple and white. Figure 13.41a shows the smooth and wrinkled kernel textures in corn (*Zea mays*). These differences in texture are due to the difference in sugar levels in the kernels. Kernels with a high sugar content take up more water and swell more than kernels with a high starch content. As the kernels dry out, the greater loss of water from the sugary kernels causes them to become wrinkled.

TABLE 13.8 Alleles of some genes in plants

Gene function	Alleles and their action
Flower colour in delphinium	***P*** purple ***p*** white
Kernel colour in corn	***Pr*** purple (see figure 13.41b) ***pr*** yellow
Kernel texture in corn (see figure 13.41a)	***Su*** smooth (starchy) ***su*** wrinkled (sugary)
Mature fruit colour in capsicum (see figure 13.42)	***R*** red ***r*** yellow

Figure 13.41b shows the purple and yellow kernels in corn, while figure 13.42 shows some of the mature fruit colours in capsicum.

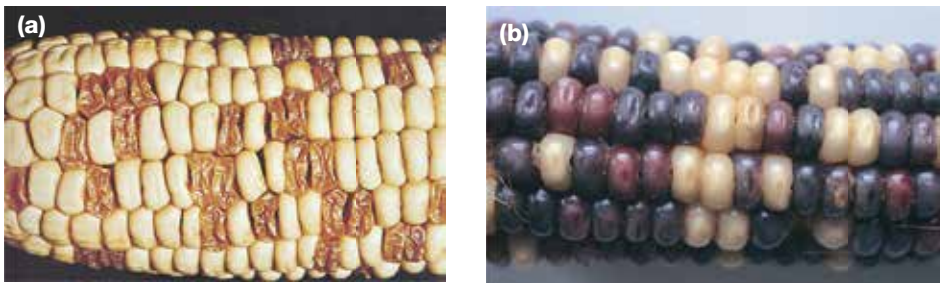

FIGURE 13.41 Corn showing: **(a)** wrinkled (sugary) and smooth (starchy) kernels and **(b)** purple and yellow kernels

FIGURE 13.42 Various colours in mature fruit of capsicum (*Capsicum annum*)

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Unit 2 AOS 2 Topic 1 Concept 2

Genes and alleles
Concept summary and practice questions

KEY IDEAS

- One gene can exist in a number of different forms called alleles.
- A gene controls a general function and its alleles produce specific expressions of that function.
- A gene controls a general trait and its alleles act to produce specific expressions of the trait.
- Each allele of a gene can be identified by its specific action.
- Some genes can be seen to have two alleles but in other cases multiple alleles exist.

QUICK CHECK

15 Fill in the following gaps with the term gene or allele.
a The _____ that produces short fur length in cats
b The _____ controlling fur length in cats

16 Refer to table 13.6. What is the phenotype and sex of a person with the genotype I^BI^B, MM?

17 A cob of corn consists of many individual cobs that are the offspring of a pair of parents. In one particular cob it is seen that some of the cobs are smooth and swollen but a smaller number are wrinkled and shrunken. This variation is due to the action of a single gene with two alleles. Using table 13.8, suggest which alleles of this gene might give rise to these two phenotypes.

BIOCHALLENGE

As part of the Deciphering Developmental Disorders (DDD) project, a survey was carried out on almost 7000 people to identify whether or not they would wish to be informed on a range of matters in the event that a researcher was to make a chance discovery or a so-called 'incidental finding' relating to their genomes. Figure 13.43 shows the results of this survey, published in April 2015.

The survey posed questions related to the following:

- *life-threat, can be prevented* — conditions that are life-threatening and can be prevented
- *carrier* — tells if a person is a carrier of a condition that could be relevant to their children
- *medications* — demonstrates how a person might respond to different medications or drugs (e.g. statins, anti-depressants)
- *useful later in life* — information that is not immediately relevant but could be useful later in life (e.g. relating to a very late onset cancer or predisposition to strokes)
- *ancestry* — tells about the person's ancestry
- *life-threat, cannot be prevented* — conditions that are life-threatening and cannot be prevented
- *not serious health importance* — is not likely to be of serious health importance (e.g. mild eyesight problems)
- *uncertain* — information that is uncertain and cannot be interpreted at the moment.

1. Identify the four groups of participants who participated in this survey.
2. What was the general view in regard to receiving information about conditions that are life-threatening and can be prevented?
3. Did attitudes change if these life-threatening conditions could not be prevented?
4. What about conditions that are serious (but not life-threatening) and cannot be prevented?
5. What about conditions that are serious (but not life-threatening) and can be prevented?
6. Which three categories had the highest proportions of participants wanting to receive that information?
7. Which two categories had the lowest proportions of participants wanting to receive that information?
8. Some categories show very little difference in the responses between the different groups of participants. Which groups of participant show the most marked difference in their response to the various situations?
9. Which might be your own responses to incidental information of various kinds arising from your genome?

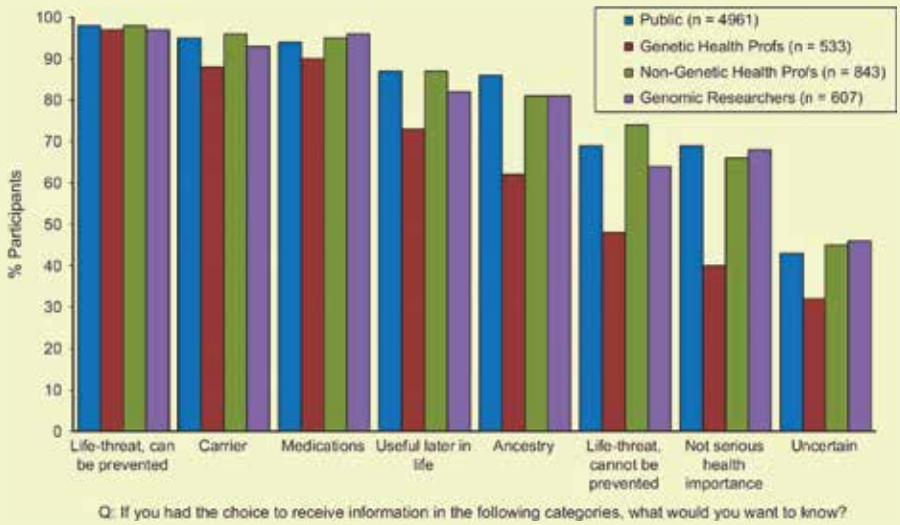

FIGURE 13.43 Results of the DDD project survey show that most people would prefer to know about their genetic information.

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Chapter review

Key words

adenine (A)
allele
base pair
base sequence
Chargaff's rule
comparative genomics
complementary base pair
cytosine (C)
deoxyribose
deoxyribonucleic acid (DNA)
dihybrid
dissociation
DNA sequencer
dominant
double helix
enhancer
gene
gene duplication
genome
genomics
guanine (G)
histone
horizontal gene transfer
Human Genome Project (HPG)
hybridisation
hydrogen bonds
'junk' DNA
metabolomics
microbiome
microbiomics
monohybrid
ncRNA gene
noncoding DNA
nucleic acid
nucleosome
nucleotide
open reading frame
promoters
protein-coding genes
proteomics
re-association
recessive
retrovirus
ribonucleic acid (RNA)
ribosomal RNA (rRNA)
short tandem repeats (STRs)
single nucleotide polymorphism
thymine (T)
transcriptomics
transfer RNA (tRNA)
transforming factor

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map on the Human Genome Project. You may use other words in drawing your map.

2 **Using the web to access information** ➜ Use the internet to research the history of genomics and answer the following questions.
- **a** Who discovered the four different bases (A, T, C and G) that are present in nucleotides, the building blocks of DNA? When? (Uracil is found in another nucleic acid, ribonucleic acid (RNA).)
- **b** Who was the first person to identify DNA? When? What did he call it?

3 **Developing explanations** ➜ Suggest explanations for the following.
- **a** The statement that 'Genes are made of DNA' is absent from textbooks published before the mid-1940s.
- **b** In a DNA double helix, the number of adenine molecules can be used to predict the number of thymine molecules.
- **c** In a single strand of DNA, the number of adenine molecules cannot be used to predict the number of thymine molecules.
- **d** In a DNA double helix, the ratio (A + C)/(T + G) is equal to 1.

4 **Evaluating information** ➜ Refer to pages 499–500 relating to the discovery of the double helix structure for DNA. Using Watson and Crick as examples of scientists, identify the following statements as true or false and briefly explain your choice.
- **a** Scientists might spend more time planning experiments than doing them.
- **b** Scientists start investigations without reference to the work of other scientists.
- **c** Discoveries occur only in laboratories as a result of experiments.
- **d** Unplanned inspiration can play a role in scientific discoveries.

5 **Demonstrating knowledge and understanding** ➜
- **a** What is Chargaff's rule?
- **b** After demonstrating that the proportions of A and T and of C and G were about equal in the DNA from many organisms, Chargaff and his co-workers wrote:

> A comparison of the molar proportions reveals certain striking, but perhaps meaningless, regularities.
>
> —1949

Does this fact suggest that scientists will be aware of the importance of facts or regularities that they discover? Explain.
- **c** The 1953 paper describing Watson and Crick's 3D model of DNA appeared in the journal *Nature*, vol. 171, p. 737. Visit a library or search the internet and locate this article. Does this article suggest that major discoveries can be explained only in long articles that are difficult to understand?

6 **Interpreting data** ➜ Samples of DNA were analysed and the following proportions of bases were found on the nucleotide subunits:

DNA	A	C	G	T
Sample 1	1.2	1.2	1.2	1.2
Sample 2	0.8	0.8	0.4	0.4
Sample 3	1.0	0.7	0.7	1.0

a Identify which, if any, of the samples could be double helical DNA.
b Identify which, if any, could not be double helical DNA.
c Briefly explain the reason for your answers in parts (a) and (b).

7 **Demonstrating understanding** ➜ The following is part of the nucleotide sequence of one chain in a DNA double helix:

. . . T A T G G G C A T G T A A T G G G C . . .

a Identify the base sequence of the complementary strand.
b What holds the two chains of DNA together in a double helix?

8 Suggest explanations in biological terms for the following observations.
a The first genome to be sequenced was that of the virus phiX174.
b Genomic studies indicate that some protein-coding genes have been conserved across many organisms from diverse classes.

9 **Making distinctions** ➜ Which of the following entries refer to a gene? Which refer to the particular alleles of a gene?
a The . . . that controls eye colour in humans
b The . . . that produces blue eye colour in humans
c The . . . that produces non-blue eye colour.

10 **Discussion question** ➜ The following statement appeared in November 2014.

> Ultimately, the goal is for all of us to have our genomes sequenced and available as a medical reference for our clinical care.
>
> —William Biggs, 'iCommunity Newsletter', November 2014

Another statement is as follows.

> It may be decades before interactions between genes, behavior and environment are understood well enough to provide substantial utility to warrant individualized recommendations based on genomic profiles. Furthermore, behavior change interventions that take advantage of some of the more unique aspects of genetic risk information are in their infancy.
>
> —Kurt D Christensen and Robert C Green, 'How could disclosing incidental information from whole-genome sequencing affect patient behavior?', vol. 10, no. 4, 10.2217/pme.13.24

Discuss with your classmates your thoughts about these statements. Identify any positive perspectives that you as a group identify in favour of the statements and any negative standpoints that are identified against the statements.

CHAPTER

14 Chromosomes: carriers of genes

FIGURE 14.1 A scanning electron micrograph of some double-stranded chromosomes (dyads). The DNA in these chromosomes has been replicated; this means that the chromosomes are composed of two sister chromatids. The inset shows TH Morgan, an American geneticist, whose experiments in 1910 with the fruit fly (*Drosophila melanogaster*) revealed that chromosomes are the carriers of the genes.

KEY KNOWLEDGE

This chapter is designed to enable students to:

- develop knowledge and understanding that chromosomes are packages of DNA containing the genetic material of organisms
- distinguish between autosomes and sex chomosomes
- recognise that chromosomes occur as homologous pairs that, in the case of the autosomes, carry the same gene loci
- identify the abnormalities that underpin human chromosomal disorders including Down syndrome
- gain understanding that the chromosomes of an organism can be shown as various presentations.

ODD FACT

Autumn crocus is not a crocus. It can be distinguished from true crocuses by the presence of 6 stamens. True crocuses have just three stamens.

FIGURE 14.2 Autumn crocus flowers, also known as naked ladies and meadow saffron. The flowers appear some time after the leaves have died off — hence the common name 'naked ladies'.

Chromosomes: how many?

A small plant (*Colchicum autumnale*) that grows across southern Europe has the common names meadow saffron, autumn crocus and naked lady. The name 'naked lady' is due to the fact that after the leaves of the plant appear in spring they die off, and the flowers appear in autumn on their own (see figure 14.2).

This simple but beautiful plant is poisonous. Deaths have occurred, often after a person has mistaken the plant for wild garlic and eaten its bulb-like corm. The poison in the autumn crocus is an alkaloid, known as **colchicine**. This poison was to play an important role in establishing the correct count of the human chromosomes in somatic cells, that is, discovering that the diploid number ($2n$) of chromosomes is 46.

Treatment of plant and animal cells with colchicine stops mitosis. Colchicine acts by interfering with spindle formation by binding to and disrupting the microtubules that form the structural elements of the mitotic spindle. If the spindle is faulty, the migration of chromosomes at anaphase cannot occur. Instead, the chromosomes are left at metaphase of mitosis. So, dividing cells treated with colchicine will stop their progress through the cell cycle at metaphase.

Two techniques were critical in establishing that the normal number of chromosomes in a human somatic cell was 46 ($2n = 46$). These techniques were (1) the use of **hypotonic shock treatment** of dividing cells, which causes the contents of the nucleus including the chromosomes to spread, and (2) the use of colchicine to arrest the dividing cells at metaphase, which causes the chromosomes to contract and thicken. As a result, the cell sample contains a higher proportion of cells at metaphase than normal. The combination of hypotonic shock and colchicine treatments produces so-called **metaphase spreads**, in which the chromosomes can be viewed, each clearly distinguishable and nonoverlapping. Figure 14.3 shows a typical metaphase spread of human chromosomes arrested at metaphase by virtue of a pretty little flowering plant: the autumn crocus.

FIGURE 14.3 A metaphase spread of human chromosomes. Note that the chromosomes are spread out and do not overlap. As a result of colchicine treatment of dividing cells the proportion of cells at metaphase was increased. (Why? Because they cannot proceed further!) The chromosomes in the lower left-hand corner are from another cell and they are at late prophase.

In 1956, two scientists, Tjio and Levan, published a scientific paper that correctly reported the diploid number of human chromosomes as 46 (JH Tjio and A Levan, 'The chromosome number of man', *Hereditas*, vol. 42, no. 1-2, 1956). This number was based on clear images of chromosomes made using hypotonic shock and colchicine treatment techniques. For decades before 1956 the

accepted diploid number of human chromosomes was 48, based on images in a scientific paper published in 1921.

Contrast the clarity of the chromosomes in figure 14.3 with those in figure 14.4, which shows drawings of human chromosomes from a textbook published in 1934 and identifies the diploid number as 48. This crowded image of overlapping chromosomes was the best that could be obtained at this time — very different from the clear images obtained by Tjio and Levan in 1956.

ODD FACT

In the early years of the twentieth century published counts of diploid human chromosomes ranged from as low as eight to as high as 50. A paper published in 1921 identified the number as 48 and that was the accepted figure until the Tjio and Levan paper of 1956.

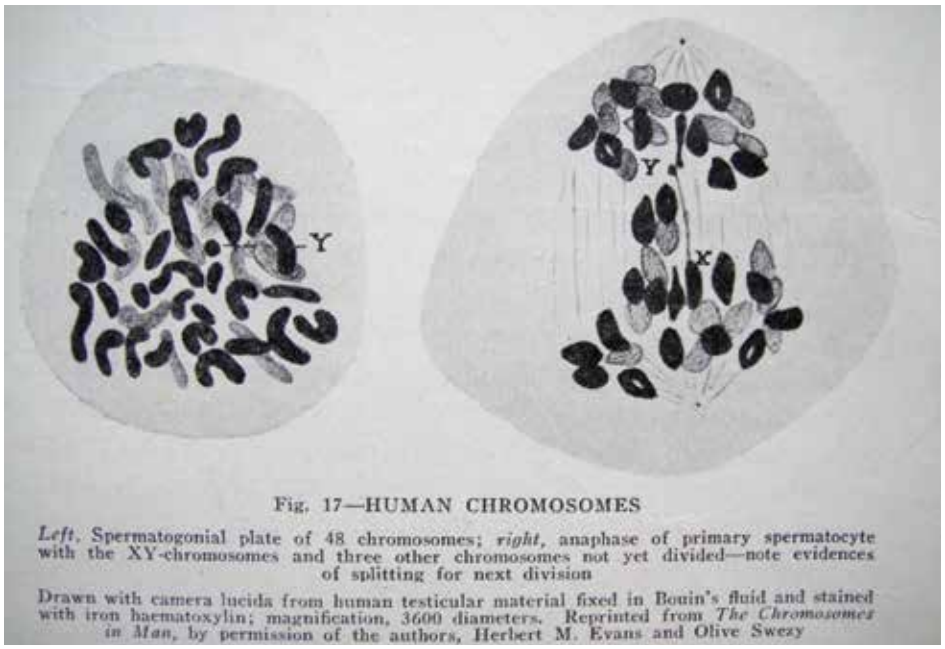

Fig. 17—HUMAN CHROMOSOMES

Left, Spermatogonial plate of 48 chromosomes; *right*, anaphase of primary spermatocyte with the XY-chromosomes and three other chromosomes not yet divided—note evidences of splitting for next division

Drawn with camera lucida from human testicular material fixed in Bouin's fluid and stained with iron haematoxylin; magnification, 3600 diameters. Reprinted from *The Chromosomes in Man*, by permission of the authors, Herbert M. Evans and Olive Swezy

FIGURE 14.4 Drawing of human chromosomes from a textbook published in 1934. The chromosome number is identified here as 48.

(*Source:* LC Dunn, *Heredity and Variation*, The University Society, New York, p. 46, 1934.)

The diploid number of chromosomes in human somatic cells is $2n = 46$ and the haploid number of chromosomes present in mature human gametes (eggs and sperm) is $n = 23$.

Other species of plants and animals have their characteristic diploid and haploid chromosome numbers. Table 14.1 identifies the diploid number of chromosomes in several animal and plant species.

TABLE 14.1 Diploid numbers of chromosomes in somatic cells of various species. What number would be expected in the sperm and egg cells of a rabbit?

Species	Diploid number ($2n$)
Animal	
chicken (*Gallus gallus*)	78
butterfly (*Lysandra nivescens*)	190
cat (*Felis catus*)	38
dog (*Canis familiaris*)	78
bilby (*Macrotis lagotis*)	19 (male) 18 (female)
garden snail (*Helix aspersa*)	54
honeybee (*Apis mellifera*)	32
housefly (*Musca domestica*)	12
leopard seal (*Hydrurga leptonyx*)	34
platypus (*Ornithorhynchus anatinus*)	52
rabbit (*Oryctolagus cuniculus*)	44
Eastern tiger snake (*Notechis scutatus*)	34
fruit fly (*Drosophila melanogaster*)	8
ant (*Myrmecia pilosula*)	2

(continued)

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TABLE 14.1 *(continued)*

Species	Diploid number (2*n*)
Plant	
crimson bottlebrush (*Callistemon citrinus*)	22
drooping she oak (*Casuarina stricta*)	26
edible pea (*Pisum sativum*)	14
ginkgo (*Ginkgo biloba*)	24
Iceland poppy (*Papaver nudicaule*)	14
kangaroo paw (*Anigozanthos flavidus*)	12
Ovens wattle (*Acacia pravissima*)	26
pineapple (*Ananas comosus*)	50
river red gum (*Eucalyptus camaldulensis*)	22
silky oak (*Grevillea robusta*)	20
silver wattle (*Acacia dealbata*)	26
Sydney blue gum (*Eucalyptus saligna*)	22
tomato (*Lycopersicon esculentum*)	24
corn (*Zea mays*)	20

Organising chromosomes

A metaphase spread of human chromosomes is viewed through a microscope and the chromosomes are seen to be arranged randomly. In another metaphase spread the chromosomes would have different random arrangements. Contrast the two different arrangements of the same diploid set of chromosomes in figure 14.5. In figure 14.5a, the chromosomes are arranged randomly as a metaphase spread. In figure 14.5b, the chromosomes are organised by size and centromere position into matching or homologous pairs in an arrangement known as a **karyotype**.

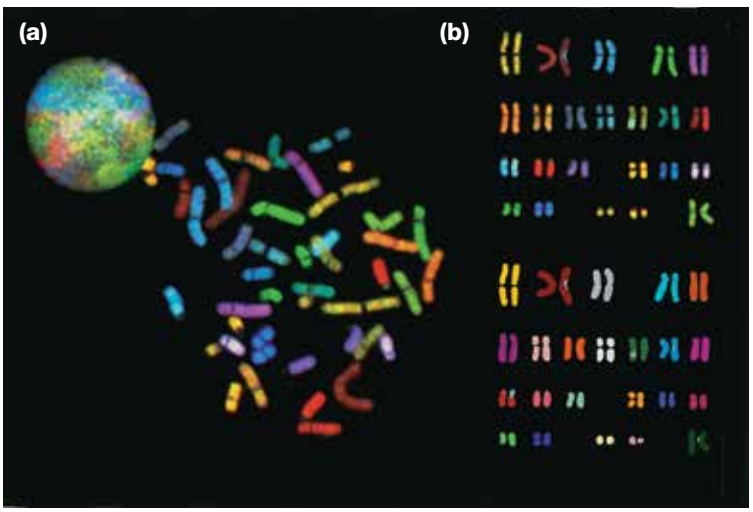

FIGURE 14.5 Spectral karyotyping of human chromosomes **(a)** Metaphase plate showing random arrangement of chromosomes after the simultaneous hybridisation of 24 differentially labelled chromosome painting probes **(b)** Organisation of the chromosomes into an arrangement called a karyotype. The image was acquired using spectral imaging through a custom-designed filter cube from Chroma Technology. (SKY™ is a registered trademark of Applied Spectral Imaging.) (Image courtesy of Evelin Schröck, Stan du Manoir, Thomas Ried and Chroma Technology)

Karyotypes are used to assist in the analysis of the chromosomes that are present in cells. In a karyotype, the chromosome images are organised in a pattern according to an international convention. Such an arrangement enables any abnormality in either number or structure of the chromosomes to be quickly identified (see figure 14.6).

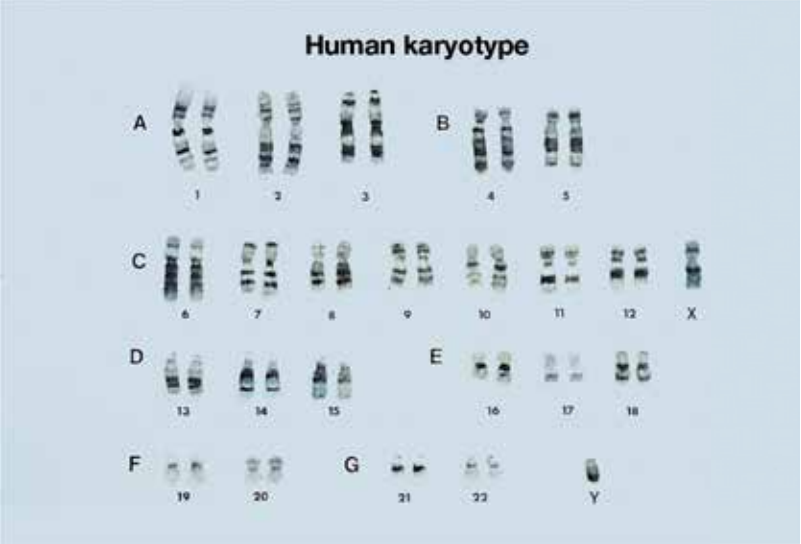

FIGURE 14.6 Chromosomes of a normal human male arranged into a karyotype. These chromsomes have been treated with a particular staining technique that results in a distinctive pattern of light and dark bands on each chromosome. How might this assist identification of matching (homologous) pairs of chromosomes?

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As well as using conventional stains, chromosomes can also be stained using a range of probes with fluorescent labels that bind to specific segments of DNA on the different human chromosomes. Figure 14.7 shows a karyotype with these fluorescent labels. Each chromosome has a distinctive colour.

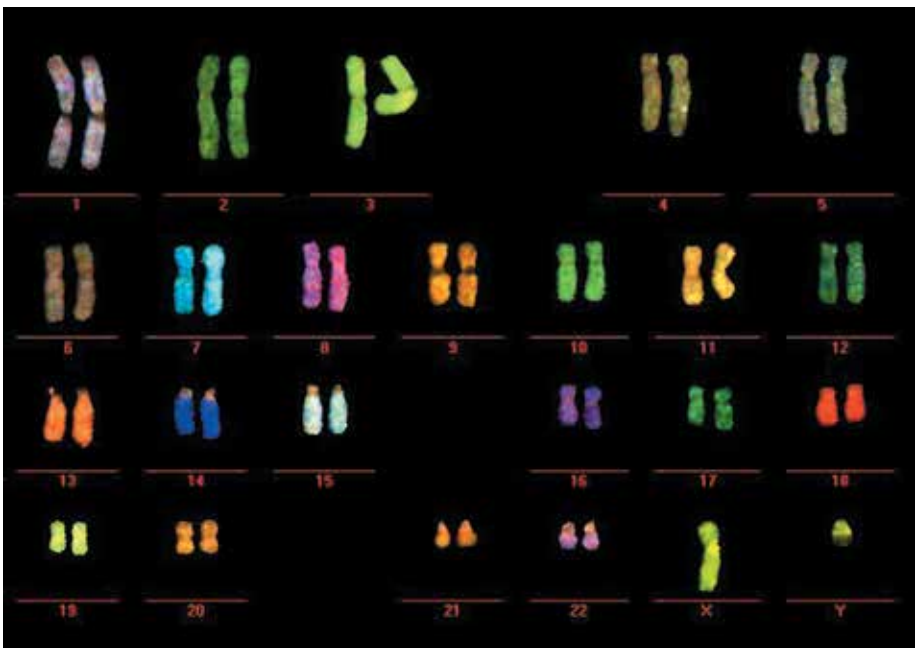

FIGURE 14.7 A spectral karyotype showing the distinctive colours of each human chromosome. Each homologous pair of chromosomes fluoresces with a distinctive colour as determined by the colour of specific fluorescent probes that bind to specific sequences in the DNA of each particular chromosome.

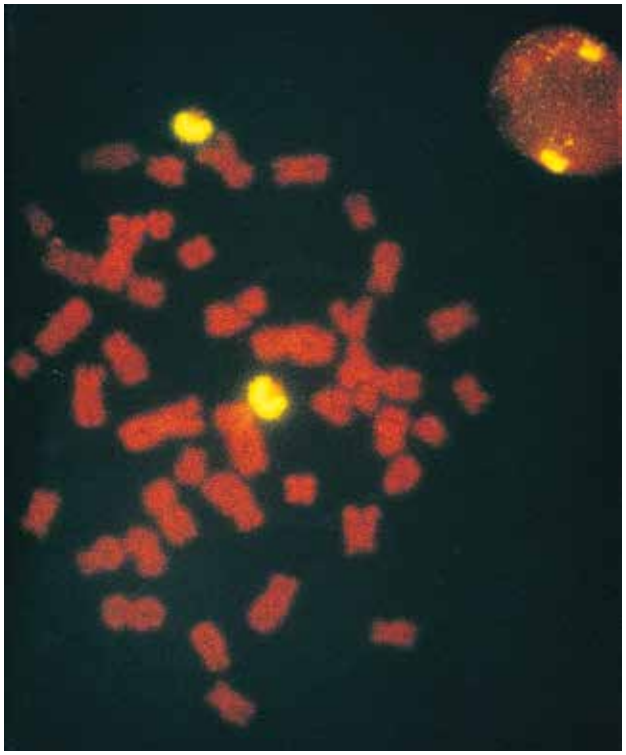

FIGURE 14.8 A fluorescent probe that appears bright yellow has been mixed with chromosomes. The probe is specific for the Y chromosome. At how many sites has the Y-specific probe become bound? The second cell (upper right) is at metaphase of mitosis.

A type of fluorescent staining called **FISH** (fluorescent in-situ hybridisation) can be used to identify specific chromosomes or short segments of specific chromosomes. Figure 14.8 shows the fluorescent labelling of the human Y chromosome where a labelled probe specific to a segment of DNA on the Y chromosome has been used to distinguish it from the other human chromosomes.

Another representation of human chromosomes is called an **ideogram**. Ideograms are schematic representations of chromosomes that show their relative sizes and the distinctive banding pattern of each chromosome (see figure 14.9). These banding patterns are produced using a specific staining.

The 46 human chromosomes from a normal human male can be arranged into 23 pairs of chromosomes, consisting of 22 matched pairs and one 'odd' pair that is made up of one larger X chromosome and a smaller Y chromosome. In a normal female, a similar arrangement is seen, except that there are two X chromosomes and no Y chromosome. The pair of chromosomes that differs between the sexes makes up the **sex chromosomes**. A shorthand way of denoting the pairs of chromosomes for each sex is as follows — normal human male: 46, XY, and normal female: 46, XX. (Note that the number indicates the total number of chromosomes including the sex chromosomes and the letters denote the sex chromosomes.) A similar pattern is seen in other mammals where the female typically has two X chromosomes and the male has one X and one Y chromosome. This is not the case in other animal groups.

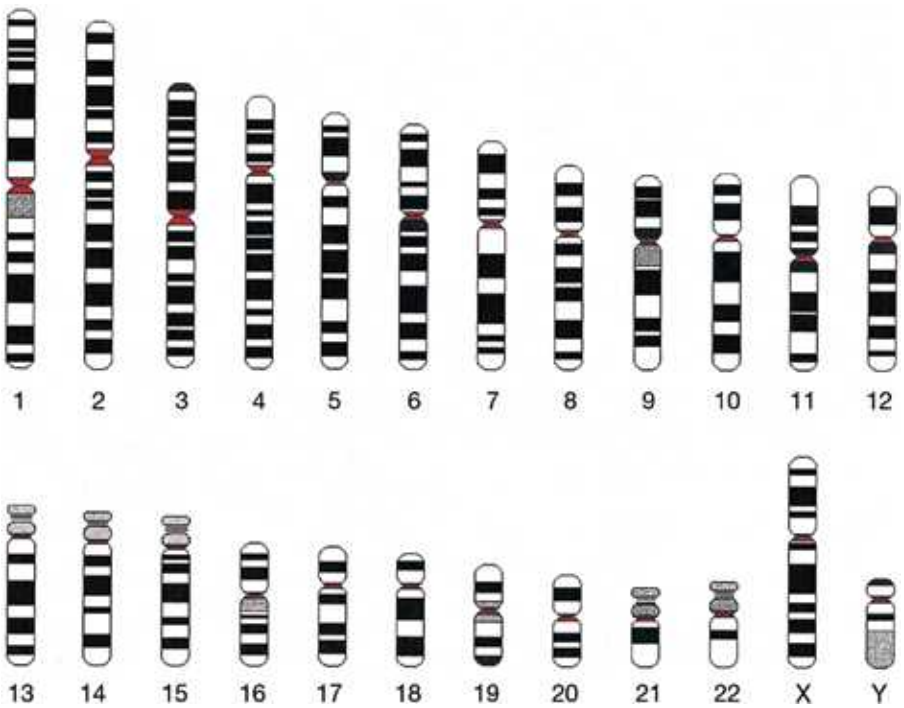

FIGURE 14.9 An ideogram of human chromosomes showing the stylised representation of the chromosomes

The 22 matched pairs of chromosomes present in both males and females are termed autosomes. These different autosomes can be distinguished by:

- their relative size
- the position of the **centromere**, which appears as a constriction along the chromosome. In some cases, the centromere is near the middle (e.g. the number-2 chromosome in figure 14.6), while in others it is close to one end (e.g. the number-13 chromosome in figure 14.6).
- patterns of light and dark bands that result from special staining techniques.

Autosomes are identified by the numbers 1 to 22 in order of decreasing size; the number-1 chromosomes are the longest, and the number-21 and number-22 chromosomes are the smallest. The larger the chromosome, the more DNA it contains and usually the greater the number of genes that it carries.

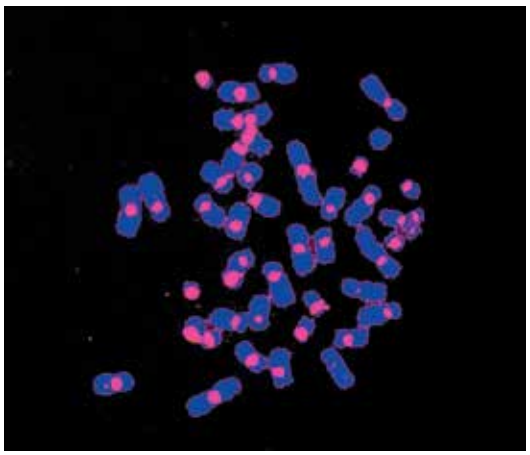

FIGURE 14.10 Human chromosomes with their centromeres made visible with a probe labelled with a pink fluorescent dye that binds to the centromeric DNA of all chromosomes. The remainder of the chromosomes have been stained with a blue fluorescent dye. Can you identify a chromosome with a centromere near the end of the chromosome?

The members of each matching pair of chromosomes, such as the two number-5 chromosomes, are said to be homologous. Nonmatching chromosomes, such as a number-5 chromosome and a number-14 chromosome are said to be **nonhomologous**.

At a particular location along its length, each chromosome has a constriction that is known as a centromere. In human chromosomes, the DNA at the centromere contains about one million base pairs and much consists of repeated sequences of bases. Figure 14.10 shows the chromosomes from a dividing white blood cell where the chromosomes have been hybridised with a pink fluorescent probe that binds to the DNA of the centromere. The centromere is surrounded by a structure, known as the **kinetochore**, that is made of protein. The kinetochore forms the attachment point for the spindle fibres that are necessary for the orderly movement of chromosomes during both cell division (mitosis) and gamete formation (meiosis). This orderly movement of chromosomes ensures that each daughter cell formed by mitosis has a double (diploid) set of chromosomes and that gametes formed by meiosis contain a single (haploid) set of chromosomes.

Human chromosomes, like the chromosomes of other eukaryotes, have distinctive ends. Chromosome ends are known as **telomeres** and they consist of DNA made up of many thousands of repeats of short sequences of base pairs. In your chromosomes, the repeated sequence is TTAGGG. Telomeres prevent chromosomes sticking together and they enable complete replication of chromosomes to occur. To review telomeres, refer to figure 9.20 on page 405.

Analysing karyotypes

Mistakes in chromosome numbers or abnormalities of single chromosomes can produce congenital disorders. In addition, specific chromosome abnormalities are associated with various cancers and these chromosome changes can indicate the likelihood of remission. Scientists who specialise in the study of human karyotypes are known as **cytogeneticists**.

Today, in hospital cytogenetic laboratories, images of chromosome sets from cells are captured by a camera attached to a microscope (see figure 14.11). The images are then transferred to a computer where a scientist uses special software, such as CytoVision®, that analyses the chromosomes from cells and automatically generates a karyotype (see figure 14.11). The chromosomes in a minimum of 15 cells must be examined before a karyotype can be decided. This computer-based automation has increased the capacity of hospital laboratories to prepare the karyotypes that are important in diagnosis of conditions such as Down syndrome, where an extra number-21 chromosome is present, or Prader-Willi syndrome, in which a small deletion of the number-15 chromosome occurs.

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FIGURE 14.11 A scientist in a cytogenetic laboratory analyses a patient's chromosomes under a microscope and studies the display on a computer screen.

Wrong numbers and other errors

Various changes can occur involving chromosomes, including:

- changes in the total number of chromosomes
- changes involving part of one chromosome
- changed arrangements of chromosomes.

Changes in total number

Some newborn babies have an abnormal number of chromosomes in their cells. A baby may have an additional chromosome, giving a total of 47 instead of the normal 46. **One additional chromosome or one missing chromosome typically has deleterious effects** on development and, for most chromosomes, death occurs during early development and the pregnancy never proceeds to term.

A pregnancy may still be carried to term if the chromosomal changes involve a few particular chromosomes (see table 14.2). The most common chromosomal anomaly seen in human populations is **Down syndrome (DS)**, in which there is an additional copy of the number-21 chromosome. When three copies of a chromosome occur, instead of the typical pair of chromosomes, a cell or an organism is said to be **trisomic** for that chromosome. When one member of the typical pair of chromosomes is missing, the condition is termed **monosomy**. Monosomy causes embryonic death, except for a monosomy involving the sex chromosomes.

Using the shorthand mentioned on page 526 to show the karyotype, for example, 46, XX, a missing sex chromosome is usually indicated with the symbol 'O'. If an extra entire autosome is present, this is shown by the chromosome number with a plus sign in front of it, for example, +21. A plus or a minus sign after the chromosome number indicates that only part of a chromosome is either present (+) or missing (–), and either a 'p' (short) or a 'q' (long) symbol is used to denote which arm of the chromosome is involved. Table 14.2 gives some examples of shorthand notations of a karyotype.

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TABLE 14.2 Some examples of chromosome changes and approximate incidence rates. Which syndrome is an example of a trisomy? A monosomy? The XYY condition does not have a clinical name.

Chromosome change	Resulting syndrome	Approximate incidence rate
Addition: whole chromosome		
extra number-21 (47, +21)	Down syndrome	1/700 live births
extra number-18 (47, +18)	Edwards syndrome	1/3000 live births
extra number-13 (47, +13)	Patau syndrome	1/5000 live births
extra sex chromosome (47, XXY)	Klinefelter syndrome	1/1000 male births
extra Y chromosome (47, XYY)	n/a	1/1000 male births
Deletion: whole chromosome		
missing sex chromosome (46, XO)	Turner syndrome	1/5000 female births
Deletion: part chromosome		
missing part of short arm of number-4 (46, 4p–)	Wolf-Hirschhorn syndrome	1/50 000 live births
missing part of short arm of number-5 (46, 5p–)	cri-du-chat syndrome	1/25 000 live births

Changes to parts of chromosomes

Changes can occur that involve part of a chromosome, such as:

- **duplication**, in which part of a chromosome is duplicated (see figure 14.12a)
- **deletion**, in which part of a chromosome is missing (see figure 14.12b), as in cri-du-chat syndrome, for example, so named because affected babies have a cat-like cry (see table 14.2).

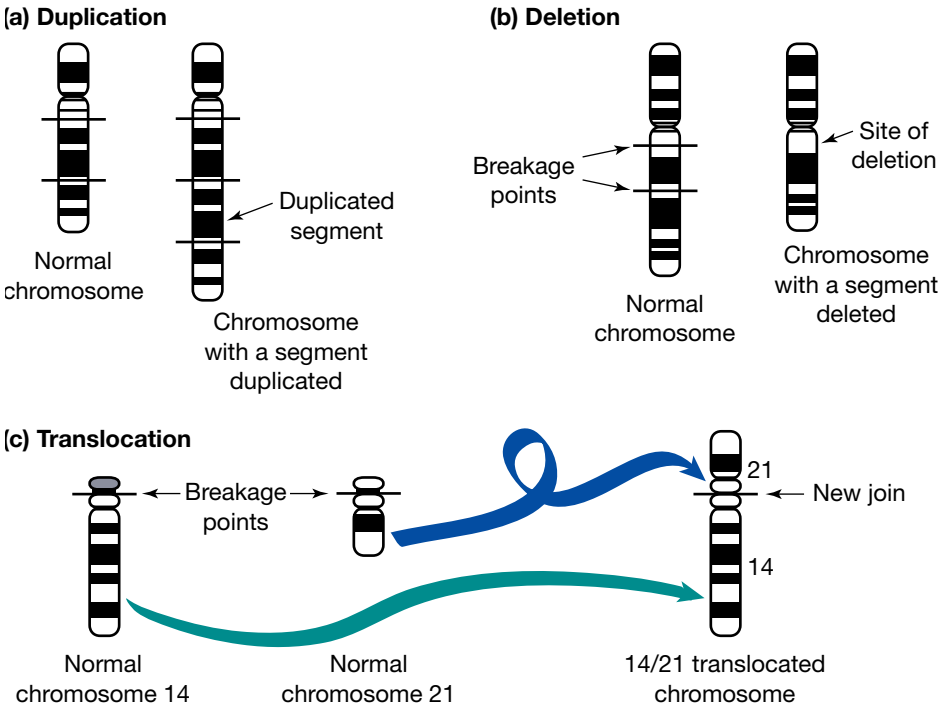


FIGURE 14.12 **(a)** Normal chromosome and the same chromosome showing a duplication **(b)** Normal chromosome and the same chromosome showing a deletion **(c)** An example of a 14/21 translocation

Re-arrangements of chromosomes

Structural changes may occur in which the **location of a chromosome segment is altered** so that it becomes relocated to a new region within the karyotype. Such a change is known as a **translocation**. One example is related to a special case of Down syndrome when part of the number-21 chromosome becomes physically attached to a number-14 chromosome (see figure 14.12c). **The parental origin of the chromosomes is also important.** Normally a child inherits one member of each chromosome pair from each of its parents. If both copies of a particular chromosome are inherited from one parent, instead of the usual one from each parent, abnormalities of development result. For example, **Angelman syndrome**, characterised by poor motor coordination and mental retardation, can result if an **embryo** inherits both of its number-15 chromosomes from its mother and none from its father.

A case of Down syndrome

Michael (see figure 14.13a) is a young boy who has 47 chromosomes in his body cells, instead of the normal 46. His karyotype shows the presence of an extra number-21 chromosome, which is typical of the condition Down syndrome. This karyotype can be denoted as 47, XY, +21 (where '47' denotes the total number of chromosomes, 'XY' denotes the sex chromosomes present, and '+21' denotes the identity of the extra chromosome).

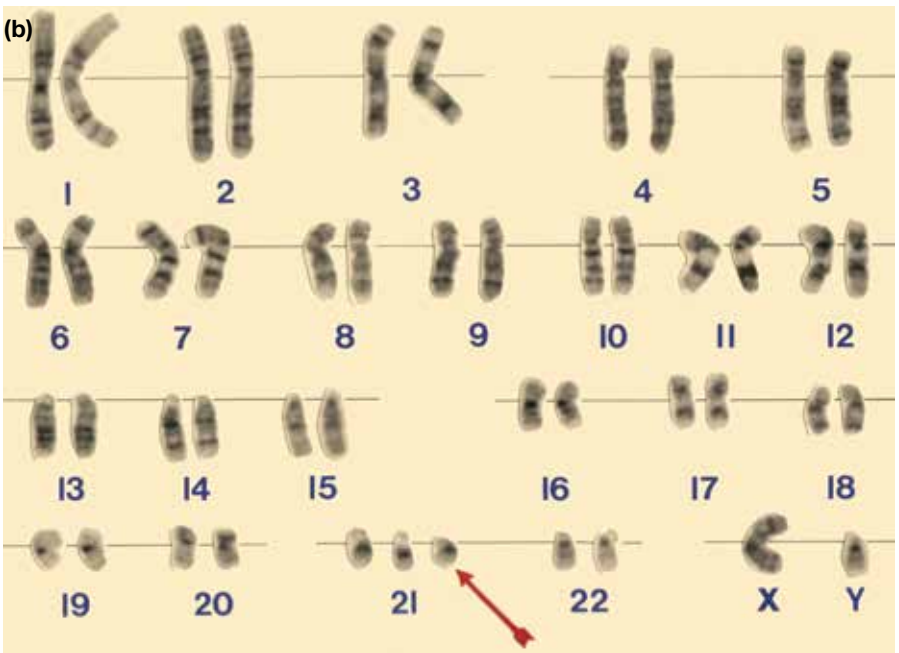
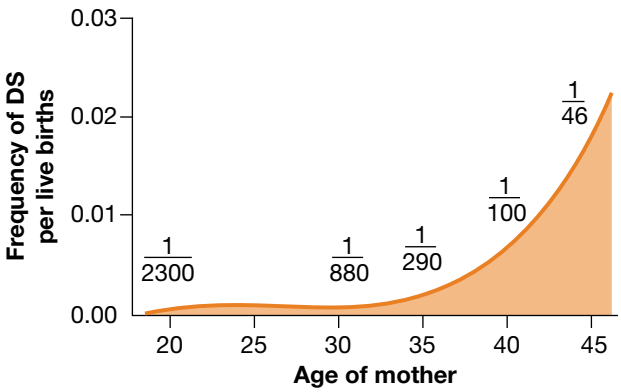


FIGURE 14.13 (a) Michael, pictured aged 11, is a DS boy who enjoys using a computer, which is one of his many interests. **(b)** A typical karyotype from a DS male like Michael. Which chromosome is present as a trisomy?



About one in 700 babies born in Australia has an extra number-21 chromosome, but the rate differs according to the age of the mother (see figure 14.14). The risk of having a DS baby increases with maternal age; the risk for mothers aged 20 is about 1/2300, while the risk for mothers aged 40 is about 1/100.

FIGURE 14.14 Incidence of DS births for mothers of different ages. How does the risk of a DS baby for a 40-year-old woman compare with that for a 20-year-old? Increased father's age also increases the risk, but to a lesser extent.

The presence of an extra number-21 chromosome produces various symptoms including a fold on the inner margin of the upper eyelid, a smaller than normal mouth cavity and distinctive creases on the palms of the hands and the soles of the feet. The trisomy condition in which three separate copies of the number-21 chromosome are present in the karyotype is the most common form of DS. In most cases, the extra number-21 chromosome is transmitted via an abnormal egg with 24 chromosomes, including two number-21 chromosomes. If this egg is fertilised by a normal sperm (with 23 chromosomes including one number-21 chromosome), a DS embryo will result (see figure 14.15).

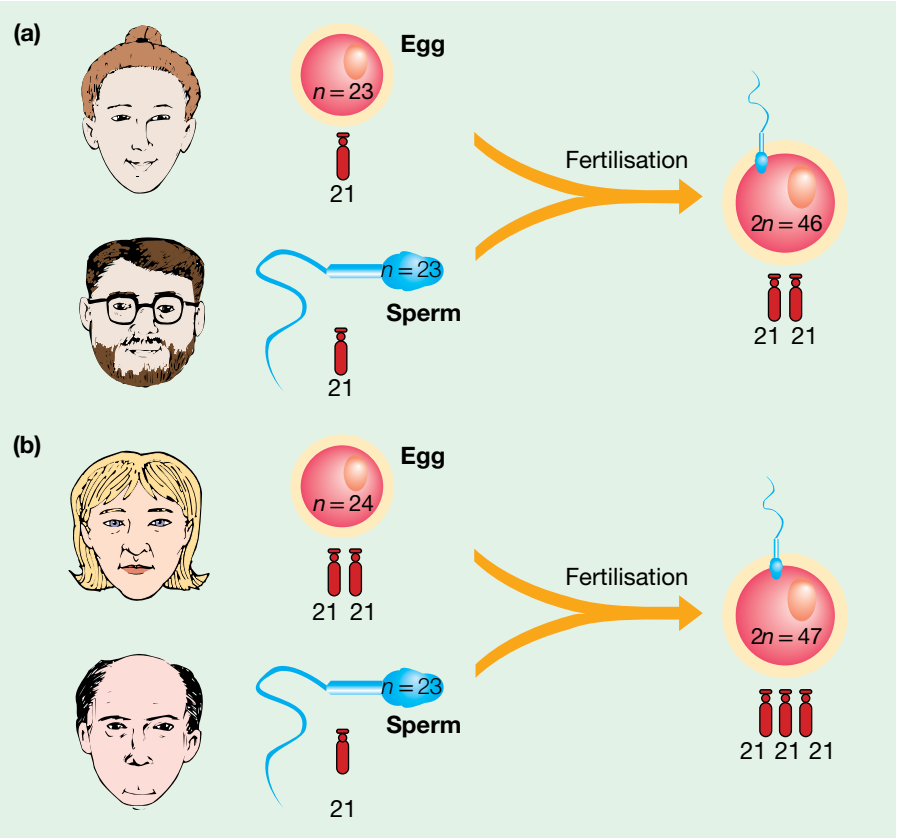


FIGURE 14.15 **(a)** Fertilisation of normal gametes **(b)** Possible gametes involved in fertilisation to produce a DS zygote (In both (a) and (b), the number-21 chromosomes are shown separately.)

An abnormal egg results when, during the process of egg formation by meiosis in the ovary, **the normal separation of the two copies of chromosome 21 to opposite poles of the spindle does not occur. This type of error is known as a nondisjunction** and is unpredictable. For parents who have a DS child who is a result of nondisjunction during egg formation in the mother (or during sperm production in the father), the risk of a second child with DS is low and is determined by the mother's age. When a child with DS is born, new challenges arise for the family concerned. Read the box on page 535, about Jane, a young woman with DS, as told by her mother.

Another form of DS: translocation

Each year in Australia, a few babies are born who show all the clinical signs of DS. Their karyotype, however, shows just 46 chromosomes, instead of the 47 expected in DS. So, what has happened?

In these cases, a third number-21 chromosome is present, but it is not a separate chromosome. Instead, the extra number-21 is joined to another chromosome, for example, the number-14 chromosome, through a translocation (see figure 14.16). As a result, the total number of chromosomes in somatic cells of this rarer form of DS is 46.

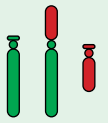
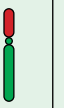
Leanne's parents	Total number of chromosomes	View of number-14 and number-21 chromosomes	Possible gametes
	45		Type A Type B  Type C Type D
	46		

FIGURE 14.16 A translocation form of Down syndrome in which the condition is inherited. Note that the mother can produce four kinds of egg in terms of their chromosomal make-up. Baby Leanne resulted from the fertilisation of an egg of type C with a normal sperm. What would result when an egg of type B was fertilised? A fertilised type-D egg would die. Why?

Baby Leanne has DS. Examination of her chromosomes showed a total of 46 chromosomes. The third copy of the number-21 chromosome is attached to one of her number-14 chromosomes. This type of DS is called translocation DS, because the extra number-21 chromosome has been transferred to an unusual location on another chromosome.

When a translocation DS baby is detected, the chromosomes of its parents are also investigated because many cases of translocation DS are inherited. When this is the case, one of the parents is found to have 45 instead of the expected 46 chromosomes (see figure 14.16) because this parent has one of the number-21 chromosomes translocated to another chromosome. In these cases, the chance that the next child will be affected is theoretically about one in three but in reality is about one in 10.

Errors in sex chromosomes

During gamete formation by meiosis, critical events include the orderly disjunction of homologous chromosomes to opposite poles of the spindle. In some cases, nondisjunction of homologous chromosomes may occur, for example, at anaphase 2 of meiosis, such that a gamete may have two copies of one chromosome instead of the normal single copy, or a gamete may be lacking a copy of one chromosome (see figure 14.17). The failure of homologous chromosomes to separate to opposite poles of their spindle at anaphase, or nondisjunction, during meiosis creates some gametes with an extra chromosome and some with a missing chromosome.

If nondisjunction events such as these involve one of the sex chromosomes, the fertilisation of an abnormal gamete by a normal gamete will produce a zygote with an imbalance in its sex chromosomes. Table 14.3 shows some possible abnormal outcomes, as well as the normal XX female and the normal XY male outcomes. Remember that the 'O' does not denote a chromosome, it denotes that a chromosome is missing. Gametes that are the result of a nondisjunction at anaphase 2 of meiosis are shown in red.

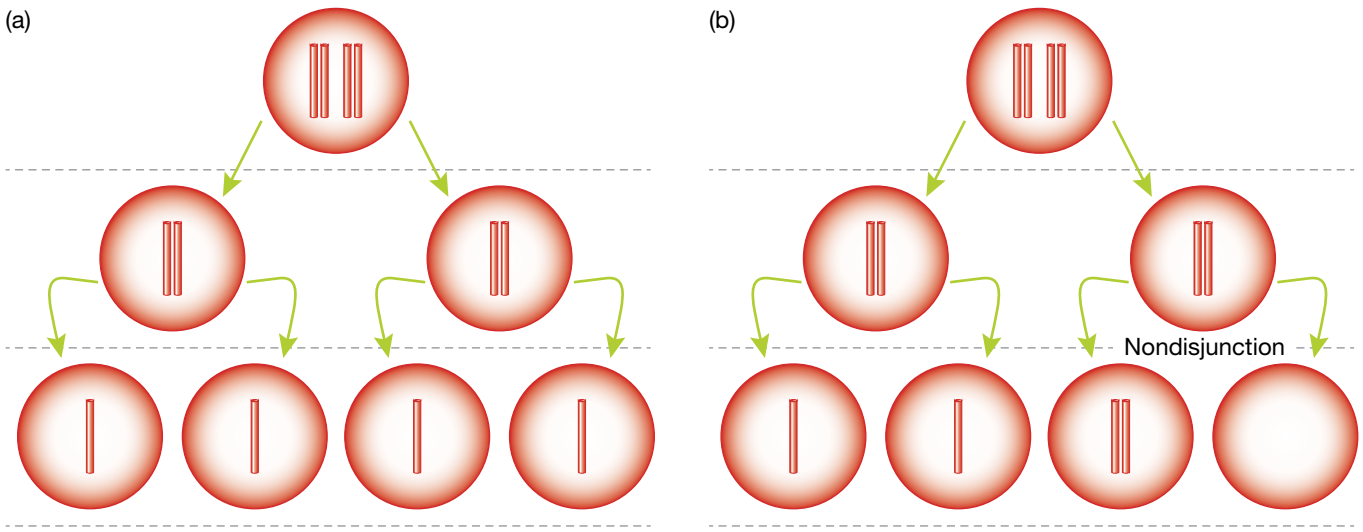


FIGURE 14.17 **(a)** The disjunction of a chromosome pair during an error-free meiosis. The duplicated pair of homologous chromosomes in the cell in the top of the diagram undergoes two anaphase separations to produce four gametes, each with a single copy of the chromosome. **(b)** The result of a nondisjunction of homologous chromosomes in anaphase 2 of meiosis

TABLE 14.3 Possible outcomes, in terms of sex chromosomes of fertilisation of an egg by a sperm, where in some cases one gamete is abnormal because of a nondisjunction of the sex chromosomes at anaphase 2 of meiosis

Egg of female parent	Sperm of male parent	Resulting zygote
X	X	XX, normal female
X	Y	XY, normal male
XX	X	XXX, triple X female
XX	Y	XXY, Klinefelter syndrome
X	XY	XXY, Klinefelter syndrome
O	X	XO, Turner syndrome
X	O	XO, Turner syndrome
O	Y	OY, nonviable
X	YY	XYY, double Y male

Of the possible outcomes, two result in a person with clinical abnormalities: Turner syndrome (45, XO) and Klinefelter syndrome (47, XXY). Persons with Turner syndrome are female and display clinical signs including sterility because of the absence of a uterus. Persons with Klinefelter syndrome are male and display clinical signs that include sterility and often female-type breast development. In contrast, females who are 47, XXX and males who are 47, XXY show no clinical signs, are fertile and typically would be unaware of their less usual chromosomal status.

If we compare the situation between the autosomes and the sex chromosomes, it becomes apparent that changes to the numbers of autosomes are far more drastic in their effects than changes to the numbers of sex chromosomes.

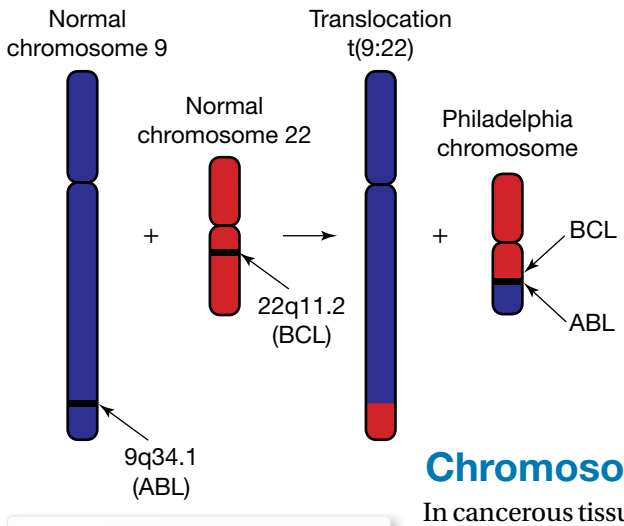


FIGURE 14.18 Diagram showing the reciprocal exchange that occurs between chromosome 9 and chromosome 22 in chronic myeloid leukaemia. The relocation of the **ABL** and the **BCR** genes into close proximity on the Philadelphia chromosome has been shown to be the cause of chronic myeloid leukaemia.

All cases of monosomy of an autosome are nonviable resulting in embryonic death, but the monosomy XO (Turner syndrome) is viable. This indicates that two copies of each autosome are essential for prenatal development. In contrast, even with only one X chromosome, prenatal development proceeds and the affected female survives into adulthood. However, the absence of both X chromosomes creates a nonviable situation.

Only a few cases of trisomy of an autosome are viable, and of these only trisomy 21 (Down syndrome) normally survives into adulthood. In contrast, a person with a XXX trisomy shows no clinical signs. (We will see in chapter 15 why this is the case — it is called X inactivation.)

Chromosomal changes in cancer

In cancerous tissues multiple changes occur in the chromosomes of cells, such as where part of one chromosome becomes attached to a nonhomologous chromosome, or extra copies of chromosomes are present or chromosomes are missing.

For example, more than 90 per cent of patients with chronic myeloid leukaemia have a chromosomal change that produces a so-called Philadelphia (Ph) chromosome. The Ph chromosome is seen in bone marrow cells and it consists of the bulk of the number-22 chromosome to which part of the number-9 chromosome is attached. Likewise, the number-9 chromosome carries the missing part of the number-22 chromosome (see figure 14.18). This chromosomal change where an exchange of segments occurs between two nonhomologous chromosomes is termed a **reciprocal translocation**, in this case denoted t(9;22). Karyotypes using the FISH staining restricted to just two chromosomes can assist in identifying these changes, such as the reciprocal translocations in chronic myeloid leukaemia (see figure 14.19).

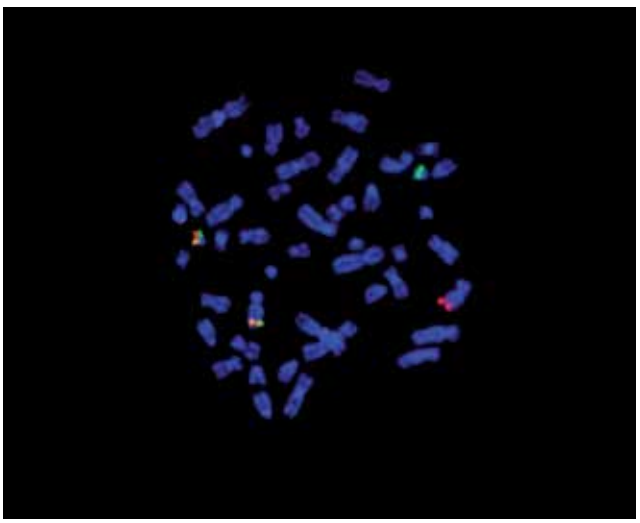


FIGURE 14.19 FISH staining of the metaphase chromosomes using fluorescent probes that bind specifically to the **ABL** gene (red) on chromosome 9 and the **BCR** gene (green) on chromosome 22, in a cell from a person with chronic myeloid leukaemia. Can you pick the Ph chromosome? Note the mixture of coloured probes on the small chromosome at the left — this is the Ph chromosome that consists of most of chromosome 22 with a small segment of chromosome 9 attached.

JANE'S STORY, AS TOLD BY HER MOTHER

'Jane is the third of four children born into our family. When she was born, little did we realise the extent to which our ideas about disability and life chances would change. We were shocked, saddened and confused about what it might mean to have a child with Down syndrome. We didn't know very much about it; however, we were fortunate to have doctors who provided us with as much information as possible and urged us to treat her just like any other baby. Jane received the same attention, the same love and the same opportunities for learning and socialising that her brothers experienced.

Jane's early development proceeded through the same stages as for other children, but more slowly. She sat up at 10 months, crawled at 15 months, walked when she was 26 months old and talked by the time she was three and a half. We came to believe that Jane could learn to do most things that other children learn, but that the learning process would take longer. She was happy to watch others but wouldn't necessarily initiate action as much as other children do, so we ensured that Jane was actively involved in as many play experiences as possible.

When Jane was three and a half, she attended a Day Training Centre for the Intellectually Handicapped, as such centres were called then. She became involved in music, painting, solving jigsaws, and so on. However, she was still doing much the same things two years later and her opportunities for academic learning were very limited. We believed that Jane was capable of learning much more than was expected of her at the centre. When Jane was five, she had the opportunity of attending the local kindergarten for two days a week where she socialised with children with a much broader range of abilities. At six, Jane began to learn how to read. Having been a primary teacher, I taught Jane at home and was delighted to find that she learned with relative ease. From then on, we never assumed what Jane may or may not be capable of learning, but provided opportunities for her to learn. At this time the integration debate began, and it reinforced my conviction that Jane should attend her local school with her brothers and neighbourhood peers. So when Jane was seven, she was admitted at our local school and had her needs met in the same way as students. Although Jane was two years older than most of the other children, she was very small and was at their level developmentally, so her placement was appropriate.

In looking for secondary school options for Jane, we were delighted when she was accepted into a small Catholic girls' school that catered for individual differences in an inclusive way. Jane attended secondary school for five years, after which time the work was becoming too complex and difficult for her, so a job placement seemed to be a more appropriate option. Her integration into the mainstream of education broadened Jane's options for integration into the workforce. Since leaving school she has been employed in fast-food businesses and in retail stores. For nearly 15 years she has been employed in a Target store under a productivity-based pay scheme, whereby she is paid according to her level of productivity, as measured against the average worker. Under this scheme, she receives a disability pension reduced according to her wage. She now needs less support and has even had some long-service leave.

Jane knows that she has Down syndrome and has a simple understanding of what that means genetically, but she doesn't see herself as disabled. Indeed, she continues to learn and has reached a level of independence that we would not have believed possible.

She has had piano lessons and is interested in TV, books, music and dancing. She is capable of travelling to and from work, shopping by herself, operating quite complex video, DVD and internet technology, arranging social outings with her friends and making appointments for herself. Jane has had lessons in cooking and budgeting to enable her to achieve greater independence. Although Jane received her 'L' plates ready for driving lessons, she didn't in fact take them. The important thing is that she had the opportunity to learn.

FIGURE 14.20 Jane in 2012

KEY IDEAS

- Each species has a characteristic number of chromosomes, known as the diploid number, typically present in body (somatic) cells.
- Human chromosomes in body cells exist in pairs, normally 23 pairs.
- The 23 pairs of human chromosomes include 22 pairs of autosomes, present in both sexes, and one pair of sex chromosomes, XX in the female and XY in the male.
- Chromosome sets can be organised into karyotypes.
- An ideogram is a stylised diagrammatic representation of chromosomes.
- Additional or missing entire chromosomes or parts of chromosomes are readily identified from an analysis of karyotypes.
- Certain syndromes result from chromosomal changes.
- Cancers are associated with chromosomal changes.

QUICK CHECK

1 Identify a key difference between the members of the following pairs.
   - **a** Ideogram and karyotype
   - **b** Autosome and sex chromsome
   - **c** Haploid and diploid
   - **d** Centromere and kinetochore
   - **e** Monosomy and trisomy
   - **f** Deletion and duplication of a chromosome

2 Identify whether each of the following statements is true or false.
   - **a** Colchicine is a poison that arrests dividing cells at metaphase.
   - **b** The two number-3 chromosomes constitute a nonhomologous pair.
   - **c** Prader-Willi syndrome involves a small deletion of chromosome 15.
   - **d** Two forms of Down syndrome occur, a trisomy form and a translocation form.

3 Briefly explain why the chromosomal make-up of a person is more easily analysed using a karyotype than a metaphase spread.

4 What is the Philadelphia chromosome?

Chromosomes: genes carriers

Mendel (see chapter 13) postulated that his factors were separate particles, behaving independently of each other. However, experiments by W Bateson (1851–1926) and RC Punnett (1875–1967) in England in the early 1900s showed that in some crosses with peas a particular variation (red flower colour) tended to be inherited with another specific variation (erect petal shape). The factors concerned behaved as if they were physically coupled. Yet, in other crosses with peas the same variants were very rarely inherited together, as if they repelled each other and 'refused to enter the same gamete'. These crosses produced red flowered offspring that nearly always had hooded petals and only rarely had erect petals (see figure 14.21).

FIGURE 14.21 Pea flowers vary in colour and petal shape. If independent assortment occurs, red flowers would be expected to show erect petals just as commonly as hooded, and likewise for purple flowers. What result did Bateson and Punnett observe?

FIGURE 14.22 This idea was first postulated by Sutton (1902) and Boveri (1903), but the first experimental evidence came only in 1910 from TH Morgan's laboratory.

Bateson and Punnett's observations that some of Mendel's factors did not behave independently when moving into gametes provided an early clue that these factors were not free-floating particles in cells but were organised into larger structures. These structures were soon to be identified as chromosomes. In 1902, in the United States, Walter Sutton (1876–1916) recognised that the thread-like structures seen in cells and known as chromosomes (*chromo* = coloured; *soma* = body) provided a mechanism for the operation of Mendel's laws. Based on the parallels that he observed in the behaviours of **Mendel's factors** and of chromosomes, Sutton came to the conclusion that Mendel's factors were located on the chromosomes (see figures 14.22 and 14.23). Just as a map can be drawn showing the location of towns along a road, a **chromosome map** can be drawn showing the location of genes along its length. These 'maps' show how genes form **linkage groups**.

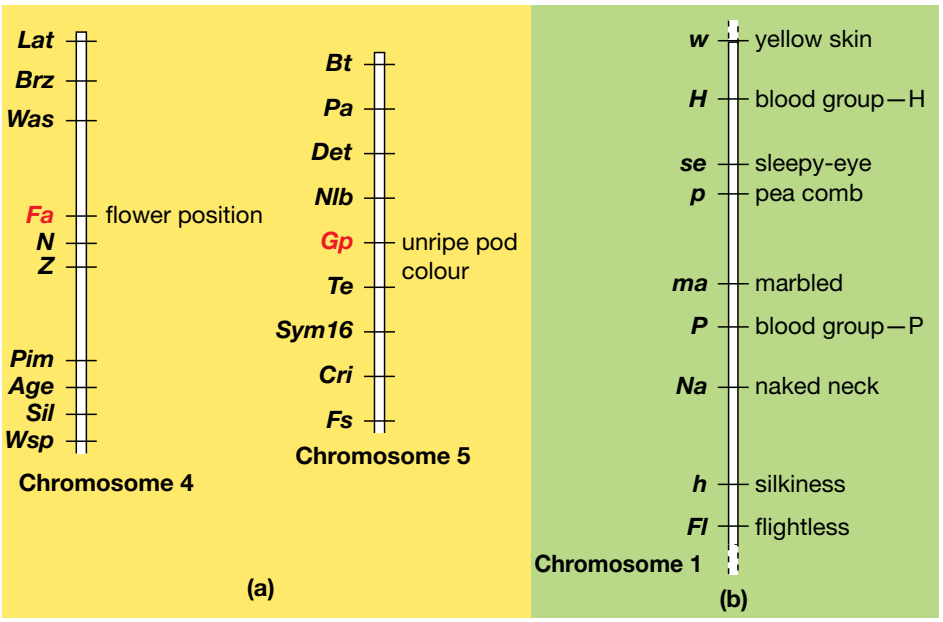


FIGURE 14.23 Genes are located on chromosomes. **(a)** Linked group of genes on chromosomes 4 and 5 of the edible pea (*Pisum sativum*). The genes highlighted in red are two of the seven genes that Mendel used in his crosses (refer to figure 13.27). **(b)** One of the linkage groups in the domestic fowl (*Gallus domesticus*)

Sutton did not carry out any experimental crosses — instead he synthesised the results of other scientists, recognised patterns and made the key link between the chromosomes studied by cytologists and the genes studied by geneticists (see table 14.4).

TABLE 14.4 Parallels between the behaviour of genes and the behaviour of chromosomes, expressed in modern terminology

Genetic behaviour	Chromosomal behaviour
segregation of the members of each pair of alleles into different gametes	separation (disjunction) of the members of each pair of matching chromosomes into different gametes (see figure 14.24)
random assortment of the alleles of different genes into gametes	random orientation of different pairs of chromosomes across the cell equator prior to their separation during gamete formation (see figure 14.25)

Figures 14.24 and 14.25 show **the parallel relationship between the behaviour of genes and chromosomes during meiosis.**

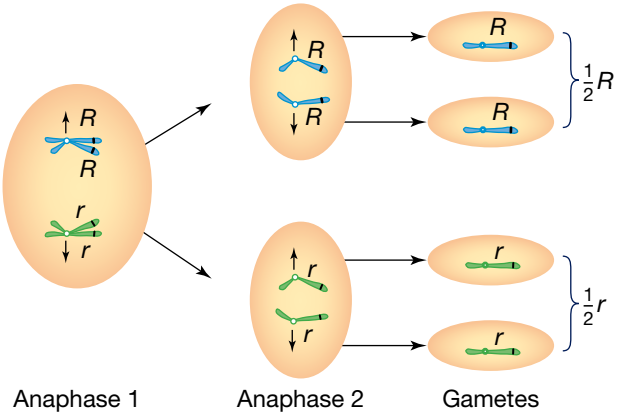


FIGURE 14.24 Disjunction of matching chromosomes into different gametes results in segregation of alleles.

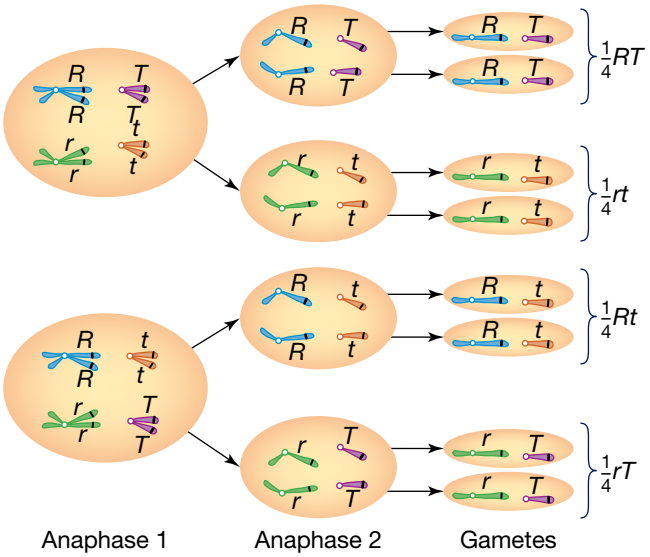
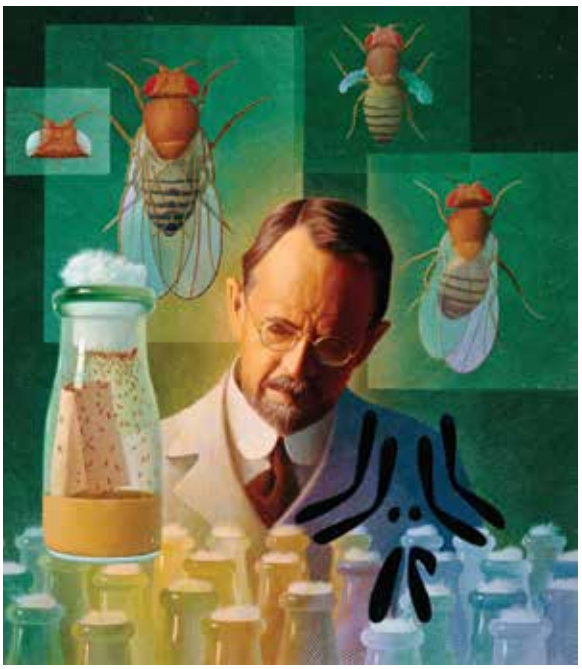


FIGURE 14.25 Random orientations of nonmatching chromosomes lead to independent assortment of genes into different gametes.



The parallel behaviour of chromosomes and genes provided strong evidence for Sutton's conclusion that genes were located on chromosomes. However, it was not until 1910 that the first specific gene was demonstrated to be located on a specific chromosome. This was done by TH Morgan (1866–1945) (see figure 14.26). Morgan and his co-workers at Columbia University (United States) confirmed Sutton's conclusion. They showed that factors (genes) were not free particles like peas in soup, but were organised into larger structures: chromosomes. They showed that when genes were located close together on homologous chromosomes specific alleles of these linked genes tended to be inherited together. Morgan's findings explained the strange observation of Bateson and Punnett. Clearly, the genes controlling pea flower shape (hooded and erect) and pea flower colour (red and blue) were located close together on the same chromosome.

FIGURE 14.26 Thomas Hunt Morgan with fly drawings. Morgan used fruit flies (*Drosophila melanogaster*) in his experiments that showed that genes were located on chromosomes. In 1933, Morgan was awarded a Nobel Prize for his contribution to genetics.

Table 14.5 provides data on the human chromosomes in terms of their length in base pairs (bp) and the approximate number of genes that each carries.

TABLE 14.5 The human chromosomes as revealed by DNA sequencing

Chromosome	Length (bp)	Number of genes (bp)
1	248 956 422	2000
2	242 193 529	1300
3	198 295 559	1000
4	190 214 555	1000
5	181 538 259	900
6	170 805 979	1000
7	159 345 973	900
8	145 138 636	700
9	138 394 717	800
10	133 797 422	700
11	135 086 622	1300
12	133 275 309	1100
13	114 364 328	300
14	107 043 718	800
15	101 991 189	600
16	90 338 345	800
17	83 257 441	1200
18	80 373 285	200
19	58 617 616	1500
20	64 444 167	500
21	46 709 983	200
22	50 818 468	500
X (sex chromosome)	156 040 895	800
Y (sex chromosome)	57 227 415	50

Chromosome and sex determination

The wife of King Farouk of Egypt had given birth to three healthy daughters. In 1948, Farouk divorced his wife because she had not produced a male heir. Was this reasonable?

In mammals, birds and some reptiles, the sex chromosomes are important in determining sex. This is because they carry certain genes that are critical in sex determination, such as the **SRY** gene on the mammalian Y chromosome, which controls testis formation. This mode is known as **genetic sex determination (GSD)** (see table 14.6).

TABLE 14.6 Genetic sex determination involving sex chromosomes

Animal group	Chromosome system
mammals and some reptiles	XX female; XY male
birds and some reptiles	WZ female; ZZ male
some insects	XX female; XO male

Mammals: the XX/XY system

The sex of a human fetus can be predicted before birth on the basis of the sex chromosomes present — **two X chromosomes indicate a female, while one X and one Y chromosome indicate a male.** A similar XX/XY situation applies with a few rare exceptions to other mammals. All the normal eggs produced by a human female during meiosis contain one X chromosome as well as 22 nonhomologous autosomes. In contrast, male mammals produce two kinds of sperm. All normal human sperm have 22 nonhomologous autosomes but some carry one X chromosome and others carry one Y chromosome (see figure 14.27).

ODD FACT

The platypus has 10 sex chromosomes: five Xs and five Ys.

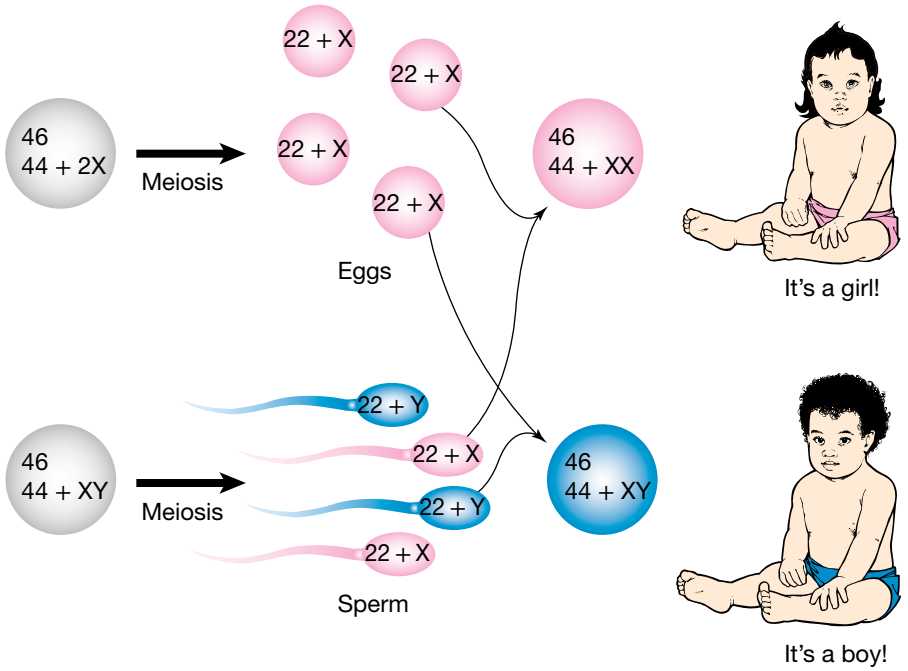


FIGURE 14.27 Which parent determines the sex of a baby? Was King Farouk reasonable in divorcing his wife?

ODD FACT

As expected, female swamp wallabies (*Wallabia bicolor*) are XX but normal males are exceptional in that they have one X chromosome and two Y chromosomes — one smaller one (denoted Y1) and one larger one (Y2).

The WZ/ZZ system

Sex chromosome differences also occur in birds but the arrangement is different from mammals. Male birds have two similar sex chromosomes that are known as Z chromosomes. In contrast, the pair of sex chromosomes in female birds comprises one W and one Z chromosome, and so it is the female parent

FIGURE 14.28 Green turtle hatchlings emerge from a nest in the sand of a northern Queensland beach. Crocodiles also have ESD.

in these groups that determines the sex of the offspring. This WZ/ZZ genetic system of sex determination is also seen in some reptiles, such as snakes and monitor lizards (e.g. goannas), and in amphibians, such as some frog species. Tiger snakes (*Notechis* spp.), for example, have a total of 34 chromosomes with males having two Z chromosomes and females having one Z and one W chromosome.

Reptiles — other means

It was discovered that **in some reptiles the sex of offspring depends on the incubation temperature of the eggs.** This is an example of **environmental sex determination** (ESD), and is seen in green turtles (*Chelonia midas*) (see figure 14.28). Female turtles lay an average of 110 eggs and bury them in the sandy beaches along Australia's tropical coastline. After laying, the female turtles return to the sea. Male turtle hatchlings result from eggs that are incubated at high temperatures (above 31 °C), female hatchlings are produced when the incubation temperature is lower (27 °C and below), while at intermediate temperatures (around 29 °C) about equal numbers of both sexes are produced.

ODD FACT

We tend to think of sex as determined for life, but individual fish of several species have the ability to change sex during their lifetimes.

KEY IDEAS

- Genes are located on chromosomes.
- The first suggestion that genes were located on chromosomes was made by Sutton in 1902.
- Evidence for the location of genes on chromosomes came from observations by Sutton in 1902 on the parallels between the behaviours of genes and those of chromosomes.
- In 1910, Morgan and his co-workers carried out the first experiments that demonstrated that genes were located on chromosomes.
- Genes that are located on the same chromosome are said to be linked and form a linkage group.
- Various mechanisms of sex determination exist in Kingdom Animalia.

QUICK CHECK

5 What behaviour of chromosomes in meiosis gives rise to the segregation of alleles of one gene into different gametes?

6 Who was the first scientist to provide experimental evidence that genes are located on chromosomes?

7 Identify whether each of the following statements is true or false.
- **a** Sex determination in mammals is typically an XX/XY system.
- **b** A female bird would be expected to have a WZ sex chromosome pair.
- **c** The sex of a mammal is determined by the genetic contribution of its male parent.

BIOLOGIST AT WORK

Lisette Curnow — genetic counsellor

FIGURE 14.29
Lisette Curnow

When I completed my degree in biological science, I knew that, while I enjoyed laboratory work and had a real interest in science, especially genetics, I couldn't see myself in the lab long term. Having heard about genetic counselling as an emerging profession, I liked the idea of combining my genetic interest with dealing with people in a clinical setting. The role of a genetic counsellor is to provide accurate information and options, together with counselling and support to individuals or families whose lives are impacted in some way by a genetic condition in themselves, their children or their extended family. It is a particularly important field given the dramatic advances that are being made in genetics, and complex information needs to be imparted to the public in a clear and concise way.

The convenor of the Postgraduate Diploma in Genetic Counselling (run through Melbourne University) recommended that I try to develop some counselling skills to see if that was something I would like to do. I volunteered at Lifeline, a telephone counselling service that puts volunteers through a fairly comprehensive training program, an experience that I found to be invaluable in determining whether I was interested in counselling and had any skills in the area. I subsequently completed the Graduate Diploma in genetic counselling, then travelled for 12 months, combining backpacking with six months of work experience at the Hospital for Sick Children in Toronto. On my return to Melbourne, I took up some volunteer work before embarking on my Master of Health Sciences (Genetic Counselling) degree. This gave me a real interest in research and I developed skills I have been able to use in my job.

While completing my masters, I worked part time in cancer genetics at Peter MacCallum Cancer Institute. This work involved meeting with individuals with a very strong family history of cancer to assess whether they may carry an inherited mutation in one of the cancer-predisposing genes. While testing for cancer predisposition is still limited, it may be available for families who meet 'high risk' criteria for breast cancer and some forms of bowel cancer. Assessment of people to see if they meet these criteria is done by genetic counsellors and other relevant clinicians (such as geneticists, oncologists, gastroenterologists and breast surgeons) through the various cancer genetics services.

I later worked in developing cancer services at the Royal Children's Hospital before moving into the role as genetic counsellor to the Royal Children's Hospital. This was a job with paediatric focus where part of my role involved dealing with abnormal cystic fibrosis results from newborn screening (the heel-prick test that is carried out on every baby born in Victoria a couple of days after birth). I also attended the weekly paediatric clinic where I saw a range of patients, such as families who may have a child with a new diagnosis of a genetic condition, or a family member who is concerned about their risk of being a carrier of a condition that is present in the family. I now work primarily in adult neurogenetics and coordinate the predictive testing program for Huntington's disease (HD) in Victoria. This is a program that enables individuals at risk of HD (a debilitating adult-onset neurodegenerative disease) to find out whether they will develop the condition. This role allows me to meet people who constantly amaze me with their resilience.

I am also fortunate to be involved in coordinating the genetics component of the Master of Genetic Counselling course, as well as frequently giving lectures to various groups. Finally, I squeeze as much research as possible into my schedule as I am perfectly positioned to access valuable information regarding the impact of today's genetic technology on the public.

Our genetic knowledge is constantly evolving and, as genetics does not discriminate, the families we meet are necessarily varied and multifaceted. This ensures that there is rarely a dull moment in my day-to-day work, and we regularly encounter difficult ethical dilemmas that prompt stimulating discussions among my colleagues as we try to resolve the best way forward for our clients. The interpretation of complex genetics and technology for the people it affects every day is an extremely challenging yet rewarding field in which to work.

BIOCHALLENGE

Use the **Human Genome Resources** weblink in your eBookPLUS.

The small diagram of the human chromosomes at the upper left-hand corner allows you to click on a chromosome and see the detailed genetic information that is carried on each chromosome. **eBook*plus***

1 Click on chromosome 21. The new screen display (see figure 14.30) will show you an ideogram of chromosome 21 and will indicate the positions of 20 of the 726 genes located on this chromosome.

   Note how the genes are designated by capital letters (and, in some cases, number(s)). Don't be overwhelmed at the amount of information! This exercise is simply to show you the remarkable detail that now exists about the human genome.

2 Now click on the 9 at the top of the screen display to see an ideogram of the human chromosome 9.

   One of the 20 genes shown on this ideogram is the **ABO** gene. Click on the ABO link and see the information that is available about this gene. Scan this information and answer the following questions:
   - **a** What type of gene is the **ABO** gene?
   - **b** What protein does this gene encode?

3 **a** Now return to the starting page in the weblink and use the Find A Gene box, located in the left-hand column, to find the chromosome on which the **HTT** gene that controls production of the protein huntingtin is located. Once you have the chromosomal location, click on the gene name for further information about the gene, and identify an inherited disorder caused by an altered form (allele) of the gene. Record your data in table 14.7.

TABLE 14.7

Gene symbol	Chromosome location	Inherited disease
HTT		
CFTR		
DMD		
HBB		

b Repeat the procedure in part (a) for the following genes.
- i The **CFTR** gene that encodes the cystic fibrosis trans-membrane conductance regulator (refer to chapter 1, pp. 36–7)
- ii The **DMD** gene that controls production of the muscle protein dystrophin, which if abnormal results in Duchenne muscular dystrophy
- iii The **HBB** gene that controls production of the beta polypeptide chains of the adult haemoglobin A molecule

FIGURE 14.30 Screenshot from the National Center for Biotechnology Information (NCBI) website

Chapter review

studyon
Unit 2
AOS 2
Topic 2
Chromosomes
Sit topic test

Key words

Angelman syndrome
autosome
centromere
chromosome map
colchicine
cytogeneticist
deletion
Down syndrome (DS)
duplication
embryo
environmental sex determination
FISH staining
genetic sex determination (GSD)
homologous
hypotonic shock treatment
ideogram
karyotype
kinetochore
linkage groups
Mendel's factors
metaphase spread
monosomy
nondisjunction
nonhomologous
reciprocal translocation
sex chromosomes
telomere
translocation
trisomic

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map relating to chromosomes. You may use other words in drawing your map.

2 **Demonstrating knowledge** ➜ Where would you locate each of the following?
- **a** Human cells undergoing meiosis
- **b** Haploid cells in a cat
- **c** Cells containing 20 unpaired chromosomes in a mouse
- **d** The genetic instruction for your ABO blood type

3 **Demonstrating your understanding** ➜ Use words and/or diagrams to identify the differences, if any, between the items in each of the following pairs.
- **a** Haploid and diploid
- **b** Autosome and sex chromosome
- **c** Somatic cell and germline cell
- **d** Gene and allele

4 **Recognising patterns** ➜ A newborn baby showed facial abnormalities and other signs including deformed kidneys and nails, and an unusual way of clenching its fist. Its karyotype was prepared (see figure 14.31). Examine this karyotype.

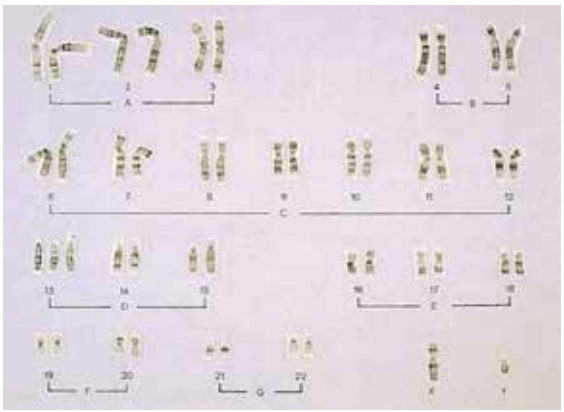


FIGURE 14.31

- **a** What is the total number of chromosomes?
- **b** What is the sex of the baby?
- **c** What abnormality is visible in the karyotype?
- **d** What name is given to this condition?

5 Match the processes in column A to the outcome in column B.

Column A	Column B
meiosis	exchange of segments occurs between homologous chromosomes
crossing over	haploid gametes produced from a diploid cell
disjunction of homologous chromosomes	diploid number of chromosomes restored, one set from each parent
independent disjoining of nonhomologous chromosomes	alleles of one gene segregate from each other
fusion of gametes at fertilisation	random combinations of different genes produced in gametes

6 **Demonstrating knowledge and understanding** ➜ Some chromosomes, when present as a trisomy in a human, produce obvious signs or clinical conditions in the affected person and are typically diagnosed soon after birth.
- **a** Which chromosomes are these?
- **b** How would these conditions be diagnosed?
- **c** Briefly explain how a trisomy can be produced.
- **d** A student stated: 'Strange how the number-1 and the number-2 chromosomes are not examples of clinically recognised trisomies. It must be that they are never involved in a nondisjunction. It looks like only a few chromosomes are subject to that kind of error.'

  Carefully consider this statement and indicate whether or not you agree with this student and give a reason for your decision.

7 Applying understanding → Write the shorthand form of the karyotype of each the following.

- **a** Normal male
- **b** Female with Turner syndrome
- **c** Male with an extra Y chromosome
- **d** Female with Down syndrome
- **e** Male with Klinefeleter syndrome
- **f** XXX female

8 Demonstrating knowledge → Figure 14.32 shows some 'maps' for three human chromosomes. On these chromosomal maps, the symbols 'p' and 'q' are used to denote the short and the long arm of a chromosome. (The 'p' comes from the French *petit* meaning short. Why 'q'? It's the next letter in the alphabet.)

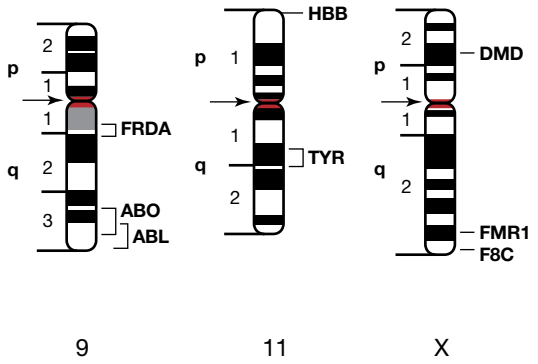


FIGURE 14.32

- **a** What representation of the chromosomes is shown in this figure?
- **b** What is the chromosomal location of the following genes?
  - i The gene that controls your ABO blood type
  - ii The gene that controls production of the beta chain of your haemoglobin
  - iii One of the genes that is translocated to become part of the Philadelphia chromosome
  - iv The gene that controls the production of the protein dystrophin in your muscles

9 Making predictions → The short arm of a chromosome is denoted by the symbol 'p'. A particular chromosomal disorder can be shown by the symbol 46, XY, 5p–.

- **a** Predict the meaning of this notation.
- **b** Check the chapter text and give a name to this human chromosomal disorder.
- **c** Would you predict that the condition 45, XX, 5– would have a name to refer to clinical signs seen in an affected person? Briefly explain your decision.

10 Exploring the web → Use the **Genes and disease** weblink in your eBookPLUS. From this website you can access any human chromosome and see the ideograms that show the locations of the genes for major human diseases and disorders that are located on that chromosome. By clicking on the symbol of the gene you can gain some information about the disease associated with that disease.

eBook*plus*

- **a** Go to chromosome 4 and check out the disease that results from an altered form of the **HD** gene. Write three sentences that summarise some key features of this disease.
- **b** Go to the X chromosome and choose the **DMD** gene. Write three sentences that summarise some key features of this disease.
- **c** Check out five other chromosomes and record the symbol of one gene and its associated disease in the following table.

Chromosome no.	Gene symbol	Disease

11 Applying understanding in a new context → Karyotypes can be prepared from cells of other organisms. Figure 14.33 overleaf shows the karyotype of an Amur tiger, called TaeGuek, whose genome was the first of that species to be sequenced.

Examine this karyotype and answer the following questions.

- **a** What is the sex of this tiger?
- **b** What is the diploid number of the tiger?
- **c** Show this karyotype in shorthand form.
- **d** Is there any evidence of an error in chromosome number? Explain your decision.
- **e** How many chromosomes would you expect to see in normal gametes from this tiger?
- **f** What reasonable prediction (it may not be correct, but that does not matter) would you make about the karyotype of a domestic cat? Briefly explain the reasoning behind your prediction.

12 Discussion question → In the past, the only test for the presence of chromosomal abnormalities in a fetus was through the use of a procedure known as amniocentesis. Amniocentesis is an invasive screening test that involves obtaining a sample of the amniotic fluid that surrounds the fetus by passing a needle into the uterus. Because this procedure has a one-in-one-hundred risk

of causing a miscarriage about 40 per cent of women offered amniocentesis decline to have amniocentesis as they risk losing a healthy fetus.

More recently, a non-invasive screening test has become available that can detect chromosomal and some other abnormalities. This test detects fetal cells in a sample of the mother's blood. This test has a 99 per cent accuracy rate.

Data from the Department of Health in the United Kingdom show that the availability of this non-invasive test has led to a 34 per cent increase in pregnancy terminations in the 3-year period from 2011 to 2014.

Some findings:

- The highest proportion of terminations (693) were due to the detection of Down syndrome.
- A small number of terminations (10) were due to the detection of cleft palate, a treatable condition.
- At least one woman had a termination after a false positive test for a chromosomal abnormality.

Hayley Goleniowska, the mother of an 8-year-old daughter with Down syndrome has commented: 'In quieter moments I weep to think of what we could lose . . . It's not the test that worries me, it's how it is implemented.'

Dr Bryan Beattie, a fetal medicine consultant, has commented: `The real issue next, in around two or three years' time, will be an ethical one — where do you stop? Do you screen for breast cancer genes, for Huntington's — or taking it a step further, test for eye and hair colour?'

Source: J MacFarlane, 'New blood test blamed as women choosing to abort babies with Down's syndrome and other serious disabilities soars 34% in three years', *Mail on Sunday*, 14 June 2015.

Discuss these comments with a group of your classmates.

FIGURE 14.33 Karyotype of TaeGuek, an Amur tiger

CHAPTER

15 Genotypes and phenotypes

FIGURE 15.1 Different phenotypes can be seen in these dogs' chocolate, black and cream coat colours. In this chapter we will explore visible phenotypes as the expressions of underlying genotypes, examine how gene expression can be influenced by environmental and epigenetic factors, and identify differences between monogenic and polygenic traits.

KEY KNOWLEDGE

This chapter is designed to enable you to:

- become familiar with the use of symbols to denote genotypes
- identify dominant and recessive phenotypes and understand their differences
- recognise that the expression of genes can be influenced by environmental factors and by epigenetic factors
- develop knowledge and understanding of polygenic inheritance.

Baby Rose and the CFTR gene

Baby Rose, daughter of Sarah and Daniel, was the third addition to the Trengarth family. Her arrival was especially welcome as Rose was the first sister for her two male siblings, James and Trent, and the first daughter for Sarah and Daniel. At birth Rose seemed a healthy baby. About a day after her birth, a heel prick blood sample was taken from Rose. This was done as part of the routine screening test that is carried out on newborn babies Australia-wide. The test result showed that she had **cystic fibrosis** (CF).

CF is an inherited disorder and the gene responsible is the **CFTR** gene on the number-7 chromosome. The CFTR gene encodes a trans-membrane protein that controls the transport of chloride ions across the plasma membrane. (Refer to chapter 1, pp. 36–7 for more details on the role of this transporter protein and the effects of a faulty transporter protein, in particular one that causes the mucus of the lungs to be thick and sticky.) The diagnosis of CF was unexpected as neither parent had ever heard of CF and each stated 'No one in our family has ever had it'.

ODD FACT

Australia-wide, newborn babies are screened for several conditions including cystic fibrosis, phenylketonuria, galactosemia and primary congenital hypothyroidism (see p. 590).

Cystic fibrosis is the most common inherited single-gene disorder seen in Caucasians of northern European descent, and in their derived populations in Australia, Canada and New Zealand. CF occurs equally in females and in males. The incidence of CF in Caucasians is generally stated to be about 1 baby in every 2500 live births, but in other populations, such as Asian and Pacific Islander populations, the incidence is much lower.

CF cannot be cured but the development of affected babies is carefully monitored, watching for any bacterial infections of the lungs that are rapidly treated. Other treatments include pancreatic enzyme replacement and physiotherapy sessions to assist in removing the thick sticky mucus from the lungs.

The **CFTR** gene has several different forms, or alleles. The various alleles result from small differences in the base sequence of the **CFTR** gene which affect the ability of the protein that it encodes to perform its normal transporter function.

For the shorthand notation of different alleles of one gene, the practice is to use variants of the same letter(s) of the alphabet, as follows:

- Where a gene has two phenotypic expressions or alleles, such as 'trait present' and 'trait absent', or 'red' and 'white' flower colour, symbols such as ***A*** and ***a***, or ***R*** and ***r*** or ***D*** and ***D'*** might be used, depending on the dominance relationship between the two alleles. Usually, the letter chosen relates to one of the phenotypic expressions of the gene, such as ***R*** for red flower colour.
- Where a gene has multiple alleles, each having a different phenotypic expression, a common letter is still used, but with the addition of superscripts to the common letter, for example, I^A, I^B and ***i***, or ***C***, c^b, c^s and c^a.

So, in the case of the **CFTR** gene, the allele that produces the normal transporter protein can be denoted by the symbol ***C***. We can group the alleles which produce a defective transporter protein that causes a person's mucus to be thick and sticky, and these can be denoted using the symbol ***c***. Because the **CFTR** gene is an autosomal gene, located on the number-7 chromosome, baby Rose has two copies of this allele and so is genotype ***cc***.

What is a phenotype?

Baby Rose's cystic fibrosis is her **phenotype**. **A phenotype is the visible or measurable expression of the genetic make-up of an organism's structure and/or functioning,** often in terms of one gene. In baby Rose's case, her phenotype for the **CFTR** gene is an abnormal transporter protein that produces the clinical signs of cystic fibrosis, including the thick and sticky mucus in her lungs and pancreatic ducts.

Other examples of phenotypes in various organisms include:

- red, green, orange and yellow fruit colours in capsicums (refer to figure 13.42, p. 517)
- short leg length and normal leg length in sheep (*Ovis aries*) (see figure 15.2a)
- blood types A, B, AB and O in people
- purple, white and yellow kernel colour in corn (*Zea mays*)
- beaked, round, flattened and elongated fruit shapes in tomatoes (*Solanum lycopersicum*) (see figure 15.2b)
- presence and absence of fur and eye pigment in kangaroos (*Macropus* spp.)
- ability and inability to differentiate between the colours, red and green, in people
- requirement or non-requirement for the amino acid arginine, for growth in yeast (*Saccharomyes cerivisiae*).

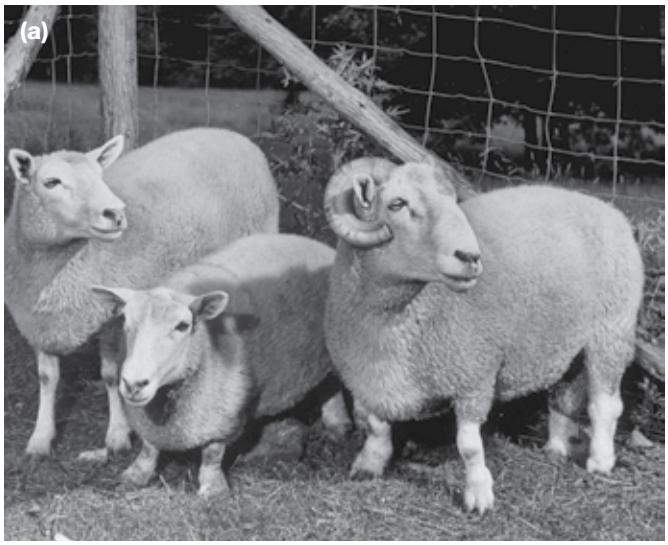


FIGURE 15.2 A phenotype is the visible, measurable or detectable effect of a gene on the structure and/or functioning of an organism. Examples of phenotypes include: **(a)** leg length in sheep, with the abnormally short legs of an Ancon sheep seen here in comparison with the normal leg length and **(b)** shape and colours of tomato fruits.

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Phenotypic differences can be seen not only in eukaryotic species, but also in microbial species. One significant phenotypic difference that affects human health is the emergence of resistance to antibiotics in many bacterial species. For example, *Staphylococcus aureus* (also known as golden Staph) includes some strains that are sensitive to one or more antibiotic drugs and some that are resistant to virtually all the current useful antibiotics. These antibiotics include methicillin, which interferes with the synthesis of a component of the bacterial cell wall, and erythromycin and streptomycin, which attack the bacterial ribosomes.

Different strains of one bacterial species as well as different bacterial species can be distinguished as being either drug-sensitive or drug-resistant using **antibiotic sensitivity testing** in a laboratory (see figure 15.3). In this test, a specific bacterial species is allowed to grow across the surface of a gel in a Petri dish. The gel contains all the nutrients required for growth and the bacterial growth appears as a white film. Discs impregnated with different antibiotics (or with different concentrations of the same antibiotic) are placed on the plate and the antibiotic will diffuse from the disc into the gel. If the bacteria are sensitive to the antibiotic on a disc, the bacteria in the area will die and this appears as a clear area around the disc.

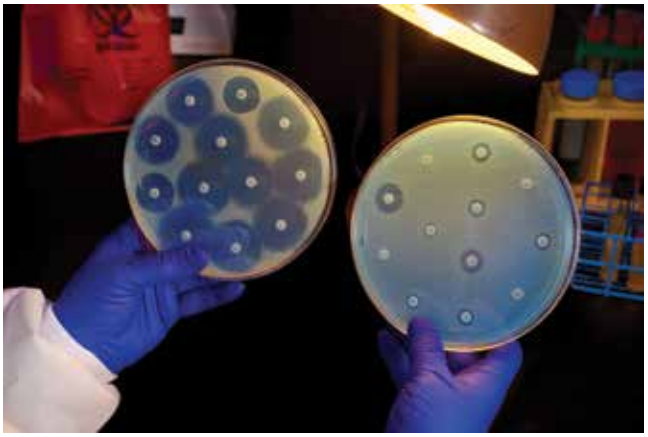

FIGURE 15.3 Results of antibiotic sensitivity testing of various antibiotics against two strains of bacteria. Which strain of bacteria (left or right plate) is more sensitive to the antibiotics?

A phenotype may be expressed as a single feature of an organism's structure or functioning, such as purple kernel colour in corn. In other cases, however, the responsible gene produces a phenotype that shows multiple effects on several organs. This is the case for CF where the lungs, pancreas and sweat glands all show phenotypic effect. The CF phenotype is seen in the lungs which produce abnormally thick and sticky mucus that causes breathing difficulties and increases the risk of lung infections. The CF phenotype is also seen in the pancreas where the thick mucus blocks the pancreatic ducts preventing the release of its digestive enzymes into the gut so that digestion is impaired. And the CF phenotype is seen in the sweat glands that produce abnormally salty sweat.

Many phenotypes are the physical or physiological expression of a single gene. However, in some cases, a visible phenotype may be the result of an interaction between genes at two or more gene loci. For example, all cats are genetically tabby cats as they all have the **TABBY** gene that determines the pattern of tabby striping, either mackerel or blotched. However, these patterns are only displayed if the cat also has at least one copy of the agouti allele (***A***) of the **ASIP** gene. If the cat has two identical alleles of the recessive non-agouti allele (***aa***), the tabby pattern will not show — instead the cat will be one solid colour (see table 15.1).

The genetics of cat colour involves many genes and many interactions between these genes.

TABLE 15.1 One example of the interaction between two genes in cats. Which gene determines whether or not a cat will display its phenotype in terms of tabby striping?

Genotype at ASIP locus	Genotypes at TABBY locus	Phenotypes	
AA homozygous agouti	Ta^MTa^M Ta^Mta^b ta^bta^b	mackerel pattern mackerel pattern blotched pattern	
Aa heterozygous agouti	Ta^MTa^M Ta^Mta^b ta^bta^b	mackerel pattern mackerel pattern blotched pattern	
aa homozygous non-agouti	Ta^MTa^M Ta^Mta^b ta^bta^b	solid colour (no stripes) solid colour (no stripes) solid colour (no stripes)	

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What is a genotype?

The underlying genetic make-up that determines an organism's phenotype is called its **genotype**. A genotype is not visible, only its phenotypic effects can be seen or measured. A genotype is the combination of the particular alleles of a gene or genes that are present and active in a cell or in an organism and determine a specific aspect of its structure or functioning.

In diploid organisms, the genotype is typically written as a pair of alleles. This is the case for autosomal genes for both females and males. If the two alleles of a gene are identical, for example, ***CC***, the genotype (and the organism concerned) are said to be **homozygous**. If the two alleles are different, the genotype is described as **heterozygous**, for example, ***Cc***.

The only exceptions are the genotypes of males for **X-linked** and **Y-linked genes**, that is, genes on the X chromosome and genes on the male-exclusive major segment of the Y chromosome. For these genes only, the genotype of a normal male consists of just one allele and is described as being **hemizygous** (*hemi* = half). In baby Rose's case, the genotype that underlies her cystic fibrosis phenotype is homozygous recessive genotype ***cc***. The encoded instruction at the **CFTR** gene locus on both of her number-7 chromosomes is 'make defective transporter protein'. We will see later that the genotypes of both of baby Rose's parents are heterozygous ***Cc***. Baby Rose inherited one ***c*** allele from her mother and another ***c*** allele from her father. When an autosomal gene has two alleles, for example, ***F*** and ***f***, the maximum number of different genotypes possible in a diploid organism is three, namely ***FF***, ***Ff*** and ***ff***. However, when a gene has multiple alleles, more genotypes are possible; if a gene has three multiple alleles, six different genotypes are possible, if four multiple alleles exist then 10 different genotypes are possible. Refer to table 13.7 on page 515 to review some examples of genes with multiple alleles. Can you identify the six genotypes possible for the three multiple alleles of cats shown in table 13.7?

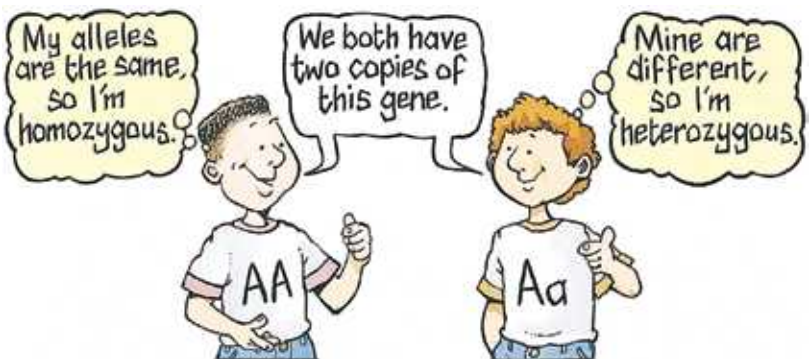
Next we will look more closely at genotypes, using mainly human examples.

Genotypes for autosomal genes

Both females and males have two copies of each gene located on an autosome; these are termed **autosomal genes**. While people share identical genes, they may differ in the specific alleles they possess.

Each person has two copies of the **ABO** gene on their pair of number-9 chromosomes. However, people may have different alleles of that gene. One person may have two copies of the ***i*** allele, another person may have one copy of the I^A allele and one copy of the ***i*** allele, yet another person may have one copy of the I^B allele and one copy of the ***i*** allele. The particular combination of alleles of a gene is that person's genotype in terms of that gene.

The gametes produced by a homozygous person, such as genotype I^AI^A, will be identical, with all having the same allele. The gametes produced by a heterozygous person, such as genotype I^AI^B, will be of two kinds, with half having the I^B allele and half having the I^A allele.



Genotypes for genes on the sex chromosomes

The sex chromosomes are the X and the Y chromosomes. The DNA of each chromosome contains genes, and because of their size differences, the X chromosome has many more gene loci than the Y chromosome (see figure 15.4).

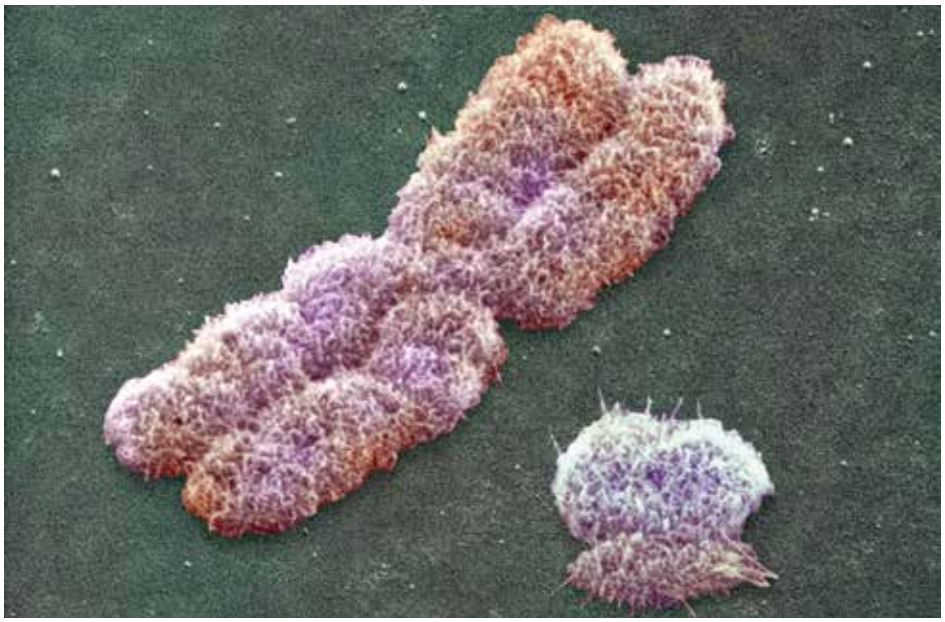


FIGURE 15.4 The human sex chromosomes magnified 10 000 times. The X chromosome (left) is much larger than the Y chromosome and carries about 800 genes; in contrast, the Y chromosome carries about 50 genes.

ODD FACT

In AD 200, a Jewish edict exempted a boy from circumcision if his two brothers had bled to death. Their male cousins were also exempted.

People have been aware for a long time that some conditions, such as certain colour vision defects and a blood-clotting disorder (haemophilia) that occur in particular families, appear more often in males than in females. Why?

This is because the genes controlling colour vision and blood clotting are located on the X chromosome and are not represented on the Y chromosome. To be affected, females must inherit two copies of the particular allele; males are affected if they have just one allele so males more commonly show the trait.

When a gene is located on a sex chromosome, the traits controlled by its alleles do not appear equally in both sexes.

FIGURE 15.5 Children with muscular dystrophy take part in play group therapy.

Genes on the X chromosome

Many genes are located on the human X chromosome (X-linked), including the **DMD** gene, located on the short arm of the X chromosome (refer to figure 14.32, p. 545). This gene controls production of the muscle protein dystrophin, which is found on the membrane of skeletal muscle cells. The **DMD** gene has two alleles. When only abnormal dystrophin is produced by muscle cells, a disorder called Duchenne muscular dystrophy results. This disorder is extremely rare in females but it affects about 1 in every 3500 male babies. Affected males suffer slow but irreversible loss of the muscle function and are confined to a wheelchair usually before they reach their teens (see figure 15.5). Death usually occurs before or in early adulthood.

Males have only one X chromosome and so have one allele of this gene. A male has a hemizygous genotype, and is either ***M*** or ***m***. (These genotypes are shown as ***M*** (Y) and ***m*** (Y), where the (Y) denotes the Y chromosome.) Males affected by Duchenne muscular dystrophy have the hemizygous genotype ***m*** (Y).

Normal females with two X chromosomes have two alleles of the **DMD** gene. A female with the heterozygous ***Mm*** genotype is not affected by muscular dystrophy, nor is a female with a genotype ***MM***. Affected males invariably inherit the ***m*** allele from a heterozygous mother, but not an affected father. (Why?)

Other genes on the X chromosome include the:

- **OPN1LW** gene, responsible for the protan form of red–green colourblindness that results from defective red receptors in the retina of the eye
- **F8** gene, responsible for the classical blood-clotting disorder, haemophilia A, that results from defective or absent factor VIII
- **F9** gene, responsible for a second blood-clotting disorder, called Christmas disease, that is due to defective or absent factor IX
- **IDS** gene, responsible for Hunter syndrome in which complex carbohydrates (mucopolysaccharides) build up in cells producing deleterious physical and mental effects
- **GLA** gene, responsible for Fabry disease, a lysosome storage disease
- **BTK** gene, responsible for an X-linked form of agammaglobulinemia, a condition in which antibody-forming cells of the immune system are not formed
- **G6PD** gene, responsible for deficient production of enzyme glucose-6-phosphate-dehydrogenase, which can result in bouts of severe anaemia, often precipitated by environmental factors.

All genes that are termed X-linked genes occur *exclusively* on the X chromosomes.

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Genes on the Y chromosome

The Y chromosome has a number of distinctive features. Small segments of DNA at each of the ends of the Y chromosome are homologous with DNA segments on the X chromosome. Can you suggest why this might be the case? During prophase of meiosis, homologous chromosomes synapse (pair up) in preparation for migrating to different poles of the spindle. The presence of regions of the Y chromosome that are homologous to regions on the X chromosome means that during meiosis in males the sex chromosomes can pair and then separate (disjoin) correctly.

Most (more than 95%) of the Y chromosome is not shared with any other chromosome — it is specific to males only. This DNA consists of about 23 million base pairs and it is the location of about 50 genes, all Y-linked. Y-linked genes occur exclusively on the Y chromosome.

Included among the genes located on the Y chromosome is the **SRY**, or sex-determining, gene that controls production of a protein involved in testis formation in the human embryo. (This gene is also known as the testis-determining factor.) The early embryo has undifferentiated gonads — they are neither testes nor ovaries. The testis-forming protein takes effect in about the sixth week of embryonic development, causing the gonads to develop as testes. In the absence of this protein, the gonads differentiate to form ovaries.

Very rarely, a person who is chromosomally 46, XY has an altered and inactive form of the **SRY** gene. What sex will this person display? Such a person cannot be male because of the lack of the testis-determining factor that is the product of the normal **SRY** gene. The XY combination of sex chromosomes results in a normal male only if the SRY that controls the production of testis-determining factor is active. This person is a rare XY female.

At birth such a baby appears with the external characteristics of a normal female. However, she has no ovaries; instead she has traces of gonadal tissue only. It is not until this girl shows delayed puberty that this condition, known

as **Swyer syndrome**, would be discovered. Hormone replacement therapy is used to initiate the development of female secondary sex characteristics including breast development.

Included among genes located on the male-specific portion of the Y chromosome are the:

- **AMELY** gene that controls the organisation of enamel during tooth formation
- **SOX21** gene that encodes a protein SOX-21, which controls some hair loss conditions
- **AZF** gene that encodes a protein which is important in sperm formation. Deletions of part or all of this gene result in **azoospermia**, with males having no sperm in their semen.

KEY IDEAS

- A phenotype is the visible or measurable expression of the genetic make-up of the structure and/or functioning of an organism.
- A phenotype is often the physical or physiological expression of a single gene.
- A phenotype may sometimes result from interactions between genes at two or more gene loci.
- A genotype is the genetic make-up of an organism that determines its phenotype.
- Genes and the traits they control can be described in terms of their chromosomal locations, that is autosomal or X-linked or Y-linked.
- Genotypes are homozygous or heterozygous, except for the hemizygous genotypes of males for Y-linked and X-linked genes.

QUICK CHECK

1 Identify a key difference between the terms:
   a phenotype and genotype
   b homozygous, heterozygous and hemizygous.
2 Identify whether each of the following statements is true or false.
   a The **CFTR** gene has its locus on the number-7 chromosome.
   b The cystic fibrosis phenotype involves just the lungs.
   c The genotype of a person who is affected by cystic fibrosis could be heterozygous ***Cc***.
   d A person's genotype in terms of hair colour can be observed and measured.

Relationship between expression of alleles

If you are simultaneously given two instructions that are mutually exclusive, such as 'Turn left at the next corner!' and 'Turn right at the next corner!', you can carry out only one instruction. However, for two other instructions, such as: 'Paint the door yellow' and 'Paint the door green', you might carry out both instructions by producing a bi-coloured yellow and green door. Similar situations can be recognised for the phenotypes produced by genes.

Complete dominance

Rose, the baby of Sarah and Daniel, was diagnosed as having cystic fibrosis. The **CFTR** gene on number-7 chromosome that encodes the transporter

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protein involved in cystic fibrosis has two alleles, ***C*** and ***c***. The ***C*** allele gives the instruction 'Make normal active transporter protein', while the ***c*** allele gives the instruction 'Make an abnormal inactive transporter'.

A person with the heterozygous ***Cc*** genotype has two mutually exclusive genetic instructions, but such a person produces an active transporter protein, makes normal mucus secretions and so is free of cystic fibrosis. From this, we can conclude that the disease-free condition with normal mucus secretions is **dominant** to cystic fibrosis with abnormal thick mucus. The relationship between the alleles of the **CFTR** gene are shown in table 15.2. Note that baby Rose with her ***cc*** genotype can produce only an inactive abnormal transporter protein and so has cystic fibrosis.

TABLE 15.2 Relationship between allele of the **CTRF** gene

Genotype	Phenotype
homozygous ***CC***	normal mucus
heterozygous ***Cc***	normal mucus
homozygous ***cc***	thick, sticky mucus (cystic fibrosis)

To decide whether a trait is dominant or recessive, the phenotype of a heterozygous organism is identified. The trait that is expressed in this phenotype is the dominant trait. Alleles that control dominant traits are usually symbolised by a capital letter; for example, the allele ***S*** controls the dominant short fur length trait in cats. Alleles that control recessive traits are symbolised by the lower case of the *same* letter; for example, the allele ***s*** controls the recessive long fur length in cats.

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Being a carrier

In genetics, the term **carrier** refers to a heterozygote that has the allele for a recessive trait but does not show the trait. In people, alleles may be carried for hidden recessive traits that do not affect normal functioning, such as straight hairline and blood type O. However, some alleles that are carried by heterozygotes are for recessive disorders, such as cystic fibrosis or albinism (see table 15.3).

TABLE 15.3 Some dominant and recessive human traits. Heterozygotes carry alleles for recessive traits but their effects are not expressed. What genotype is necessary for a recessive trait to be expressed for an autosomal gene?

Dominant trait	Recessive trait
peaked hairline (widow's peak) (***W***) (see figure 15.6)	straight hairline (***w***)
free ear lobes (***F***)	attached ear lobes (***f***)
mid-digital hair present (***G***)	mid-digital hair absent (***g***)
shortened fingers (brachydactyly) (***S***)	normal length fingers (***s***)
normal pigmentation (***A***)	pigmentation lacking (albinism) (***a***)
non-red hair (***R***)	red hair (***r***)
normal secretions (***C***)	cystic fibrosis (***c***)
dwarf stature (achondroplasia) (***N***)	average stature (***n***)
Rhesus positive (Rh +ve) blood (***D***)	Rhesus negative (Rh –ve) blood (***d***)

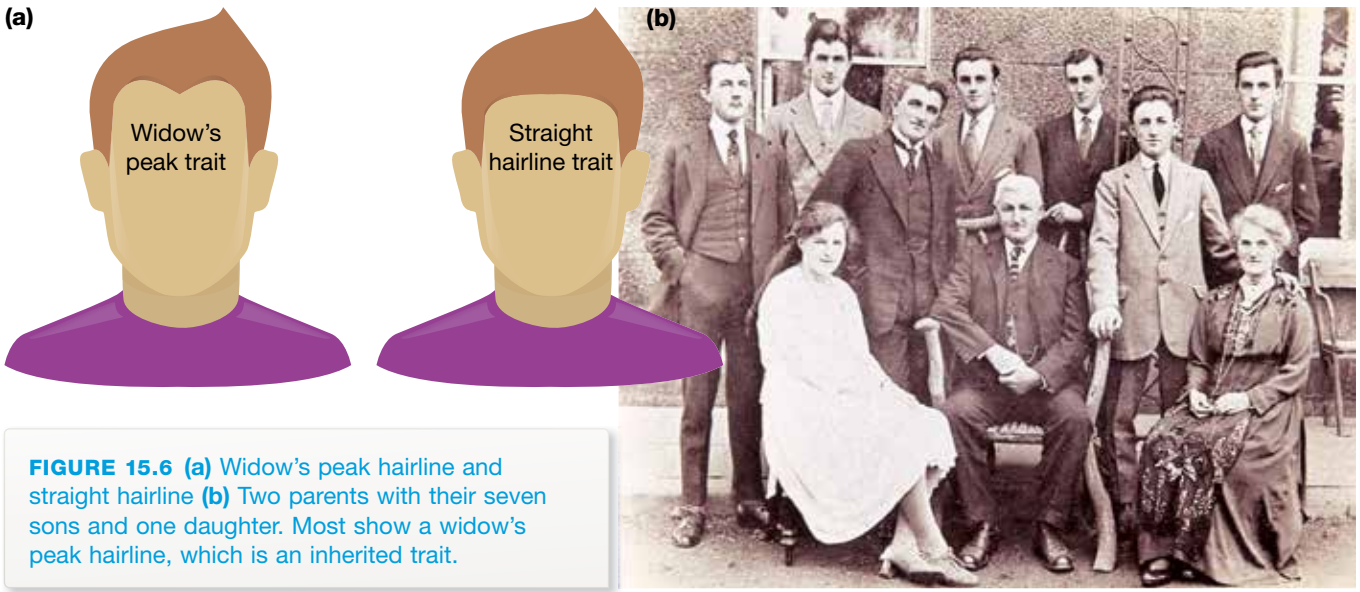

FIGURE 15.6 **(a)** Widow's peak hairline and straight hairline **(b)** Two parents with their seven sons and one daughter. Most show a widow's peak hairline, which is an inherited trait.

Most often, heterozygotes are *not* aware of their carrier status for an allele controlling a recessive trait. Parents may realise they are carriers only when they have a baby with a recessive disease. Sarah and Daniel, the parents of baby Rose, were unaware that they were both genotype ***Cc***, and so were carriers of an allele that resulted in cystic fibrosis until Rose was born. People with heterozygous genotypes sometimes know that they are carrying a 'hidden' allele. Consider the case of Maria. Both Maria's sister and her cousin have thalassaemia, a recessive inherited disorder affecting the haemoglobin in red blood cells. Maria wondered if she was a carrier. A simple test done through the Thalassaemia Society in Melbourne confirmed that Maria was a carrier of thalassaemia with the heterozygous genotype ***Tt***.

If the genotype of an individual is unknown but could be either ***Aa*** or ***AA***, this may be denoted as ***A***– (where ' – ' represents either allele).

Co-dominance

The **ABO** gene, located on the number-9 chromosome, has three alleles that determine antigen production (see table 13.6, p. 514). Antigen A and antigen B occur on the surface of the red blood cells of some people. Depending on which antigens are present, blood is typed as group A, B, AB or O. The presence (or absence) of a particular antigen is inferred by adding specific antibodies and observing the result (see figure 15.7). Antibodies used to type blood are *anti-A antibodies* and *anti-B antibodies*. Anti-A antibodies cause clumping or agglutination of red blood cells with antigen A. Anti-B antibodies cause clumping of red blood cells with antigen B.

Look at the reaction of the blood sample from Tran (column 3). His blood clumped when anti-A antibodies were added, so his red blood cells have antigen A and he has the allele I^A. Tran's blood also clumped when anti-B antibodies were added, so his red blood cells have antigen B and he must also have the allele I^B. Tran's genotype is heterozygous I^AI^B. Because **both traits are expressed in the heterozygote, these two alleles show co-dominance**. Alleles showing co-dominance are denoted by a capital letter with a superscript added to distinguish between them. Table 15.4 shows that the phenotypic actions of both the I^A and I^B alleles are dominant to the action of the ***i*** allele, and so blood group O is recessive to the other blood types.

As well as co-dominance, you may see terms such as partial dominance and incomplete dominance in various genetics books.

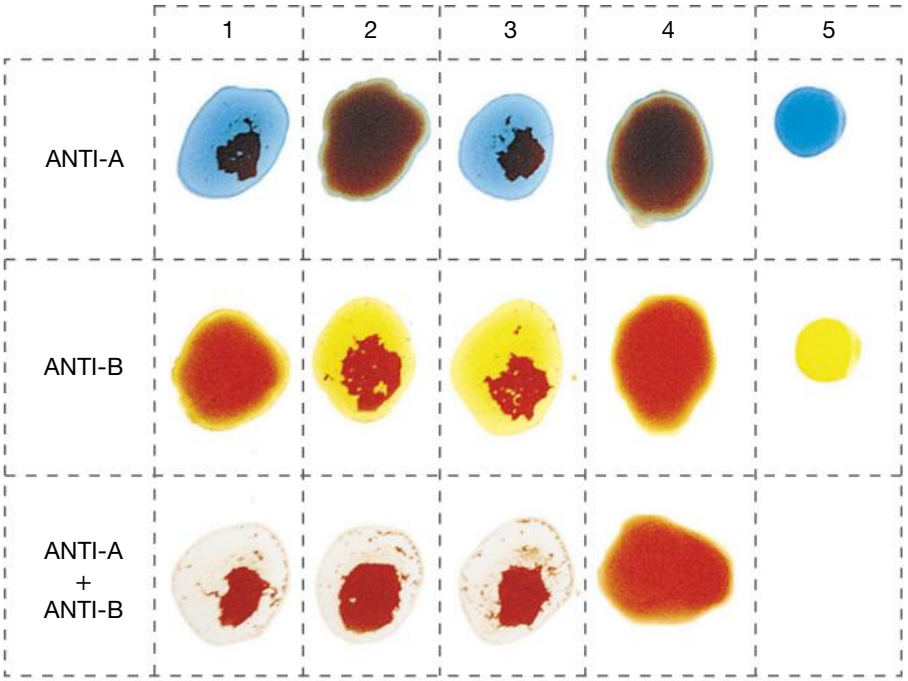

FIGURE 15.7 Addition of specific antibodies to blood samples causes cells to 'clump' or agglutinate when the corresponding antigen is present on the surface of the red blood cells.

TABLE 15.4 Relationship between genotypes and phenotypes for the **ABO** gene. What relationship exists between the I^A and the I^B alleles? Between the I^B and the i alleles?

Genotype	Instructions carried by alleles	Phenotype
homozygous I^AI^A	'produce antigen A'	blood type A
homozygous I^BI^B	'produce antigen B'	blood type B
homozygous ii	'produce neither antigen A nor B'	blood type O
heterozygous I^AI^B	'produce antigen A' and 'produce antigen B'	blood type AB
heterozygous I^Ai	'produce antigen A' and 'produce neither antigen'	blood type A
heterozygous I^Bi	'produce antigen B' and 'produce neither antigen'	blood type B

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Genes and alleles in domestic animals

Like people, plants and other animals carry genetic instructions or genes on their chromosomes. Figure 15.8 identifies some phenotypes due to the action of common alleles in several domestic mammals: cat (*Felis catus*), dog (*Canis familiaris*) and horse (*Caballus equus*).

Look at the alleles of the three genes identified in the cats. Can you suggest why only the third cat shows a pattern of tabby stripes? What is the phenotypic action of the ***G*** allele in horses? What interaction appears to exist between the three genes in the horses?

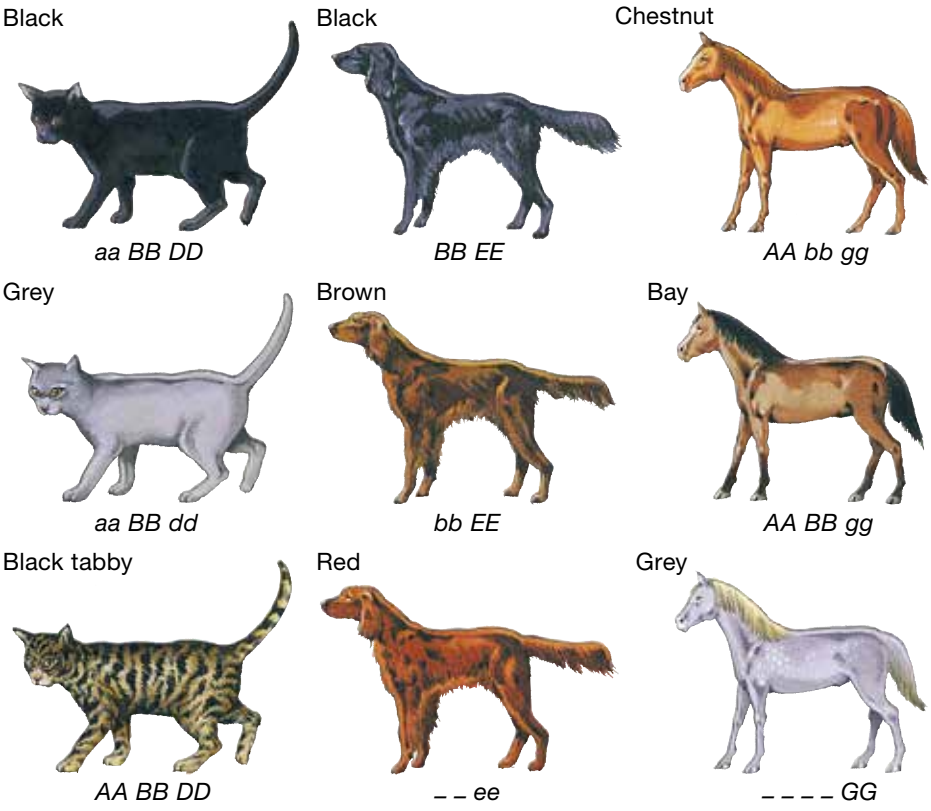

FIGURE 15.8 Some phenotypes in domestic mammals and their possible genotypes. The dash symbols cover any and all combinations of the alleles in the position occupied by the dashes. So, for the third dog in the row, the – – symbol can mean ***BB*** or ***Bb*** or ***bb***.

Environment interacts with genotype

The phenotypes shown in figure 15.8 are expressions of the underlying genotypes. However, a phenotype is not always produced exclusively by the genotype. In some cases, the phenotype is a result of the interaction between the genotype and environmental factors:

genotype + environment ⟶ phenotype

Many environmental factors, both external and internal, act on an organism so that its final phenotype is due to varying contributions of genotype and environment.

The phenotype due to a particular genotype may appear only in one specific environment. In a different environment, another phenotype may appear. Let's examine some examples of how environmental factors can affect the phenotype.

ODD FACT

For a fetus, its environment is the mother's uterus. A mother's actions — drinking alcohol, smoking — can change this environment and affect the phenotype of the fetus.

PKU and dietary-controlled phenotype

The inherited disorder, phenylketonuria (PKU) results from the action of the gene that controls production of an enzyme known as *phe hydroxylase*. Babies that inherit the homozygous recessive genotype ***pp*** from their parents cannot produce this enzyme. If these babies are fed diets that include proteins that contain normal quantities of the amino acid, *phe*, the babies will suffer brain damage and become mentally retarded, so early diagnosis is critical. However, if these babies are fed a special diet that includes proteins with very low levels of *phe*, the babies will not suffer brain damage and **will show a normal phenotype.**

In this case, the phenotype of a child with genotype ***pp*** depends on the internal environment that is controlled by the diet:

genotype pp + HIGH phe diet ⟶ phenotype: PKU
genotype pp + LOW phe diet ⟶ phenotype: normal

Figure 15.9 shows dietary items that are low in the amino acid phenylalanine (Phe). The availability of these special foods make it easier for families to cater for a child with PKU.

FIGURE 15.9 Products available for a wide range of metabolic disorders, including PKU. Each product has a particular use and excludes one or more amino acids or other compounds. In the case of PKU, the restricted amino acid is phenylalanine (Phe). Special low-protein bread, biscuits, mixes and pasta are also available.

Cats and temperature

Figure 15.10a shows some Siamese kittens. At birth, these kittens are all white. A few weeks later, the kittens begin to develop pigmentation, first along the edges of their ears. Gradually the pigment spreads until the kittens show the characteristic colouring on the face, ears, feet and tail. This pattern of colour change is due to an interaction between the cats' genotypes and their environment.

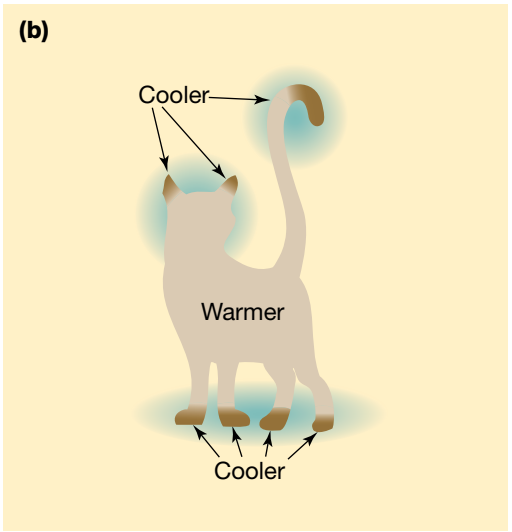

FIGURE 15.10 **(a)** Red point and seal point Siamese kittens. What colour were they at birth? **(b)** How does the environment affect their colouring?

Siamese cats have a particular form of a gene that codes for the production of tyrosinase. This enzyme catalyses one step in the production of pigment:

$$\text{precursor} \xrightarrow{\text{tyrosinase}} \text{pigment}$$

In Siamese cats, the particular form (allele) of this gene produces a tyrosinase enzyme that is heat sensitive. **This enzyme can catalyse the step in the production of pigment when the temperature is lower than the core body temperature only.** Siamese kittens undergo embryonic development in a warm uterine environment and so are born unpigmented (white). Pigment appears first on the coolest parts of their bodies — the ear margins — and then on other extremities (figure 15.10b).

Plants and soil pH

Hydrangea plants (see figure 15.11) produce **blooms with colours that depend on the acidity or alkalinity (pH) of the soil** in which they are growing. The colour is due to pigments known as anthocyanins, which are located in membrane-bound sacs within the petal cells. In soil with an acidic pH these pigments are a bright blue, while at alkaline pH they are a pink or red.

FIGURE 15.11 When grown in acid soil hydrangeas produce deep blue flowers. In contrast, when grown in alkaline soil the flower colour is pink or red. Is variation in flower colour in hydrangeas under genetic or environmental control?

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Unit 2 AOS 2 Topic 3 Concept 3 **Factors affecting phenotypes** Concept summary and practice questions

Broad beans and black urine

The **G6PD** gene, an X-linked gene, encodes the protein that acts as the enzyme glucose-6-phosphate dehydrogenase. Females with the homozygous ***gg*** genotype and males with the hemizygous ***g*** genotype are deficient in this enzyme. Normally, these persons do not display phenotypic effects of this deficiency. However, exposure to certain environmental factors can produce marked phenotypic effects. One such environmental factor is a substance in broad beans (*Vicia fava*). If persons with the enzyme-deficient genotype eat broad beans, this can cause their red blood cells to break down so that they suffer severe anaemia and the products of this breakdown can appear in their urine, causing it to be blackened. A similar reaction can occur if these persons are exposed to other compounds, including the anti-malarial drug primaquine and naphthalene, the compound found in moth balls.

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Interactivity
Generating the phenotype
int-0178

KEY IDEAS

- One gene can exist in a number of different forms called alleles, each identified with a specific phenotype.
- When two different alleles are both expressed in the phenotype of a heterozygote, they are said to be co-dominant.
- The phenotype of an organism can be the result of an interaction between its genotype and the environment.
- The phenotype may on occasion be the result of an interaction between two or more genes.
- To decide whether a phenotypic trait is dominant or recessive the phenotype of the relevant heterozygous organism must be identified.
- Phenotypes may be due to an interaction between genotypes and environmental factors.

QUICK CHECK

3 Identify a key difference between the following.
   a Autosomal and X-linked
   b X-linked and Y-linked genes
   c Compete dominance and co-dominance
   d Dominant and recessive phenotype
4 List an example of:
   a an X-linked gene
   b a phenotype that is the result of a interaction between the genotype and the environment
   c a Y-linked gene.
5 What information would you need in order to decide which of two alleles produced the dominant phenotype?

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Unit 2 AOS 2 Topic 3 Concept 4

Polygenic inheritance
Concept summary and practice questions

Polygenic inheritance

So far in this chapter we have dealt mainly with **monogenic** traits (*mono* = one). These are traits that are controlled by a single gene. Monogenic traits typically show **discontinuous variation**; that is, the expression of the single gene involved produces just a few discrete and non-overlapping phenotypes, often just two categories. So, for the **CFTR** gene, two phenotypes are seen: unaffected and cystic fibrosis. For Mendel's sweet peas, flowers are white or purple and for tabby cats, the pattern of stripes is either mackerel or blotched. Traits that show discontinuous variation are typically qualitative and are described in words.

In contrast, some inherited traits are controlled by a several genes, each having a small, but cumulative effect on the phenotype. These genes are called **polygenes** and the traits that they control are said to be **polygenic** (*poly* = many). Typically, the phenotypes produced by polygenes form many classes that show **continuous variation**. If a large sample is taken, the values form a continuum. Human traits under polygenic control that show continuous variation include height and skin colour. Traits that show continuous variation are typically quantitative and are often described in numerical values, such as a height of 168 cm, 150 cm or more than 170 cm.

Figure 15.12 shows a simplified representation of discontinuous and continuous variation.

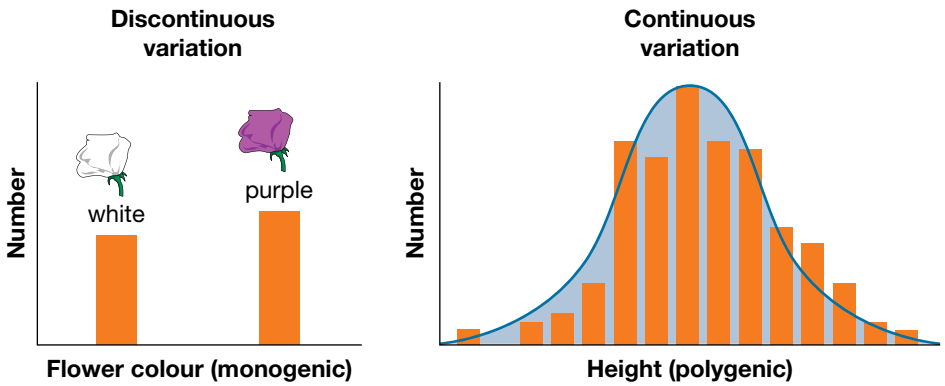

FIGURE 15.12 **(a)** Discontinuous variation is seen when the phenotypes for a particular trait fall into a few — often just two — non-overlapping distinct groups or classes. This type of variation is seen in traits controlled by a single gene. **(b)** Continuous variation is seen when phenotypes for a trait fall into many classes. This type of variation is seen in traits that are under polygenic control.

Other examples of polygenic traits are the fat content of cows' milk, the mass of bean seeds, maximum speed of thoroughbred horses and plant height in tobacco plants. It is interesting to note that, unlike tobacco plants, plant height in Mendel's pea plants is a monogenic trait with his plants falling into two categories 'tall' and 'short'.

Polygenes and human height

Adult human height exhibits a large range of phenotypes. Most typically height phenotypes range from under 1.5 m to over 2.1 m. Adult height can be affected by factors such as the occurrence of illnesses in childhood and childhood diet. However, adult height is known to have a strong genetic component. Given that this trait does not show discontinuous variation but rather shows continuous variation across a range, it is reasonable to conclude that height is not controlled by a single gene.

Height is a polygenic trait with a number of genes, each having a small but additive effect on adult height. We can summarise a simple model of polygenic inheritance of height as follows:

- A number of polygenes contribute to adult height.
- Each polygene has two alleles, the plus (+) allele that contributes a small amount to an increase in height above a base value, and the minus (–) allele that does not add to the trait.
- The phenotypic action of each polygene is equal so that, for example, the + + – – genotype shows the same phenotype as the + – + – genotype.
- The greater the number of + alleles, the greater the increase in height above the base value.
- Polygenes do not show dominance or recessiveness, but act in a cumulative manner.

So, for the polygenic trait of height in human adults, it is reasonable to predict that the distributions of height in a large sample of adults will show a **bell-shaped distribution**. Figure 15.13 shows such a bell-shaped distribution of heights in female and male adults.

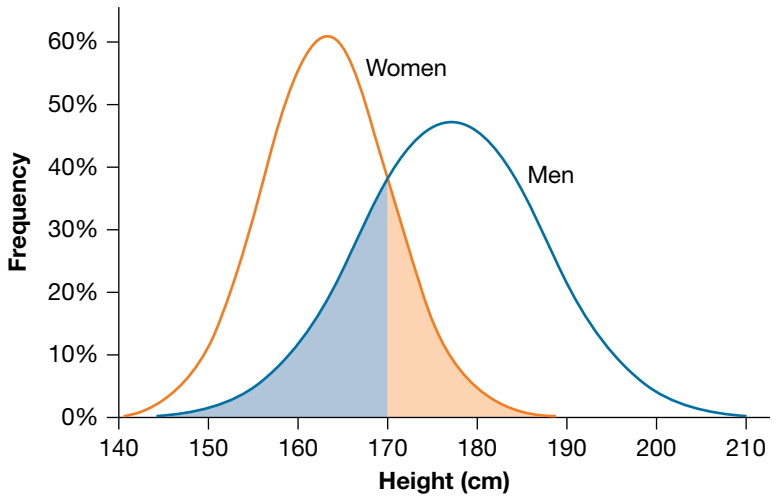

FIGURE 15.13 Bell-shaped distribution of height in human female and male adults. The frequency of each height is shown on the vertical axis. What is the most common height in females? In males? What is the approximate height range for males?

Eye colour is a polygenic trait

The assumptions for the operation of polygenic inheritance as outlined in the previous section are ideal. In real life, there will be some deviations from these assumptions, for example, in human eye colour. In the determination of eye colour, all polygenes do not contribute equally to the phenotype. As we will see, one gene makes a major contribution to the eye colour phenotype.

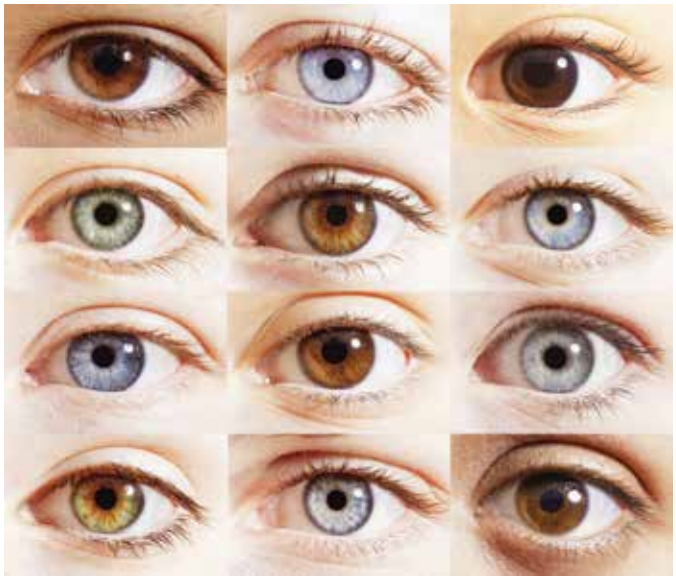

FIGURE 15.14 Eye colour variation in people. Eye colour is not simply either brown or blue — many other colours exist.

Eye colour in people depends on (1) the amount of **melanin** pigment present in cells of the iris of the eye, known as **melanocytes** and (2) the numbers of these melanocytes. At one end of a spectrum is 'blue eye colour' that occurs in an iris with small numbers of melanocytes, each with low levels of pigment. At the other end of the spectrum is 'brown eye colour' that occurs when high levels of melanin pigment are present in larger numbers of melanocytes. In between are various eye colours including hazel and green (see figure 15.14).

The gene that plays a major role in the determination of eye colour is the **OCA2** gene on chromosome 15. This gene encodes a protein involved in melanin production and it has the alleles ***B*** and ***b***. Persons with the ***bb*** homozygous genotype at this locus are *usually* blue eyed and those with the genotypes, either ***BB*** or ***Bb*** are *usually* brown eyed. Clearly, that is not the end of the story, because people do not have either blue or brown eye colour — a range of other eye colours exist.

In fact, eye colour in humans is a polygenic trait. In addition to the involvement of the **OCA2** gene, eye colour is now known to be influenced by at least seven other genes that are involved in some aspects of melanin production. The action of these genes can affect the amount of melanin pigment in the eye. These genes can interact with the **OCA2** gene and, in some cases, reduce its expression so that, less commonly, a person with the ***BB*** or ***Bb*** genotype will have blue eyes instead of the expected brown eye colour. This explains why on rare occasions two blue-eyed persons can have a brown-eyed child. Such a brown-eyed child is a result of the action of polygenes, not marital infidelity.

Explaining polygenic inheritance

Skin pigmentation is another polygenic trait. If we use the assumptions outlined on page 562 and assume that two genes are involved in skin colour, we can see how polygenic inheritance can create many phenotypes.

Table 15.5 shows a simple model of polygenic inheritance of skin colour.

TABLE 15.5 A simple model of polygenic inheritance of skin colour

Number of plus (+) alleles	Possible genotype(s)		Degree of pigmentation
	Gene 1	Gene 2	
4	+ +	+ +	very dark
3	+ + + –	+ – + +	dark
2	+ + + – + –	– – + – ++	intermediate dark
1	+ – – –	– – + –	slightly dark
0	– –	– –	light

In reality, skin colour is more complex than this model suggests and probably involves at least four polygenes. The degree of skin pigmentation can also be affected by environmental factors, such as exposure to UV radiation.

In general, as the number of polygenes increases, the number of possible variations in a trait also increases, as shown in table 15.6.

TABLE 15.6 Increase in the number of polygenes correlates to an increase in the number of possible variations in a trait.

Number of polygenes	Number of variations possible
2	5
3	7
4	9
n	$2n + 1$

Where the number of polygenes is n, the number of possible variations is $2n + 1$. So, if $n = 8$ polygenes, the number of possible variants in a population is 17. The following box describes a case study of polygenes in action.

POLYGENES IN ACTION

As a result of ultra-sonography, Kym and her husband, Joe, knew that she would soon give birth to twins. Kym's ancestors are Irish and she has fair skin; Joe has intermediate dark skin, which he says came from his West Indian father. Joe's mother is English.

The couple have a son, Jimmy, whose skin colouring is midway between that of the parents. They expected that the twins would also have skin colouring midway between their own colouring.

Healthy dizygotic (non-identical) twin girls were born. One girl, Jasmine, is fair and her skin colour is as light as her mother's. The other girl, Carly, has a dark complexion, with a skin colour as dark as her father's. Can this event be explained?

Figure 15.15 shows the genotypes of Kym and Joe. Joe can produce three kinds of sperm:

$$++ \text{ and } +- \text{ and } --$$

In contrast, all of Kym's eggs are $--$.

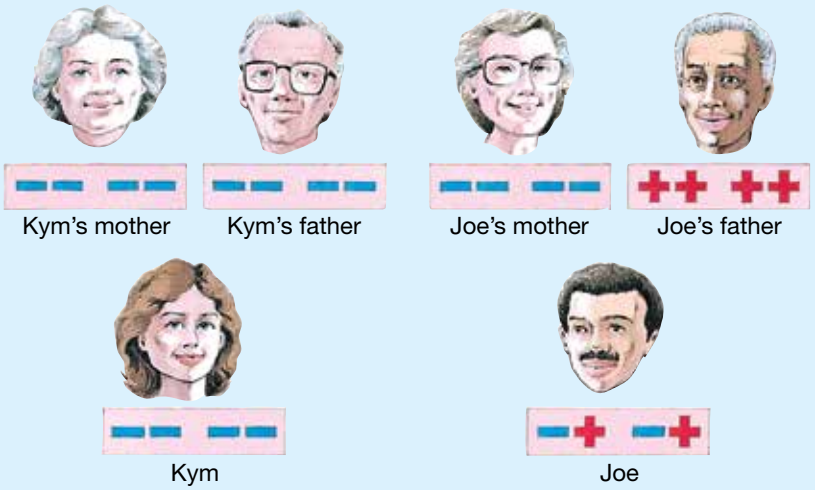

FIGURE 15.15 Simple model of inheritance of skin pigmentation

Jasmine resulted from the fertilisation of an egg ($--$) by a sperm ($--$). Carly resulted from the fertilisation of an egg ($--$) by a sperm ($++$). Can you identify a possible combination of egg and sperm that produced Jimmy?

We have seen how the variation in human skin pigmentation can be explained on the basis of polygenic inheritance. Polygenic inheritance also applies to traits in other organisms, such as butterfat content of milk in cows, length of cobs in corn, size of hens' eggs, body mass in poultry and extent of white spotting in Holstein cattle.

The alleles of each polygene are inherited in a Mendelian fashion; that is, the members of each pair of alleles segregate to different gametes and the assortment of one polygene is independent of that of other polygenes. So, for example, an organism with the genotype $++\ --\ ++$ for a polygenic trait can only produce gametes carrying the information $+-+$. In contrast, an organism with the genotype $+-\ +-\ +-$ can produce a large number of different kinds of gametes including $+++$, $---$, $+-+$ and $-+-$. Can you identify other kinds?

Polygenes in action in corn

The length of a corn kernel can range from about 5 cm to about 21 cm in different varieties of corn. We can account for this range of variation if we assume that:

- four polygenes are involved in determining length of a mature corn cob
- the base length of a cob is about 5 cm for corn grown under standard conditions
- each polygene has two alleles: a plus (+) allele and a minus (–) allele
- each plus (+) allele adds 2 cm to the base length when corn is grown under standard conditions
- each minus (–) allele contributes nothing to the base length.

The maximum number of plus alleles that a corn plant can have is eight and the minimum is zero. Table 15.7 shows how this model can generate a range of variation in cob length seen in different corn varieties.

TABLE 15.7 A model for cob length in corn based on a system of four polygenes. Sample genotypes only are shown for the alleles at each of the four loci. Can you write another genotype for the three plus allele situation?

Number of plus (+) alleles	Sample genotypes				Length of mature cob (cm)
	Locus 1	Locus 2	Locus 3	Locus 4	
0	– –	– –	– –	– –	5
1	– –	+ –	– –	– –	7
2	+ +	– –	– –	– –	9
3	– –	– +	– +	+ –	11
4	+ +	– –	+ –	+ –	13
5	– –	+ +	+ –	+ +	15
6	+ +	– –	+ +	+ +	17
7	– +	+ +	+ +	+ +	19
8	+ +	+ +	+ +	+ +	21

KEY IDEAS

- Monogenic traits show discontinuous variation, with a few discrete classes.
- Inherited variation in some traits is due to the action of polygenes.
- Polygenic traits are controlled by a number of genes.
- Polygenic inheritance generates many phenotypes that show continuous variation.
- Simple models of polygenic inheritance can be constructed.

QUICK CHECK

6 Identify whether each of the following statements is true or false.
- **a** Polygenic traits typically show discontinuous variation.
- **b** The greater the number of polygenes, the greater the number of possible phenotypic classes.
- **c** All the gametes of an organism with the genotype + + – – would be + –.
- **d** Polygenic traits measured over a large sample of people would be expected to show a bell-curve type distribution.

7 If skin colour were controlled by four polygenes, how many phenotypic classes would be possible?

Epigenetics

What is **epigenetics**? The term *epi*genetics literally means 'above' genetics or 'in addition to' genetics or 'on top of' genetics. Epigenetics is the study of how cells with identical genotypes can show different phenotypes. Such phenotypic differences are not due to differences in the base sequences of the DNA of their genes. In addition, these differences are stable within an organism and, in some cases, these differences can be transmitted across generations. So, as well as traditional Mendelian inheritance, another kind of inheritance exists, namely **epigenetic inheritance**.

FIGURE 15.16 Identical twins have been shown to have identical genomes. This means that, as expected, they have identical genotypes. In some cases, differences in their phenotypes may be due to the action of epigenetic factors.

Epigenetics refers to all changes to genes, apart from changes to their base sequences, that bring about phenotypic changes. Epigenetic factors are factors that can bring about these changes. Such factors are external to DNA, but act on DNA and turn genes permanently 'on' or 'off'. Epigenetic factors may underlie some of the differences seen the phenotypes of identical twins, since these differences cannot be explained by differences in their genotypes (see figure 15.16).

Epigenetic factors

Epigenetic factors can change how DNA in cells is packaged or how it is labelled.

Packaging of DNA in cells may be tight or may be open. (Refer to figure 13.23, p. 498 to review how DNA is packaged around histone proteins.) Genes in segments of DNA that are tightly packaged are silenced, while genes in segments of DNA with open packaging are active in transcribing polypeptide gene products.

Labelling DNA is like adding a 'tag' that does not alter the base sequences of genes but can either silence genes or make them active. **Methyl groups** (–CH3) are one example of an epigenetic tag. Methyl groups can be added to any C base alongside a G base in DNA. (Addition of methyl groups is called methylation.) Active genes are found to have fewer methyl groups than inactive genes, so it appears that tagging genes by the addition of methyl groups to their C–G bases can change gene expression and permanently switch those genes 'off'.

Once established, epigenetic tags remain for the life of a cell and are transmitted to all daughter cells derived from that cell. Usually they are not passed on to the next generation. Typically the DNA of a fertilised egg is cleared of the epigenetic tags. In some cases, however, the epigenetic tags on the DNA are not erased but instead are conserved and passed to the next generation(s).

Examples of epigenetic inheritance

Some examples of epigenetic inheritance include:

- *Cell differentiation*. The cells of a human embryo, and later a fetus, are all derived from a single fertilised egg by a series of mitotic cell divisions. During embryonic development, cells will develop along different pathways; for example, some cells will differentiate as brain cells (neurons), some will develop into smooth muscle cells and some into liver cells. All the various

cell types — more than 200 cell types in total — have the same genotypes, but different sets of genes are active in each cell type. Epigenetic factors produce the changes that start various stem cells down different developmental paths.

- *X-inactivation*. The somatic cells of normal female mammals have two copies of the X-chromosome. Early in embryonic development, one of the X chromosomes in each somatic cell is inactivated, switching off all its genes. The epigenetic tags that cause the inactivation of a particular X chromosome are transmitted to all the daughter cells produced by subsequent mitotic cell divisions, so that the same X chromosome remains inactive.
- *Imprinted genes*. Imprinted genes refer to genes whose expression is affected by their parental origin. Children born with a small deletion of one of their number-15 chromosomes will show one of two different phenotypes. Which phenotype is displayed depends on whether the chromosome with the deletion came from the mother or from the father. If from the father, the clinical phenotype is that of Prader-Willi syndrome; if from the mother, the clinical phenotype that is displayed is Angelman syndrome (see figure 15.17).

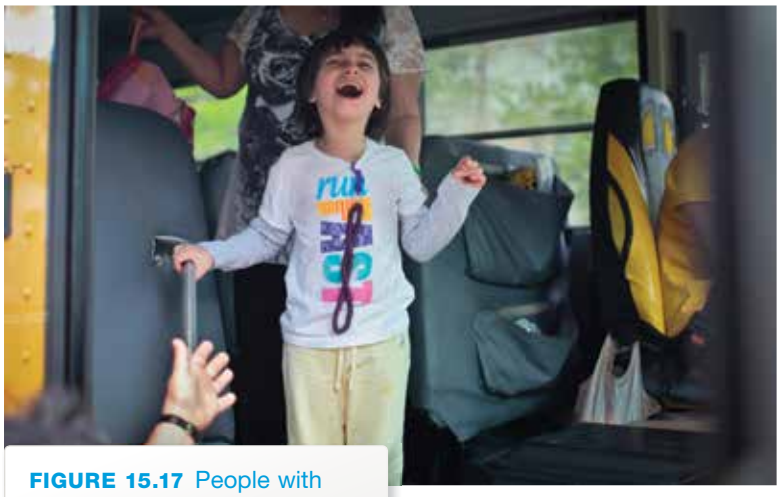

FIGURE 15.17 People with Angelman syndrome have jerky movements, smile frequently and laugh often.

- *Chemical action*. Vinclozolin is a commercial fungicide. If ingested by mammals, it interferes with sperm formation. In an experiment, pregnant rats were injected with vinclozolin and, as expected, the male offspring produced reduced numbers of sperm with lower than normal mobility. However, an interesting finding was that if these male rats managed to mate their sons showed the same defect, and this defect was then passed to males in the next generation. The chemical did not cause a mutation of the DNA of the original male. What was observed in the three generations of male rats was a change in the level of methylation of their DNA.

KEY IDEAS

- Epigenetics is the study of how cells with identical genotypes can show different phenotypes.
- Epigenetic factors act on DNA but do not change the DNA base sequence.
- Methylation of C bases in DNA is one kind of epigenetic factor.
- Packaging of DNA is another means by which epigenetic factors can act.

QUICK CHECK

8 Identify whether each of the following statements is true or false.
- **a** Epigenetic inheritance is an alternative name for Mendelian inheritance.
- **b** Once an epigenetic tag is in place within a cell it will remain for the life of that cell.
- **c** Some epigenetic tags can pass across generations.
- **d** Development of different cell types in an embryo involves the action of epigenetic factors.

9 Give an example of an epigenetic change that can be transmitted across generations.

BIOCHALLENGE

1 a Identify the gender, in terms of external features, of each of the following.

i Person A — XY chromosomes, with a normal **SRY** gene
ii Person B — normal XX chromosomes
iii Person C — XY chromosomes, but an inactive **SRY** gene
iv Person D — XY chromosomes with a deletion of the entire **SRY** gene

Add your decisions to table 15.8.

b Now, for a challenge. Predict the gender, in terms of external features, of the following.

i Person E — XX chromosomes. This person is the result of fertilisation of a normal egg by a sperm formed by meiosis during which a crossing-over event between the X and Y chromosome occurred that caused the **SRY** gene on the Y chromosome to be relocated to the X chromosome.
ii Person F — XY chromosomes. This person has a very rare condition known as complete androgen insensitivity syndrome because of a change in the **AR** gene on the X chromosome. The normal allele of this gene makes the proteins that are the androgen receptors on cells. These receptors are needed for cells to respond to androgen hormones, including testosterone. The changed allele stops the androgen receptors from working so that the cells are non-responsive to testosterone. (Testosterone is essential for the development of testes and for the appearance of the male physical characteristics.)

Add your decisions to table 15.8.

TABLE 15.8

Person	Predicted gender
A	
B	
C	
D	
E	
F	

2 For the 1992 Olympic Games, the International Olympic Committee (IOC) introduced a new gender identification test to prevent males, disguised as females, from competing in women's events. This test was intended to 'prove' that competitors were indeed female. The test was a 'blanket' test as it covered all female competitors.

The new test was one for the presence of the **SRY** gene. The test for the **SRY** gene detects the presence of sequences of DNA from that gene. All women entrants in Olympic events were required to undergo this test.

For each of the six persons identified in question 1, identify the gender that would be assigned to each as a result of the SRY gene test.

Add your decisions to table 15.9.

TABLE 15.9

Person	Gender from SRY testing
A	
B	
C	
D	
E	
F	

3 Blanket gender testing was abolished before the Sydney 2000 Olympics because of many concerns.

Suggest why this happened.

Chapter review

Key words

antibiotic sensitivity testing
autosomal gene
azoospermia
bell-shaped distribution
carrier
co-dominance
continuous variation
cystic fibrosis
discontinuous variation
dominant
epigenetic inheritance
epigenetics
genotype
hemizygous
heterozygous
homozygous
melanin
melanocytes
methyl group
monogenic
phenotype
polygene
polygenic
Swyer syndrome
X-linked gene
Y-linked gene

Questions

1 **Making connections** ➜ Use at least eight of the chapter key words to draw a concept map relating to genotypes and phenotypes. You may use other words in drawing your map.

2 **Linking concepts from earlier chapters** ➜ Phenotypes seen in bacterial species include sensitivity to particular antibiotic drugs. The antibiotic streptomycin interferes with bacterial ribosomes.
   - **a** Identify a reason that streptomycin is effective in killing some bacteria.
   - **b** Would you predict that streptomycin would be effective for treating just one infection caused by one kind of bacteria only or would you predict that it would be generally effective against several bacterial infections? Briefly explain your decision.

3 **Applying knowledge and understanding** ➜ The genetic control of height differs in tobacco plants and pea plants.
   - **a** What are the differences in the genetic control of height in these two plant species?
   - **b** Make a rough sketch that shows height classes in a group of pea plants.
   - **c** Now make a rough sketch that shows height classes in tobacco plants.

4 **Demonstrating understanding and suggesting explanations** ➜ In tobacco plants (*Nicotiana* sp.), flower length is under the control of four polygenes, with each plus allele adding an equal amount to the baseline value of this trait and each minus allele having no effect. The genotypes of three plants follow.

   Plant P + + + + − − + −
   Plant Q + − + − + − + −
   Plant R + + + + − − − −

   The plants were grown under comparable conditions.
   - **a** Which plant would be expected to have the longest flowers?
   - **b** How many different kinds of gametes could plant R produce?
   - **c** How many different kinds of gametes could plant Q produce?

5 In dairy cattle, the level of butterfat in milk varies from a high value of about 6.6 per cent to a low of about 2.6 per cent and this trait is under the control of polygenes. Develop a simple model to account for this range of butterfat content based on four polygenes.
   - **a** What baseline value have you assumed?
   - **b** What is the contribution of each plus (+) allele?

6 Peach, the cow, has a genotype of + − + − + − + − for butterfat level. Samson, the bull, has an identical genotype. Which, if any, of the four calves below could result from the mating of Peach and Samson? Explain.

   Calf 1 + + + + + + + +
   Calf 2 − − − − − − − −
   Calf 3 + − + − + − + −
   Calf 4 − − + + − − + +

7 Explain the following observations.
   - **a** Most children with cystic fibrosis are born into families with no history of this disorder.
   - **b** Normal males have just a single copy of the DMD gene that encodes the dystrophin protein, while females have two copies.
   - **c** A polygenic trait that is controlled by a greater number of polygenes shows more phenotypes than a polygenic trait that is controlled by fewer genes.
   - **d** A monogenic trait would be expected to show just a few non-overlapping phenotypic classes.

8 **Demonstrating knowledge** ➜ Using standard notation, write a possible genotype for an X-linked gene for each of the following.
   - **a** A female who is homozygous at the gene locus concerned
   - **b** A normal male
   - **c** A female with an XXX sex chromosome make-up
   - **d** A male with Klinefelter syndrome

9 Developing explanations ➜ Leaves of white oak trees (*Quercus alba*) can show two different phenotypes (see figure 15.18).

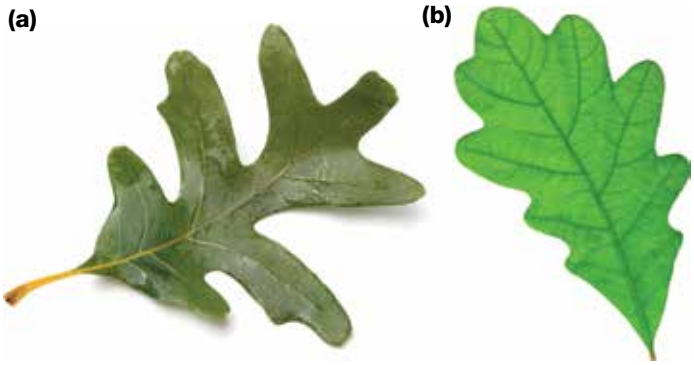

FIGURE 15.18 Two phenotypes of white oak trees (*Quercus alba*)

Further examination revealed that the leaves with the shape shown in figure 15.18a grow on areas of trees that are exposed to full sunlight, while the leaves shaped as in figure 15.18b are located in areas shaded from the sun.

a Do the leaf cells on areas of the same tree exposed to sunlight have the same genotype as those growing in shaded areas? Briefly explain.

b Which of the following is the best biological explanation for the variation in leaf shape on the same tree?

i The tree wants to increase the surface area of the shaded leaves in order to maximise photosynthesis.

ii The phenotype of the leaves is due, not only to the genotype, but is also influenced by an environmental factor, namely, light intensity.

iii The genotypes of the leaves change in response to the different environments in which the leaves are growing.

10 Recognising and using allelic notation ➜

a Identify, as fully as possible and including genders, the phenotypes that correspond to the following genotypes. The allelic symbols are those from table 13.7 on page 515.

i ***Hh*** ii ***Cc*** iii ***aa***
iv ***m*** v ***M***

b Using the allelic notation in table 13.7, write possible genotypes for the following persons.

i A male hemizygous for red–green colour blindness

ii A male with normal pigmentation, but whose child has the albinism phenotype

iii A female carrier of Duchenne muscular dystrophy

iv A female homozygous for Rhesus positive blood type

v A male with group O blood type

11 Formulating explanatory models ➜ You are given the following information about a particular species of flowering plant:

- Flower colour in this plant species is under genetic control.
- Two flower colours, red and white, are seen in flowers of this plant.

a Based on this information, identify a probable explanation for the inheritance of flower colour in this plant.

b You are later told that, as well as white and red flower colours, other colours are seen in this plant species, including pale pink, medium pink and intense pink.

Given this additional information, how, if at all, would you change your explanation for the inheritance of flower colour in this plant species?

12 Using skills of understanding and analysis ➜ Consider the small number of genes that are located on the short regions of the Y chromosome that are homologous to corresponding regions of the X chromosome.

a For any one of these genes, how many copies are present in a human cell?

b Can these genes be correctly labelled as Y-linked genes? Briefly explain your decision.

c Can these genes be correctly labelled as X-linked genes? Briefly explain your decision.

d Can these genes be correctly labelled as autosomal genes? Briefly explain your decision.

e There is another term 'pseudo-autosomal' that describes genes that are not located on an autosome, but behave as if they were autosomal genes. Might this be an appropriate label for the few genes that are present on both the X and the Y chromosome? Briefly explain your decision.

CHAPTER

16 Genetic crosses: rules of the game

FIGURE 16.1 This wallaby shows a condition known as albinism, in which pigment is lacking from the skin, eyes and fur. Her joey has normal pigmentation. A similar condition occurs in people and in other vertebrates. In this chapter we will explore how the alleles of one or more genes are transmitted from parents to offspring, examine different patterns of inheritance, and consider aspects of genetic screening and genetic testing.

KEY KNOWLEDGE

This chapter is designed to enable you to:

- predict the outcomes of classical monohybrid crosses and test crosses
- distinguish between the results of a dihybrid cross involving two genes that assort independently and those from a cross involving two linked genes
- enhance understanding of the biological consequence of crossing over
- gain skills in the analysis of human pedigrees and recognise key features of different patterns of inheritance
- develop awareness of genetic testing of adults and embryos.

Making melanin pigment

ODD FACT

Two types of melanin pigment exist: black eumelanin and yellow phaeomelanin.

The **TYR** gene is just one of many genes on the human number-11 chromosome. The **TYR** gene encodes a protein that functions as the enzyme, **tyrosinase**. This enzyme catalyses a step in the pathway that produces the pigment, **melanin**. Melanin pigment is seen in the hair, the skin and the irises of a person's eyes. Melanin pigment is present not only in people, but also in other vertebrate species in their skin, eyes and fur (in the case of mammals), feathers (in the case of birds) and scales (in the case of reptiles).

Melanin pigmentation is produced in a multi-step pathway in special cells known as **melanocytes**. The enzyme tyrosinase catalyses one step in the pathway that produces melanin. Without a functioning tyrosinase enzyme, melanin production cannot occur and this results in a condition known as **albinism**. Figure 16.2 shows some examples of albinism in other species.

FIGURE 16.2 Albinism exists across many different species.

The **TYR** gene in humans has two common alleles:

- allele ***A*** that produces normal tyrosinase enzyme, resulting in normal pigmentation
- allele ***a*** that produces a faulty protein that cannot act as the tyrosinase enzyme, resulting in a lack of pigment (albinism).

Persons with genotypes ***AA*** or ***Aa*** have normal pigmentation. In contrast, persons with the ***aa*** genotype lack a functioning tyrosinase enzyme and so have albinism. From this, we can conclude that normal pigmentation phenotype is **dominant** to albinism.

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Unit 2 | AOS 2 | Topic 4 | Concept 6

Monohybrid cross
Concept summary and practice questions

Rules of the genetic game

Let us now look at a cross involving the alleles of the **TYR** gene. This is a **monohybrid cross** because it involves the alleles of just one gene at a time. When the alleles of two genes are involved, the cross is termed a **dihybrid cross**. **A monogenic cross involves the segregation of alleles of the same gene into separate gametes.** This segregation, or separation, occurs when homologous chromosomes disjoin at metaphase 1 of meiosis (refer to figure 11.14).

Tracey and John are planning their next pregnancy. One of their first-born non-identical twin children, Fiona, has the condition of albinism and the parents want to know about the chance of this condition appearing in their next child. Figure 16.3 shows the chromosomal portraits of Tracey, John and their twins. Both parents are carriers of albinism and have the genotype ***Aa***.

FIGURE 16.3 Genotypes and phenotypes of Tracey, John, Fiona and Tim for the **TYR** gene controlling pigment production

	Tracey	John	Fiona	Tim
Chromosomes	11 11	11 11	11 11	11 11
Genotype	***A a***	***A a***	***a a***	***A A***
Phenotype	Normal pigment	Normal pigment	Albino	Normal pigment

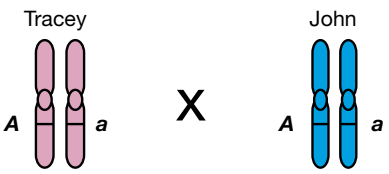


FIGURE 16.4 Cross of Tracey and John for the **TYR** gene

ODD FACT

The chance of an event can be expressed as a fraction ($\frac{1}{4}$), a percentage (25%), a ratio (1 in 4, 1:4) or a decimal (0.25). When a decimal number is used, the value 0 represents an impossible occurrence and a chance of 1 represents a certainty. So, the chance that you will run a two-minute mile today is 0 and the chance that you will take a breath in the next half hour is 1.

Monohybrid crosses: pigment or not?

For the **TYR** gene on the number-11 chromosome, which controls pigment production, the cross can be seen in figure 16.4.

During meiosis, the pair of number-11 chromosomes disjoin, carrying the alleles to different gametes. Tracey's eggs have *either* the ***A*** allele *or* the ***a*** allele. This also applies to the sperm cells produced by John. This separation of the alleles of one gene into different gametes that occurs during meiosis is known as the *segregation* of alleles. For each parent, the chance of a gamete with ***A*** is 1 in 2 and the chance of a gamete with ***a*** is also 1 in 2.

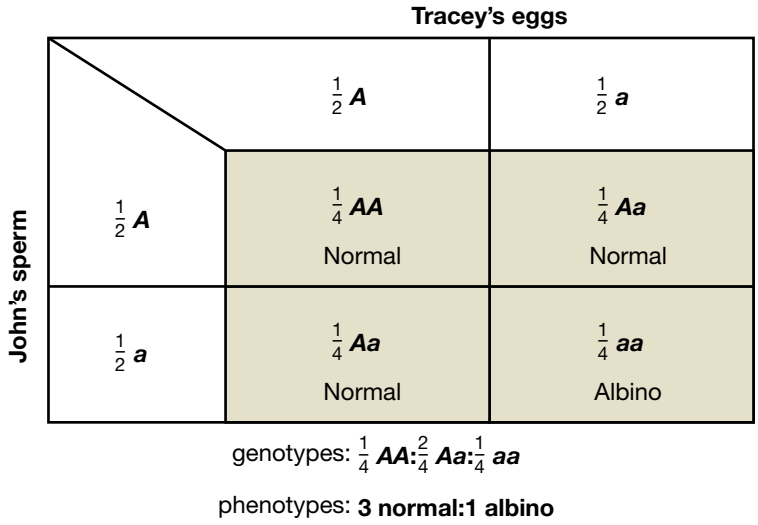
These probabilities can also be incorporated into a **Punnett square** (figure 16.5). The ***AA*** and the ***Aa*** genotypes both result in normal pigmentation. The ***aa*** genotype causes albinism.

A Punnett square shows the *chance* of each possible outcome, *not* what will happen. So, Tracey and John asked, 'What is the chance that our next child will have albinism?' The answer to their question is 1 in 4, or $\frac{1}{4}$. The chance that their next child will have normal pigmentation is $\frac{3}{4}$. If the next child has normal pigmentation, what is the chance that this child will be a heterozygous carrier of albinism? Look at the Punnett square: there are three ways a child with normal pigmentation can result, so the chance that this child will be a heterozygous ***Aa*** carrier of albinism is 2 in 3.

The fractions, such as $\frac{1}{2}$ or $\frac{1}{4}$, that appear in a Punnett square identify the chance or probability of various outcomes. So, for example, Tracey is heterozygous ***Aa*** with two different alleles at the **TYR** gene loci. The chance that her ***A*** allele will go to a particular egg cell is 1 in 2; likewise the chance that her ***a*** allele will go to that egg cell is also 1 in 2. (This situation is like tossing a coin.

There are two possible outcomes, namely heads (H) and tails (T), so when a coin is tossed, the chance of H is $\frac{1}{2}$ and the chance of T is $\frac{1}{2}$.)

FIGURE 16.5 Punnett square for a monohybrid cross: ***Aa*** × ***Aa***



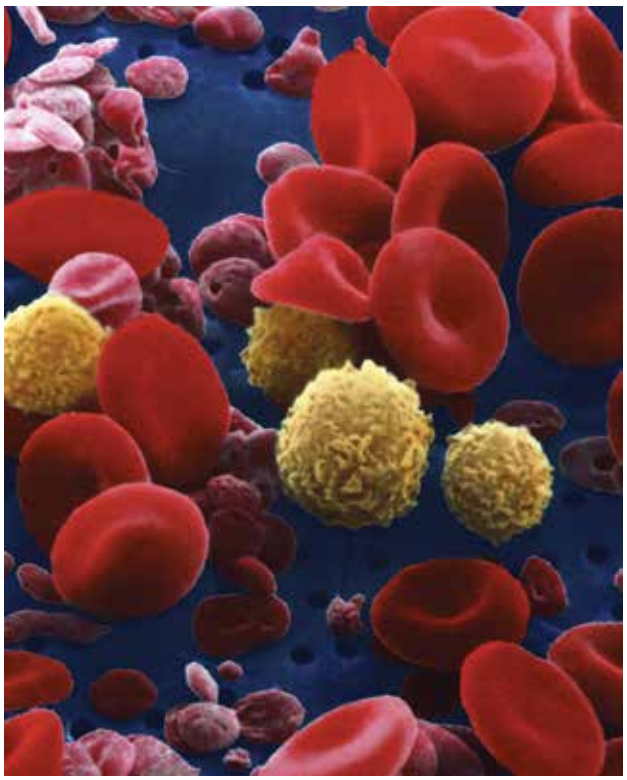


FIGURE 16.6 Blood cells consist mainly of red blood cells. Also present here are white blood cells (yellow) and platelets. The ABO blood types relate to antigens that can be present on the plasma membrane of red blood cells.

Since John is also heterozygous ***Aa***, a similar situation exists in regard to his sperm cells: each of his sperm cells must carry either the ***A*** allele or the ***a*** allele. This accounts for the $\frac{1}{2}$ ***A*** and the $\frac{1}{2}$ ***a*** entries along the top and down the left-hand side of the Punnett square.

What about the $\frac{1}{4}$ entries within the Punnett square? This is the chance of two independent events occurring, such as Tracey's egg with an ***A*** allele being fertilised by John's sperm with an ***A*** allele. **The chance, or probability, of two independent events occurring is the product of the chance of each separate event**, that is, $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$.

Let's look at another monohybrid cross involving this family.

Monohybrid cross: ABO blood type

The four blood groups in the ABO blood system are A, B, AB and O. These different blood group phenotypes are controlled by the **ABO** gene on the number-9 chromosome. Each phenotype is determined by the presence or absence of specific proteins, known as **antigens**, on the plasma membrane of the red blood cells (see figure 16.6).

In the Australian population, type O is the most common blood group (about 49%) and type AB is the rarest (about 3%). Table 16.1 shows the antigens that determine the ABO blood types.

TABLE 16.1 ABO blood types and corresponding antigens present on red blood cells. What antigens are present in a person with O type blood?

Antigens present on red blood cells	ABO blood group	Frequency in Australian population*
antigen A	A	38%
antigen B	B	10%
antigens A and B	AB	3%
neither antigen	O	49%

* based on Australian Red Cross data

Tracey and John are both blood group B and their twins are both blood group O. This means that both parents have the heterozygous genotype I^Bi, while the twins have the genotype ii (see figure 16.7). The cross between Tracey and John for the **ABO** gene is shown in figure 16.8.

FIGURE 16.7 Genotypes and phenotypes of Tracey, John, Fiona and Tim for the **ABO** gene controlling ABO blood types

	Tracey	John	Fiona	Tim
Chromosomes	I^B i 9 9	I^B i 9 9	i i 9 9	i i 9 9
Genotype	$I^B\,i$	$I^B\,i$	$i\,i$	$i\,i$
Phenotype	Group B	Group B	Group O	Group O

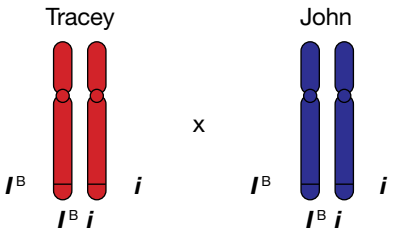


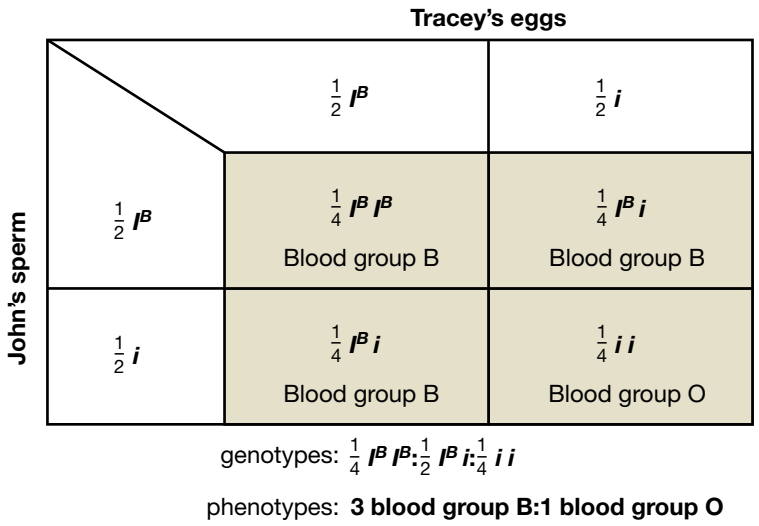
FIGURE 16.8 Cross of Tracey and John for the **ABO** gene

ODD FACT

In 1902, an Austrian pathologist, Karl Landsteiner (1868–1943), was the first to recognise that any human blood sample could be classified into one of four possible blood types that he named groups A, B, AB and O.

Disjunction of the number-9 chromosomes during meiosis in Tracey means that her eggs have *either* one I^B allele *or* one i allele and the chance of each type is $\frac{1}{2}$. John's number-9 chromosomes also disjoin during meiosis. Likewise, his sperm cells have *either* one I^B allele *or* one i allele.

Again, we can show the chances of the various outcomes in a Punnett square (see figure 16.9).



genotypes: $\frac{1}{4}\,I^B\,I^B$:$\frac{1}{2}\,I^B\,i$:$\frac{1}{4}\,i\,i$

phenotypes: **3 blood group B:1 blood group O**

FIGURE 16.9 Punnett square showing outcome of the cross: $I^Bi \times I^Bi$

In summary, the chance that Tracey and John's next child will be blood group B is 3 in 4 and the chance that it will be blood group O is 1 in 4. Remember that ratios, such as 3 to 1, identify the chance or the probability of a particular outcome occurring; they do not identify a certain outcome.

In this section, you have seen how this monogenic inheritance operates in a human family. In the following sections, you will see examples of monogenic crosses in other organisms.

Monohybrid crosses: other organisms

Sweet peas

In sweet peas (*Lathyrus odoratus*), purple flower colour (***P***) is dominant to white (***p***) (see figure 16.10). What happens if a pure breeding purple-flowering plant is crossed with a pure breeding white-flowering plant? **Pure breeding** means that the plant is homozygous for the allele in question, and such a plant can produce only a single kind of gamete.

FIGURE 16.10 One gene in sweet peas controls flower colour and has the alleles ***P*** (purple) and ***p*** (white), with purple being the **dominant phenotype**.

This cross can be shown as follows:

parental phenotypes	purple	×	white
parental genotypes	***PP***		***pp***
possible gametes	***P***		***p***
possible offspring		all are purple, ***Pp***	

Note that all the offspring from this cross are heterozygous purple (***Pp***).

What is the expected outcome if these heterozygous purple plants are crossed?

FIGURE 16.11 Punnett square showing the possible outcome of crossing two heterozygous purple plants

Gametes	***P***	***p***
P	***PP*** purple	***Pp*** purple
p	***Pp*** purple	***pp*** white

genotypes: 1 ***PP***:2 ***Pp***:1 ***pp***

phenotypes: 3 purple:1 white

Details of the parents are as follows:

parental phenotypes	purple	×	purple
parental genotypes	***Pp***		***Pp***
possible gametes	***P*** and ***p***		***P*** and ***p***

We can now use a Punnett square to show the possible outcome of this cross (see figure 16.11).

Thus, from the cross of two heterozygous purple plants, the chance that the offspring will show the dominant purple colour is 3 in 4 and the chance that they will show the recessive white phenotype, is 1 in 4. What is the chance that a purple-flowered offspring will be homozygous ***PP***?

FIGURE 16.12 The grey fur of this cat advertises its genotype as being homozygous recessive, ***dd***, at the **MLPH** gene locus. Its white areas are due to the action of an allele of another gene.

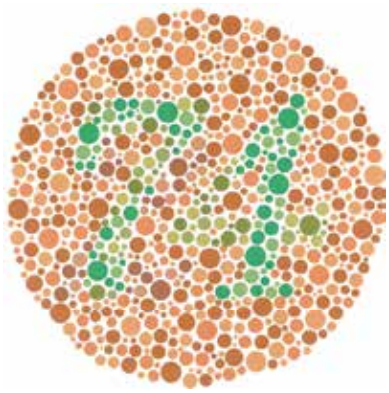


FIGURE 16.14 Example of one Ishihara colour plate. Where a person with normal vision sees the number 74, a person with red–green colourblindness may see this as 21. (*Note:* This reproduction of an Ishihara colour plate is not a valid test for colour vision.)

Dilute cats

In cats, the **MLPH** gene on the cat chromosome C1 controls the packing or density of pigment granules in melanocytes of their fur. This gene has the alleles, dense (***D***) and dilute (***d***). In the dominant dense phenotype, pigment granules are numerous and evenly packed along the length of the fur; in the recessive dilute phenotype, the pigment granules are clumped and unevenly distributed. The dense phenotype is seen, for example, in black cats that have the genotype ***DD*** or ***Dd***. The dilute phenotype is seen in grey cats with the genotype, ***dd*** (see figure 16.12).

Consider the cross of two black cats that are heterozygous ***Dd*** at the **MLPH** gene locus.

The details of the parents are as follows:

parental phenotypes	black	×	black
parental genotypes	***Dd***		***Dd***
possible gametes	***D*** and ***d***		***D*** and ***d***

We can use a Punnett square to show the outcome of the cross of these heterozygous black cats (see figure 16.13).

Gametes	***D***	***d***
D	***DD*** black	***Dd*** black
d	***Dd*** black	***dd*** grey

genotypes: 1 ***DD***:2 ***Dd***:1 ***dd***

phenotypes: 3 black:1 grey

FIGURE 16.13 Punnett square showing the possible outcome of crossing two heterozygous black cats

It may be seen that the chance that a kitten will show the dominant black phenotype is 3 in 4 and the chance that it will show the recessive grey phenotype is 1 in 4.

Monohybrid crosses: X-linked genes

So far, we have looked at monohybrid crosses involving autosomal genes. What happens in a monohybrid cross when the gene involved is located on the X chromosome? Refer to the box on page 600 to read about the crosses involving an **X-linked gene** that were carried out by TH Morgan. Morgan was the first to demonstrate that one particular gene was located on one particular chromosome (refer to figure 14.1).

People normally have three colour receptors (red, green and blue) in the retina of their eyes. These receptors allow us to differentiate colours, such as red from green. Inherited defects in colour receptors cause various kinds of colourblindness, which can be identified by specific screening tests. One such test, administered by a professional under controlled conditions, involves the use of coloured images known as **Ishihara colour plates** (see figure 16.14).

The **CBD** gene on the human X chromosome controls one form of red–green colourblindness. Normal colour vision (***V***) is dominant to red–green colourblindness (***v***). Table 16.2 shows the genotypes and phenotypes for this X-linked **CBD** gene. Examine this table. Note that females have two copies of the X chromosome and so must have two copies of any X-linked gene. This means that females will be either homozygous or heterozygous for X-linked genes. In contrast, males have only one X chromosome and so must have just one copy of any X-linked gene. This means that males are hemizygous for X-linked genes.

TABLE 16.2 Genotypes and phenotypes for the X-linked **CBD** colour vision gene. The '***V***' and the '***v***' symbols denote the different alleles of this gene. Because the Y chromosome pairs with and then disjoins from the X chromosome during meiosis, it is included here. (The Y chromosome does not carry any gene for colour vision, and is denoted (Y).)

Sex	Sex chromosomes	Genotype	Phenotype
female	**XX**	***VV***	normal colour vision
		Vv	normal colour vision
		vv	red–green colourblindness
male	**XY**	***V***(Y)	normal colour vision
		v(Y)	red–green colourblindness

Could two people with normal colour vision produce a child with red–green colourblindness? Let's consider the cross of a heterozygous ***Vv*** female and a male who has normal colour vision. Could a child from this cross be colourblind? If so, what is the chance of this outcome?

The details of the parents are as follows:

parental phenotypes	female: normal vision	×	male: normal vision
parental genotypes	***Vv***		***V*** (Y)
possible gametes	***V*** and ***v***		***V*** and Y

The gametes of the male parent will have *either* an X chromosome with the ***V*** allele *or* a Y chromosome.

We can now use a Punnett square to show the expected outcomes of this cross (see figure 16.15).

Gametes	***V***	***v***
V	***VV*** female normal vision	***Vv*** female normal vision
(Y)	***V*** (Y) male normal vision	***v*** (Y) male colourblind

genotypes: 1 ***VV***:1 ***Vv***:1 ***V*** (Y):1 ***v*** (Y)

phenotypes: 2 females with normal colour vision:1 male with normal colour vision:1 colourblind male

FIGURE 16.15 Punnett square showing the possible outcomes of crossing a heterozygous ***Vv*** female with a male who has normal colour vision

In summary, this particular cross could produce a colourblind child, but that child can only be a son, not a daughter. The chance of a colourblind son from this cross is 1 in 4. The chance of a colourblind daughter from this cross is 0.

Monohybrid crosses: some variations

We have seen in the previous sections that the expected result from the cross of two parents heterozygous at an autosomal gene locus is a 3:1 ratio of offspring showing the dominant phenotype to those showing the recessive trait.

Variations from the expected 3-dominant:1-recessive phenotypic ratio from a cross of two heterozygotes can occur. This can happen, for example, when:

- the relationship between the alleles of the gene is one of co-dominance; or
- one of the alleles is lethal in the homozygous condition (see below).

Co-dominant alleles

Co-dominance refers to a situation in which both alleles of a heterozygous organism are expressed in its phenotype (refer to chapter 15, p. 556). For example, in cattle (*Bostaurus*), coat colour is controlled by an autosomal gene with the alleles C^R and C^W. The relationship between these two alleles is one of co-dominance. The coat colour of heterozygous cattle is called roan and it consists of a mixture of red hairs and white hairs. Figure 16.16 shows the phenotypes of the three possible genotypes.

genotype:	$C^W C^W$	$C^R C^R$	$C^R C^W$
phenotype:	White	Red	Roan

FIGURE 16.16 Genotypes and phenotypes in cattle for alleles of a coat colour gene that have a co-dominant relationship. Note that both alleles are expressed in the heterozygous roan cattle.

Gametes	C^R	C^W
C^R	$C^R C^R$ red	$C^R C^W$ roan
C^W	$C^R C^W$ roan	$C^W C^W$ white

genotypes: 1 $C^R C^R$:2 $C^R C^W$:1 $C^W C^W$

phenotypes: 1 red:2 roan:1 white

FIGURE 16.17 Punnett square showing the possible outcomes of crossing two heterozygous roan cattle

Consider the cross of two heterozygous roan cattle. Will the outcome be the typical 3:1 ratio?

We can show the parental details as follows:

parental phenotypes	roan	×	roan
parental genotypes	$C^R C^W$		$C^R C^W$
possible gametes	C^R and C^W		C^R and C^W

We can now use a Punnett square to show the outcome of the cross of two heterozygous roan cattle (see figure 16.17).

Where the allelic relationship is one of co-dominance, the expected result from the cross of two heterozygotes is a ratio of 1:2:1 of red:roan:white (rather than 3:1).

FIGURE 16.18 An $A^y a$ yellow mouse (right) with the common agouti aa mouse (left)

Lethal genes

Some genotypes can result in death early in embryonic development. Offspring with such lethal genotypes do not develop and so do not appear among the offspring of a cross. How does this affect the expected ratio of offspring? Let's look at an example.

One gene in mice has the alleles A^y (yellow coat colour) and a (agouti coat colour). Yellow coat colour is dominant to the agouti coat colour (see figure 16.18). However, the A^y allele in a double dose is lethal, causing death in early embryonic development. In terms of lethality, the A^y allele is a recessive lethal.

What would be expected from the cross of two mice, each with a heterozygous $A^y a$ yellow genotype?

We can show the parental details as follows:

parental phenotypes	yellow	×	yellow
parental genotypes	$A^y a$		$A^y a$
possible gametes	A^y and a		A^y and a

We can now use a Punnett square to show the outcome of the cross of these heterozygous yellow mice (see figure 16.19).

Gametes	A^y	a
A^y	~~$A^y A^y$~~	$A^y a$ yellow
a	$A^y a$ yellow	aa agouti

genotypes: 2 $A^y a$:1 aa

phenotypes: 2 yellow:1 agouti

FIGURE 16.19 Punnett square showing the possible outcomes of crossing two heterozygous yellow mice. Which genotype does not appear?

The potential $A^y A^y$ offspring die in very early embryonic development, even before they are implanted in the wall of the uterus. As a result, these potential offspring are never detected. Evidence of the recessive lethal nature of the A^y allele comes from the fact that litter sizes from these crosses are smaller than average and, in addition, yellow mice are always heterozygous, never homozygous.

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Unit 2 AOS 2 Topic 4 Concept 7

Monohybrid test cross
Concept summary and practice questions

Monohybrid test crosses

An organism that shows the dominant phenotype may have one or two copies of the allele that determines that phenotype, that is, it may be homozygous TT or heterozygous Tt. This situation can be denoted by the genotype T–, where the minus symbol denotes either T or t. In this case, a monohybrid **test cross** can be used to identify its genotype. A monohybrid test cross is a special kind of cross in which an organism of uncertain genotype (T–) is crossed with a homozygous recessive organism (tt).

In reality, today, it is possible to identify genotypes more directly by examining the relevant part of an organism's genome, without the need to carry out a test cross and produce numbers of offspring.

However, let's use the example of a black cat whose parentage is unknown. Such a cat has dense pigmentation and so could have the genotype either DD

or ***Dd***. What are the possible outcomes of a test cross of this black cat with a homozygous recessive grey cat with dilute colouring? The result will reveal whether the black cat is homozygous dense or heterozygous dense.

The black-coated parent has dense colouration. If the black cat is homozygous ***DD***, he cannot sire any kittens with dilute coloured (grey) fur. Why? He can pass on only a ***D*** allele to all his offspring and, in consequence, all kittens must have dense (black) coloured fur.

If, however, the black cat is heterozygous ***Dd***, he can produce two types of gamete: ***D***-carrying sperm and ***d***-carrying sperm. When combined with the mother's gametes, which must all be ***d***-carrying eggs, both black kittens and grey kittens can result (see figure 16.20).

Gametes	***D*** (from dad)	***d*** (from dad)
d *(from mum)*	***Dd*** black	***dd*** grey

genotypes: 1 ***Dd***:1 ***dd***

phenotypes: 1 black:1 grey

FIGURE 16.20 Possible outcomes of monohybrid test cross of heterozygous black male cat with grey female cat

Note that the two possible phenotypes are expected to appear in equal proportions. The chance of a grey kitten is 1 in 2, and the chance of a black kitten is also 1 in 2. These probabilities do *not* mean that in a litter of four kittens two will be black and two will be grey. The appearance of just one grey kitten is sufficient evidence to conclude that the black-furred parent is heterozygous ***Dd***. It would not be valid to conclude that the black-furred parent was homozygous ***DD*** on the evidence of a litter of five black kittens because this outcome can occur by chance (see figure 16.21).

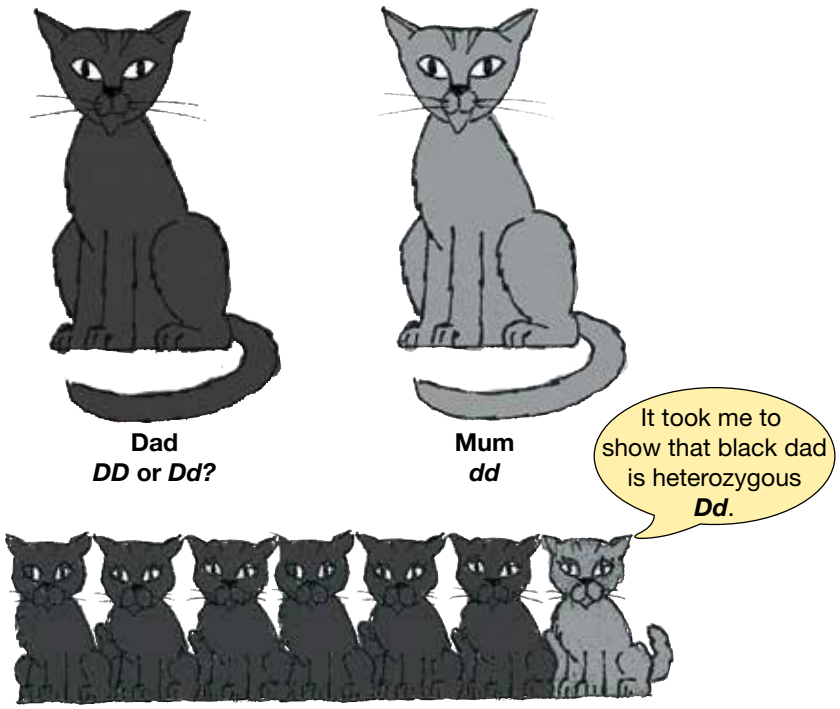

FIGURE 16.21 The outcome of this test cross depends on the genotype of the parent showing the dominant trait, in this case, dense fur colour (black). If homozygous ***DD***, this cat cannot sire any grey kittens; if heterozygous, ***Dd***, the cat could sire grey kittens.

KEY IDEAS

- Monohybrid crosses involve the alleles of one gene.
- Monohybrid crosses of two heterozygotes can be shown as a Punnett square, with parental gametes on the outside and the possible genotypes in the inner 2 × 2 block.
- In terms of phenotypes, the expected result of a monohybrid cross of two heterozygotes is 3:1, showing the dominant and the recessive traits respectively.
- A test cross is the cross of an organism with a known homozygous recessive genotype and another that shows the dominant phenotype but whose genotype is unknown.
- Patterns of inheritance of X-linked genes are characterised by an unequal occurrence of phenotypes by sex.
- Under certain conditions, the cross of two heterozygotes may not produce the expected 3:1 ratio of offspring showing the dominant trait to offspring showing the recessive trait, such as codominance or lethal genes.

QUICK CHECK

1 Identify whether each of the following statements is true or false.

a The appearance of four black kittens in a litter from the cross of a black cat of uncertain genotype and a grey cat would prove that the black cat was homozygous ***DD***.

b An organism with genotype ***Rr*** could produce gametes carrying ***R*** and gametes carrying ***r***.

c Organisms homozygous for a trait controlled by a single gene would be expected to produce two kinds of gametes.

d An X-linked trait can appear only in males.

e A mouse embryo with one copy of the lethal yellow allele would not be expected to develop.

f Two alleles that have a relationship of co-dominance would be expected to be expressed as three distinct phenotypes.

g In a monohybrid cross, a homozygous parent can produce just one kind of gamete.

Dihybrid crosses: two genes in action

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Dihybrid cross
int-0180

A dihybrid cross involves the alleles of two different genes. Let us first consider two genes that are located on different (nonhomologous) chromosomes, such as the **ABO** gene on the number-9 chromosome and the **TYR** gene on the number-11 chromosome.

Genes on nonhomologous chromosomes are said to be unlinked. When two genes are unlinked, the alleles at one gene locus behave independently of those at the second locus in their movements into gametes. When two genes are unlinked, this is expressed by using a semicolon to separate the alleles of one gene from those of the second gene, for example, ***Aa***; ***Bb***.

Let's now return to Tracey and John and look at their genotypes for the **ABO** and the **TYR** genes. Both Tracey and John are heterozygous at each gene locus (see figure 16.22).

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Dihybrid cross: independent genes
Concept summary and practice questions

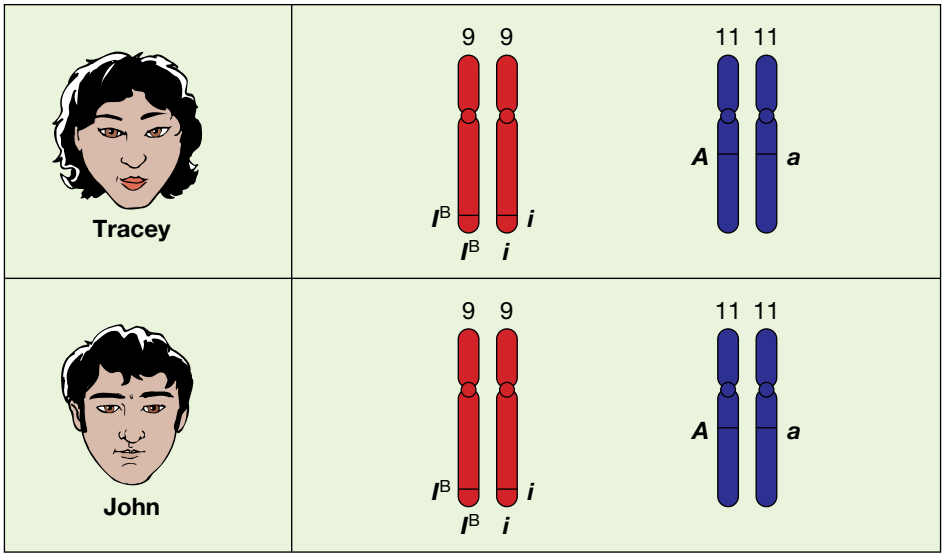

FIGURE 16.22 Genotypes of Tracey and John for two unlinked genes. Both are heterozygous at the two gene loci. The numbers 9 and 11 denote the human chromosomes.

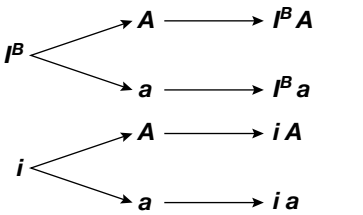

FIGURE 16.23 All the possible normal gametes produced by meiosis in a person with the heterozygous genotype I^Bi; Aa

What are the possible outcomes of a cross between Tracey and John?

Because the genes are unlinked, each parent can produce four kinds of gametes in equal numbers, as shown in figure 16.23. The various combinations of alleles of different genes are the result of allele segregation and of the independent assortment of genes in meiosis.

We can summarise the genetic information about Tracey and John as follows:

parental phenotypes	blood group B normal pigment	×	blood group B normal pigment
parental genotypes	I^Bi ; Aa		I^Bi ; Aa
possible gametes	$I^B A$, $I^B a$, $I A$ and $I a$		$I^B A$, $I^B a$, $I A$ and $I a$

The dihybrid cross between Tracey and John can be shown in two different ways. Firstly, a dihybrid cross can be shown as a combination of two monohybrid crosses (see figure 16.24). The chance that Tracey and John's next child will have albinism is 1 in 4 and the chance that the next child will be blood group O is also 1 in 4. So the combined probability that the next child will have albinism and be blood group O is $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$.

Locus 1	Locus 2	Offspring and chance
Aa x Aa	Ii x Ii	$AAII$: $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$
↓	↓	$Aaii$: $\frac{1}{2} \times \frac{1}{4} = \frac{1}{8}$
$\frac{1}{4}$ AA : $\frac{1}{2}$ Aa : $\frac{1}{4}$ aa	$\frac{1}{4}$ II : $\frac{1}{2}$ Ii : $\frac{1}{4}$ ii	$AaIi$: $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$
		$aaii$: $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$
		etc.

FIGURE 16.24 Looking at a dihybrid cross. What is the chance of an $aaII$ offspring? Note that, for convenience, the B superscript has been omitted from symbols inside the square, but you should remember that where the I appears, it is the I^B allele.

Alternatively, a dihybrid cross can be shown as a Punnett square, with all the possible parental gametes shown across the top and down the side of the square (see figure 16.25). Combining these various gametes in a Punnett gives all the possible genotypes that can occur in offspring of these parents. These 16 different genotypes can be grouped into four different phenotypes as shown at the bottom of the Punnett square.

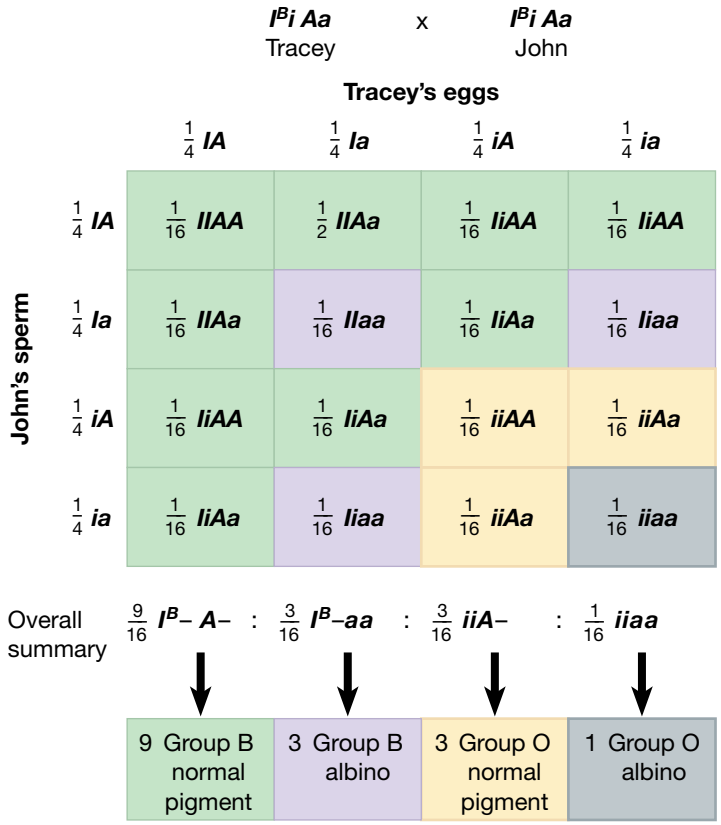

FIGURE 16.25 Punnett square showing the cross of Tracey and John. Note that in the overall summary statement below the Punnett square, the 'dash' symbol (–) means that the second allele in the genotype can be either of the two possible alleles. So, for example, ***A***– denotes both ***AA*** and ***Aa***.

In summary, the expected phenotypic result from a dihybrid cross of two heterozygotes is 9:3:3:1, where the $\frac{9}{16}$ refers to offspring showing both dominant traits, the two $\frac{3}{16}$ refer to offspring showing one of the dominant traits and the $\frac{1}{16}$ refers to offspring showing both recessive traits.

Now let's review another cross. In cats, one gene controls the presence of white spotting and has the alleles ***W*** for white spotting and ***w*** for absence of white spots. White spotting is dominant to absence of white spots. A second unlinked gene controls fur length and has the alleles ***S*** for short fur and ***s*** for long fur. The short fur phenotype is dominant to long fur. What is the expected outcome of the cross of two cats, heterozygous at each gene locus, that is, with genotypes ***Ww***; ***Ss***?

Based on the summary above, we can predict that the expected outcome is 9 white spotted with short fur:3 white spotted with long fur:3 no white spots with short fur:1 no white spots with long fur. These ratios can be expressed as probabilities, such as a 9 in 16 chance of showing both dominant traits, a 3 in 16 chance of showing one only of the dominant traits, a 3 in 16 chance of showing the other dominant trait and a 1 in 16 chance of showing both recessive traits.

Dihybrid test crosses

In a dihybrid test cross, one parent is homozygous recessive, for example, genotype ***ppqq***. The other parent in a dihybrid test cross is heterozygous, for example, genotype ***PpQq***. (How does this compare with a monohybrid test cross?)

In the past, dihybrid test crosses were used to identify the linkage relationship between two genes, for example, the white spotting gene and the fur length gene. These two genes are on separate chromosomes, that is, they are unlinked and will assort independently. In reality, as with monohybrid testing, today direct investigation of the genome provides the answer to the question: are two genes linked or not? But to further understand this concept, let's look at a test cross of these two genes.

The details of the parents are as follows:

parental phenotypes:	white spotted and short fur	×	no white spots and long fur
parental genotypes	***Ww*; *Ss***		***ww*; *ss***
possible gametes	***WS*, *Ws*, *wS*** and ***ws***		all ***ws***

Putting these into a Punnett square, we can see the outcome of this dihybrid test cross in figure 16.26.

Gametes	***WS***	***Ws***	***wS***	***ws***
ws	***Ww Ss*** white spots short fur	***Ww ss*** white spots long fur	***ww Ss*** no spots short fur	***ww ss*** mo spots long fur

genotypes: 1 ***Ww Ss***:1 ***Ww ss***:1 ***ww Ss***:1 ***ww ss***

phenotypes: 1 white spot short fur:1 white spot, long fur:1 no spot, short fur:1 no spot, long fur

FIGURE 16.26 Possible outcomes of dihybrid test cross

A dihybrid test cross can show whether or not two genes are assorting independently and so are unlinked. If unlinked, a dihybrid test cross will yield a 1:1:1:1 ratio of the four possible phenotypes.

What about linked genes?

Genes do not float around the nucleus like peas in soup. Each gene has its chromosomal location or **locus**.

The genes that are located on one chromosome form a **linkage group**. Figure 16.27 shows three of the linkage groups in the tomato (*Lycopersicon esculentum*). The total number of linkage groups in an organism corresponds to the haploid number of chromosomes. Thus, the tomato with a diploid number of 24 has 12 linkage groups.

In humans, there are 22 autosomal linkage groups plus the X- and the Y-linkage groups, making a total of 24. Figure 16.28 shows just a few of the genes in the linkage groups on five human chromosomes.

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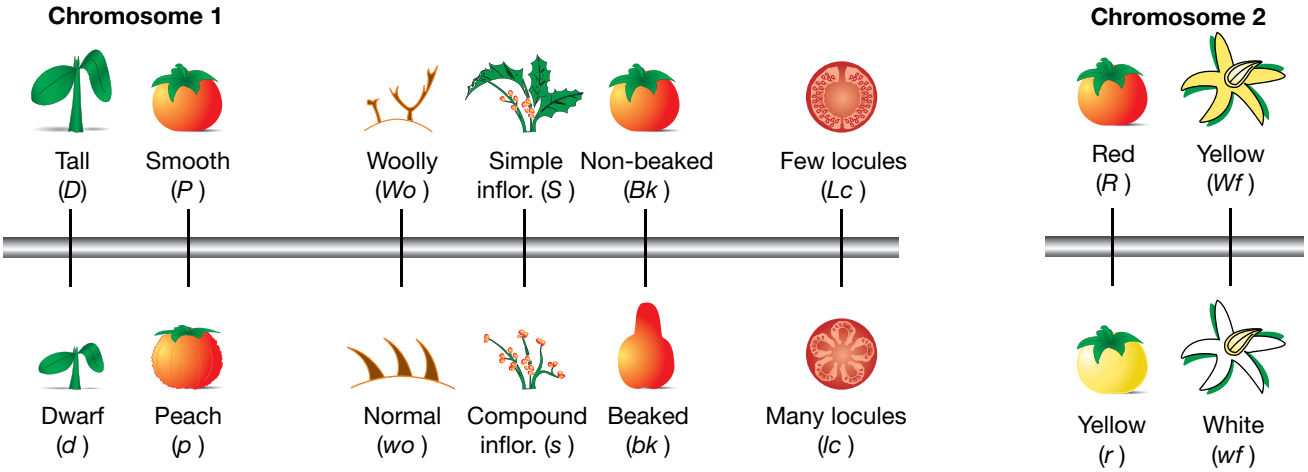
Behaviour of linked genes

Earlier in this chapter (refer to p. 582) we explored the inheritance of unlinked genes. Such genes are typically located on nonhomologous chromosomes and their alleles assort independently into gametes.

Linked genes are located close together on a chromosome. The combinations of their alleles on homologous chromosomes tend to stay together (see figure 16.29), but they can, on occasions, be separated by **crossing over** during meiosis. The closer together on a chromosome that the allelic forms of two different genes are, the more tightly they are linked and the less likely they are to be separated by crossing over during gamete formation by meiosis. The consequence is that the more widely separated on a chromosome, the more likely that the alleles of two different genes will be separated by crossing over.

The **RHD** gene, which controls Rhesus blood type, and the **EPB41** gene, which controls the shape of red blood cells, are close together on the number-1 chromosome and so are said to be linked.



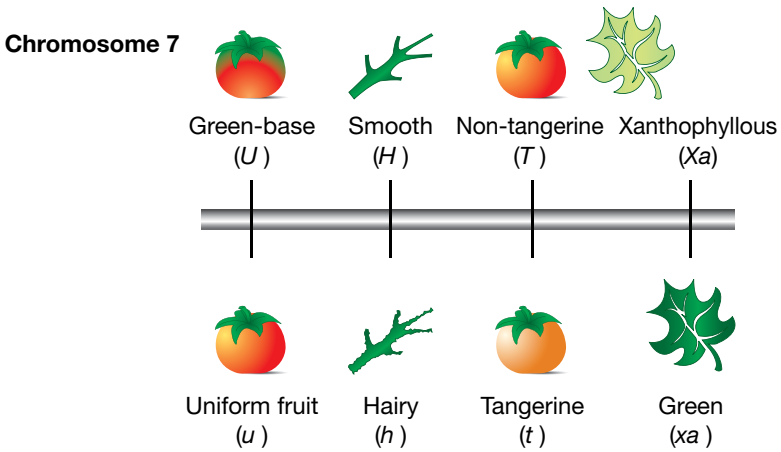


FIGURE 16.27 Three of the 12 linkage groups in the tomato

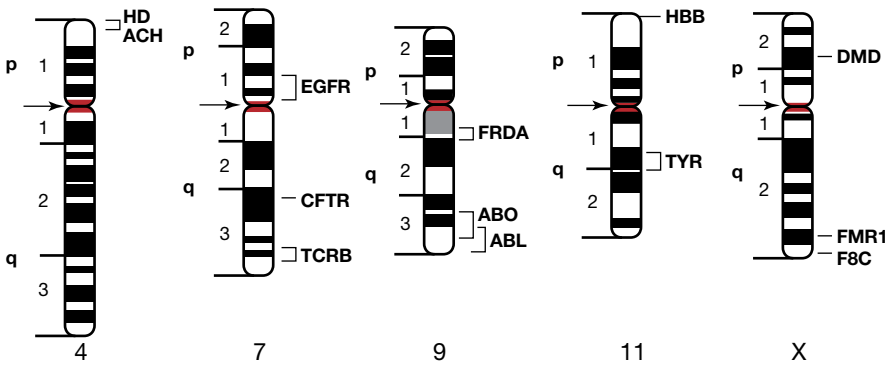


FIGURE 16.28 A chromosome map showing a very small sample of the genes that form part of five linkage groups

Sarah has elliptical red blood cells and is Rhesus positive; her genotype is ***Dd Ee***. Dave has normal red blood cells and he is Rhesus negative; his genotype is ***dd ee***. Consider the cross between Sarah and Dave shown in figure 16.30.

The figure shows the arrangements of the alleles of the two genes on the chromosomes in Sarah and David. Their genotypes can be written as ***DE/de*** and ***de/de*** respectively. Because the **RHD** and the **EPB41** genes are physically close together on the number-1 chromosome, alleles of these two genes do *not* behave independently, as is the case for the **TYR** and the **ABO** genes.

Because the loci of two linked genes are physically close, the particular combination of alleles of the genes that are present on parental chromosomes tend to be inherited together more often than alternative combinations.

Linked genes can also be denoted in other ways when the allele arrangements are known. For example:

$\frac{A\ b}{a\ B}$ OR ***Ab/aB*** OR $\frac{A\ b}{a\ B}$

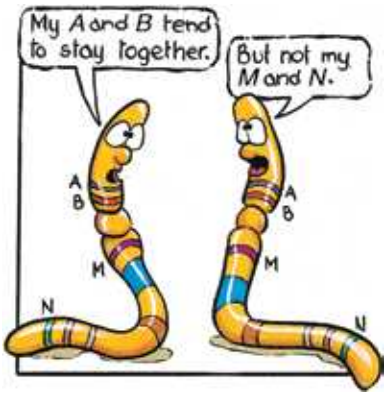


FIGURE 16.29 Alleles of closely linked genes are more likely to be inherited together than the alleles of widely separated genes. Why?

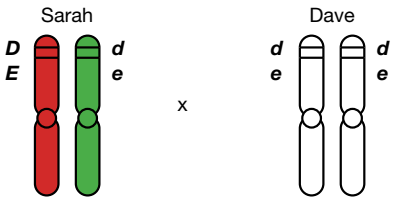


FIGURE 16.30 Independent assortment of alleles of two linked genes

These combinations of alleles can, however, be broken by crossing over during meiosis so that new combinations of alleles are generated. The chance that this occurs depends on the distance between the two linked genes.

Sarah can produce both ***DE*** eggs and ***de*** eggs and the chance of each type is equal. These eggs are called **parental**, or **noncrossover**, **eggs** because they are identical to the original allele combinations present in Sarah. Crossing over and an exchange of segments can occur anywhere along the paired number-1 chromosomes. When an exchange occurs between the **RHD** locus and the **EPB41** locus, **recombinant**, or **crossover**, **eggs** result. Sarah's recombinant eggs are ***De*** and ***dE***.

Crossing over occurs between all paired chromosomes during meiosis. A crossover point is more likely to occur between two genes that are widely separated on a chromosome than between two gene loci that are closer together. The closer the genes, the smaller the chance of a crossover. Because the loci of the **RHD** gene and the **EPB41** gene are very close on the number-1 chromosome, the chance of a crossover occurring between them is small. As a result, Sarah's eggs are more likely to transmit the parental than recombinant types. We will assume that for these two genes the chance of each kind of parental (noncrossover) gamete is 0.49 and the chance of each type of recombinant gamete is 0.01.

Since Dave is homozygous, he produces only ***de*** sperm cells — a 1.0 chance.

A Punnett square can be drawn up to show the chance of production of each kind of gamete, and the chance of each possible offspring (figure 16.31).

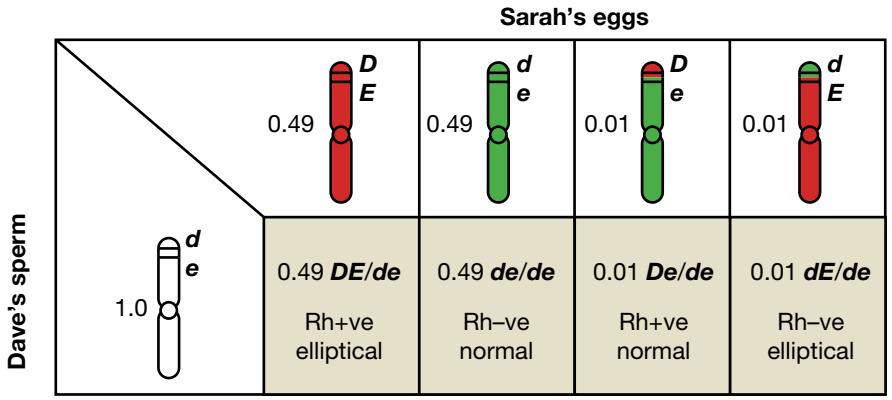


FIGURE 16.31 Punnett square showing the chance of production of each kind of gamete, and the chance of each possible offspring for Sarah and Dave

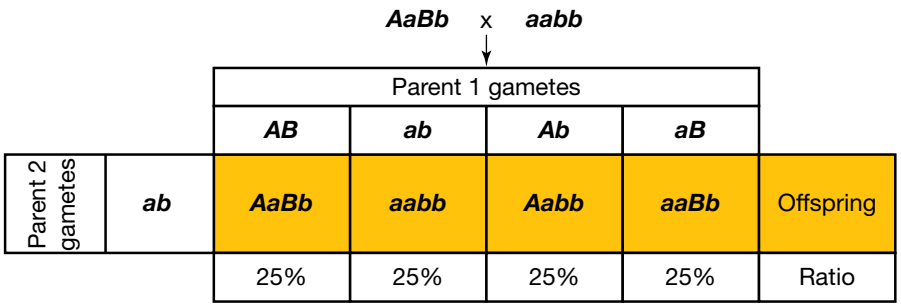
For Sarah and Dave, what is the chance of a child with Rh negative blood and elliptical red blood cells? This phenotype corresponds to the genotype ***dE/de***. The chance of this offspring is 0.01 or 1/100.

Detecting linkage

Are two gene loci linked? This question may be explored by looking at the results of a particular test cross of a known double heterozygote (***Aa Bb***) with a double homozygous recessive (***aa bb***). If the two gene loci are not linked, the genes will assort independently and the outcome of the test cross will be four classes of offspring in equal proportions (see figure 16.32).

If the two gene loci are linked, the outcome of the test cross can reveal that linkage. There will be four classes of offspring but the proportions of these will not be equal. Instead, there will be an excess of offspring from parental gametes and a deficiency of offspring from recombinant gametes.

Linked gene loci are located close together on the same chromosome (separated by a distance of no more than 40 map units) and do not assort independently.



Because of equal numbers of each kind of offspring, we can conclude that the genes are not linked but assort independently, and the chromosome make-up of the cross is:

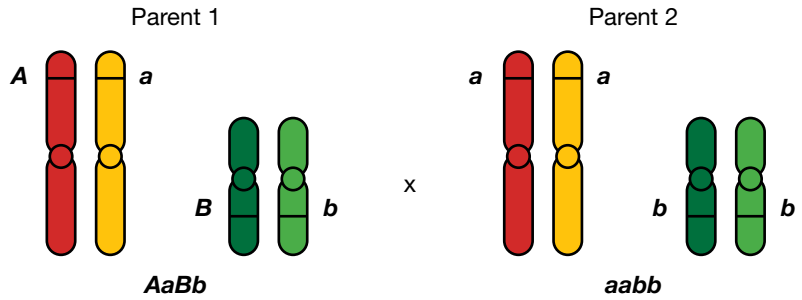


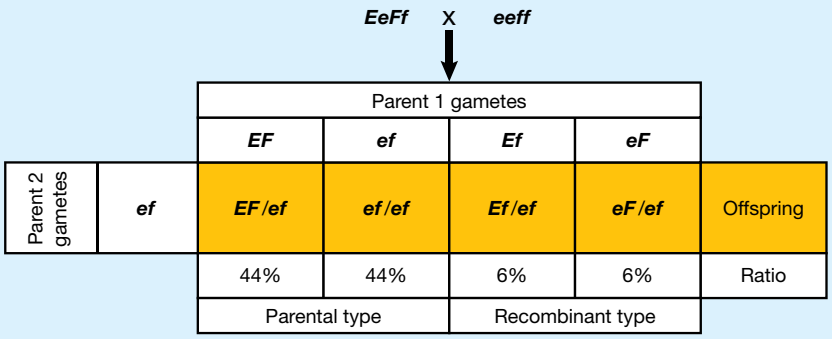
FIGURE 16.32

ESTIMATING DISTANCE BETWEEN LINKED GENES

From the results of a test cross with linked genes, it is possible to estimate the distance between the gene loci. This estimate is based on the percentage of recombinant offspring.

$$\text{Distance between loci} = \frac{100 \times \text{number of recombinant offspring}}{\text{total number of offspring}}$$

The percentage of recombinant offspring corresponds to the number of map units separating the two genes. So, if there are 12 per cent total recombinant offspring, then the loci of the two genes are separated by about 12 map units (see figure 16.33).



Because of unequal numbers of parental and recombinant offspring, we can conclude that the genes are linked, the genotypes can be written as shown in the table above and the chromosome make-up of the cross is:

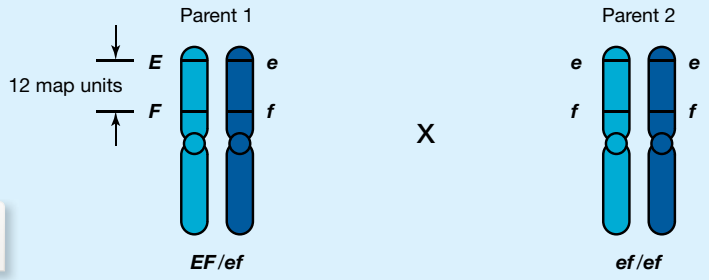


FIGURE 16.33

Predicting outcomes of crosses for linked genes

When a test cross is carried out with two genes that are known to be linked and are separated by a known number of map units (but fewer than 40), the outcome of the cross can be predicted. For example, if two linked genes are separated by, say, 8 map units, then a test cross involving these genes will produce about 8 per cent of the recombinant type offspring and about 92 per cent of the parental type offspring. The actual genotypes and phenotypes of the recombinant offspring depend on which alleles of the two genes were together originally on the one chromosome in the heterozygous parent, before any crossing over occurred during gamete formation. For example, the test cross ***RT/rt*** × ***rt/rt*** gives 8 per cent recombinant offspring. The cross ***Rt/rT*** × ***rt/rt*** also gives 8 per cent recombinant offspring. However, the genotypes of the recombinant offspring differ in each case as shown in figure 16.34.

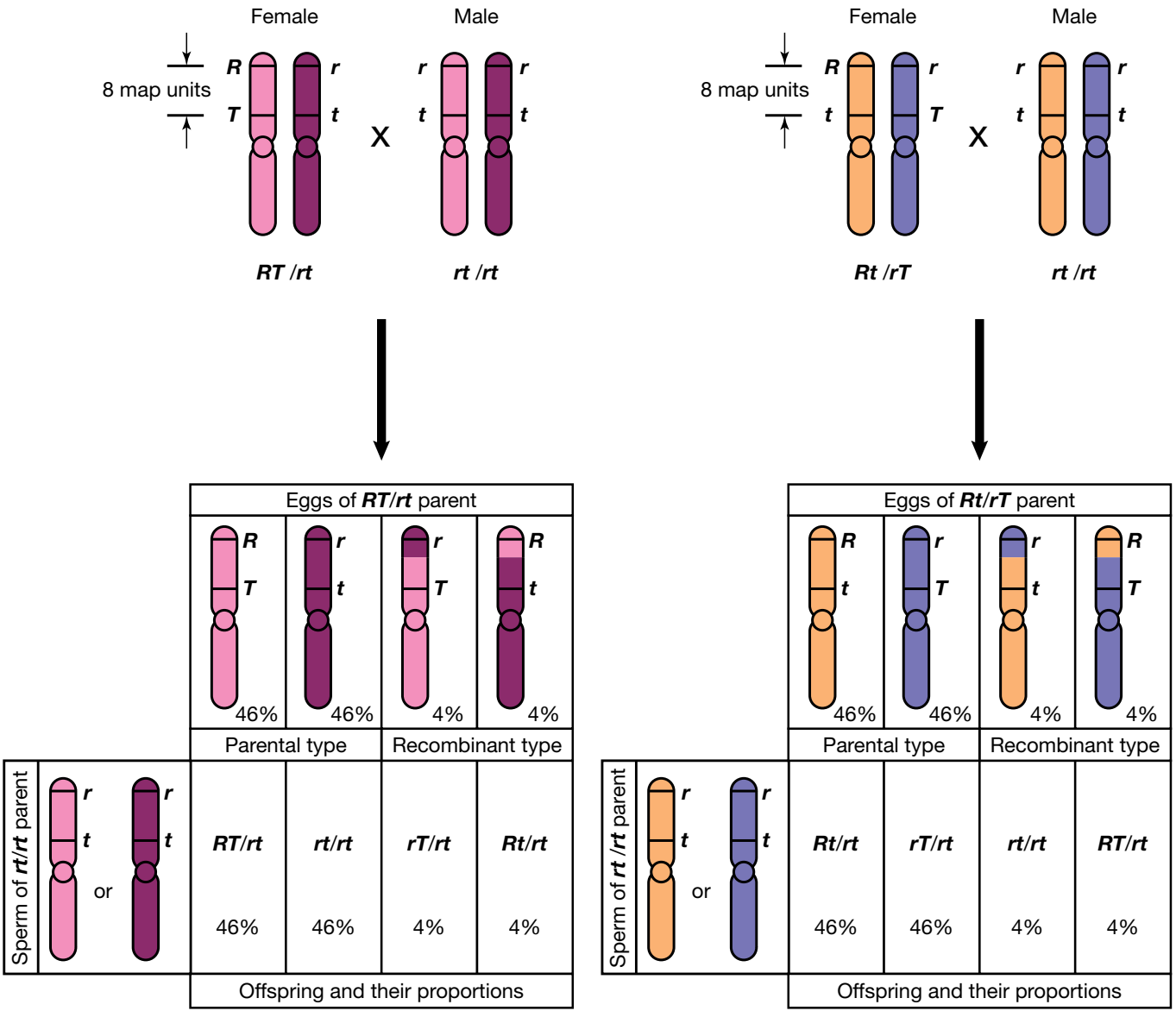


FIGURE 16.34

Note that the outcome of a test cross involving two linked genes allows you to deduce how the alleles of the genes are arranged on the chromosomes of the heterozygous parent.

KEY IDEAS

- Dihybrid crosses involve alleles of two different genes.
- The outcome of a dihybrid cross of two heterozygotes is four phenotypes in the ratio of 9:3:3:1.
- A dihybrid test cross may be used to identify whether or not two genes are linked.
- The closer two linked genes are, the less the chance that crossing over will separate the parental arrangement of alleles.
- When genes are linked, parental gametes are formed in addition to smaller numbers of recombinant gametes.

QUICK CHECK

2 Identify whether each of the following statements is true or false.
- **a** An organism heterozygous at two gene loci will produce two kinds of gametes.
- **b** An offspring from a dihybrid cross of two heterozygotes has a 1 in 16 chance of showing both recessive traits.
- **c** The expected outcome from a dihybrid test cross is four phenotypes in the ratio of 1:1:1:1.

3 What is the difference between a parental and a recombinant gamete?

4 A person has the genotype **Rt/rT**. Will he produce more gametes of type ***RT*** than ***Rt***?

studyon
Unit 2 AOS 2 Topic 4 Concept 10
Genetic screening
Concept summary and practice questions

Genetic testing and screening

Genetic screening refers to the testing of segments of a population, as part of an organised program, for the purpose of detecting inherited disorders. In genetic screening, testing is available to all members of a population group even if they have no obvious signs of any disorder. One example of genetic screening is the testing of all newborns for several inherited disorders (see below).

Genetic screening is carried out when:

1. members of the population being screened can benefit from early detection of an inherited disorder
2. a reliable test exists that, in particular, does not produce false negative results. (A false negative occurs when an affected person fails to be detected by the test.)
3. the benefit is balanced against costs (including financial cost)
4. appropriate systems are in place to provide treatment and other follow-up services.

Genetic testing refers to the testing of an individual, most commonly an 'at risk' person. Such testing may be for various reasons, for example, determining the person's risk of being affected by an inherited disorder where a family history of disorder is present, or determining the genetic risk of offspring of known carriers of genetic disorders (see below).

Genetic screening

In Australia, newborn babies are screened shortly after birth for a number of inherited disorders. These conditions are rare, do not show symptoms at birth and most commonly occur in babies where there is no family history of the disorder. If not identified early, these disorders can have serious negative consequences on a baby's mental and physical development. Parents must give their informed consent for the genetic screening of their baby.

Figure 16.35 shows the procedure for newborn screening (NBS) that starts with the informed consent of the parents. More than 99 per cent of parents give their consent for NBS.

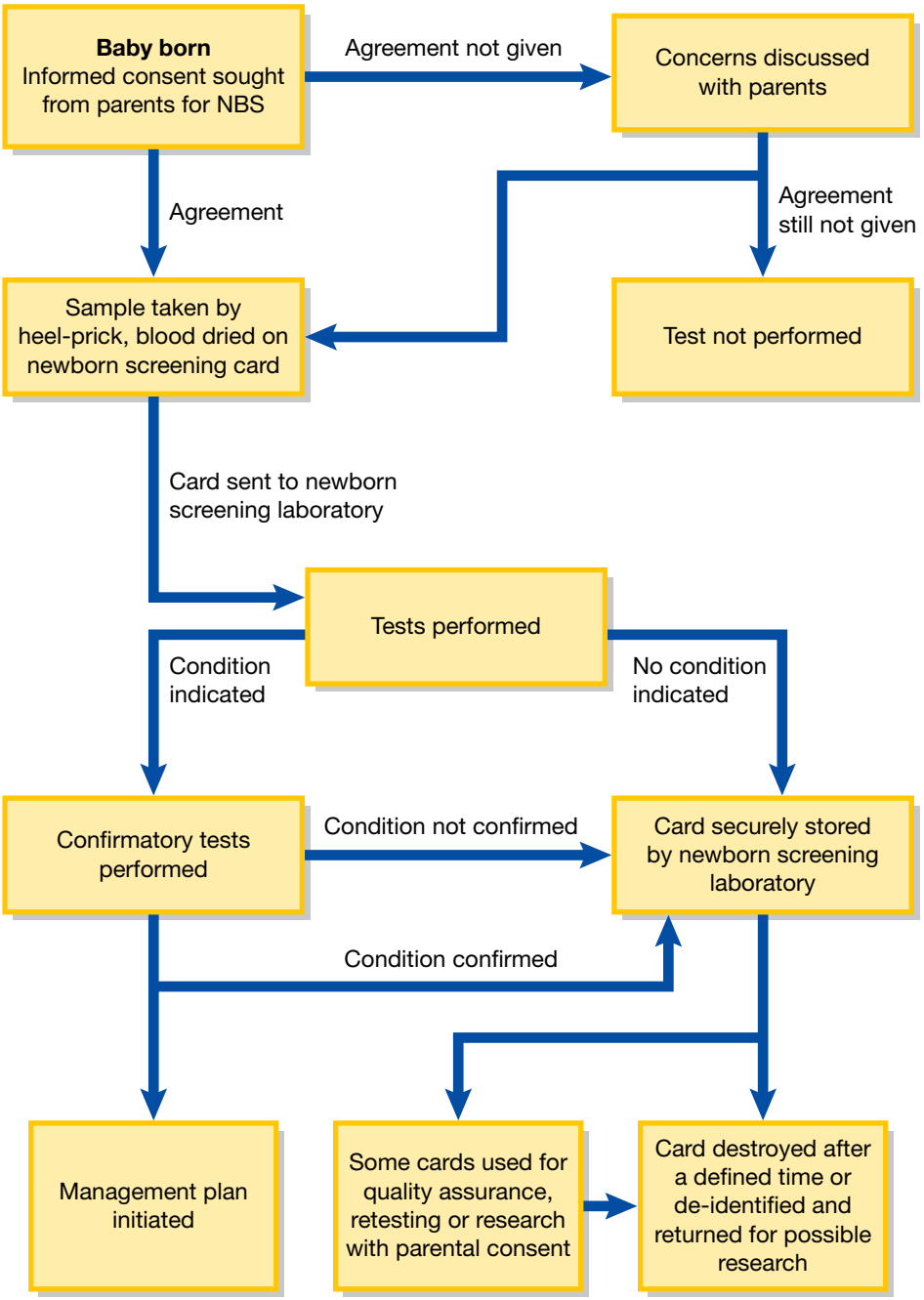


FIGURE 16.35 Procedure for newborn screening (NBS)

The genetic disorders for which screening is performed in Australia are:

- *phenylketonuria*. Phenylketonuria (PKU) is an inherited disorder that occurs in about one in every 10 000 babies. An affected person fails to produce a particular liver enzyme (phenylalanine hydroxylase) and so is unable to metabolise the amino acid phenylalanine (Phe) to tyrosine. The build-up of phe results in brain damage. With early detection of the condition and supply of a diet with low levels of phenylalanine (refer to figure 15.9, p. 559), a baby with PKU will develop normally, both mentally and physically.
- *cystic fibrosis*. **Cystic fibrosis (CF)** is an inherited disorder that occurs in about one in every 2500 babies. A person with CF produces abnormal secretions that have a serious adverse effect on the function of the lungs and on digestion. Recent advances in treatment have greatly improved the prognosis for these babies, so early diagnosis and treatment are important.

- *galactosaemia*. Galactosaemia is an inherited disorder that occurs in about one in every 40 000 babies. Lactose, a disaccharide in milk, is digested into galactose and glucose, which then enter the bloodstream. A baby with galactosaemia lacks the enzyme that metabolises galactose and dies if untreated because of the build-up of galactose in the blood. Prompt treatment with special milk that does not contain lactose completely prevents the development of this condition. (This is another example of an interaction between genotype and environment determining a person's phenotype.)
- *congenital hypothyroidism*. Hypothyroidism is a disorder caused by a small or improperly functioning thyroid gland, or even its complete absence, and occurs in about one in every 3500 babies. Untreated, a baby with hypothyroidism lacks the thyroid hormone and has impaired growth and brain development. Early treatment with a daily tablet of thyroid hormone means the baby develops normally, both physically and mentally.

How is genetic screening of babies carried out?

In the first few days after birth a baby's heel is pricked and a few drops of blood are placed on a card made of special absorbent paper, rather like blotting paper (see figure 16.36a and b). This sample is sent to a laboratory where tests for the genetic disorders identified above are carried out on the dried blood. In addition, testing for some other rare metabolic disorders may also occur.

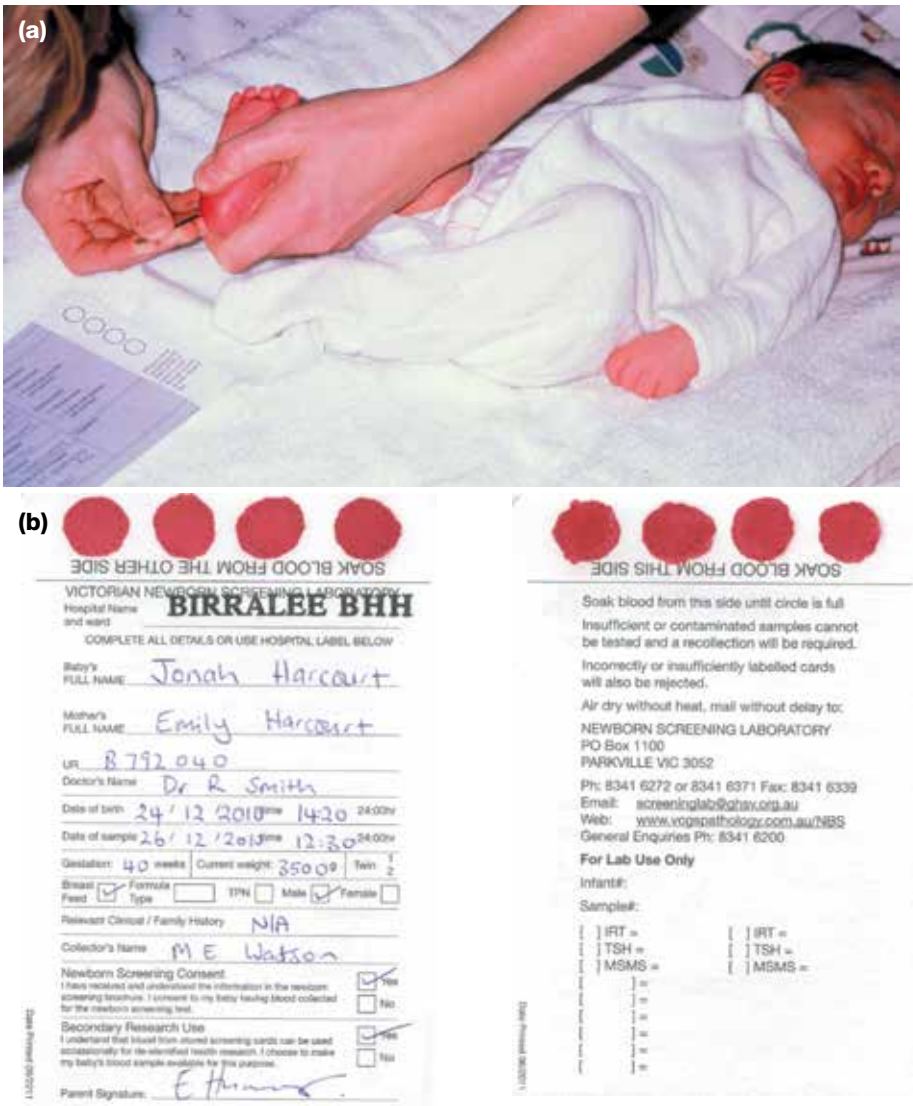


FIGURE 16.36 **(a)** Nurse taking a blood sample from the heel of a baby a few days after its birth. The blood sample is transferred onto a special card. **(b)** Newborn screening card with blood samples from a baby

In the case of screening for PKU, a technology known as mass spectrometry is used. This instrument can directly measure the level of phe and other amino acids in a baby's blood. Figure 16.37 shows the levels of phe in the blood of a normal baby who has the liver enzyme needed to metabolise phe compared with that of a baby who lacks the liver enzyme and has PKU. Note the difference between the levels of phe in the blood of the two babies.

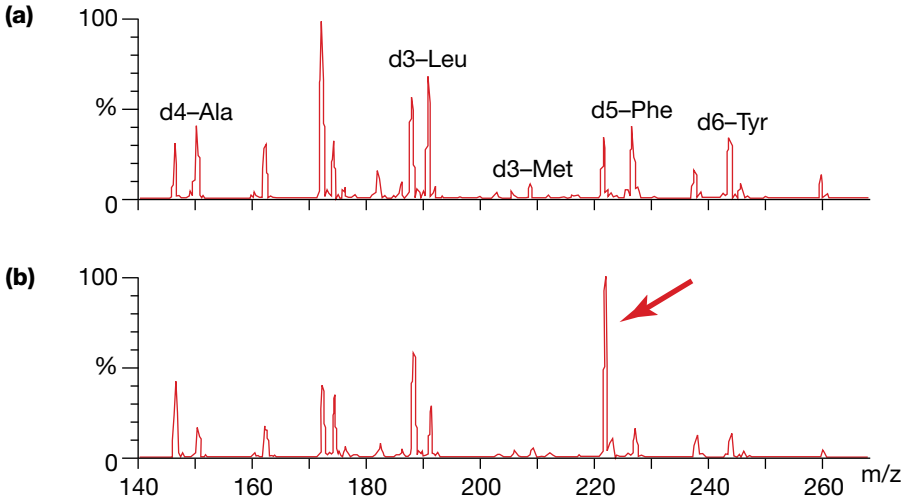


FIGURE 16.37 Mass spectrometry scans showing: **(a)** normal amounts of amino acids in baby's blood and **(b)** severely elevated phe in blood of an untreated baby with PKU (red arrow).

ODD FACT

Across Australia, more than 200 different genetic (DNA) tests are available through more than 40 laboratories.

Genetic testing

Genetic testing refers to the scientific testing of an individual's genotype. In general, the availability of genetic testing in Australia is affected by decisions about which tests are ethically acceptable and by a cost–benefit analysis of specific tests. A referral from a medical practitioner is typically needed for medical genetic testing and, if it proceeds, pre- and post-test counselling is required.

Genetic testing may be carried out for various reasons, for example, on people who are at high risk of inheriting a faulty gene, based on their family history of occurrence of an inherited disorder.

Such persons include:

- women from families with a history of breast or ovarian cancer. Development of these cancers is associated with two faulty genes, **BRCA1** and **BRCA2**. Genetic testing of such women can identify whether or not they have inherited one of these genes, which would place them at a much higher risk of developing breast and/or ovarian cancer. Knowing her genotype enables a woman to make an informed decision about any strategies to reduce her risk
- a person whose parent died from Huntington's disease (HD), a later onset inherited dominant phenotype that causes progressive dementia and involuntary movements. The onset of HD is in adulthood, with the first signs appearing only when the person reaches their mid- to late-thirties. Persons in their late teens or twenties who are at risk of HD may wish to have **pre-symptomatic genetic testing** to find out if they have inherited the ***HD*** allele from their affected parent. This testing is performed only after counselling is given. Counselling is also required following the testing.

Other reasons for genetic testing of an individual may include:

- to identify paternity in situations of disputed paternity
- to diagnose a suspected inherited condition in a person who shows certain symptoms
- to guide medical treatment of a person
- to identify the carrier (heterozygous) status of a person for an inherited condition
- for forensic purposes.

ODD FACT

Angelina Jolie is a high profile actor who, after discovering that she had inherited a **BRCA** gene from her mother, elected to have a double mastectomy and made her decision public.

Genetic testing offers the advantage of giving certainty in an otherwise uncertain situation and allaying fears when testing shows that a person has not inherited a particular genetic defect. However, the disadvantages of genetic testing are that, in spite of pre-test and post-test counselling, some persons may not be able to cope with finding out that they have inherited a faulty allele which has serious clinical consequences. Also a test result for one person may have implications for family members of that person. If a person is tested and finds that he has a faulty allele that will cause major problems in later life or place him at high risk of a particular disease, should this person advise other members of their family, such as siblings? What about a potential marriage partner?

KEY IDEAS

- Genetic screening refers to screening of a large population group for inherited disorders.
- Genetic testing refers to the testing of the genetic status of an individual.
- Screening is carried out on all newborn babies in Australia.
- Genetic testing of individual persons may occur for many different reasons.

QUICK CHECK

5 Identify whether each of the following statements is true or false.
- **a** In Australia, newborns are screened for all inherited disorders.
- **b** Genetic testing may be carried out for forensic purposes.
- **c** Some genetic tests are carried out only after pre- and post-test counselling.

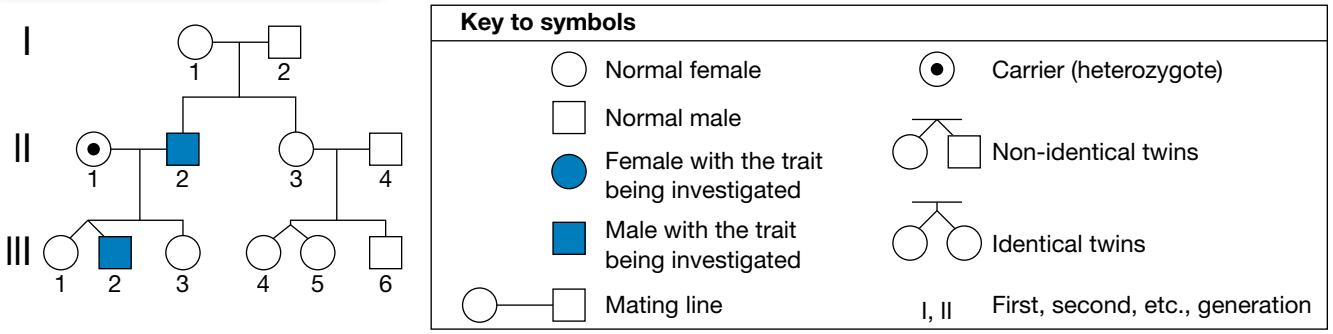
6 What are the two genes associated with a higher risk of breast and ovarian cancer?

Family pedigrees: patterns of inheritance

A family portrait is an important record of events in the life of a particular family. Photographs of groups of family members are commonly taken on occasions such as a wedding, a twenty-first birthday party or a graduation. A different kind of family picture can be made to show the inheritance of a particular trait. This kind of picture is called a **pedigree**. **In drawing a human pedigree, certain symbols are used** (see figure 16.38). To provide evidence in support of a given mode of inheritance, a pedigree should show:

1. an adequate number of persons, both affected and unaffected
2. persons of each sex
3. preferably three generations.

FIGURE 16.38 A pedigree and explanation of symbols used



The pattern of inheritance of a trait in a pedigree may provide information about the trait. The pattern may indicate whether:

- the trait concerned is dominant or recessive
- the controlling gene is located on an autosome or on a sex chromosome.

However, a single pedigree may not always provide conclusive evidence.

Autosomal dominant pattern

Figure 16.39 shows the pattern of appearance of familial hypercholesterolaemia in a family. This is an inherited condition in which affected individuals have abnormally high levels of cholesterol in their blood. Affected individuals are at risk of suffering a heart attack in early adulthood. The gene concerned is the **LDLR** gene located on the short arm of chromosome 19. Abnormally high blood cholesterol level (***B***) is dominant to normal levels (***b***). So, hypercholesterolaemia is expressed in a heterozygote.

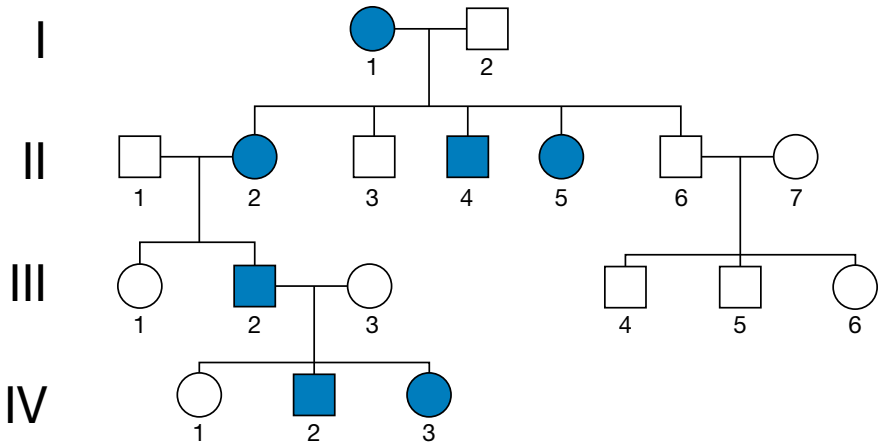


FIGURE 16.39 Pedigree for highly elevated blood cholesterol levels, an autosomal dominant trait. Does every affected person have at least one affected parent?

An idealised pattern of inheritance of an autosomal dominant trait includes the following features:

- Both males and females can be affected.
- **All affected individuals have at least one affected parent.**
- Transmission can be from fathers to daughters and sons, or from mothers to daughters and sons.
- Once the trait disappears from a branch of the pedigree it does not reappear.
- In a large sample, approximately equal numbers of each sex are affected.

Other autosomal dominant traits include:

- Huntington's disease, a degenerative brain disorder; controlled by the **HD** gene on the short arm of the number-4 chromosome
- achondroplasia, a form of dwarfism; controlled by the **ACH** gene on the short arm of the number-4 chromosome
- familial form of Alzheimer disease; controlled by the **AD1** gene on the long arm of the number-21 chromosome
- defective enamel of the teeth; controlled by the **DSPP** gene on the number-4 chromosome
- neurofibromatosis, the 'Elephant man' disease; controlled by the **NF1** gene on the number-17 chromosome
- familial breast cancer; controlled by the **BRCA1** gene on the number-17 chromosome
- lip pits and cleft palate; controlled by the **IRF6** gene on the number-1 chromosome.

Cleft palate can have several other causes, besides a genetic cause.

Autosomal recessive pattern

Figure 16.40 is a pedigree showing the pattern of inheritance of oculo-cutaneous albinism, a condition in which pigmentation is absent from skin, eyes and hair. Albinism (*a*) is an autosomal recessive trait.

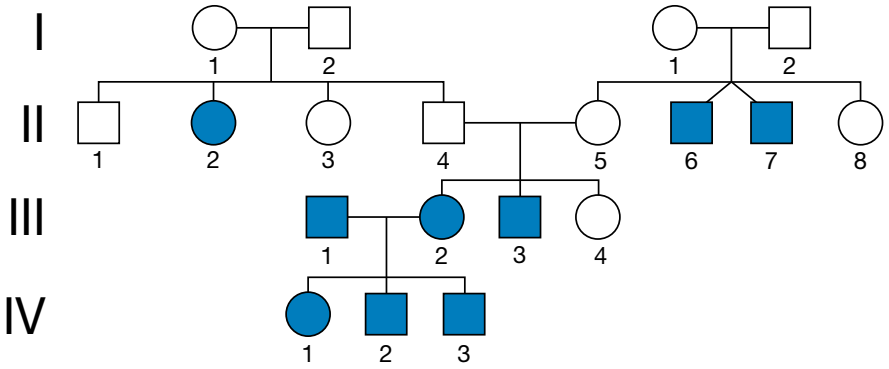


FIGURE 16.40 Pedigree for albinism, an autosomal recessive condition. Can a person show an albino phenotype even though neither parent has the condition?

An idealised pattern of inheritance of an autosomal recessive trait includes the following features:

- Both males and females can be affected.
- **Two unaffected parents can have an affected child.**
- All the children of two persons with the condition must also show the condition.
- The trait may disappear from a branch of the pedigree, but reappear in later generations; that is, it can 'skip a generation'.
- Over a large number of pedigrees there are approximately equal numbers of affected females and males.

Other autosomal recessive traits include:

- cystic fibrosis; controlled by the **CFTR** gene on the number-7 chromosome
- thalassaemia, a blood disorder; controlled by the **HBB** gene on the number-11 chromosome
- Tay-Sachs disease, a degenerative disease of the central nervous system that causes death in infancy and is common in Jewish people of middle-European ancestry; controlled by the **HEXA** gene on the number-15 chromosome
- Wilson disease, a disease in which copper metabolism is abnormal; controlled by the **WND** gene on the number-13 chromosome
- insulin-dependent diabetes mellitus-1; controlled by the **IDDM1** gene on the number-6 chromosome
- phenylketonuria; controlled by the **PKU** gene on the number-12 chromosome
- red hair colour and fair skin (see figure 16.41); controlled in part by the **MC1R** gene on the number-16 chromosome
- a form of osteogenesis imperfecta ('brittle bones'), a disorder affecting the collagen protein of bones; controlled by the **COL1A1** gene on the number-17 chromosome
- galactosaemia, a disease in which a person cannot metabolise the simple sugar (galactose) found in milk; controlled by the **GALT** gene on the number-9 chromosome.

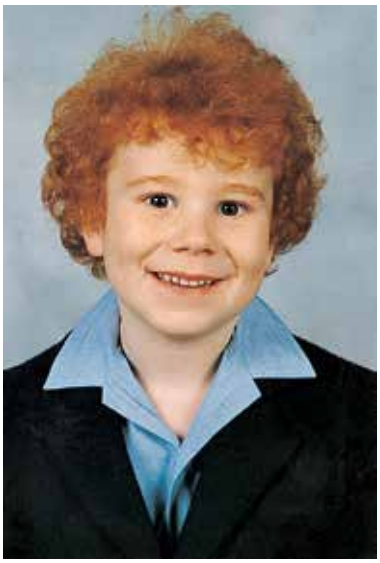


FIGURE 16.41 Simon's red hair is an example of an autosomal recessive trait. Must his parents also have red hair?

X-linked dominant pattern

Figure 16.42 shows a pedigree for one form of vitamin D–resistant rickets in a family. This form of rickets is an X-linked dominant trait, controlled by the **XLHR9** gene located on the X chromosome and is expressed even if a person has just one copy of the allele responsible.

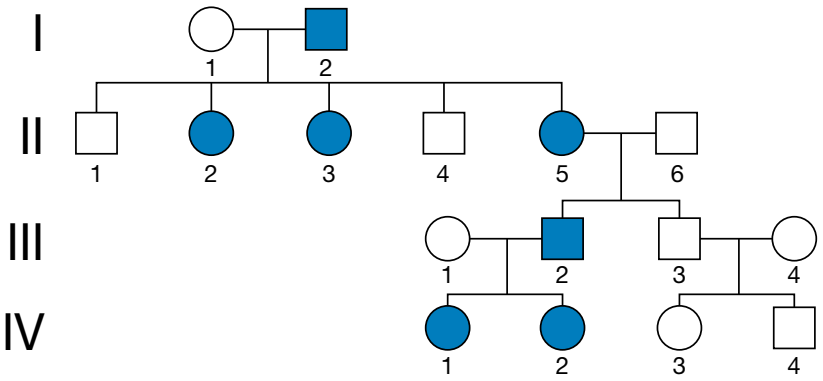


FIGURE 16.42 Pedigree for vitamin D–resistant rickets, an X-linked dominant condition. Look at the daughters and sons of affected males. What pattern is apparent? Could daughters of person III-3 show the trait?

ODD FACT

Rett syndrome occurs almost exclusively in females, because affected males typically die before birth, apart from a few who survive to term but die not long after birth. This suggests that the presence of one normal allele can compensate in part for the defective allele.

An idealised pattern of inheritance of an X-linked dominant trait includes the following features:

- **A male with the trait passes it on to all his daughters and none of his sons.**
- A female with the trait may pass it on to both her daughters and her sons.
- Every affected person has at least one parent with the trait.
- If the trait disappears from a branch of the pedigree, it does not reappear.
- Over a large number of pedigrees, there are more affected females than males.

Other X-linked dominant traits include:

- incontinentia pigmenti, a rare disorder that results in the death of affected males before birth; controlled by the **IP2** gene on the X chromosome
- Rett syndrome, a neurological disorder; controlled by the **MECP2** gene on the X chromosome.

X-linked recessive pattern

Figure 16.43 shows the pattern of appearance of favism in a family. Favism is a disorder in which the red blood cells are rapidly destroyed if the person with this condition comes into contact with certain agents. These agents include substances in broad beans and mothballs.

Favism results from a missing enzyme and is controlled by the **G6PD** gene on the long arm of the X chromosome (Xq28). Favism (***f***), which occurs when the G6PD enzyme is absent from red blood cells, is recessive to the unaffected condition (***F***), which occurs when the enzyme is present. The condition of favism is inherited as an X-linked recessive and is expressed only in females with the homozygous (***ff***) genotype or in males with the hemizygous (***f***)(Y) genotype.

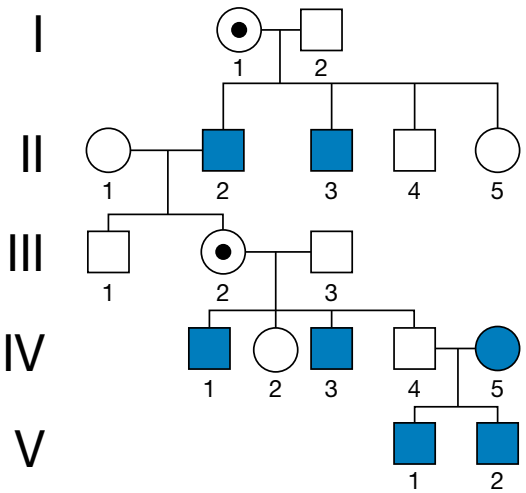


FIGURE 16.43 Pedigree for favism — an X-linked recessive disorder. Can this disorder 'skip a generation'?

An idealised pattern of inheritance of an X-linked recessive trait includes the following features:

- **All the sons of a female with the trait are affected.**
- All the daughters of a male with the trait are carriers of the trait and do not show the trait; the trait can appear in their sons.
- None of the sons of an affected male can inherit the condition from their father.
- All children of two individuals with the trait will show the trait.
- In a large sample, more males than females show the trait.

Other X-linked recessive traits include:

- ichthyosis, an inherited skin disorder; controlled by the **STS** gene on the X chromosome
- one form of red–green colourblindness; controlled by the **CBD** gene on the X chromosome
- one form of severe combined immunodeficiency disease; controlled by the **SCIDX** gene on the X chromosome
- haemophilia, an inherited blood-clotting disorder; controlled by the **F8C** gene on the X chromosome

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Autosomal recessive disorders
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Interactivity
Pedigree for X-linked dominant trait
int-0199

- one form of mental retardation, known as fragile X syndrome; controlled by the **FMR1** gene on the X chromosome
- Duchenne muscular dystrophy; controlled by the **DMD** gene on the X chromosome.

Y-linked pattern

Y-linked genes are inherited in a pattern that differs from that seen in autosomal and X-linked genes. All Y-linked genes show a pattern of **paternal inheritance** in which the DNA of Y-linked genes is transmitted exclusively from males to their sons only. The **AMELY** gene that controls the organisation of enamel during tooth development is located on the Y chromosome, and so is Y-linked. Figure 16.44 shows the pedigree for inheritance of this defective tooth enamel trait. Other traits that are Y-linked include the **SRY** gene that encodes a testis-determining factor and some other genes that affect sperm formation.

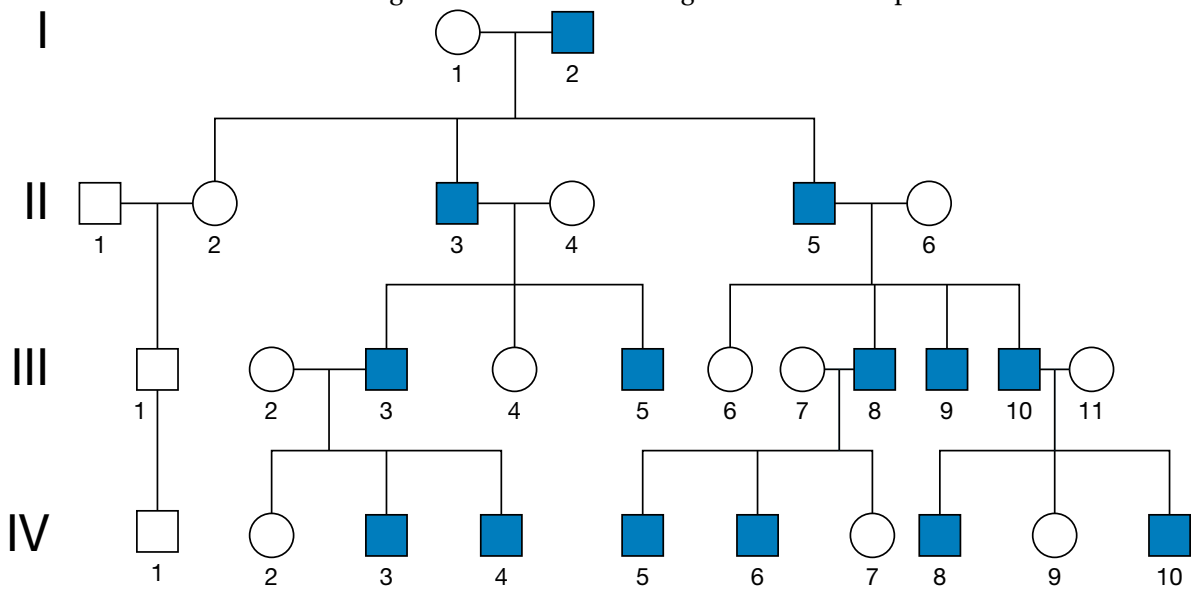

FIGURE 16.44 Pedigree for Y-linked inheritance of defective tooth enamel trait

An idealised pattern of inheritance of a Y-linked trait includes the following distinctive features:

- Only males can show the trait.
- An affected male with the trait will pass the allele to all his sons, who, in turn, will pass it to all their sons, and so on across generations.
- An affected male cannot pass the trait to his daughters.
- No affected females can appear in the pedigree.
- The trait cannot skip a generation and then re-appear.

mtDNA: maternal pattern of inheritance

Most of the DNA present in diploid human cells is present in the nuclei of these cells. The nuclear DNA contains more than 3 thousand million base pairs and, during cell division, this DNA is organised into chromosomes. In all, this DNA carries about 21 000 genes. A tiny package of DNA, termed **mtDNA**, is present in the mitochondria of the cell cytosol, and this mtDNA contains just 16 569 base pairs that carry 37 genes.

Inherited disorders due to mitochondrial genes include:

- Leber optic atrophy (LHON), which causes loss of central vision, with onset in young adults
- Kearns–Sayre syndrome, which is expressed as short stature and degeneration of the retina and oncocytoma, which is expressed as benign tumours of the kidney
- MERRF syndrome, which involves deficiencies in the enzymes concerned with energy transfers.

The transmission of mtDNA, along with the genes it carries, follows a distinctive pattern as shown in figure 16.45. Traits on mtDNA show a pattern of exclusive **maternal inheritance** with mitochondrial genes being transmitted from a mother via her egg to all her offspring, however, only her daughters can pass this trait on.

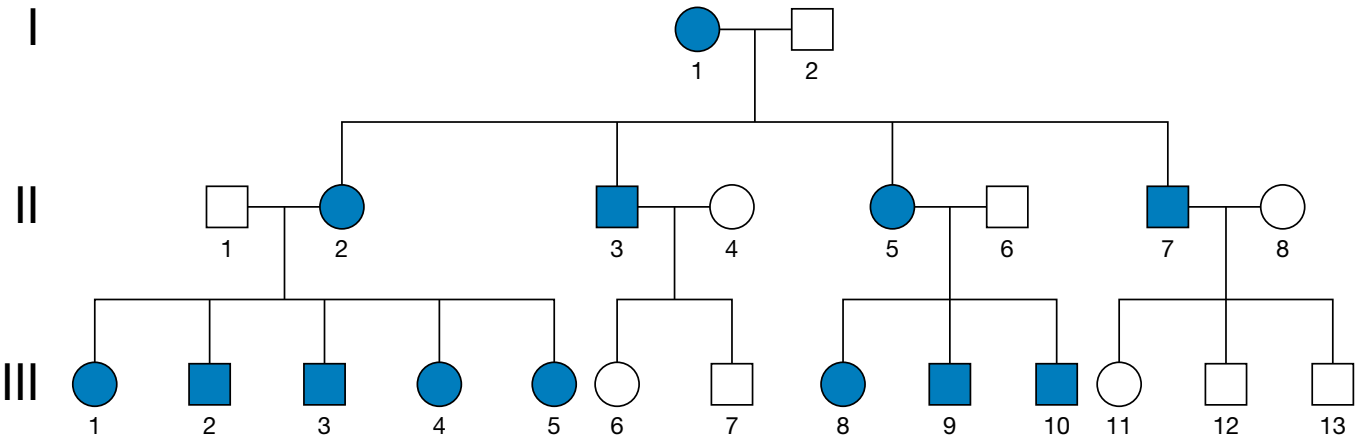

FIGURE 16.45 mtDNA pattern

An idealised pattern of inheritance of traits controlled by genes on the mtDNA includes the following features:

- Each mtDNA-controlled trait passes from a mother to all offspring, both female and male.
- While males can receive the trait from their mothers, they cannot pass it on to their children.
- Only females can transmit mtDNA traits to their children.

KEY IDEAS

- A pedigree uses symbols to show the appearance of an inherited trait across generations.
- Features of the pattern of inheritance may allow conclusions to be drawn regarding its mode of inheritance.
- Common modes of inheritance are autosomal dominant, autosomal recessive, X-linked dominant and X-linked recessive.
- Y-linked genes show a pattern of paternal inheritance.
- Mitochondrial genes show a pattern of maternal inheritance.

QUICK CHECK

7 The pattern of inheritance of a disorder in a large family shows that all persons with a particular inherited trait have at least one parent with that disorder. Suggest a likely mode of inheritance of this disorder.

8 What is the difference between paternal inheritance and maternal inheritance?

9 Identify whether each of the following statements is true or false.

a An X-linked dominant trait can be passed from a father to his daughter.

b A recessive trait can skip a generation.

c A dominant trait can never be lost from a pedigree.

d To draw reasonable conclusions about a possible mode of inheritance of a trait, a pedigree must contain adequate numbers of affected persons of both sexes and across more than one generation.

TH MORGAN AND THE FLIES

It is April 1910. Thomas Hunt Morgan (1866–1945) is in his small laboratory at Columbia University and picks up a glass bottle that contains a large number of fruit flies (*Drosophila melanogaster*). He uses these small flies, that are less than 3 mm long, for his genetic experiments because:

1. they breed easily and rapidly in captivity
2. they require little space and can be maintained in small glass containers
3. they produce large numbers of offspring, for example, a female lays up to 200 eggs just 2 weeks after mating
4. the two sexes can be readily distinguished.

In addition, *Drosophila* have a small number of chromosomes ($2n = 8$) so that their chromosomes can be readily examined and identified using a microscope and, like mammals, *Drosophila* have an XX/XY sex-determining mechanism.

Morgan suddenly becomes excited when he sees the unexpected. Among the many flies with their normal red eye colour, he notices an oddity — a male fly with white eyes.

In order to clarify the inheritance of this character, Morgan crosses this white-eyed male with a pure-breeding red-eyed female fly. As expected, Morgan finds that all the F1 flies are red-eyed and so he concludes that red eye colour is dominant to white. (So far, Mendel would not have been surprised.)

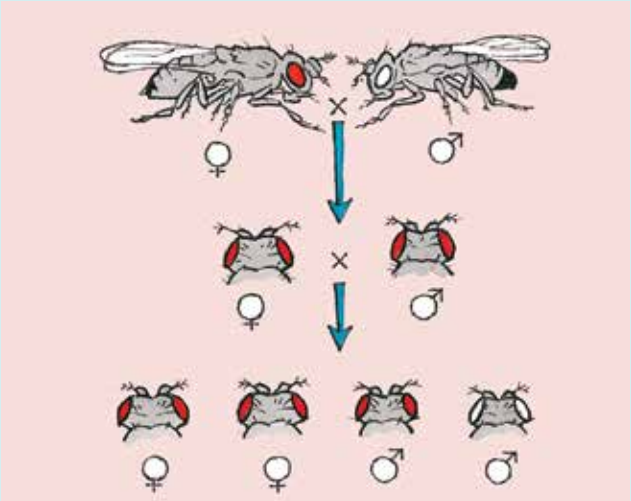

FIGURE 16.46 Results of Morgan's cross starting with a red-eyed female and a white-eyed male in the P generation. What was unusual about the F2 generation?

Morgan then crosses the red-eyed F1 flies to produce an F2 generation. In terms of eye colour, the F2 flies are of two kinds, red and white, and there is an average of about three red-eyed to one white-eyed. The red-eyed flies include both males and females as expected (still no surprise for Mendel). However, when Morgan looks more closely, he finds that all the white-eyed flies are males — not one white-eyed female is present. (This would have surprised Mendel.) Morgan's results are summarised in figure 16.46.

Morgan then carries out the reciprocal cross by mating pure-breeding white-eyed females with true-breeding red-eyed males (see figure 16.47). The result in the F1 generation is different from that obtained in his first cross. The F1 generation is quite unexpected; it consists of red-eyed females and white-eyed males in about equal numbers. Morgan then allows these flies to mate to produce the F2 generation. This generation consists of red-eyed flies, both male and female, and white-eyed flies, both male and female. How could these unexpected results be explained?

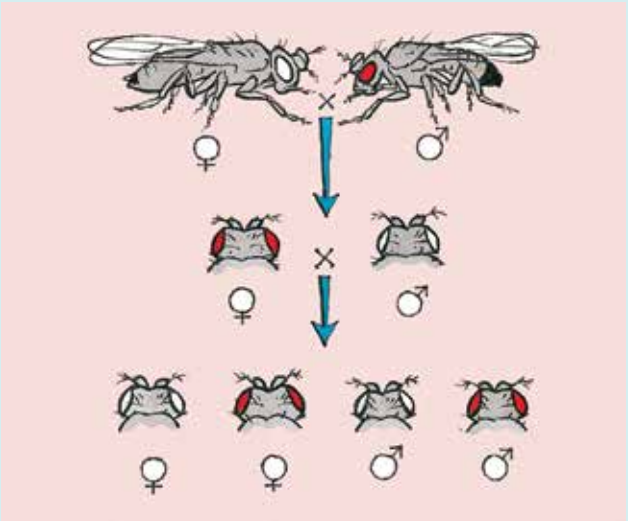

FIGURE 16.47 Result of Morgan's reciprocal cross starting with a white-eyed female and a red-eyed male. What is unusual about the F1 generation?

Like Mendel about 45 years earlier, Morgan thought about his experimental results and developed an explanation to account for these results. Morgan concluded that the gene producing the white-eyed phenotype was located on the X chromosome of *Drosophila*. By reaching this conclusion, Morgan became the first person to provide experimental evidence linking one particular gene to one particular chromosome.

This gene controls eye colour and has the alleles ***W***: red and ***w***: white and is located on the X chromosome. This gene is said to be sex-linked or more accurately X-linked. A female fly has two X chromosomes and so has two alleles of this gene and can have three different genotypes. A male fly has just one X chromosome and so has only one allele (see table 16.3).

TABLE 16.3 Genotypes and phenotypes for the X-linked gene in *Drosophila* controlling eye colour. Note that the gene is not present on the Y chromosome. In the table the symbol (Y) denotes the Y chromosome.

Sex of fly	Sex chromosomes	Genotype	Phenotype
female	XX	***WW***	red-eyed
		Ww	red-eyed
		ww	white-eye
male	XY	***W*** (Y)	red-eyed
		w (Y)	white-eyed

We can re-examine Morgan's results and show them in terms of the alleles of this X-linked gene (see figure 16.48).

Morgan later found other *Drosophila* varieties that showed the same sex-linked pattern of inheritance. He found that yellow body colour and reduced wings were also located on the X chromosome.

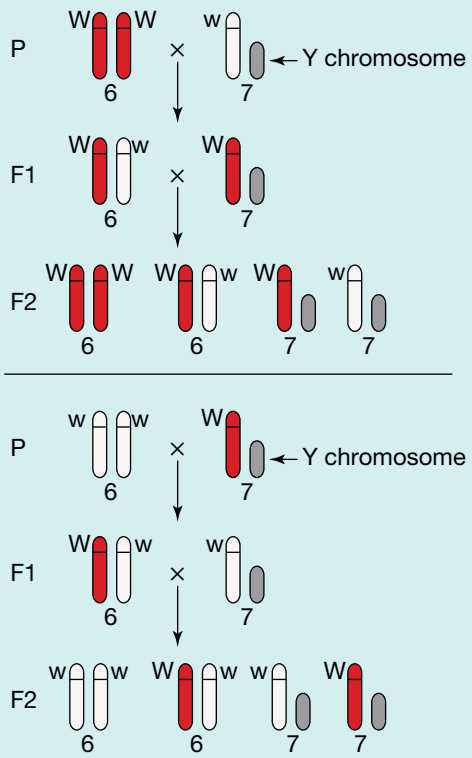

FIGURE 16.48 The pattern of inheritance for the X-linked eye colour gene in *Drosophila*. **(a)** The cross of a red-eyed female and a white-eyed male. **(b)** The reciprocal cross of a white-eyed female and a red-eyed male.

BIOCHALLENGE

Mendelian genetics in forensics

On each human autosome are regions of DNA that consist of repeats of short base sequences, often just two to four bases. These regions are known as **short tandem repeats (STRs)**. The number of sequence repeats at each location can vary in different people. At one STR locus, one person may have 10 repeats of a short base sequence on one of their chromosomes and 8 repeats on the homologous chromosome. Another person may have 12 and 17 repeats on the corresponding chromosomes, and yet another person may have 13 repeats on both chromosomes. The repeats of one STR are like alleles of one gene that separate into different gametes. The STRs on different chromosomes behave like alleles of different unlinked genes that separate independently into different gametes. However, the DNA present at each STR does not produce a visible phenotype.

Usually alleles of one gene are denoted by letters, such as ***A*** and ***a,*** and a person's genotype is shown as ***AA*** or ***Aa*** or ***aa***. The alleles of a different gene are shown by a different letter, such as ***B*** and ***b***. However, the DNA at each STR at each locus are denoted by numerals (separated by commas) that indicate the number of repeats on each chromosome. So, at one STR locus, a person's genotype might be shown as 8,10 and this person will produce gametes with either 8 repeats or 10 repeats of the sequence at that locus. At a different STR locus, the same person's genotype might be 12,17 and at a third STR locus, the person's genotype might be 13,13. Note that a person can be homozygous or heterozygous at each of the STR loci.

The expected result of the cross of two persons with the SRT repeats 15,17 and 13,19 is shown in the Punnett square in figure 16.49.

Gametes	*15*	*17*
13	*13, 15*	*13, 17*
19	*15, 19*	*17, 19*

FIGURE 16.49

Table 16.4 shows some genotypes for two adults and three children at five STR loci.

TABLE 16.4

Locus	Adult female	Adult male	Child#1	Child #2	Child #3
STR1	15,16	15,16	15,16	15,16	15,16
STR2	8,8	7,10	8,10	7,8	8,10
STR3	3,5	7,7	5,7	5,7	3,7
STR4	12,13	12,12	12,13	12,13	12,13
STR5	32,36	11,32	11,32	11,36	32,36

1 Refer to the data given in table 16.4 to answer the following questions.
   - a At the STR1 locus, what gametes could the adult female produce?
   - b At the STR2 locus, what gametes could the adult female produce?
   - c At which STR locus would the cross of the two adults be shown as 3,5 x 7,7.

2 For each of the five STR loci in table 16.4, draw a Punnett square to show the expected result of a cross between the two adults.
   - a For SRT1 locus, could each of the three children be the result of a cross between the two adults?
   - b For the SRT2 locus, could the three children be the result of a cross between the two adults?
   - c At the third, fourth and fifth SRT loci, can any one of the children be excluded as being a child of the two adults?

3 The DNA samples used to produce these STR genotypes came from the bones of skeletons that were unearthed in shallow graves near Ekaterinberg in Russia. Other lines of evidence suggested that the skeletons were those of Tsar Nicolas, his wife (the Tsarina) and three of their children (see figure 16.50). Does the DNA evidence of the short tandem repeats provide further supporting evidence?

FIGURE 16.50 Members of the Russian royal family murdered in 1917 in Ekaterinberg

Chapter review

studyon
Unit 2
AOS 2
Topic 4
Pedigree charts, genetic cross outcomes and genetic decision making
Sit topic test

Key words

albinism
antigen
chance (probability)
crossing over
cystic fibrosis (CF)
dihybrid cross
dominance
dominant phenotype
genetic screening
genetic testing
Ishihara colour plates
linkage group
linked genes
locus
maternal inheritance
melanin
melanocytes
monohybrid cross
mtDNA
parental (noncrossover) egg
paternal inheritance
pedigree
pre-symptomatic genetic testing
Punnett square
pure breeding
recombinant (crossover) egg
short tandem repeats (STRs)
test cross
tyrosinase
X-linked gene
Y-linked gene

Questions

1 **Making connections between concepts** ➜ Use at least eight of the chapter key words to draw a concept map relating to Mendelian inheritance. You may use any other words in drawing your map.

2 **Applying understanding in a new context** ➜
- **a** In cats, one autosomal gene controls fur length, with short fur (S) being dominant to long fur (s). A second autosomal gene unlinked to the first controls the density of colour and has the alleles black (***D***) and grey (***d***). Is either of these genes located on one of the sex chromosomes?
- **b** A grey male cat with long fur (cat 1) is crossed with a black female cat with short fur (cat 2).
  - i Write the genotype of cat 1 and draw a simple chromosomal picture showing this genotype.
  - ii How many kinds of gametes can cat 1 produce?
  - iii What is the phenotype of cat 2?
  - iv List all possible genotypes for cat 2.
  - v If cat 2 produced many kittens and, regardless of the phenotype of the other parent, the kittens were always black and short furred, what does this suggest about the genotype of cat 2?

3 **Developing and evaluating hypotheses** ➜ In a certain breed of dog, the coat colouring is either black or brown (also known as liver). A number of observations were made about this breed as follows:
- Brown by brown matings always produced brown pups.
- Black by black matings sometimes produced all black pups, but in other similar matings produced both black and brown pups.

Suggest a possible genetic basis for this colouring in dogs.

4 Draw a Punnett square to show the possible genotypes and phenotypes from the following crosses.
- **a** Bay mare (***Bb***) × chestnut stallion (***bb***)
- **b** Bay mare (***Bb***) × bay stallion (***Bb***)

5 **Recognising patterns** ➜ Examine the pedigrees in figure 16.51 and suggest the most likely pattern(s) of inheritance for each trait. Explain your choice(s).

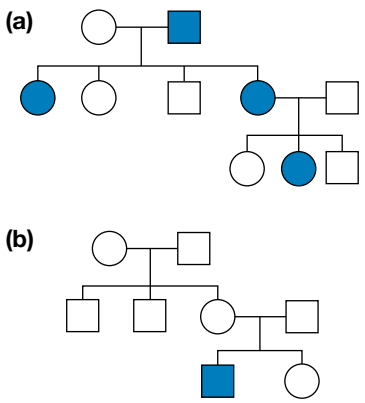

FIGURE 16.51

6 **Applying principles** ➜ Make simple drawings to show the relevant chromosome pair(s) and appropriate alleles for the following persons (refer to table 13.6, p. 514 for allele symbols).
- **a** A man with normal colour vision
- **b** A woman with normal colour vision, but who is a carrier of colour vision defect
- **c** A person with AB blood type and Rhesus negative

7 Making predictions ➜ For persons (a) and (b) in question 6:

- **a** Identify the types of gametes that they would be expected to produce.
- **b** What different kinds of children in terms of colour vision capability could they produce?
- **c** Could this couple produce a colourblind daughter? Explain.

8 Demonstrating your understanding ➜ Two genes located close together on chromosome 9 are the **ABO** gene, with the alleles I^A, I^B and i, and the **NPS** gene, with the alleles N (deformed nails) and n (normal nails). Fred is blood type O and is homozygous for normal nails. Gina is blood type AB and is heterozygous for deformed nails.

- **a** What is Fred's genotype?
- **b** What kind(s) of sperm can Fred produce?
- **c** Can crossing over affect the kinds of sperm that Fred produces? Explain.
- **d** What is Gina's genotype?
- **e** Draw Gina's pair of number-9 chromosomes showing one possible arrangement of the alleles of the two genes.
- **f** What kinds of parental (noncrossover) eggs can Gina produce?
- **g** What kinds of recombinant (crossover) eggs can Gina produce?

9 Applying principles ➜ Consider the typical features in the pedigree for inheritance of an X-linked dominant trait. Explain how this pattern would change if all affected males died in infancy.

10 Interpreting data ➜ A test cross between a heterozygous curly, green-leafed plant — genotype ***Kk Gg*** — and a recessive straight, red-leafed plant — genotype ***kk gg*** — produced the following results:

- curly, green: 42 straight, red: 38
- curly, red: 5 straight, red: 5.

- **a** Do the results support the conclusion that the genes for leaf shape and leaf colour are linked? Explain.
- **b** What result would be expected if the two genes were not linked but assorted independently?

11 Human pedigree ➜

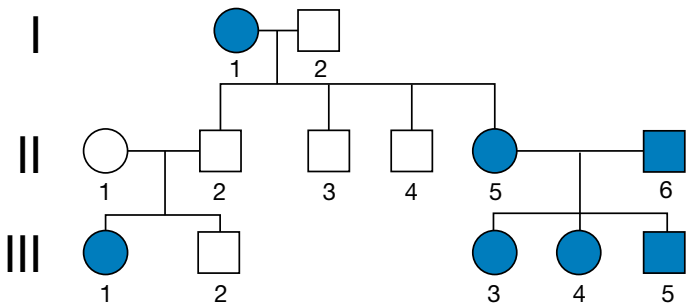

FIGURE 16.52

- **a** What mode of inheritance is shown for the trait in the pedigree in figure 16.52?
- **b** What evidence supports your decision in part (a)?
- **c** If a fourth child of II-5 and II-6 was also affected, would it change your conclusion in part (a)?
- **d** If individual II-2 was affected, would this pedigree fit an autosomal dominant mode of inheritance?

12 Applying knowledge and understanding in a new context ➜ Gavin is blood group A and Sally is blood group B.

- **a** Write the possible genotypes for Gavin.
- **b** Write the possible genotypes for Sally.
- **c** Their daughter is blood group O. Does this fact enable you to identify definitely Gavin and Sally's genotypes? Explain.
- **d** Gavin and Sally's newborn son is about to be tested for blood type. What blood type might this baby be? Justify your answer making use of a Punnett square.

13 Applying principles ➜ Figure 16.1 shows an albino wallaby (*Macropus rufogriseus*) with her normal pigmented joey.

- **a** Identify a particular cross involving this female parent that could produce this offspring. Your answer should include the identification of a gene, its alleles and the two parental genotypes involved.
- **b** What other types of offspring, if any, could result from the cross that you have identified in part (a)?
- **c** This particular female wallaby later produced an albino joey. Student P stated: 'The male parent must also have been an albino wallaby.' Student Q said: 'Not necessarily.' Which student do you think is correct? Briefly explain.

CHAPTER

17 Scientific investigations

KEY KNOWLEDGE

This chapter is designed to enable students to:

- understand scientific research methodology and the typical steps in a scientific approach
- design and conduct an experimental or an observational investigation that follows scientific process
- recognise that investigations must adhere to relevant safety, health and bioethical guidelines
- distinguish between quantitative and qualitative data sets and to assess their validity, accuracy, precision and limitations
- become familiar with the various means of representing data
- recognise the nature of scientific evidence and its distinction from opinions and anecdotes
- understand that conclusions from a data evaluation may either support or disprove a hypothesis, model or theory
- recognise characteristics of effective communication of scientific ideas.

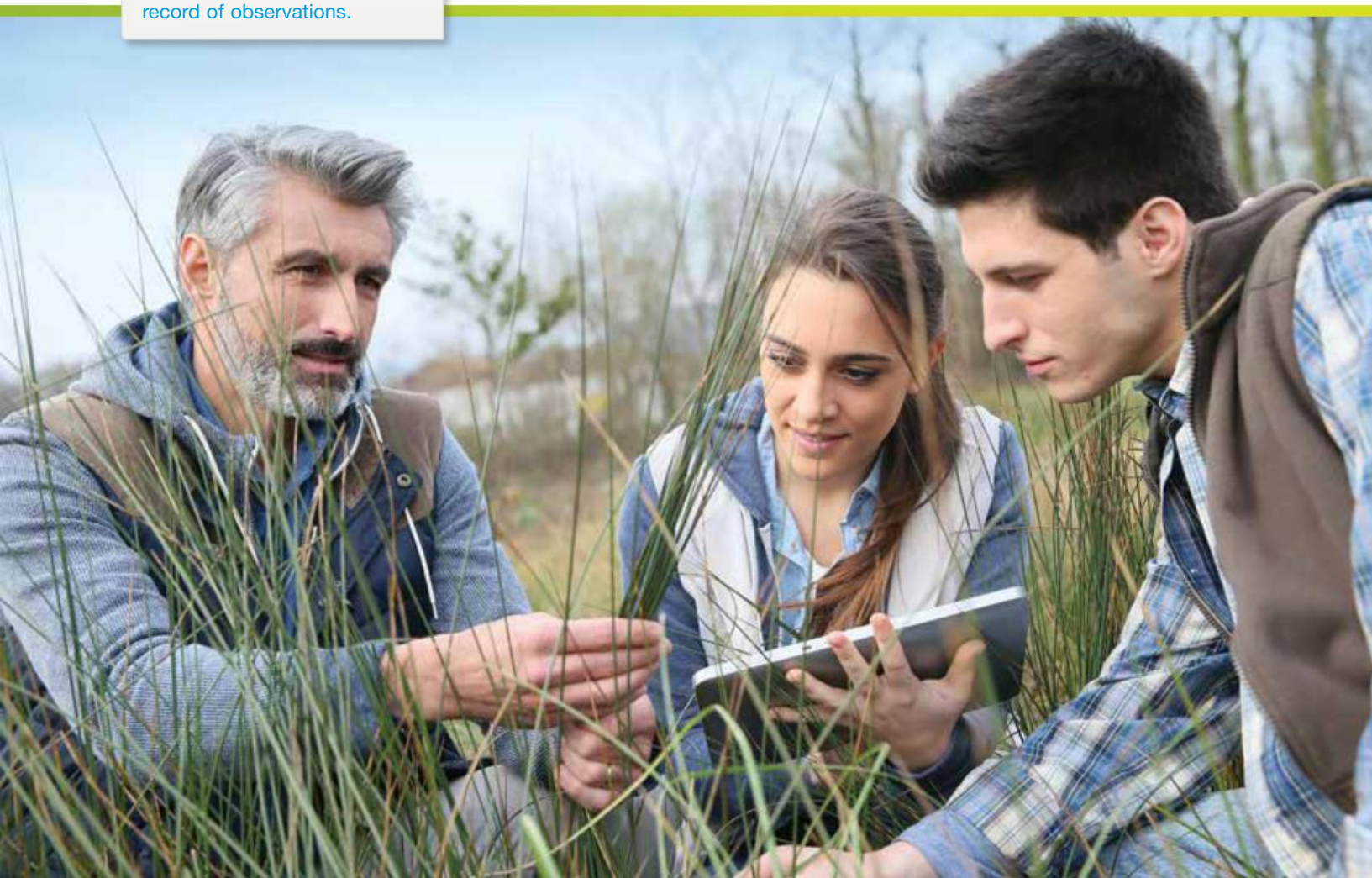

FIGURE 17.1 Scientific investigations may be carried out in a laboratory or in the field. Here we see students performing a field-based investigation under the guidance of a teacher. Note that one student is using an electronic notebook to keep a record of observations.

Knowledge from investigations

During your studies in biology, you will develop knowledge and an understanding of many concepts in new areas of study including cell structure and function, homeostatic mechanisms that enable survival, relationships in ecosystems, Mendelian genetics, and human reproduction and development. In addition to building knowledge and understanding in these specific areas of study, you will also develop an understanding of:

1. the scientific processes by which valid explanations for biological phenomena are formed and evaluated
2. the avenues of communicating biological knowledge to others.

In the following sections, we will explore the processes by which explanations in biology are developed.

Advancing knowledge in biology

How is our understanding of aspects of biology achieved? How do refinements of existing theory come about? Advances in biological knowledge typically begin with observations that raise questions for investigation, through avenues such as:

- **Carefully planned laboratory-based or field-based experiments designed to support or refute a particular hypothesis.** For example, the laboratory-based experiments of Oswald Avery during the 1940s identified the genetic material as being DNA (refer to figure 13.34 in the text) and refuted the proposal that the genetic material was protein.
- **Critical reinterpretation of previously accepted facts, producing a new framework.** For example, reptiles, such as snakes and lizards, are commonly believed to be thermo-conformers; that is, their body temperatures vary passively with the temperature of their external environments. However, studies have shown that several species of lizard are able to control their body temperatures regardless of changes in the temperature of the external environment. These lizards are thermo-regulators. Interestingly, they only regulate their core temperature when the cost of producing the necessary metabolic heat is not too high. If the cost is too high, these lizards simply let their body temperatures fall. Strictly, such reptiles are termed facultative thermo-regulators. These findings mean that the issue of temperature control in snakes and lizards is now known to be more complex than previously believed and is being reinterpreted.
- **Collection and analysis of new data.**
  - Example 1: Gregor Mendel's experimental crosses with sweet peas demonstrated that his factors (genes) were discrete particles that retained their identity across generations. This finding replaced the older concept that the factors involved in inheritance were non-particulate and lost their identity over generations through a blending process (refer to figure 13.31 in the text).
  - Example 2: The results of experiments carried out by T. H. Morgan led to the replacement of the view that Mendel's factors (genes) were free-floating particles that were always inherited independently. By analysing the offspring of crosses of specific fruit flies, Morgan and his team provided the first experimental evidence that genes were not free-floating particles but were physically located on chromosomes (refer to figure 14.26 in the text).
- **Identification and exploration of patterns or anomalies.** For example, the careful and independent observations of the German pediatrician Widukind Lenz (1919–1995) and the Australian gynecologist William McBride (1927–) identified the causal relationship between ingestion of the drug thalidomide by women during the first trimester of their pregnancies

ODD FACT

Thalidomide was withdrawn in late 1961. In 2008, thalidomide was approved for use, under rigorously controlled conditions, in the treatment of multiple myeloma and complications of leprosy.

and the occurrence of severe birth defects in their babies, including unusual limb malformations — a condition now termed thalidomide embryopathy (see figure 17.2 in this chapter and also refer to figure 12.7 in the text). Thalidomide came into clinical use, firstly in Germany in 1957, as an extremely safe tranquiliser, as a painkiller, and as an effective treatment for morning sickness in pregnant women. Thalidomide was quickly adopted for use in other countries, including the United Kingdom and Australia. The safety of thalidomide was based on the fact that overdoses caused extended sleep but did not cause death, which could occur with overdoses of other tranquillisers.

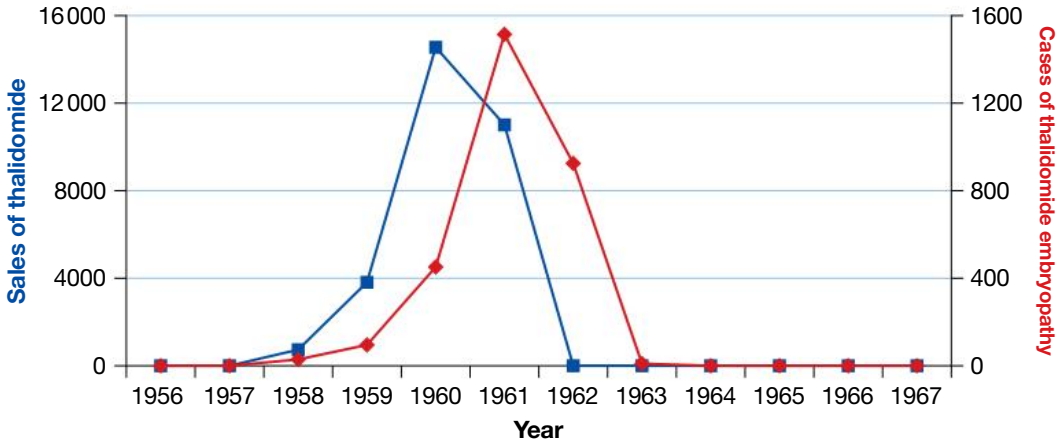

FIGURE 17.2 Line graphs showing data on the sales of thalidomide in Germany (blue dotted line) and the appearance of newborns with strange congenital malformations of the limb (red solid line), a condition that is now termed thalidomide embryopathy. Note that the pattern of appearance of malformed newborns follows the pattern of sales of thalidomide, but with a time lag of about nine months. The vertical axes denote sales of thalidomide (at left) and number of cases of malformed newborns (at right). (Data based on Lenz (1984))

FIGURE 17.3 Photo showing Sir Alexander Fleming in his laboratory. Note the stacks of Petri dishes in the corner of his workbench.

You should note that not all advances in biological knowledge are initiated from the results of carefully planned experiments. Some major advances in biology are initiated by unplanned chance events, such as a discovery in 1928 by Sir Alexander Fleming (1881–1955). Fleming was studying *Staphylococcus* bacteria that he was growing on nutrient agar in petri dishes. Some of his plates became contaminated by the growth of airborne mould spores. Instead of discarding these plates as contaminated and useless, Fleming recognised that the clear areas around the growing mould were a signal that the mould was producing a substance that inhibited bacterial growth — indeed it was, and this substance turned out to be the antibiotic penicillin.

Investigations in biology

Carefully planned investigations are one process by which biological knowledge is advanced. These investigations may be either:

- experimental studies that are carried out
  - in a laboratory
  - in the field
- observational studies.

Both experimental and observational studies generate data that can be analysed, from which conclusions can be drawn. What is the difference between experimental and observational studies?

In an experiment, an investigator deliberately exposes a group of subjects or objects of interest to a defined treatment, with the aim of observing the group's responses to that treatment. For example, biologists might investigate the effect of various dosages of a new drug on a species of pathogenic bacteria. To do this, cultures of the particular bacteria would be grown in the presence of different dosages of the drug (the treatment), and the effect on bacterial growth (the response) at each level of the drug would be observed and recorded.

FIGURE 17.4 Biologists observing and recording the growth of a bacterial culture in the presence of particular levels of a new antibiotic drug.

Figure 17.5 shows another experimental study in which a biologist is investigating the growth of a plant species under different environmental conditions.

In an observational study, an investigator collects data about the object of study but does not change the existing conditions. For example, a scientist might gather samples of water on a regular basis over several months from a river near an industrial site. These samples would be taken to the laboratory for analysis, to determine the concentrations of heavy metals in the river water over time (see figure 17.6). Refer to figure 3.30 in the text to see an example of scientists carrying out an observational study of the microbial life forms in the Movile Cave.

Other examples of observational studies are investigations carried out by biologists who gather data on the diversity and/or the abundance of species in a particular habitat. These studies often make use of quadrats at random locations along a transect line. Transects and quadrats are two ecological tools that enable biologists to quantify the relative abundance of one species or the biodiversity in an area such as a rainforest or a rocky shoreline or a sand dune.

FIGURE 17.5 A biologist examining the effect of a particular experimental treatment on the growth of seedlings.

FIGURE 17.6 An investigator collecting a sample of river water as part of an observational study of water quality at that site in the river. Why is this an observational study? Analysis of water samples collected on a regular basis over a period of time provides data on water quality at this point: for example, dissolved oxygen levels, concentrations of heavy metals or density of aquatic larvae.

Studies of changes in species abundance and biodiversity are important in tracking changes over time. Figure 17.7 shows an ecologist identifying and recording each species within a quadrat as part of an observational study of the recovery of a rainforest in northern Queensland after damage by a cyclone. Do you expect that this study would be repeated over intervals of time? In this case, the ecologist is recording her data in a notebook. As well as note-taking, other means of recording data include drawings, photographs and/or photographs. Refer to figure 8.63 in the text to see an example of students recording the abundance of an oyster species by sampling quadrats at several locations along a rocky shoreline.

FIGURE 17.7 An ecologist identifying and recording young plant species located within one quadrat as part of an observational study of the recovery of an area of rainforest in far north Queensland. Note the transect line on which the quadrat is located. The ecologist will use the quadrat to sample at several random locations along this transect line. Why sample at multiple sites rather than just one?

In the following section, you will be introduced to an observational study that ultimately led to major reforms in public health, including water supply and sewage.

The 1854 cholera epidemic

Cholera is an acute diarrhoeal disease caused by the *Vibrio cholerae* bacteria, which spread in water or food contaminated with the faeces of affected individuals. If left untreated, cholera can rapidly cause death, even within hours of infection. Severely affected individuals require rapid administration of intravenous fluids, up to six litres per day, and antibiotic treatment. Refer to chapter 1 in the text, under the section titled 'When transport goes wrong…' for details of how these bacteria cause the production of large volumes of watery diarrhoea. Many cholera epidemics and pandemics have occurred and some examples are shown in table 17.1 below. The World Health Organization estimates that, each year, three to five million people suffer from cholera, resulting in 100 000 to 120 000 deaths in developing countries.

TABLE 17.1 Some cholera outbreaks since the start of the nineteenth century. Note that not all countries affected in the various pandemics are shown. Estimates of the number of cases are available only for more recent outbreaks.

Date	Country/City	No. of cases	No. of deaths
Oct 2010 – Aug 2015	Haiti	700 000	9 000
Jul–Aug 1994	Congo	48 000	12 000
Jan 1991–Sep 1994	Peru	<1 000 000	10 000
1881–1896 fifth pandemic	Hamburg (1892)		8 600
1852–1860 third pandemic	Russia London (1853–54) Spain (1854–55)		>1 000 000 10 739 236 000
1829–1851 second pandemic	London (1849) London (1832–) Paris (1832–)		14 137 6 536 20 000

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A cluster is an aggregation of cases over a particular period in a given area without regard to whether the number of cases is more than expected.

Cholera had been raging through London during 1853 and the first half of 1854. At the end of August 1854, a localised outbreak of cholera began in the Soho district of London. Within three days, 127 deaths from cholera were recorded in Soho, and, in less than ten days, about 500 people were dead from cholera. A total of 616 deaths occurred during the two weeks of this outbreak. John Snow (1813–1858) was a doctor who lived close to the Soho district. Snow became aware that the cholera deaths were not uniformly distributed within Soho but were clustered in one area. Snow prepared a map showing the pattern of occurrence of cholera deaths within the Soho district. Figure 17.8 below is one representation of this map. Examine this map and note that the cholera deaths form a cluster that is centred around one particular pump, the Broad Street pump, marked with a yellow flag.

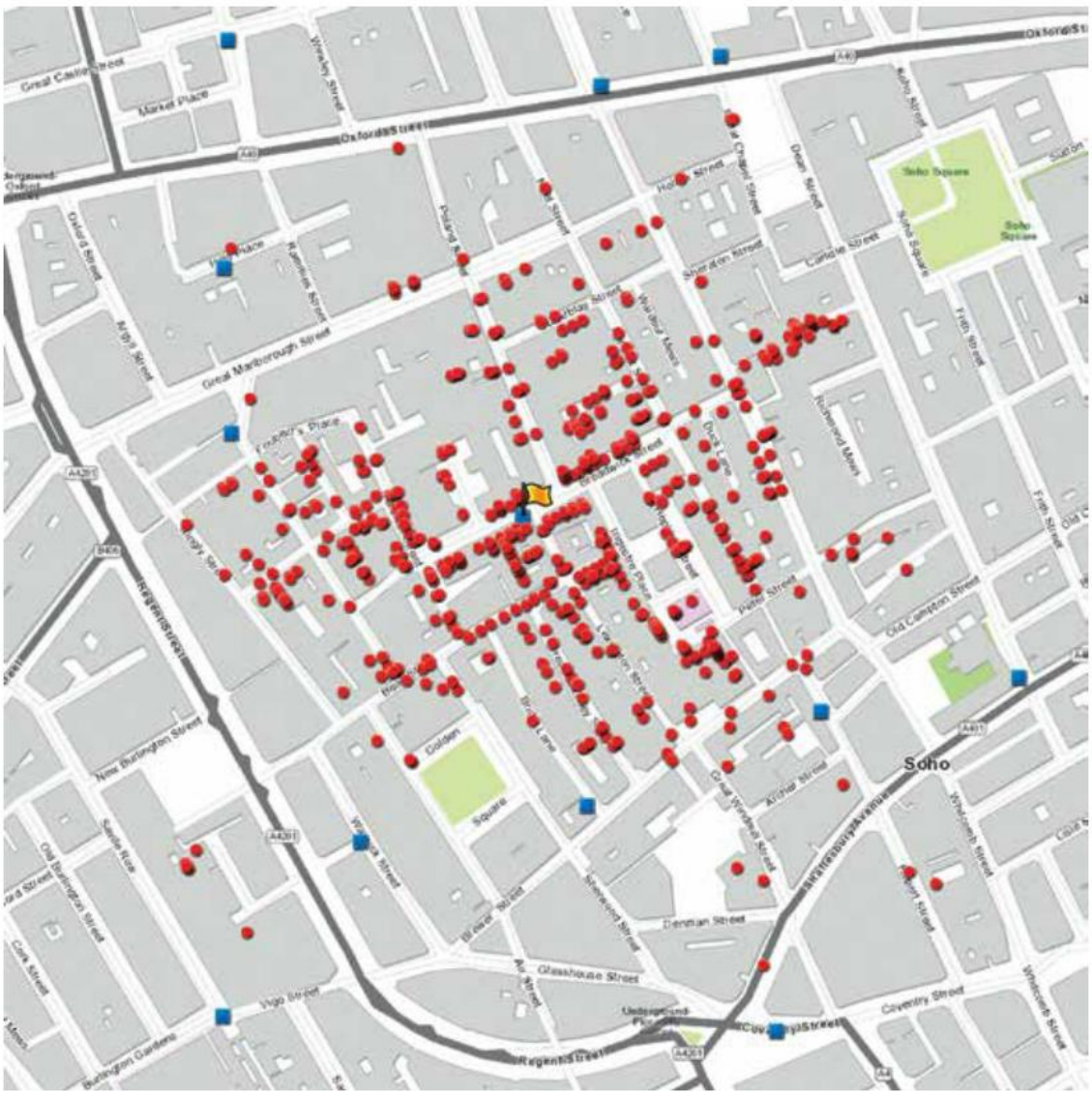

FIGURE 17.8 Representation of John Snow's map showing the deaths from cholera (red dots) in the Soho district of London in September, 1854. Also shown are the 13 street pumps (blue dots), with the Broad Street pump also marked by a yellow flag. Note the clustering of cholera deaths around this particular pump. Local residents collected water from these pumps for drinking and other purposes. (Image courtesy of Dr Don Boyes, Department of Geography and Planning, University of Toronto.)

In 1854, the prevailing medical and public view was that diseases were caused by bad or foul-smelling air filled with particles from decomposed matter. This view was the **miasma theory of disease** that was eventually replaced in the late nineteenth century by the **germ theory of disease**.

The Soho district was indeed full of foul-smelling air that came from rotting garbage and animal wastes in the streets, and from human faeces that, because of the lack of a sewage system, were typically emptied into cesspits or cesspools either under houses or in streets. Houses in Soho did not have running water. The water supply in the Soho district consisted of shallow public wells from which water could be pumped. In all, 13 pumps were located around the Soho district. People took containers to these pumps to get the water they needed for drinking, cooking and washing. Figure 17.9 shows a cartoon of a typical nineteenth century public water pump.

FIGURE 17.9 Cartoon showing children playing at a street water pump typical of those in the Soho district of London in 1854. Note the handle whose action pumps water from a shallow underground well below the pump.

The pattern of deaths clustered in one region of Soho raised the initial research question for Snow: *What was the cause of the clustering of cholera deaths in Soho?* In addition, ignoring the miasma theory of disease, Snow also wondered: *Could water from the Broad Street pump somehow be involved in the cholera deaths?*

To investigate his research question, Snow asked more questions, made observations, and gathered data concerning instances of individuals who contracted cholera and who were known to have drunk water from the Broad Street pump, such as the following:

- nine customers of a small eating place where glasses of water from the Broad Street pump were served with other refreshments
- sixteen workers from a factory in Broad Street where tubs of water from the Broad Street pump were kept on hand for the workers to drink
- residents of houses close to the Broad Street pump who used that pump for their water supply.

In addition, some individuals who lived a distance away from the Broad Street pump also died from cholera, but Snow found a link to the water from that pump to the following cases:

- Members of some Soho families who lived much closer to pumps other than the Broad Street pump died from cholera. Did this observation mean

that water from this pump was not linked to the cause of cholera? In some cases, these deaths were of children who walked from their homes to attend a school near Broad Street and, as they passed the pump, the children sometimes stopped to have a drink of water. In other cases, Snow identified that cholera deaths occurred in families who preferred the Broad Street water and chose to use that more distant pump for their water supply.

- One interesting case was that of an elderly woman who lived in West Hamstead, a cholera-free region at a distance from Soho. She died from cholera on 1 September. At first, this death appeared to have no link to the Broad Street pump. However, it was revealed by the woman's son that his mother had once lived in Soho and liked the taste of water from the Broad Street pump, so much so that she arranged for the daily delivery of a bottle of water from that pump. The woman received her last delivery of bottled water on 31 August, and she and her niece, who was visiting on that day, both died from cholera the following day.

Just as important was the data gathered by Snow about people who lived or worked close to the Broad Street pump who were ***not*** infected by cholera. This was necessary to exclude other possible sources of cholera infection. These examples included the following:

- A workhouse located very close to the Broad Street pump had more than 500 paupers in residence there. Very few deaths from cholera occurred among the inmates of this workhouse. This low figure was in marked contrast to the high death rates from cholera of people living in adjacent streets. Snow discovered that the workhouse had its own well from which water was pumped for use and, in addition, bought water from the Grand Junction Water Works, which sourced water from an uncontaminated region of the Thames River.
- Likewise, a brewery near Broad Street employed a large number of workers, but none died from cholera. Snow observed that the brewery workers had a daily allocation of beer and so drank beer rather than water. In any event, the brewery had its own well. (The fermentation processes involved in beer production kills cholera bacteria.)

Snow noted that there were no deaths from cholera among those people who did not drink water from the Broad Street pump. At the same time, he observed that everyone in Soho who died from cholera drank water from the Broad Street pump.

Snow rejected bad air (miasma) as the cause of the cholera deaths in Soho. Instead, Snow proposed that water from the Broad Street pump was the probable source of the cholera infection that raged in Soho. Based on this, Snow then refined his original research question into a working hypothesis that could be tested. His hypothesis was as follows: ***'IF water from the Broad Street pump is the cause of cholera deaths in Soho, THEN cholera deaths will decline and stop when this supply of water is stopped.'*** Note that Snow's hypothesis includes an explanation for the cholera deaths (water from the Broad Street pump) and a prediction by which the hypothesis can be tested (see if cholera deaths stop when this water supply is stopped).

Although local officials were sceptical and supported the miasma theory of disease, Snow persuaded them to remove the handle from the Broad Street pump, making it non-functional and stopping the supply of water from its underground well. The pump handle was removed on 8 September 1854 and the cholera deaths declined and stopped. However, the effect of removing the pump handle on the Soho cholera outbreak is confounded by the fact that, as may be seen in figure 17.10, by the time the handle was removed, the cholera outbreak was already declining. In any event, the relationship between the cholera deaths in Soho and drinking water from the Broad Street pump as hypothesised by John Snow was supported, and the removal of the pump handle certainly prevented any later outbreaks of cholera.

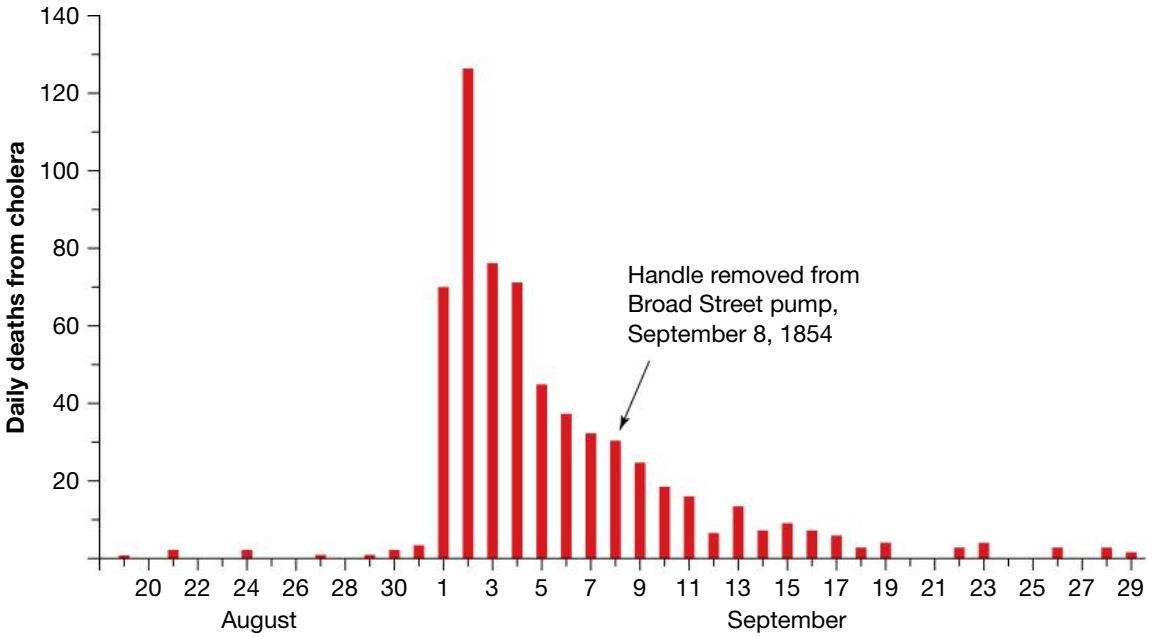

FIGURE 17.10 Bar graph showing the daily deaths from cholera in Soho over late August and early September 1854. Note that, by the time the pump handle was removed from the Broad Street pump, the local cholera epidemic was in decline.

John Snow's studies implicated the water from the Broad Street pump as the cause of cholera. He examined water samples from various pumps in Soho but was unable to demonstrate the presence of a causative agent of cholera in water from the Broad Street pump. This was not surprising. It was not until almost 30 years later, in 1883, that Robert Koch isolated pure cultures of *Vibrio cholerae* bacteria and demonstrated that these bacteria were the causative agent of cholera. Koch also showed that the mode of transmission of cholera was by ingestion of water or food contaminated with faeces from a cholera-infected person — a faecal-oral route — as happened in Soho when people drank water contaminated with faecal matter that leaked from a cesspool to the well supplying the Broad Street pump.

What was the origin of the Soho cholera outbreak? It is apparent that until August 1854, the water from the Broad Street pump was 'safe to drink' but, very suddenly, in late August, the situation changed and this water carried the causative agent of cholera. How did that water became contaminated? Evidence later emerged that, in late August, a five-month-old baby, Frances Lewis, developed severe diarrhoea, a symptom of cholera. The Lewis family lived at 40 Broad Street. Sarah, the baby's mother, related how she soaked the baby's diarrhoea-stained napkins in buckets of water and then poured the faecal-contaminated water into an opening into a leaky cesspool at the front of her house. However, this cesspool was just a metre from the well that fed the Broad Street pump. Baby Frances died from cholera on 2 September. Leakage of faecal material from the cesspool to the well under the Broad Street pump was apparently the trigger that set off the Soho cholera outbreak at the beginning of September, 1854.

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A cesspit or a cesspool is a tank with no outlet used to store human faecal wastes.

Communicating research findings

The final step in Snow's investigation was the communication of the results of his research. Snow wrote many scientific papers dealing with cholera, including the following:

- 1849: On the pathology and mode of communication of cholera Part 1. *London Medical Gazette* 44, pp. 745–52.

- 1849: On the pathology and mode of communication of cholera Part 2. *London Medical Gazette* 44, pp. 923–29.
- 1851: On the mode of propagation of cholera Part 1. *Medical Times* 24, pp. 559–62.
- 1851: On the mode of propagation of cholera Part 2. *Medical Times* 24, pp. 610–12.
- 1853: On the prevention of cholera. *Medical Times and Gazette* 7, pp. 367–69.
- 1854: The principles on which the treatment of cholera should be based. *Medical Times and Gazette* 8, pp. 180–82.

Communicating research findings acts to share information with other groups, possibly leading to further research or, in some cases, resulting in new practices and new treatments. In the case of John Snow, his actions in Soho in identifying the Broad Street pump as the source of contaminated water that caused cholera was not the end of the story. Importantly, his research on cholera made a major contribution to public health by demonstrating the need for clean water supplies and sewage systems in cities and towns, and his findings contributed to the reforms that improved public health in the nineteenth century.

John Snow carried out an important observational study of cholera deaths in Soho using a scientific approach. As part of your biological studies, you are required to design and undertake an investigation using a laboratory-based study, a field-based experimental study and/or an observational study. Your investigation should relate to an aspect of the survival of an organism or a species, noting that survival typically involves the regulation of factors within an individual organism or species. You will also be required to communicate your findings.

In the following section, we will look at the process of designing and undertaking a scientific investigation and communicating the findings of that investigation.

ODD FACT

The *John Snow* pub on the corner of Broadwick and Lexington streets in London was named in honour of Snow. Broadwick Street is the renamed Broad Street of the nineteenth century.

KEY IDEAS

- **Progress in science occurs when existing theories in science are modified or even rejected and replaced.**
- **Carefully planned investigations are one process by which biological knowledge is advanced.**
- **Scientific investigations may be experimental or observational.**
- **Experimental studies may be carried out in the laboratory or in the field.**
- **In experimental studies, investigators expose the subjects or objects of interest to a defined treatment and observe their responses to those treatments.**
- **In observational studies, investigators collect data about an object of study without changing the existing conditions.**

QUICK CHECK

1 Put the following actions of John Snow in the correct order over time:
- **a** formulating a testable hypothesis
- **b** communicating results
- **c** asking questions
- **d** gathering data
- **e** analysing results

2 State whether the following statements are true or false:
- **a** John Snow's hypothesis was tested by carrying out an experiment.
- **b** Cholera was once thought to be caused by bad air or miasma.
- **c** Snow identified the bacterial species that is the causative agent of cholera.
- **d** Advances in science may involve the rejection of an accepted theory.
- **e** An observational study is completed by collecting data.

Process of scientific investigation

Figure 17.11 summarises a scientific approach to the investigation of a research question using laboratory-based or field-based experimental studies or using observational studies.

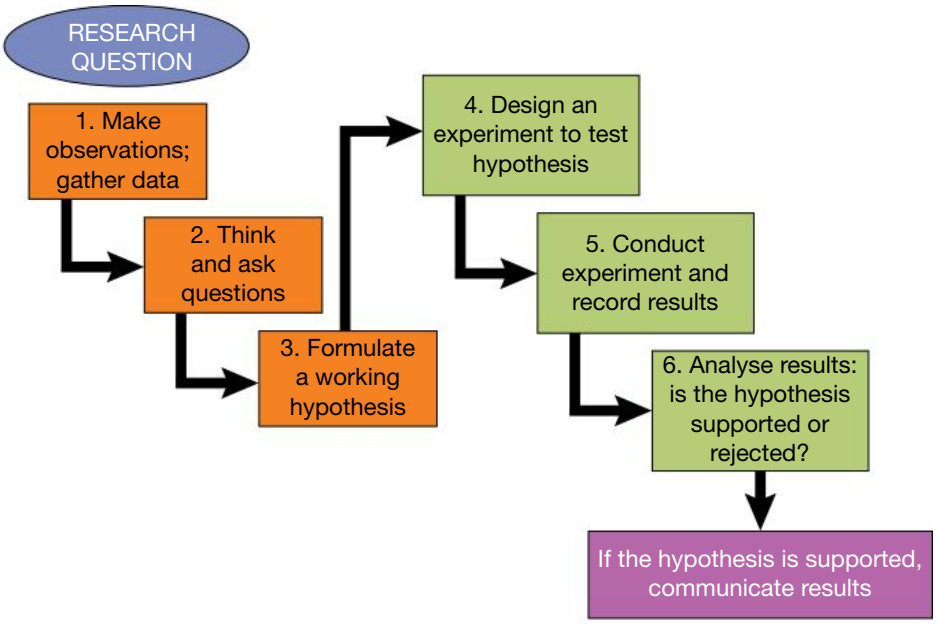
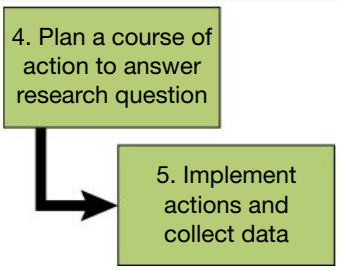


FIGURE 17.11 Diagram outlining typical steps in a scientific approach to a research question. Note that an investigation does not start with an experiment. It starts by gaining background information about the research question and by making observations and gathering data.



In the case of an observational study, steps 4 and 5 in figure 17.11 above would be amended as shown in the figure in the minor column.

Let's look at these steps in turn.

Choosing a research question

Every study, both experimental and observational, begins with a research question. In particular, a biologist might be thinking about questions such as:

- 'Is the water quality of a river near an industrial site the same as that upstream of the site?'
- 'Can a particular plant species survive under conditions of increasing salinity?'
- 'What relationship exists between light intensity and photosynthetic rate in plants?'
- 'Does humidity affect transpiration rates in a plant?'
- 'What animal behaviours contribute to the animal's survival in hot environments?'

For John Snow, his initial research question was: 'What was the cause of the clustering of cholera deaths in Soho?'

You should decide on a relevant question that you are interested in investigating through either an experimental or an observational study.

Once you have decided on your research question, you will use a scientific approach to investigate your question, as shown in figure 17.11 above and as discussed below. As you proceed through the early steps of the scientific process, your research question will be modified and will finally develop into a working hypothesis. Testing this hypothesis will be the focus of your laboratory or field experiment and/or your observational study.

Step 1. Observations produce data

Observation is a fundamental skill used by scientists to gain data — in other words, observations are a source of raw data. Observations provide the starting point of an investigation but, on their own, they do not provide explanations or answers.

FIGURE 17.12 Scientist viewing an image using a transmission electron microscope (TEM). Because its resolving power is orders of magnitude greater than that of light microscopes, a TEM can reveal remarkable details of cellular infrastructure.

Making observations and gathering data

Observations can be made directly through your senses, by using your eyes to record the green and yellow colours of the variegated leaves of a flowering plant, your hands to identify the rough texture of its stem, your olfactory sense to note the smell of its flowers, and your tongue to detect the sweetness of the fruit if it is edible and safe.

As well as the unaided senses, scientific observations are more often made using instruments that extend the power of the unaided senses, or permit accurate measurements, or enable collection of data that may otherwise be undetectable. Examples include thermometers to measure temperature, micrometers to record thicknesses, scales to measure mass, microscopes to visualise cells and cell organelles (see figure 17.12), DNA sequencers to identify the base sequences of genes, or magnetic resonance imaging (MRI) to make a medical diagnosis.

Not all observations are made using instruments in a laboratory setting. Familiar tools that can be used to gather data include digital audio recorders, video recorders and digital cameras. Tools are an important means of gathering data from people and these include questionnaires (oral or printed), surveys and interviews. Quadrats and transects are tools used in the field to gather data. Can you think of other tools for making observations and gathering data?

At the beginning of your investigation, you will gather data that provides background information relevant to your research question. You may, for example, gather some data using web searches. You may also gather other background information from books, journal articles and popular science magazines. You may talk to acquaintances or friends who you believe may have knowledge or suggestions about your research question. It is essential that you keep a logbook in which you record the activities you complete in your information-gathering sessions. For example, when you do a web search, note in your logbook the URL (Universal Resource Locator) of any websites from which you access data. See the box on logbooks at the end of this section.

Later in your investigation, your observations and data gathering will focus on recording the results of the experiments that you perform or the observations that you make in order to test your research hypothesis.

Sources of data

Data is a set of facts that are collected, observed, or generated. Data that you gather may come from primary sources or from secondary sources. **Typically, data that is gathered is raw data that must be analysed and interpreted to produce useful information.**

Primary sources of data provide direct or firsthand evidence about some phenomenon, as, for example, a research investigation, an event, an object, or community attitudes. Major sources of primary data are results of investigations reported in scholarly journals by the researchers involved, as,

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In this chapter, 'data' when used as a mass noun is singular, while 'data' used as a count noun is plural.

for example, research articles in the journal *Nature*. Other sources of primary data include video recordings of events, eyewitness accounts of events, historical documents, personal diaries, legal documents, completed questionnaires and surveys, and interview transcripts. Your completed logbook will be a primary source of data about your investigation of your research question.

Secondary sources of data are comments on or summaries and interpretations of primary data. Sources of secondary data include review articles in newspapers and popular science magazines, such as *New Scientist* or *Scientific American,* written by one person who summarises and comments on the research of others. A book about Charles Darwin is a secondary source, but a book containing transcripts of Darwin's letters is a primary source. (Why?)

Two kinds of data

Data that you gather may be quantitative or qualitative.

Some data that you gather will be recorded in numbers. For example, biologists might record a glomerular filtration rate of 132 ml per minute, a child's red blood cell count of 4.8 million per microlitre, a feverish body temperature of 41 °C, a transpiration rate of 0.25 mL per minute, a duration of the S phase of human cell cycle of about 8 hours. This type of data is termed quantitative. **Quantitative data can be both observed and measured and expressed numerically.** Can you think of other examples of quantitative data? Quantitative data can also be manipulated mathematically to produce useful statistics, such as means (averages) and standard deviations.

Other data that you collect will be expressed in word descriptions. For example, in an experiment, a student observed that treating the surface of a cut potato with iodine solution produced a purple colour. 'Purple' is an example of qualitative data. **Qualitative data is descriptive, not numerical, and can be easily observed and described, but not measured.** Other examples include descriptions of texture (rough, smooth, bristly, coarse, clammy, hairy, and so on) or smell (acrid, pungent, aromatic, sweet, musty, smoky, fragrant, and so on).

The results of laboratory experiments are most commonly quantitative data. In contrast, data gathered through the use of surveys, questionnaires and interviews are typically qualitative. What kind of data would you expect to gather if you used a survey-based investigation into community attitudes towards an issue, such as genetic testing, genetic screening, or the use of embryos as a source of stem cells?

Table 17.2 below shows examples of how some values of attributes can be expressed both qualitatively and quantitatively.

TABLE 17.2 Some attributes can be expressed either as qualitative or quantitative data. Which form provides more detailed information?

Attribute	Qualitative	Quantitative
height (person)	tall	183 cm
height (mountain)	very high	8848 m
colour	green	520 nm
sound	loud	85 dB
area (postage stamp)	small	8.75 cm^2
speed	fast	120 kms^{-1}
temperature	hot	100 °C
age (rock)	ancient	440 million years

Recording data

Scientists gather raw data or plain facts from their observations. Data must be recorded *at the time* in a suitable form, as, for example, text entries, sketches, tables, and/or diagrams in logbooks, or in field notebooks. These records may be supplemented by audio and video recordings.

FIGURE 17.13 Record keeping in a logbook is an important part of the scientific method.

KEEPING A LOGBOOK

A critical task for investigators is to keep a logbook (or field notebook). Your logbook may be a bound exercise book (not loose-leaf) or a digital document on your computer or iPad/tablet. It will contain all the details of your progress through the steps of your scientific investigation, starting from the process of deciding on your research question and through each step of your investigation, which will follow a scientific approach. Your logbook is an important and valuable document. Note that even famous biologists kept notebooks: for example, Charles Darwin kept copious records of his observations in notebooks. During his voyage on the *Beagle* in 1831–36, Darwin filled 19 field notebooks with observations and thoughts that he made during shore excursions. (To read about Darwin's voyage on the *Beagle*, see *Nature of Biology 2 Fifth Edition*, chapter 10, in the box titled *The travels of Darwin and Wallace*.)

Make sure your name is prominently displayed on the front page of your logbook along with the title of your research topic. Your research question will be a topic of interest to you related to an aspect of cellular processes or to an aspect of biological change and continuity over time.

Keep a record of every session of your investigation. Your record might include (1) the date of the session, and (2) a heading that identifies the step in your investigation.

Possible headings you might use could include:

- **Deciding on my research topic.** The starting point for your investigation will be to decide on your research topic. Briefly outline why you decided on a particular research question.
- **Background data.** Through observations, you will gather background data (facts) on your research topic that can be recorded in your logbook as written notes, sketches, diagrams and tables; you might supplement these records with other media, such as photos, video recordings or audio recordings.

Be sure to record not only the data items themselves, but also their sources, so that, if necessary, you can easily locate and revisit them. Refer to the box titled *Referencing data* later in this chapter for further detail on data sources.

(continued)

- **Questions arising.** In your logbook, record questions that arise and any thoughts that you have about your investigation. For each question, write your initial thoughts about possible answers. It does not matter if you later find that an answer is not correct. Simply record your amended answers — that's all part of a scientific approach. Identify any problems that arise during your investigation.
- **Developing my hypothesis.** Remember that a hypothesis is a tentative explanation and not simply a prediction. Refer to the section in this chapter titled *Writing a hypothesis statement* for more detail.
- **Planning my experiment.** Outline your plan using the headings: Aim, Materials, Methods, Results, Analysis of Results, Conclusions.
- **Carrying out my experiment.** Observe and record your experimental results in an appropriate form, such as tables of values in the case of quantitative data, and word descriptions in the case of qualitative data. You can later convert tabular data into other presentations, such as bar graphs and line graphs that you will incorporate into a poster presentation.
- **Analysis and evaluation of my results.** Record your interpretation of the experimental results and decide whether they support or disprove your hypothesis. Record your conclusions.

Step 2. Asking questions about data

The analysis and interpretation of raw data produces useful information. John Snow's analysis of the data that he gathered and mapped concerning cholera deaths in Soho led him to ask the question: *Did cholera deaths occur in Soho residents who did not drink water from the Broad Street pump?* This was a key question, because if no such deaths occurred, this would become evidence to support the supposition that the cholera deaths in Soho were linked to drinking water from the Broad Street pump. This question enabled Snow to refine his initial research question and formulate a working hypothesis.

As you review the background information that you have gathered from various sources, questions will arise in your mind about your research question. Record these questions in your logbook. Think about these questions and discuss them with your teacher and your classmates. This process will assist you to develop tentative conclusions and to then formulate a hypothesis that you will test through an experimental or an observational investigation.

FIGURE 17.14 Students discussing some of the data forming part of the background information to their research question.

Step 3. Formulating a hypothesis

Formulating a hypothesis is an important step in the scientific process. What is a hypothesis?

Some facts:

- A hypothesis is a tentative or provisional explanation for an observation — that is, it is an attempt to explain an observed phenomenon.
- A hypothesis is a statement, not a question.
- A hypothesis must be testable using the results of experiments or observations.
- A hypothesis must be falsifiable by a simple test or observation.

We can combine all these features into a single definition as follows:

A hypothesis is a tentative, testable and falsifiable explanation for an observed phenomenon.

If it is not an explanation, it is not a hypothesis, but . . . any explanation (correct or not) can be a hypothesis if it can be tested by observation or experimentation.

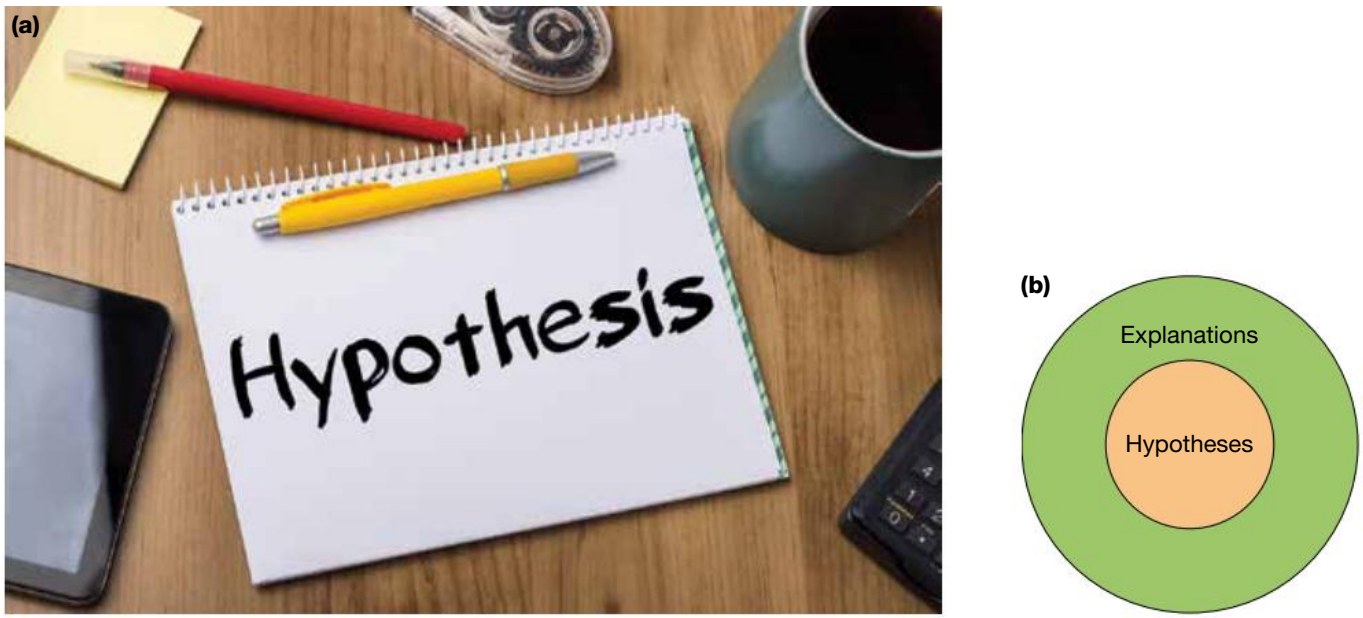

FIGURE 17.15 **(a)** Formulating a hypothesis is an essential step in a research investigation carried out using a scientific approach. **(b)** Venn diagram illustrating that all hypotheses are explanations of observed phenomena, but not all explanations are hypotheses. Only an explanation that can be tested and falsifiable is a hypothesis.

'**Testable**' means that a hypothesis can be easily tested by observations and/or experiments. Testing provides the evidence that allows a conclusion to be drawn about the hypothesis, namely that the hypothesis is either 'supported' or 'disproved (refuted).' **Scientific hypotheses are never stated as being 'proven correct'.**

A hypothesis can be any explanation for an observation *provided that it is testable*. However, not every suggested explanation can be tested. One example of an untestable explanation is the assertion that the disease known as childbed fever once common in new mothers was caused by 'unfavourable atmospheric-cosmic-terrestrial influences'. A testable hypothesis **cannot** be formulated from this. Try to complete the following statement: 'If unfavourable atmospheric-cosmic-terrestrial influences are the cause of childbed fever, then . . .'

'**Falsifiable**' means there must be a simple test, such as an observation, that could prove that a hypothesis is false. An example of a falsifiable statement is: 'All cats are black'. The testable prediction from this statement is 'If all cats are black and I see a cat, then it will be black'. This hypothesis can be readily falsified by a simple test — it simply requires seeing just one cat that is not black. However, in reality, if a hypothesis is not testable, it is also not falsifiable.

A hypothesis is a tentative, but testable, explanation for an observed phenomenon. For John Snow, the phenomenon that he observed was the cluster of cholera deaths centred on the Broad Street pump and he set about explaining this. In everyday life, you are often formulating simple hypotheses. You do this when you identify explanations for observations you make (see table 17.3).

TABLE 17.3 Examples of simple everyday hypotheses and how they can be tested.

Observation	Hypothesis	Test of hypothesis	Result	Conclusion
You turn on a torch and it does not work	Batteries are flat	Replace batteries and switch the torch on	Torch does not work	Hypothesis disproved
You are at the bus stop at the scheduled time, but no bus arrives	The bus is late	Wait and see if the bus arrives shortly	Bus arrives a few minutes later	Hypothesis supported
You turn on a torch and it does not work	The globe has blown	Replace the globe and switch the torch on	Torch works	Hypothesis supported
You become aware of the smell of burning	The toast is burning	Check toaster to see if the toast is burnt	Toast is black and smoking	Hypothesis supported
You hear the approach of blaring sirens	An ambulance is approaching	Look to identify the vehicle concerned	Police car with siren passes	Hypothesis disproved

Typically, a scientific hypothesis is formulated as an 'IF…THEN…' statement that starts with the tentative explanation and includes a prediction by which the hypothesis may be tested. In general, a good working hypothesis (regardless of whether or not it is later supported or is disproved) may have the form: 'IF hypothesis (explanation), THEN predicted outcome.' Table 17.4 shows some examples.

TABLE 17.4 Examples of some working hypotheses.

IF Hypothesis (explanation)	THEN Prediction
IF the rate of diffusion of molecules across a plasma membrane is directly related to their molecular size	THEN smaller molecules will cross the plasma membrane faster than larger molecules
IF skin cancers are caused by exposure to ultraviolet light	THEN people receiving higher UV exposures will develop more skin cancers

Hypotheses may also include an action and these have the general form: IF hypothesis (explanation) + action to be taken, THEN predicted outcome. For example:

- IF the torch batteries are flat and I replace them, THEN the torch will work again.
- IF the rate of photosynthesis is affected by the intensity of incident light and plants are illuminated with light of different intensities, THEN the rate of fixation of radioactive carbon by these plants will differ.

John Snow's hypothesis was: 'IF water from the Broad Street pump is the cause of cholera deaths in Soho, and water from this supply is turned off, THEN cholera deaths will decline and stop.'

Now consider the following statements and decide if each is an example of a working hypothesis:

Statement 1: 'Seedlings treated with organic fertiliser grow faster than similar untreated seedlings.'

No. This is simply a testable prediction. It does not include a tentative explanation.

Statement 2. 'Treating seedlings with organic fertiliser will make them grow faster than untreated seedlings.'

No. The statement is a method followed by a predicted outcome. It does not identify a tentative explanation for faster growth.

Statement 3. 'IF organic fertiliser provides essential growth factors for plants, THEN seedlings treated with fertiliser will grow faster than untreated seedlings.'

Yes. This identifies a tentative hypothesis (explanation) and a predicted outcome by which the hypothesis can be tested.

Variables in an experiment

A hypothesis usually predicts the relationship between two kinds of variables, an independent and a dependent variable. Let's look at the kinds of variables in an experiment to test a hypothesis.

In an experiment, a variable is any factor that the researcher can control or change or measure. Three kinds of variables are commonly recognised (see figure 17.16).

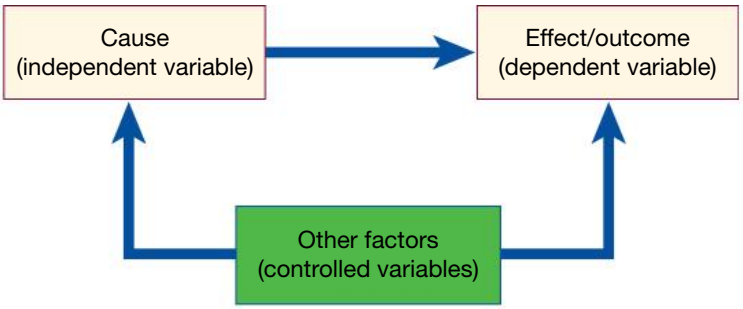

FIGURE 17.16 Diagram showing the relationships between variables in an experiment. Which interactions should you aim to prevent?

- An **independent variable** is a factor that is under the control of and is deliberately manipulated by the investigator. The investigator then observes and measures the effect of the manipulation of the independent variable on a dependent variable. For example, in an experiment investigating the relationship between the wavelength of light and the growth rate of seedlings, the independent variable that the investigator changes is the wavelength of the light. The dependent variable that is observed and measured in response is the rate of photosynthesis.

  In some studies, an investigator cannot manipulate an independent variable since it would be impractical or unethical to do so. For example, if an investigator wished to study the effect of an illegal drug on an aspect of human behaviour, it would clearly be unacceptable and unethical to ask one group of people to take such a drug. Research of this type might however be pursued using a suitable questionnaire administered to both non-drug users and drug users.
- A **dependent variable** is also termed an outcome variable. This is the factor that the investigator observes to see how it changes in response to changes in the independent variable. The changes in the dependent variable are measured and recorded. So, in the above investigation, the dependent variable is the rate of the growth of the seedlings.
- **Controlled variables** are all those other factors that the investigator must maintain at constant values through the course of an experiment. In the above experiment, the plant species used, the age of the seedlings, the temperature, availability of water, and angle of incident light are all examples of controlled variables. The controlled variables are ones that the investigator keeps the same throughout the course of the experiment. If these factors are not kept constant, they can confound the experimental results because they can cause changes in the dependent variable.

  Typically, an experiment involves one independent variable that is systematically changed, and one dependent variable whose responses to these changes are observed and measured. By changing only one variable (the independent variable) at a time, an investigator can see and measure the effect on the dependent variable.

In summary:

- the independent variable is what an investigator changes
- the dependent variable is what an investigator observes and measures
- controlled variables are what the investigator keeps constant.

Variables: categorical or numerical

The variables that are investigated in an experiment differ in their nature. They can be broadly divided into two classes — categorical variables and numerical variables. (These classes can be further subdivided, but this is not covered here.)

Categorical variables are qualitative and are expressed in words. A categorical variable can have a value that is one of a limited number of non-overlapping discrete values, and these values are expressed in words. Examples of categorical variables include the months of the year (twelve values: January to December), the days of the week (seven values: Sunday to Saturday), ownership of a smart phone (two values: Yes and No). Bar graphs are often used to display the frequencies of categorical variables in a study population.

Numerical variables are quantitative. Numerical variables can be precisely measured and they have values that are expressed in numbers. Examples of numerical variables include temperatures, masses, distances, rates of oxygen production in photosynthesis, wavelengths of light, salinity of water.

How would you classify these variables: breeds of dog? Air temperatures? Hair colours? Glomerular filtration rates of kidneys?

KEY IDEAS

- A scientific approach to an investigation is a multistep process.
- Observations produce data that may be quantitative or qualitative; the data must then be analysed to produce useful information.
- Sources of data may be primary or secondary.
- Both quantitative and qualitative data can be observed and described in words, but only quantitative data can be measured and given numerical values.
- Logbooks or field notebooks are used for the timely recording of progress through every step of an investigation.
- Hypotheses are tentative, testable and falsifiable explanations for observed phenomena.
- Hypothesis testing is a process whereby the result of an investigation provides evidence that either supports or disproves (refutes) a hypothesis.
- Variables in an investigation may be identified as independent, dependent or controlled.

QUICK CHECK

3 What is the difference between a primary and a secondary source of data?

4 What is the difference between a dependent and a controlled variable?

5 State whether the following are true or false:

a Experiments are carried out only after observations relevant to the research question are made, questions asked about these observations and hypotheses formulated.

b A research article in a scientific journal is an example of a primary source of data.

c Green light and light with a wavelength of 520 nm are the same.

d An independent variable is the variable that is systematically changed by the investigator.

e The results of an investigation can prove that a hypothesis is true.

Step 4. Designing an experiment to test a hypothesis

Designing an experiment means constructing a detailed experimental plan to test a hypothesis in advance of doing the experiment.

A typical plan might include details under the following headings that you would record in your logbook:

Title of experiment:
Aim: Purpose of the experiment, which should include the hypothesis that you are testing.

Materials: This would include the following items that should be checked with your teacher:

- The laboratory equipment and the consumables needed for your experiment, any personal safety equipment required, and their availability checked.
- Any safety issues associated with the conduct of your experiment, such as:
  - potentially hazardous chemicals
  - equipment that can pose a potential safety hazard, as, for example, electrophoretic equipment or centrifuges.

  For each safety issue identified, list in your logbook the safety controls and precautions to be taken.
- Any ethical issues associated with the conduct of your experiment, as, for example, the need to seek informed consent if your experiment will involve human subjects.

Methods: Identify your independent variable and how you will change it during the experiment. Identify the dependent variable expected to respond to these changes and identify how you will measure the changes. Identify all the controlled variables to be kept constant throughout the experiment.

Figure 17.17 shows an experimental set-up designed by a team of students to examine the following hypothesis: *IF the rate of photosynthesis in plants is dependent on the intensity of light, THEN changes in light intensity will cause a change in photosynthetic rate.* The students predicted that the direction of this change would be a fall in the rate of photosynthesis as the light intensity decreased. Check out their experimental design.

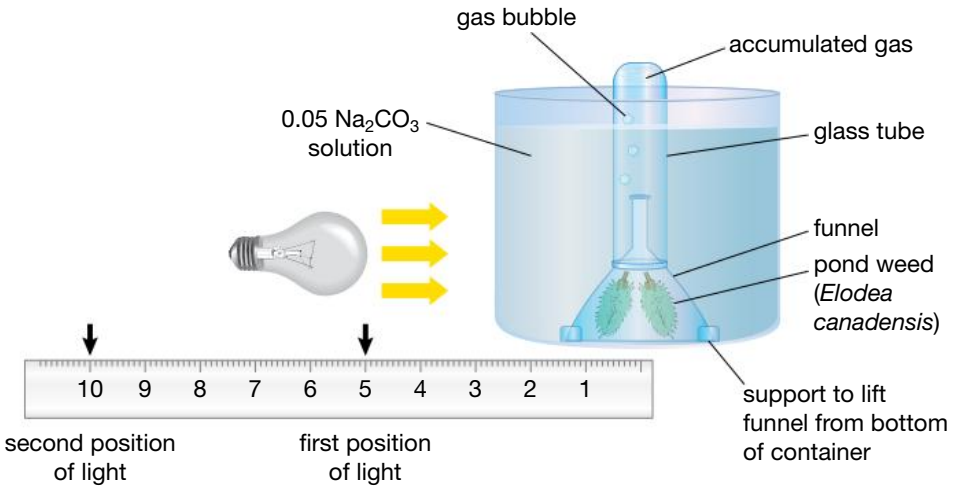

FIGURE 17.17 Diagram showing the experimental set-up used by students investigating whether a link exists between the rate of photosynthesis and the intensity of incident light.

Examine this figure and note the following:

1. The **independent variable** in this experiment is light intensity. The students varied this independent variable by progressively moving the light source along a one-metre rule. The students selected a starting point for the light source of 5 cm from the pondweed, then 10 cm, then 15 cm, then 20 cm,

after which they moved the light source in 10 cm intervals up to 50 cm away from the pondweed. This procedure gave them seven data points.

Earlier data gathering by the students led them to discover that the light intensity (I) at any point is inversely proportional to the square of the distance from the light source; that is, intensity (I) is proportional to $1/d^2$. So, the students decided to denote the light intensity at the starting point of 5 cm as 100 per cent and express the intensities at the other distances as a percentage of that value (see table 17.5 below).

2. The **dependent variable** is photosynthetic rate, but the students had to decide how this could be measured. The students considered the equation for photosynthesis and asked: *Can we easily measure the rate of disappearance of reactants or the rate of appearance of the products of this reaction?*

$$6CO_2 + 12H_2O \xrightarrow[\text{light}]{\text{chlorophyll}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

   - The students recognised that measuring photosynthetic rate could be done by measuring the rate of fixation of carbon dioxide into glucose. However, the students rejected this because this method would require providing plants with a source of radioactively labelled C (as carbon dioxide) and tracking the disappearance of carbon dioxide and/or the appearance of glucose.
   - Because water is both a reactant and a product in photosynthesis, tracking water poses a major problem. This method was also rejected by the students.

   The students decided to measure photosynthetic rate using the production of oxygen and, to visualise the appearance of oxygen, they decided to use an aquatic plant, such as *Elodea canadensis*, the common pondweed. Pondweed is often used in freshwater aquaria, and the oxygen produced by the plant appears as bubbles released from the cut end of the pondweed. In reaching this decision, the students made a number of assumptions: (i) the bubbles of gas released from the cut stem of illuminated pondweed consist of oxygen, and (ii) all the bubbles are the same volume. Using these assumptions, the rate of production of gas bubbles from the pondweed could be identified as directly proportional to the rate of photosynthesis. This meant that the students could use gas bubble production as a valid substitute for the rate of photosynthesis in the pondweed. So, in this experiment, the dependent variable is the rate of gas bubbles produced (bubbles per minute) by the pondweed.

3. The **controlled variables** in this experiment identified by the students were as follows: temperature, carbon dioxide concentration, and background lighting. The students knew that they should control these variables so that any changes they observed in the rate of gas bubble production could be identified as due to changes in light intensity.
   - To control for temperature fluctuations, the students decided to use a 20-watt light-emitting diode (LED) as the visible light source. LED lights have a heat sink that absorbs any emitted heat. A 20-watt LED has a light output that is equivalent to that of a 100-watt incandescent light. As a back-up, they decided that if they had to use another kind of light source, the large volume of water around the funnel and test tube would act as a buffer against any significant rise in temperature.
   - To control for carbon dioxide concentration, the students decided to immerse the pondweed in 0.05 M sodium hydrogen carbonate ($NaHCO_3$) solution. When dissolved in water, sodium hydrogen bicarbonate undergoes a reaction and one of the products is carbon dioxide. One student made the important suggestion to put two small blocks under the funnel

to lift it so that the sodium hydrogen carbonate solution could freely move. If this was not done, the concentration of carbon dioxide in the funnel could have depleted.
- To control for background lighting, the students decided to set up their experiment in a darkened area to minimise any stray incident lighting. Just enough light was needed to count the number of bubbles released per minute.

To record their results, the students prepared a table as shown below. Note how the light intensity decreases with increasing distance between the light source and the centre of the funnel with the pondweed.

TABLE 17.5 The rate of photosynthesis and intensity of incident light

Distance from light source (cm)	Percentage of initial light intensity	Number of bubbles per min
5	100	
10	25	
15	11	
20	6	
30	3	
40	2	
50	1	

Control groups and experimental groups

The design of many experiments includes a **control group** as well as one or more **experimental groups**. The experimental groups are exposed to the changing conditions determined by the independent variable, but the control group is independent and not affected by those conditions.

The control group serves several purposes: it can show that the experiment is working, and it can provide a baseline result against which the results of the experimental group can be compared.

In the above experiment, the control would be a set-up without pondweed. Why is this needed?

In an experiment concerned with the effect of salinity on plant growth, a control group of seedlings would be a tray of seedlings allowed to grow under conditions of zero salinity, while the experimental groups would be exposed to conditions of different salinities.

For your study, you will need to decide how many experimental groups you will need and the size of each group.

Sample size

The size of the control and experimental groups is an important factor in experimental design. The size of each group must be sufficiently large so that (1) replicate results can be obtained and a meaningful comparison made between the outcomes in the control and the experimental groups, and (2) the results from the experimental group can be seen as applicable to the larger population. The upper limit on sample size is determined by cost and space considerations and other practicalities.

Living organisms, whether they be plants, algae or animals, are an uncontrolled source of genetic variation that can interact with the variables under investigation. Sample sizes that are sufficiently large produce replicate results or observations that (3) can reduce the effects of this uncontrolled variation.

Complicated formulae exist for calculating minimum sample sizes. However, one simple rule-of-thumb is that ten observations are required for each experimental variable (see question 8 in the end-of-chapter questions).

Minimisation of bias

Bias is an intentional or unintentional influence on a research investigation as a result of systematic errors introduced by a researcher into the sampling or the testing procedures of an experiment. These biases will prejudice the research findings and raise questions about their validity and reliability.

Consider a clinical study into the effects of a new drug that involves a control group of individuals who will receive a placebo and an experimental group of individuals who will receive the drug under test. Various kinds of bias, as identified below, could affect the research findings, and various means of minimising that bias are also identified:

- **Selection bias**: This type of bias can arise unless participants are not equally and randomly assigned to the experimental and the control groups. All participants should have an equal chance of being placed in either group. Selection bias can be minimised by randomly allocating participants to each group.
- **Sampling bias**: This type of bias can arise if the participants chosen for the study are not representative of the target population. If this occurs, the research results cannot be generalised to that population. For example, findings from a study carried out using adult male subjects cannot be applied to the general population because the latter includes children and female adults. Sampling bias can be minimised by ensuring that the participants in the study are a reasonable representation of the target population.
- **Response bias**: This type of bias arises when only certain members of the target population respond to an invitation to participate in the clinical trial, resulting in an unrepresentative sample of the larger population. Response bias can be minimised by ensuring that the participants in the study are a reasonable representation of the target population.
- **Measurement bias**: This bias can arise, even unintentionally, if the people measuring the test results are aware of whether they are measuring the results of individuals in the control group or in the experimental group. There is a possibility that the people measuring the results will, even unintentionally, focus on data that supports the drug treatment. Measurement bias can be minimised ideally by designing the clinical trials as a double-blind study in which neither the participants nor the researchers know which people are in which group.

In the case of an observational study, an investigator must design a plan of action to make observations, to collect samples, perhaps over a period of time, from the area under investigation. The design will also need to identify how the analysis of the information gathered will proceed. As for an experimental study, the investigator will have a working hypothesis that will be tested.

Step 5. Conduct the experiment and record results

Your teacher will supervise your laboratory or field experiment, or your observational study, and will ensure that health and safety requirements are met. Your teacher will also ensure that your investigation is carried out according to any ethical principles that may apply.

Record your progress throughout the experiment and the results of your experiment in your logbook. Typically, if the variables in your experiment are numerical, you will set up a table and record the values of the independent variable and those of the corresponding dependent variable. If appropriate, calculate any average values.

Displaying results of investigation

Once you have your results recorded in a table, you must display your data in an appropriate form. Results can be displayed in various ways, depending on

the nature of the variables and what you want to show. Commonly used representations include:

- scatter plots or scatter diagrams
- bar graphs
- line graphs
- mapping.

Presenting results in a graph makes it easy to see relationships between the variables involved because graphs provide a visual image that can highlight trends and reveal patterns. Time sequence graphs are important because they can display key turning points in a dataset. Visual representations such as diagrams and maps are very useful tools for simplifying large amounts of data, for revealing trends, for telling stories, and for communicating information. The map of cholera deaths in Soho that was drawn by John Snow made clearly visible the clustering of these deaths around the Broad Street water pump.

Scatter plots are also termed x–y graphs. **When you have paired numerical data, a scatter plot can be used to see if a relationship exists between the two variables**, as, for example, the weights of a sample of adults plotted against their heights. Each dot represents one observation, with the position of the dot determined along the x-axis and y-axis by the value of each of the variables concerned, namely weight and height (see figure 17.18). The independent variable is plotted on the x-axis and the dependent variable on the y-axis. Note that each axis has a label and measurement units. A scatter plot can show how much one variable is affected by the other. If data points fall along a line or a curve, the variables are linked or correlated, and the closer the data points are to the line, the higher the correlation. In the figure below, a strong positive correlation is displayed. What shape would you expect in a scatter plot showing ages of a sample of adults and their reaction times?

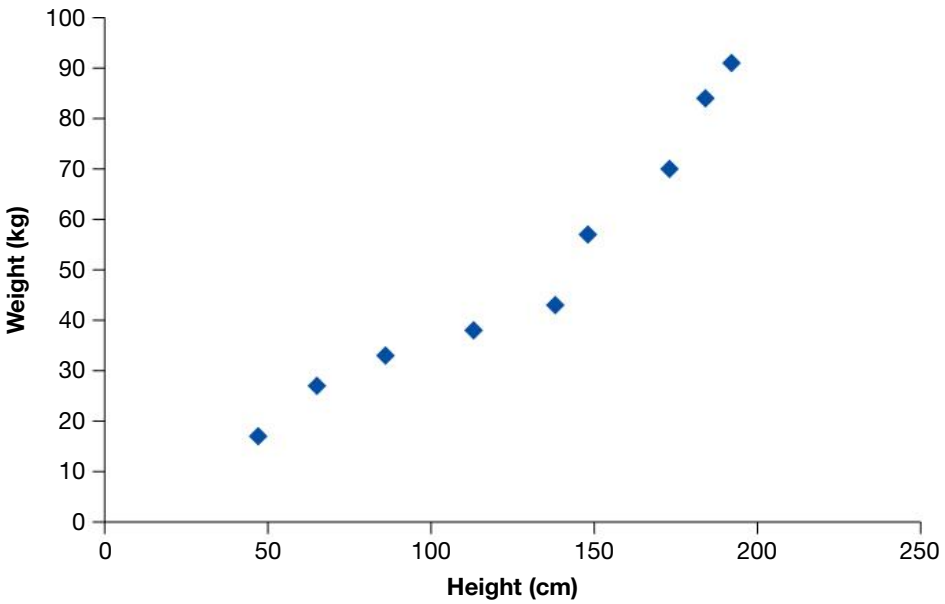

FIGURE 17.18 Scatter plot showing the relationship between the height and weight of a sample of adults.

Bar graphs can display numerical data, such as numbers or frequencies (percentages) of one or more discrete categories or groups. Figure 17.19a is a bar graph in which the vibration rates of the wings of various insects are

represented by vertical bars. The horizontal or x-axis has no scale because it simply shows categories. The vertical or y-axis has a scale showing the units of measurements — in this case, vibrations per second. Note that the bars are separated by spaces. Of the insects shown, which has the greatest wing vibration rate?

Bar graphs can also be used to compare two (or more) sets of data by using side-by-side bars, as shown in figure 17.19b. This bar graph shows the percentage increase, relative to the control, in two algal species growing under conditions with added mineral nutrients. Which nutrient caused the greatest increase? Which species of alga (A or B) showed the greater increase?

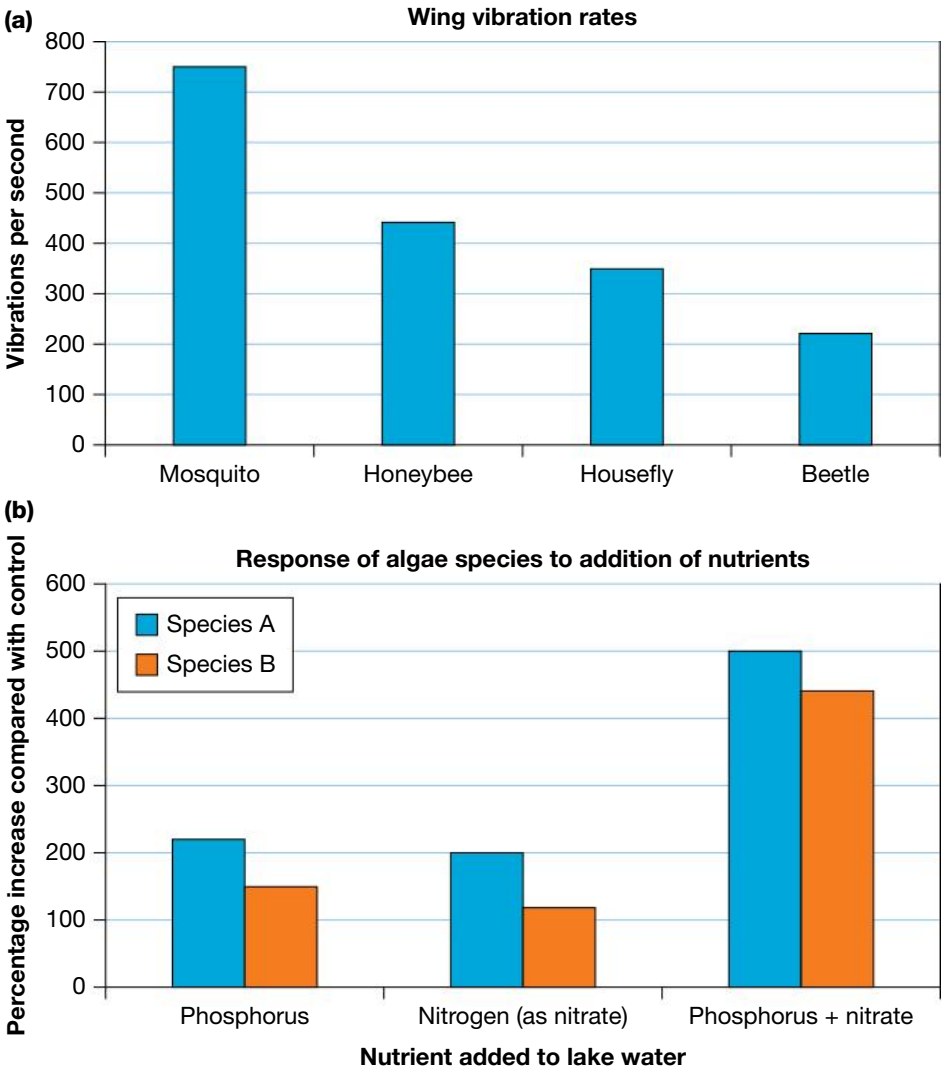

FIGURE 17.19 **(a)** Bar graph showing wing vibration rates (vibrations per second) for four insects. **(b)** Percentage increases, compared to control, of two species of algae in response to the addition of nutrients to the water in which they were growing.

Less commonly, bar graphs are drawn using horizontal bars. This orientation is used when the category label is long and complex and cannot be fitted along the x-axis. For an example, refer to figure 8.10a in the text.

Check out the bar graph in figure 8.67 in the text. How many data sets are shown on this bar graph? What story does this bar graph tell? Is it easier to tell this story in words or as a bar graph?

A **histogram** is a special kind of bar graph (see figure 17.20). In a histogram, the data represent continuous categories rather than discrete values. In contrast to the situation with a bar graph, a histogram has a scale on both the x-axis and the y-axis, and the bars are not separated by spaces.

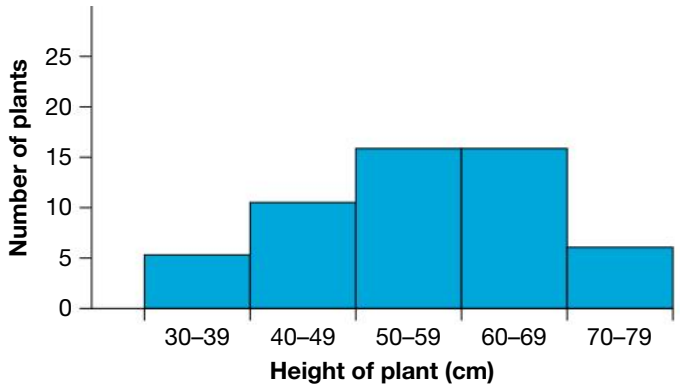

FIGURE 17.20 A simple histogram showing the results of a survey of the heights of a particular plant species growing on a moorland.

In a **line graph**, a series of dots represents the values of a variable, and the dots are joined using a straight line. Note that the ends of a line graph do not have to meet the axes of the graph. Line graphs are often used to show changes over a continuous period of time, or over space. In particular, **line graphs can show changes in a variable over time and so identify patterns, trends and turning points in a dataset.**

A line graph can be used to show the changes in a dependent variable in response to changes in an independent variable. The students investigating the relationship between light intensity and rate of bubble production showed their results as a line graph with each point showing the bubble production for a given light intensity. In this graph, the vertical axis showed the value of the dependent variable (number of bubbles per minute) and the horizontal axis showed the percentage light intensity.

Data on two variables can be plotted on the same line graph to show the change in two variables over the same time period. For example, refer to figure 8.81 in the text, which shows the variations in the population size of a prey species (moose) and its predator species (wolves) over a three-year period. What pattern is apparent?

Step 6. Analyse results and draw conclusions

Firstly, you should review your data and ask: Is the data set complete? Do you need to collect more data?

The results of any experiment will produce data that you will need to analyse. Aspects of data that you may need to consider include the following: validity, precision, accuracy, reliability, limitations of data and sources of error.

Analysing data

1. **Validity of data**: The validity of data refers to the credibility of the research results from experiments or from observations. Validity refers to both the research findings (so-called internal validity) and to the applicability of the results to other situations (so-called external validity).
   - **Internal validity refers to the degree to which the experimental procedures measure what they are supposed to measure.** Testing internal validity asks questions such as: Can the results be believed? Could another unknown variable have influenced the results? Could any cause and effect relationships identified be explained by other factors? Internal validity is favoured when an experiment is carefully designed and a scientific approach is used.

- **External validity refers to the extent to which research findings can be generalised to the greater population.** Testing external validity asks the questions: Is the sample of the population that was used in the research study representative of the greater population? Can we be reasonably sure that the results of the research are applicable to the greater population? External validity is favoured by an experimental design that includes the use of a control group, having control and experimental groups of sufficient sizes, and randomly assigning subjects to the control and test groups.

2. **Precision**: How close to one another are repeated measures of the same variable under the same conditions? If the measurements are close, as, for example, 19.5, 19.4, 19.6 and 19.5, they are precise. **Precision refers to the closeness of repeated measures or observations even if they are not accurate.** Precise values will differ from one another because of random observational error.
3. **Accuracy**: Accuracy is different from precision. **Accuracy refers to the closeness of an experimental measurement to an accepted or known value.** Accuracy in a research investigation relies on selecting the most appropriate instruments for any measuring tasks and using them correctly.

   Accuracy is an issue in a confirmatory experiment where the aim is to confirm a known value, as, for example, identifying the diploid number of the yellow fever mosquito, *Aedes aegypti*. If you concluded from your microscopic observations that the diploid number was six, then your result would be inaccurate. (The known number is $2n = 8$.) However, when an experiment is an exploratory investigation rather than a confirmatory exercise, matching an accepted value of a variable is not an issue.
4. **Reliability**: If your experiment were to be repeated a second and third time, would the results be the same? **If the same results are obtained in repeats of an experiment, the data can be said to be reliable.** Replication reduces variability in experimental results, increasing their significance and the confidence level with which a researcher can draw conclusions. Ideally, replications of experiments are carried out not only by the original investigators but, importantly, by third parties who use the same materials and the same methods as those of the original investigators.

FIGURE 17.21 Repeating a biology experiment is a means of assessing the reliability of experimental findings.

Replication is an important means of verifying experimental results and showing that they are reliable. In January 2014, a young Japanese researcher, Haruko Obokata, published in the leading science journal *Nature* an article that was hailed as a major breakthrough in stem cell research. Obokata had apparently developed a very simple method of producing pluripotent stem cells from adult somatic cells — just soak them for 30 minutes in a weak solution of citric acid. However, in spite of the simplicity of her method, no one else was able to replicate her results. In reality, Obokata had falsified and fabricated her experimental data. The fact that her results were not reproducible was critical and resulted in her retracting her research findings.

5. **Limitations of data**: The data that is gathered from the experimental results will have limitations. Limitations arise from several sources that can affect the quality of the data:
   - Experiments create artificial situations that do not necessarily represent real-life situations.
   - While every effort may be made to identify controlled variables and keep them constant throughout the course of an experiment, it is not always possible to identify and control every one of this type of variable. Therefore, the result obtained from an experiment may be confounded by the influence of an uncontrolled variable.
   - The degree on which results obtained in the laboratory can be generalised to other situations and applied in the real world is limited.

Limitations in models used in biology

As well as data limitations, **limitations exist in the models that we use in biology.** Models can be physical models, or mathematical models or conceptual models. Models can provide an explanatory framework that explains observed phenomena and helps organise myriad data into a related whole. Physical models can make an abstract concept tangible.

While they are very useful, models have their limitations.

- Because of the complexity of the processes that operate at every level of biological organisation, models cannot include all the details of the processes or the things that they represent.
- Models are necessarily approximations of the real world; for example, one model of population growth is the S curve of density-dependent growth (refer to chapter 8 in the text). This mathematical model helps predict how populations might grow over several generations; however, this model is an ideal simplification since it cannot take into account all the environmental variables that can affect populations, and so its predictions can differ from what happens in real-world populations.
- In making a concept or object concrete, a model must compromise accuracy; for example, figure 17.22 shows various molecular models of ATP, the energy supplying molecule of cells. Note, at the top of the figure, ATP is shown simply as its structural formula with chemical symbols showing the arrangement of its atoms and the bonds between them. In the middle, ATP is shown as a ball-and-stick model with atoms shown as coloured balls in their 3D positions joined by sticks that represent covalent bonds. The colour of each ball represents a particular chemical element, with carbon atoms shown as black balls, oxygen atoms by red balls, and hydrogen atoms by white balls. At the bottom, ATP is shown as a space-filling model in which the radius of each ball is proportional to the radius of the atom concerned.

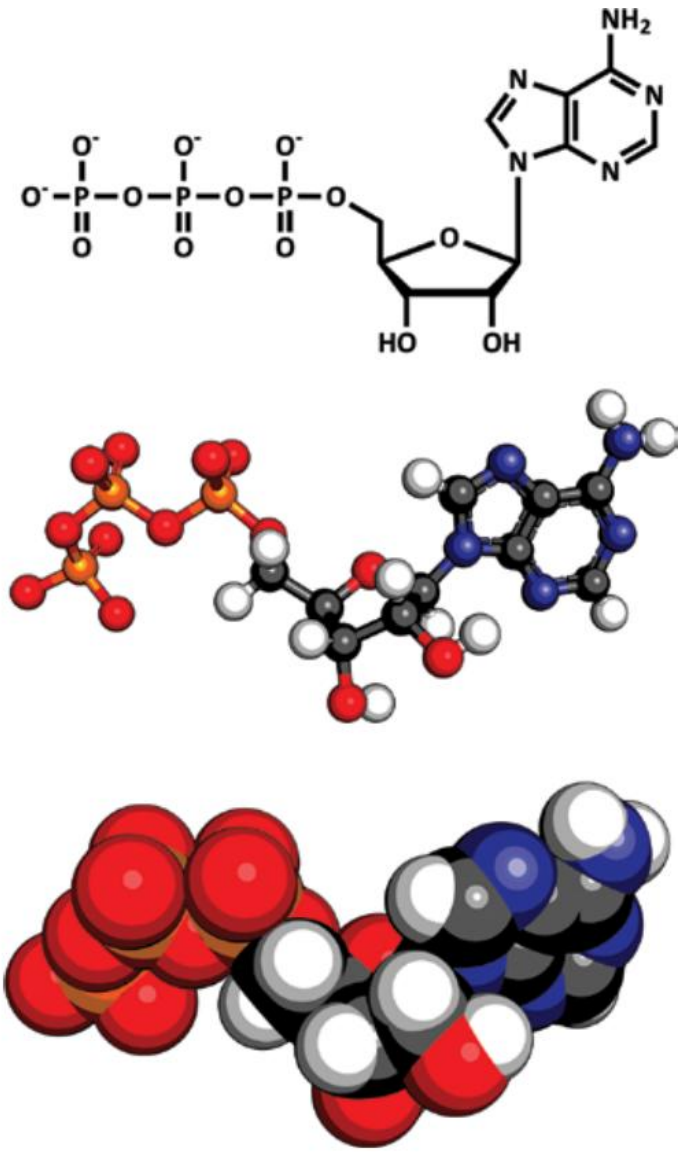

FIGURE 17.22 Molecular models of ATP, the chemical energy source of cells. At the top, the structural formula of ATP is shown. At the centre, ATP is shown as a ball-and-stick model. Which atoms are denoted by blue balls? By orange balls? At the bottom, ATP is shown as a space-filling model. Do all models show the bonds between the atoms?

Sources of error in investigations

Several sources of error can be identified in an investigation.

- **Systematic errors** produce measurements that are consistently too high or too low, for example:
  - instrumental errors that arise because an instrument, such as a weighing balance for which the zero has not been reset before use
  - environmental errors that arise because of malfunctions, such as a power outage, that affect the conditions under which an experiment is being conducted.
- **Random errors** are chance variations in measurements that are equally likely to be high as low. An example of a random error is an error of judgement when reading the smallest division on the scale of a measuring instrument, such as a micrometer, a burette or a measuring balance. However, if multiple observations are made and an average calculated, these random errors are minimised.

It should be noted that so-called human 'errors' are not errors but are mistakes that result from carelessness. Examples include gross misreading of an instrument, and writing the wrong result in your logbook, such as 40 instead of 4.0.

Hypothesis evaluation and conclusions

Evaluating a hypothesis uses the evidence from the results of the experiment that was designed to test the prediction from that hypothesis. In John Snow's investigation, his prediction was that stopping the supply of water from the Broad Street pump would reduce the incidence of cholera.

If the prediction from your hypothesis was validated by your experimental results, you should evaluate your hypothesis as 'supported' and your tentative explanation of the scientific observation now stands as a reasonable explanation. If your predicted outcome was not supported by your experimental results, you should evaluate your hypothesis as 'refuted' or 'disproven'. In that case, you might think about how you could modify your hypothesis.

Other conclusions might relate to the following questions:

- Were there any outliers in your dataset? An **outlier** apparently doesn't fit — it is a data point that is distant from all the other data points.

  If you had an outlier, what did you do about it? Rather than ignoring it, you should try to account for it. Most commonly, it will either be a systematic error or an outright mistake in measurement or in calculation, and so can be dropped. Occasionally, an outlier can be a legitimate observation that warrants further investigation.
- What future improvements can you suggest regarding your experimental design?
- In light of your experimental results, what follow-up experiments might you suggest?
- How do your research findings link to the key biological concepts relevant to your research question?

Step 7. Communicating findings

The results of a scientific investigation are typically communicated to others. In your case, you will be required to communicate the findings of your experimental or field study, or your observational study. The curriculum design identifies that this may be done using a scientific poster, a practical report, an oral communication or a digital presentation. In presenting your findings, ensure that you use correct biological terminology and relate your findings to relevant biological concepts.

When you present a conclusion, ensure that you provide the supporting evidence. However, evidence can be strong or weak. Check out table 17.6, which summarises the contrasting features of strong and weak evidence.

TABLE 17.6 Table showing the contrasting features of strong and weak evidence.

Strong evidence	Weak evidence
• is based on facts derived from studies with high internal validity	• is based on personal opinion or on anecdote
• is related to the topic	• is irrelevant or unrelated to the topic
• provides support for stated conclusions	• provides little support for stated conclusions
• is logically organised	• is not logically organised
• is free of bias	• may contain bias
• comes from a source that is trustworthy and reputable	• comes from a source that is unknown or untested

Remember: If you use any material that is the work of another person, you *must* acknowledge the material's source. Do not claim it as your own work. Acknowledgments come in two formats: a short version when it occurs in the

body of a report or a poster, and a longer version when it occurs in the *Reference and Acknowledgments* section at the end of a scientific report or poster. These two formats are described in the box at the end of this section.

If you quote the exact words of one or more sentences from a source, ensure that the quotation is enclosed within inverted commas and that the source is acknowledged at the end of the quotation. This is not necessary if you express in your own words the ideas taken from another source.

Communication in science may be done through a variety of avenues such as publications in scientific journals, science reports on TV (refer to figure 1.39 in the text), articles in popular science magazines such as *New Scientist* and *Scientific American,* newspaper articles, books, brochures from health organisations, and web-based publications, such as Web MD. The language used for communication should reflect the intended audience. A research report in a scientific journal uses language that is very different from a newspaper account of the same research.

However, communication does not guarantee immediate acceptance of the findings of a scientific investigation. In the case of the Australian researchers Barry Marshall and Robyn Warren, their research into the cause of peptic ulcer disease and gastritis eventually led to a complete revolution in the treatment of these conditions. By demonstrating that peptic ulcer disease was the result of infection of the stomach lining by *Helicobacter pylori* bacteria, Marshall and Warren recognised that this condition could be completely cured using a short course of antibiotics and stomach acid inhibitors.

At the time, these were chronic and often disabling conditions, believed to be the result of stress and lifestyle. Sufferers required lifelong treatment and, in some cases, even drastic steps such as surgical removal of part of the stomach. Marshall and Warren published a detailed summary of their research findings in 1985. These findings were initially dismissed by specialists in the field (gastroenterologists). By the mid 1990s, however, the research findings of Marshall and Warren had become mainstream, and the treatment of peptic ulcer disease and gastritis by a short course of antibiotics was routine. The ultimate vindication of Marshall and Warren's research came in 2005 when they were co-recipients of the 2005 Nobel Prize in Physiology or Medicine.

REFERENCING DATA SOURCES

The examples below are based on the *Harvard Style Guide* published by Monash University in 2012; available at the library website of Monash University.

For each type of publication, the first style (A) gives full details and is used in reference lists at the end of manuscripts or posters. The second style (B) is short and is used in the body of the text of a manuscript or a poster.

- **Online authored articles**:
  Style A: Author name and initial/s (Year of publication) Title of document. Retrieved on [date] from http:// URL
  Example: **Geggel L (2016) Snakes used to have legs and arms . . . until these mutations happened. Retrieved on 4 Nov 2016 from www.livescience.com/56573-mutation-caused-snakes-to-lose-legs.html**

  If the online article is undated, put (n.d.) in place of the date

  If there is no author, use the first line of the text of the article in place of the author's name

  If there are up to three authors, list them all.

  If there are more than three authors, only use the name of the first author and follow it by the phrase 'et al' (meaning and others).

  Style B: Example: **(Geggle 2016)**
- **Books**
  Style A: Author name and initial/s (Year of publication) *Book title*. (Edition if applicable.) Place of publication, publisher. Page number(s) you accessed.
  Example: **Langley P & Jones M (2013) The search for Richard III: The king's grave. London, John Murray.**

If there are more than three authors, only use the name of the first author and follow it by the phrase 'et al.'
Style B: Example: **(Langley & Jones 2013)**

- **Journal articles**:
  Style A: Author name (year of publication) *Title of article*. Title of journal. Volume number. Page numbers.
  Example: **Smith SL (2007) *Stature estimation of 3–10 year children from long bone lengths.* J Forensic Sci vol. 52 pp. 538–546.**

If there are more than three authors, only use the name of the first author and follow it by the phrase 'et al.'
Style B: Example: **(Smith 2007)**

- **TV programs:**
  Style A: Title of program (date) (TV program), channel identification.
  Example: **Gene editing made simple 2016, television program, ABC Sydney 30 August.**
  Style B: Example: **(Gene editing 2016)**

KEY IDEAS

- Designing an experiment means constructing a detailed experimental plan to test a hypothesis in advance of doing the experiment.
- Control and experimental groups are typically incorporated into the design of an experiment.
- Bias is an intentional or unintentional influence on a research investigation as a result of systematic errors introduced by a researcher into the sampling or the testing procedures of an experiment.
- Results of investigations may be presented using visual representations, including graphs, diagrams and maps.
- Data may be assessed in terms of attributes, including validity, accuracy, precision, and reliability.
- Evaluation of hypotheses results in hypotheses being either supported or refuted, but never proven.
- Communication of the findings from scientific investigations is an important step in a scientific approach.

QUICK CHECK

6 What is a double-blind study?
7 What kind of bias is minimised by using a double-blind study?
8 Identify one advantage of showing the numerical values of two variables in a scatter plot, rather than in a table.
9 A student group gathered data on the abundance of several species along a transect line. Suggest how this data set might be displayed. (If you want a clue, check out figure 8.67 in the text.)
10 What is the difference between precision and accuracy in relation to data?
11 How does a systematic error differ from a random error in an investigation?
12 Identify four channels of communication for the findings of scientific investigations.

Chapter review

studyon
Sit exam

Key words

accuracy
bar graphs
categorical variables
control group
controlled variables
dependent variable
experimental groups
falsifiable
germ theory of disease
histogram
independent variable
limitations of data
line graph
measurement bias
miasma theory of disease
numerical variables
outlier
precision
random errors
reliability
response bias
sampling bias
scatter plots
selection bias
systematic errors
testable
validity of data

Questions

1 **a** Identify three features of a scientific hypothesis. In medieval times, 'explanations' of the cause of the plague included divine punishment for sin.
b Is it possible to formulate a hypothesis to test this explanation? Explain.

2 **Identify the following statements as true or false:** ➜
a Interpretation follows data collection.
b The dependent variable in an experiment must be kept constant throughout the course of an experiment.
c If your experimental result causes you to reject the hypothesis under test, this means that you made a mistake in your experiment.
d A scientific investigation starts by carrying out an experiment.

3 **You conduct an experiment and record the data. You notice some of the data doesn't fit with what you expected or doesn't agree with the other data. Which of the following actions should you take?** ➜
A Toss it out because it looks wrong.
B Figure out what you want the data to show and then decide if you will keep it.
C Try to identify why this occurred, then decide if it should be kept or discarded, and discuss it in your result analysis.

4 **Which of the following is a requirement for a good hypothesis?** ➜
A You need to make the hypothesis broad so that the data can support it or reject it.
B You need to be able to design and conduct an experiment that can test the hypothesis.
C You need to know in advance whether or not the hypothesis is true.

5 **Examine figure 17.23.** ➜
a What data is shown by the blue bars?
b What is represented by the black line graph?
c In which two months did the rainfall show the greatest deviation below the long-term average?
d In which two months did the rainfall show the greatest excess above the long-term average?

6 **Identify a key difference between the members of the following pairs.** ➜
a independent and dependent variables
b qualitative and quantitative data
c control group and experimental group
d primary and secondary sources of data
e categorical variable and numerical variable
f an experimental study and an observational study
g data and conclusions

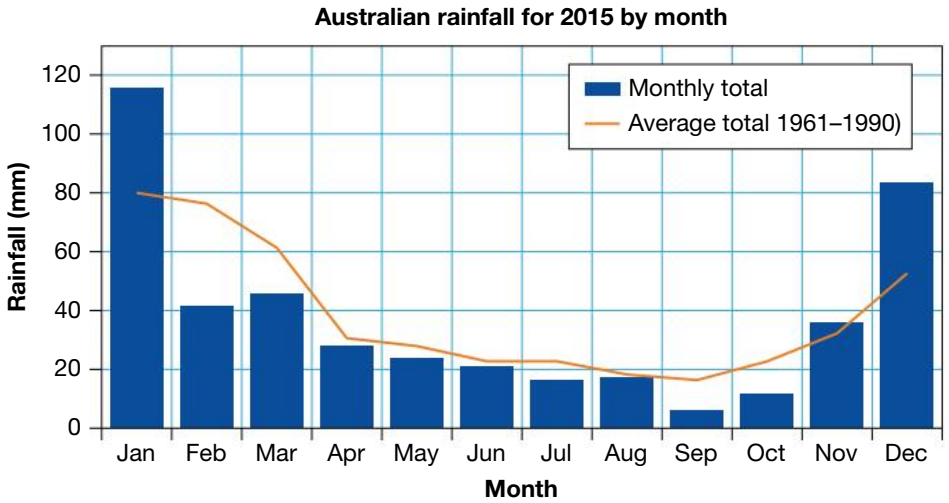

FIGURE 17.23 Australian rainfall for 2015 by month

7 Consider an apple. ➜

a Identify pieces of three quantitative data that you could observe.

b What instruments, if any, would you need to make these observations?

c Identify three pieces of qualitative data that you could observe.

d What instruments, if any, would you need to make these observations?

8 You wish to see if a new drug is an effective treatment for asthma. One hundred volunteers are randomly divided into two groups (A) and (B). Members of group B are given the drug and members of group A are given a placebo in the form of a sugar pill. ➜

a Which is your test group and which is your control group?

b This experiment was carried out as a double-blind study.

i What does this mean?

ii What is the advantage of this procedure?

c A student said, 'Wouldn't it be better to use all 100 volunteers in a larger test group, rather than split the volunteers into a test group of 50 and a control group of 50?' How would you respond to that student?

9 A joint report by the Australian and Queensland governments details the health of the Great Barrier Reef using a variety of measures, one of which is the concentration of herbicides that are inhibitors of a key stage of photosynthesis (PSII). Figure 17.24 shows the maximum concentrations of these herbicides in the Mackay Whitsundays region of the Great Barrier Reef from 2008–09 to 2014–15. ➜

a Suggest one or more possible sources for these herbicides.

b What would be the expected impact of these herbicides on the seagrasses in these areas? Explain your answer.

c How might high levels of herbicides affect the ecology of the reef?

The different colours of the bars denote the categories of herbicide in terms of their impact on photosynthesis, with category 5 having no impact and category 1 having the greatest impact on photosynthesis.

d Where and in which years did the highest and most damaging herbicide concentration occur?

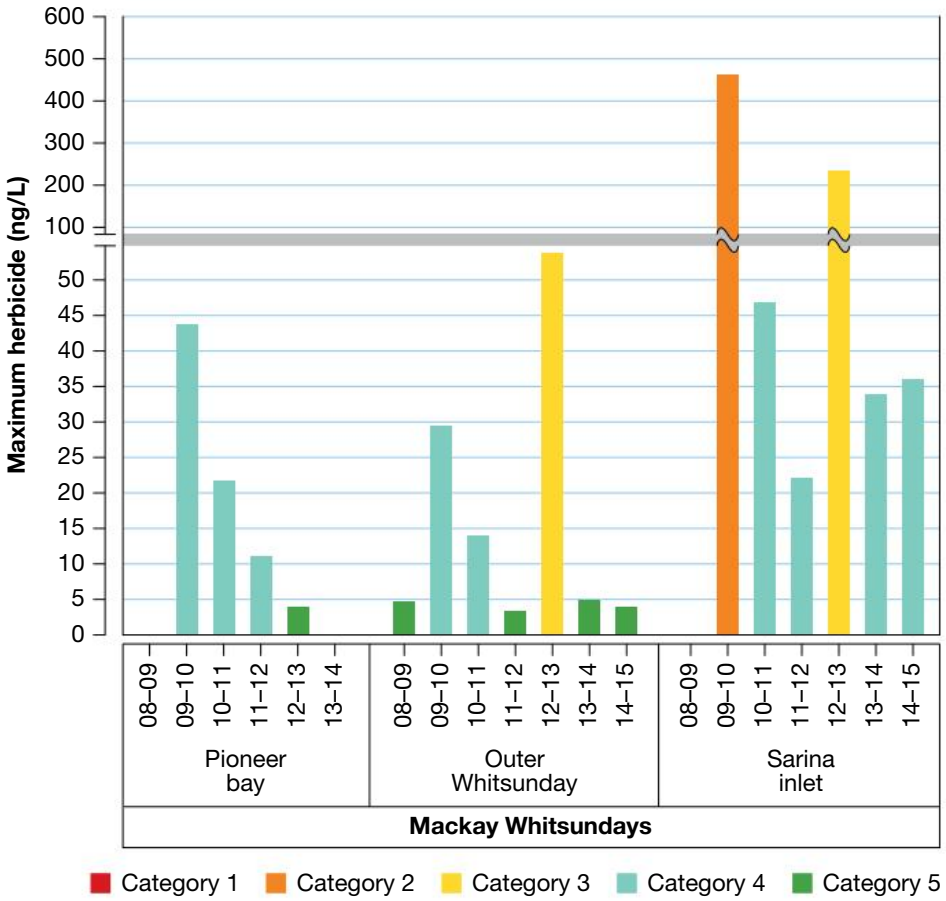

FIGURE 17.24 Bar graph showing the maximum concentrations of herbicides that inhibit photosynthesis in the period from 2008–09 to 2014–15 in three regions of the Mackay Whitsundays region of the Great Barrier Reef. Note the break and the change of scale in the vertical axis. (Source of data: Great Barrier Reef Report Card 2015: Marine results page 14.)

10 Consider a simple experiment to investigate the relationship between wavelength of light and growth rate in which trays of seedlings are grown under conditions with different wavelengths. ➜

- **a** Identify the independent variable in this experiment.
- **b** Identify the dependent variable.
- **c** Identify at least four controlled variables that should be identified by the investigator.
- **d** Which kind of variable is:
  - i kept constant throughout the experiment
  - ii manipulated by the investigator during the experiment
  - iii observed during the experiment and changes recorded?
- **e** Would a sample size of two seedlings, one test and one control, be a good design? Explain.

11 Consider the following data: ➜

- i labelling of S, M, L, XL, XXL on items of clothing
- ii labelling of 300 mL, 600 mL, 1 litre, 2 litre on drink cartons
- iii values of 73 °C, 86 °C, 54 °C, and 92 °C identified as maximum daily temperatures
- iv classification of cats as Birman, Siamese, Tonkinese, Manx, Russian Blue.

- **a** Which, if any, are examples of a categorical variable?
- **b** Which, if any, are examples of a numerical variable?

12 Examine the graph titled *Phytoplankton and Zebra Mussels in the Hudson River* shown at the Cary Institute weblink and answer the following questions: ➜

- **a** What kind of graph is this?
- **b** What variable is represented by the blue data points?
- **c** What variable is represented by the red data points?
- **d** Phytoplankton are microscopic photosynthetic organisms found in bodies of freshwater. What was the peak concentration of phytoplankton in the Hudson River?
- **e** The concentration of chlorophyll a has been used as a substitute for the concentration of phytoplankton. Can you suggest why this was done?
- **f** What trend is apparent in the phytoplankton population over the period shown?
- **g** Zebra mussels (*Dreissena polymorpha*) are filter feeders, and this non-native species reached the Hudson River in 1991. What happened to the phytoplankton population in the period after 1991?
- **h** Write a hypothesis that might explain the sudden and persistent decline in the phytoplankton population.
- **i** Suggest how this hypothesis might be tested.

eBookplus
Weblink
Cary Institute

13 Consider the hypothesis: *IF the growth rate of plants depends on the duration of sunlight they receive, and seedlings are exposed to varying periods of light, THEN seedlings exposed to longer periods of light will grow faster than those exposed to shorter periods.* ➜

- **a** Identify the independent variable.
- **b** Identify the dependent variable.
- **c** State the prediction that would be used to test this hypothesis.
- **d** Suggest a possible means by which the growth rates might be measured.
- **e** Identify three controlled variables that would need to be taken into account when designing an experiment to test this hypothesis.

14 Consider the following table that shows the results of an experiment that looked at the effects of salinity on plant growth: ➜

- **a** How many replicates were used in the control group? In each experimental group?
- **b** Why not use just two or three?
- **c** What is the independent variable in this experiment?
- **d** What is the dependent variable?
- **e** Identify three possible controlled variables.

TABLE 17.7 The effects of salinity on plant growth.

Concentration of salt water (mg/L)	Replicates: seedling root length (mm)										Average length
	1	2	3	4	5	6	7	8	9	10	
0 (control)	20	16	16	9	14	13	13	10	12	10	13.3
0.75	14	22	13	14	15	16	11	16	17	10	14.8
1.5	15	19	12	18	10	7	0	9	4	13	11.8
3	9	7	6	6	16	11	10	17	11	6	9.9
6	1	1	0	0	0	0	0	0	0	0	0.2
12	1	0	0	0	0	0	0	0	0	0	0.1

Glossary

A

abiotic factor: nonliving factor, such as weather, that can affect population size

acacia shrubland: major vegetation type dominated by mulga, a species of *Acacia*, occurring in arid inland Australia

accessory pigments: pigments, other than chlorophyll, that trap light energy and transfer it to chlorophyll

active transport: movement of dissolved substance across a plasma membrane in an energy-requiring process that results in a net movement of that substance against a concentration gradient from a region of lower concentration to a region of higher concentration

acute hypothermia: occurs when a person is suddenly exposed to extreme cold

adaptation: features that appear to equip an organism for survival in a particular habitat

adenine (A): one of the bases (A) found in the nucleotides that are the building blocks of DNA (and RNA)

adenosine triphosphate (ATP): compound that is the common source of chemical energy for cells and whose structure comprises one adenosine molecule and three phosphate molecules

aerobic respiration: the breakdown of glucose to simple inorganic compounds in the presence of oxygen and with release of energy that is transferred to ATP

albinism: inherited condition in which pigment production does not occur normally; in the form known as oculo-cutaneous albinism, pigment is absent from the skin, hair and iris

alcoholic fermentation: anaerobic respiration in yeasts

alleles: the different forms of a particular gene

allelochemicals: substances produced by plants that prevent or limit damage by herbivores

allelopathy: a form of competition involving the release of a chemical by one plant species that inhibits the growth of other species

allograft: where skin from another person may be grafted onto the burned area of a victim

amensalism: any relationship between organisms of different species in which one organism is inhibited or destroyed, while the other organism gains no specific benefit and remains unaffected in any significant way

anaerobic respiration: respiration that occurs without the involvement of oxygen; the end products of anaerobic respiration in human muscle are lactic acid and carbon dioxide

anaphase: stage of mitosis during which single-stranded chromosomes move to opposite poles of the spindle fibre within a cell

antenatal: pre-birth development in humans

antibiotic: naturally occurring substance that inhibits the growth of, or destroys, bacteria and other micro-organisms

antidiuretic hormone: hormone produced by neurosecretory cells in the hypothalamus; increases reabsorption of water into the blood from distal tubules and collecting ducts of nephrons in the kidney

antigens: proteins on the plasma membrane of the red blood cells, the presence or absence of which determines phenotype

aorta: major artery that carries oxygenated blood away from the heart to body tissues

aortic aneurysm: a balloon-like bulge in the wall of the aorta that results from the force of the blood being pumped through the aorta

aquaporins: channel proteins that are specific for the facilitated diffusion of water molecules

Archaea domain: one of the three domains in the Woese system of classification that includes those prokaryotic organisms known as archaeans

asexual reproduction: method of producing offspring that does not involve the fusion of different gametes, for example, binary fission

atherosclerosis: a condition that results when the arteries become clogged with fatty substances, known as plaques or atheroma, that can result in an aneurysm

atrium: chamber of vertebrate heart that receives blood from veins; also called auricle

autograft: a transplant of healthy skin from one area of a person to a damaged area of the same person

autophagy: breakdown by lysosomes of non-functioning cell organelles that are old and/or damaged and in need of turnover

autosomal genes: have two copies of each gene located on an autosome
autosome: any one of a pair of homologous chromosomes that are identical in appearance in males and females of a species
autotrophs: organisms that, given a source of energy, can produce their own food from simple inorganic substances; also known as producers

B

bacteria: (singular = bacterium) microscopic, usually unicellular organism, and member of Kingdom Monera
Bacteria domain: one of the three domains in the Woese system of classification that includes those prokaryotic organisms known as bacteria
base pairs: any of the pairs formed between complementary bases in the two nucleotide chains of DNA, such as A–T and C–G; can also refer to any complementary pairs formed between a DNA chain and an RNA chain
base sequence: specific order of nucleotides (bases) along a DNA (or an RNA) chain
behavioural activities: activities that an animal performs in response to internal and external stimuli
binary fission: process of cell multiplication in bacteria and other unicellular organisms in which there is no formation of spindle fibres and no chromosomal condensation
binomial system of naming: system of naming organisms, introduced by Linnaeus, in which all species are given a two-part scientific name, the first part being the generic name and the second being the trivial (specific) name
biodiversity: total variety of life forms, their genes and the ecosystems of which they are a part; biodiversity can relate to planet Earth or to a given region
biogenesis: accepted view that new cells are produced from existing cells
biomimicry: a developing discipline that is increasingly affecting human life through the development of new designs and products
biotic factor: living factor, such as predators or disease, that can affect population size
blastocyst: a hollow fluid-filled structure, called a blastocyst, with an inner mass of cells surrounded by an outer layer of cells
blood circulatory system: mechanism that delivers nutrients and oxygen to all cells of a multicellular organism
Bowman's capsule: part of a nephron surrounding a glomerulus in the kidney

C

calcitriol: hormone that increases calcium levels in the blood and contributes to bone strength
cancer: a disease in which cells divide in an uncontrolled manner, forming an abnormal mass of cells called a tumour
carnivore: organism that kills and eats animals
carrier protein: protein that binds to specific substance and facilitates its movement; may be carrier for lipophilic hormone for transport in the blood; also refers to proteins that facilitate movement across the plasma membrane
Cell Theory: unifying theory of biology that identifies all living things as being made of cells
cell wall: semi-rigid structure located outside the plasma membrane in cells of plants, algae, fungi and bacteria
cellular respiration: process of converting chemical energy of food into a form usable by cells, typically ATP
cellulose: complex carbohydrate composed of chains of glucose molecules; the main component of plant cell walls
centromere: position where the chromatids are held together in a chromosome
Chargaff's rule: regularity observed by Chargaff that, in DNA, the relative proportions of A and T are equal and, similarly, the proportion of C is equal to that of G
chemical energy: potential energy stored in substances that becomes available when certain types of chemical reactions occur
chemosynthesis: autotrophic bacteria that use energy from chemical reactions to synthesise organic matter from inorganic substances
chenopod shrubland: major vegetation type dominated by saltbushes (*Atriplex* spp.) and bluebushes (*Maireana* spp.); occurs in arid regions with salty soils
chlorophyll: green pigment required for photosynthesis that traps the radiant energy of sunlight
chloroplast: chlorophyll-containing organelle that occurs in the cytosol of cells of specific plant tissues
chromatid: one of the strands in a double-stranded chromosome
chromatin: stained material in the nucleus of a eukaryotic cell
chromosome: thread-like structure composed of DNA and protein, and visible in cells during mitosis and meiosis
cilia: (singular = cilium) in eukaryote cells, whip-like structures formed by extensions of the plasma membrane involved in synchronised movement

cladistics: in reference to classification, the grouping of organisms according to the number of derived characters that they share
cladodes: fine green branches that carry out photosynthesis in plant species where leaves are very reduced
cladogram: diagram, based on cladistic study, that shows the inferred relationship between different groups of organisms
class: taxonomic grouping consisting of members of related orders
classification: artificial process of organising things into groups according to one or more criteria
clones: groups of cells, organisms or genes with identical genetic make-up
co-dominance: relationship between two alleles of a gene such that a heterozygous organism shows the expression of both alleles in its phenotype; sometimes termed partial dominance or incomplete dominance
cohesion: the tendency of molecules of the same kind to stick together
commensalism: association between two different species in a community in which one benefits and the second apparently neither gains nor is harmed
community: biological unit consisting of all the populations living in a specific area at a specific time
comparative genomics: comparative study of the genomes of several species
competition: interaction between individuals of the same or different species that use one or more of the same resources in the same ecosystem
complementary base pair: the base pair between two strands of DNA
conduction: involves heat transfer by immediate physical contact with another object at a different temperature
congenital malformation: birth defect that can result from exposure to certain chemicals (teratogens) during critical periods of organ development, in particular during the embryonic stage of development
consumers: organisms that obtain their energy and organic matter by eating or ingesting the organic matter of other organisms; also termed heterotrophs
contact inhibition: cells which stop dividing if they begin to overgrow adjacent cells.
continuous variation: type of variation in which members of a population vary across a range
convection: the process of heat transfer resulting from the mass movement of air (or water)
core body temperature: temperature of internal cells of the body; in humans, core temperature is around 37 °C
coronary angioplasty: nonsurgical intervention to address blockages or narrowing of coronary arteries
coronary bypass graft surgery: surgical procedure that is used if the damage to coronary arteries is severe in which the blocked part of a coronary artery is bypassed by grafting another blood vessel above and below the blocked segment of the coronary artery
corpus luteum: tissue that forms in the follicle in the ovary of mammals after the egg is released and which produces progesterone
countercurrent exchange system: situation in which two fluid systems flowing adjacent to each other, but in opposite directions, enables the transfer of heat or compounds from one system to the other by diffusion
crossing over: event that occurs during meiosis after synapsis; involves an exchange of corresponding segments of non-sister chromatids of homologous chromosomes and can result in new combinations of alleles of linked genes
crypts: intestinal infoldings, located between intestinal villi and where the intestinal stem cells are positioned
cuticle: waxy layer on the outer side of epidermal cells; waxy outer layer on leaves
cycads: an ancient group of palm-like land plants that produce toxic compounds
cystic fibrosis: a condition, inherited as an autosomal recessive, in which an affected person produces abnormal mucus secretions
cytokinesis: division of cytoplasm occurring after mitosis
cytoplasm: formed by cell organelles, excluding the nucleus, and the cytosol
cytosine (C): one of the pyrimidine bases found in the nucleotides that are the building blocks of DNA (and RNA)
cytoskeleton: network of filaments within a cell
cytosol: fluid contents only of a eukaryotic cell

D

deciduous: trees or plants that lose their leaves seasonally
decomposers: organisms, such as fungi, that can break down and absorb organic matter of dead organisms or their products
deletion: type of chromosome change in which part of a chromosome is lost
density-dependent factor: factor whose impact on members of a population is dependent on the size of the population
density-independent factor: factor whose impact on members of a population is not affected by the size of the population

deoxyribonucleic acid (DNA): nucleic acid containing the four bases — adenine, guanine, cytosine and thymine — which forms the major component of chromosomes and contains coded genetic instructions
deoxyribose: five-carbon sugar that forms one component of the nucleotides found in DNA
derived characters: modified features that were not present in the common ancestor of a group but evolved later in some members only of the group; features useful in cladistic analysis
dermal tissues: tissues of the skin
dermis: underlying part of the skin
desiccation: drying out
detritivores: organisms that eat particles of organic matter found in soil or water
detritus: fragments of organic material present in soil and water
dichotomous key: means of identifying organisms based on a series of questions, each able to be answered by selecting one of two alternatives
differential reproduction: occurs when different inherited varieties in a population vary in their rates of production of viable offspring
dihybrid: refers to a cross in which alleles of two different genes are involved
dihybrid cross: refers to a cross in which alleles of two different genes are involved
diploid number: refers to organisms or cells having two copies of each specific chromosome, that is, having a paired set of chromosomes
discontinuous variation: type of variation in which members of a population can be grouped into a few non-overlapping classes with regard to expression of a trait
dissociation: separation of a double-stranded DNA molecule into its single strands, which occurs when the hydrogen bonds stabilising the two strands are broken, such as by heating
diversity: measure of 'species richness' or the number of different species in a community
DNA barcoding: a new and rapid means of differentiating species based on the DNA sequence of a particular gene
DNA sequencing: process of determining the order of bases along one chain of a DNA segment
domains: three major groups — Bacteria, Archaea and Eukarya — each containing several kingdoms
dominant: refers to a trait that is expressed in the heterozygous condition; also refers to a trait that requires only a single copy of the responsible allele for its phenotypic expression
dormancy: condition of inactivity resulting from extreme lowering of metabolic rate in an organism
double helix: three-dimensional structure of DNA consisting of two nucleotide chains coiled in a regular manner
Down syndrome (DS): chromosomal disorder due to the presence of an additional number 21chromosome, either as a separate chromosome (trisomy- or triplo-DS) or attached to another chromosome (translocation DS)
drought-resistant seeds: seeds able to withstand periods of deficiency in rainfall compared with the average
duplication: type of chromosome change in which part of a chromosome is repeated
dyad: double-stranded chromosomes line up during metaphase

E

ecology: study of communities in their habitats and the interactions between them and their environment
ecosystems: biological units comprising the community living in a discrete region, the non-living surroundings and the interactions occurring within the community and between the community and its surroundings
ectoderm: a primary germ layer
ectothermic: organism whose body temperature is governed by external sources of heat
eggs: female gamete produced in an ovary
electron transport chain: third stage of aerobic respiration in which electrons are transferred along a series of compounds known as cytochromes to be finally accepted by oxygen; energy released during this process results in the major yield of ATP
embryo: early stage of a developing organism; in humans includes the first eight weeks of development
embryo splitting: process of separating the totipotent cells of a very early embryo, so that the resultant cells are each able to form a complete embryo
embryonic stem cell: undifferentiated cells obtained from early embryonic tissue and capable of differentiating into many cell types
emphysema: a respiratory disease in which the alveoli become progressively and permanently damaged
endocrine system: system of ductless glands that produce hormones and release them directly into the bloodstream
endemic: unique to a country, do not occur naturally in any other parts of the world
endocytosis: bulk movement of solids or liquids into a cell by engulfment
endoderm: a primary germ layer
endoparasites: organisms that live inside another organism (the host) and obtain food from it, such as a tapeworm

endoplasmic reticulum (ER): cell organelle consisting of a system of membrane-bound channels that transport substances within the cell
endosymbiosis: a special case of symbiosis where one of the organisms lives inside the other
Endosymbiosis Theory: see endosymbiosis, a theory proposed by Lynn Margulis
endothermic: organism whose body heat is generated from internal metabolic sources
endotoxin: toxins produced by an organism and released only when the organism disintegrates
enucleated cell: refers to a cell from which the nucleus has been removed
ephemeral: refers to plant species that germinate, grow and produce seed within a short period of weeks
epicormic shoot: growth occurring from dormant buds under the bark after crown foliage is destroyed
epithelial tissues: cover flat surfaces
erythrocytes: red blood cells
eukaryote: cell or organism with a membrane-bound nucleus
eukaryotic: describing cells that have a membrane-bound nucleus
exoparasite: parasite that lives *on* its host
exponential growth: population growth that follows a J-shaped curve but cannot continue indefinitely
extinct: refers to a species of which no living members exist
extracellular fluid: also called tissue fluid; the fluid that surrounds and bathes the membranes of nearly all cells
extremophile: microbe that lives in extreme environmental conditions, such as high temperature and low pH

F

facilitated diffusion: form of diffusion involving a specific carrier molecule for the substance that diffuses
facultative anaerobe: organism that can live regardless of whether oxygen is present or not
family: taxonomic grouping consisting of members of related genera
fermentation: process of anaerobic respiration in yeasts that results in alcohol formation
fertilisation: union of egg and sperm to form a zygote
fetus: developing human baby from week nine to birth
field guides: identification tools containing verbal descriptions and/or images of organisms found in a particular region
FISH staining: fluorescence *in situ* hybridisation, a technique using a fluorescent probe to detect a specific DNA sequence in its chromosomal location
flagella: (singular = flagellum) whip-like cell organelles involved in movement
fluid mosaic model: a model which proposes that the plasma membrane and other intracellular membranes should be considered as two-dimensional fluids in which proteins are embedded
fluorescence microscope: microscope in which cells are labelled with fluorescent probes and when irradiated with light of a particular wavelength, the probes are excited and fluoresce
follicle: structure in an ovary where an egg develops
follicle-stimulating hormone (FSH): hormone, produced by the pituitary gland, that stimulates the growth of ovarian follicles and the ripening of an egg
food chain: one kind of representation to show chemical energy flow within an ecosystem beginning with producers
food web: one kind of representation of energy flow in an ecosystem; a food web comprises interrelated food chains
fossil: evidence or remains of an organism that lived long ago
free-standing water: water available for an animal to use, including to drink

G

G1 checkpoint: occurs at the G1 (Gap 1) stage of interphase, the cell is ready to undergo division so a check of the DNA of the cell occurs
G2 checkpoint: where the replicated DNA of the cell is checked for completeness and lack of damage. If the cell passes this checkpoint, it can then advance to the mitosis stage of the cell cycle.
gametes: eggs or sperm cells
gastrulation: the name given to the complex cell migrations that re-organise the inner cell mass of the embryo blastocyst into a three-layered structure
gene: inherited instruction carried on a chromosome; specific segment of DNA carrying an instruction encoded in its base sequence for a specific protein product
gene duplication: where a second copy of a gene appears in a genome
generic name: name of the genus to which an organism belongs; first part of a scientific name
genetic screening: testing of persons to detect those with the allele responsible for a particular genetic disorder
genetic testing: testing of persons to detect those with the allele responsible for a particular genetic disorder
genetic variation: variation exhibited among members of a population owing to the action of genes

genome: sum total of the genes present in a cell or an organism
genomics: study of the entire genetic make-up or genome of a species
genotype: refers to both the double set of genetic instructions present in a diploid organism and to the genetic make-up of an organism at one particular gene locus
genus: (plural = genera) taxonomic group consisting of members of related species
germ layers: ectoderm, mesoderm and endoderm
gestation period: time from fertilisation to birth
glomerulus: cluster of capillaries inside the Bowman's capsule of a nephron
glucagon: hormone produced by alpha cells of the pancreas that acts on liver cells resulting in increased release of glucose from the liver cells into the bloodstream
glycogen: a polysaccharide that is the storage carbohydrate in liver and muscle tissue
glycolysis: a process that does not require oxygen where glucose is broken down to pyruvate
glycoprotein: combination formed when a carbohydrate group becomes attached to the exposed part of a trans-membrane protein
goitre: extreme swelling of the thyroid gland
Golgi complex: organelle that packages material into vesicles for export from a cell (also known as Golgi apparatus or Golgi body)
gonads: organs in which gametes are formed; ovaries or testes
gram-positive bacteria: group of microbes within the Bacteria domain that includes members responsible for many human and animal infectious diseases
grana: (singular = granum) stacks of membranes on which chlorophyll is located in chloroplasts
growth hormone: somatotropin; large peptide hormone that stimulates body growth
guanine (G): one of the purine bases present in the nucleotides that are the building blocks of DNA (and RNA)

H

haploid: having one copy of each specific chromosome: that is, having a set of unpaired chromosomes
haustoria: (singular = haustorium) thin strand of tissue through which a plant parasite makes connection with its host
heat stroke: a critical and life-threatening condition; symptoms include high core body temperature in excess of 41 °C, slurred speech, hallucinations and multiple organ damage
hemiparasitism: form of parasitism in which a plant parasite obtains some nutrients and water from its host plant but also makes some of its own food through photosynthesis
hemizygous: in a male mammal, describes the genotype with respect to any gene carried on either the X or the Y chromosome, which comprises just a single allele for each gene
herbarium: (plural = herbaria) institution where scientific collections of plant specimens are held
herbivore–plant relationship: one of many relationships existing between different species in a community, this one being the interaction between plants and the animals that eat them
herbivore: organism that eats living plants or parts of them
hermaphrodite: organism that has both egg-producing and sperm-producing organs
heterotroph: organism that ingests or absorbs food in the form of organic material from their environment; also known as a consumer
heterozygous: refers to a diploid cell or organism whose genotype for a particular gene comprises two different alleles. This state may be denoted, for example, as ***Aa***.
histotoxic hypoxia: the inability of cells to use any oxygen; caused by inhibition of the cytochrome oxidase enzyme
holoparasitise: form of parasitism in which a plant parasite depends completely on its host for nutrients and water
homeostasis: condition of a relatively stable internal environment maintained within narrow limits
homologous: refers to members of a matching pair of chromosomes
homozygous: refers to a diploid cell or organism whose genotype for a particular gene comprises two identical alleles. This state may be denoted, for example, as ***AA*** or ***aa***.
horizontal gene transfer: acquisition of a new gene by a species as a result of transfer from another species
hormone: in animals, chemicals produced in an endocrine gland that are released into and transported via the bloodstream to other parts of the body where they act; in plants, chemicals produced in small amounts in cells in one part of a plant that act on other cells involved in growth and development
host: organism on or in which a specific parasite lives
Human Genome Project (HPG): international project directed at the identification of the sequence of the more than three billion bases in the human genome
humidity: measure of the amount of water vapour in the atmosphere
hummock grassland: major vegetation type dominated by spinifex grasses and occurring over one-quarter of Australia
Hurler syndrome: abnormal accumulation of complex carbohydrates

hybridisation: pairing between single-stranded complementary DNA segments from organisms from the same or even different species
hydrogen bonds: weak, non-covalent bonds that form between complementary nucleotides in different DNA strands; hydrogen bonds are responsible for stabilising the structure of the DNA double helix
hydrolysis: a chemical reaction where a water molecule is added
hydrophilic: refers to substances that dissolve easily in water; also called polar
hydrophobic: refers to substances that tend to be insoluble in water; also called non-polar
hydrothermal vents: regions at the ocean depths where mineral-laden superheated water escapes from the Earth's crust, typically through a 'chimney' composed of precipitated mineral deposits
hyperglycaemia: a condition where glucose levels in the blood rise above normal
hyperthermia: condition in which an individual has an extremely low body temperature and is at risk of death
hyperthyroidism: condition in which there is an overabundance in thyroid hormone production
hypertonic: having a higher concentration of dissolved substances than the solution to which it is compared
hypoglycaemia: glucose levels in the blood drop below normal
hypothalamus: tiny region of the brain below the thalamus that controls various essential functions, including those associated with the autonomic nervous system
hypothermia: condition in which an individual has an extremely low body temperature and is at risk of death
hypothyroidism: condition in which there is a deficiency in thyroid hormone production
hypotonic: having a lower concentration of dissolved substances than the solution to which it is compared

I

ideogram: stylised representation of a haploid set of chromosomes arranged in order of decreasing size
induced pluripotent stem cell: stem cell that has been genetically reprogrammed to return to an undifferentiated embryonic state through the addition of four specific embryonic genes, which encode proteins that are known to keep stem cells in an undifferentiated state
insensible water loss: loss of water vapour from the lungs and their passages on exhalation
insulating layer: layers of fat under the skin of mammals that retain heat within the body
insulin: hormone produced by beta cells of the pancreas that acts to increase the uptake of glucose from the blood by body cells
insulin resistant: where the body cells of a person do not respond to the insulin that is produced
integral proteins: fundamental components of the plasma membrane that are embedded in the phospholipid bilayer
internal fertilisation: union of sperm and egg occurring inside the body of the female parent
interphase: in the mitotic cell cycle, period of cell growth and DNA synthesis
interspecific competition: competition for resources in an ecosystem involving members of one species and members of other species
interstitial fluid: fluid that fills the spaces between cells and bathes their plasma membranes
intraspecific competition: competition for resources in an ecosystem involving members of the same species
Ishihara colour plate: coloured plate that contains a red or green number or shape embedded in a circle of dots random in colour and size; used to test for red–green colourblindness
isotonic: having the same concentration of dissolved substances as the solution to which it is compared

K

karyotype: specific complement of chromosomes present in a cell or an individual arranged in an organised manner according to an agreed convention
keratinocytes: several layers of living cells that are gradually pushed upwards, becoming flattened and eventually forming part of the outermost region of dead cells of the epidermis
ketone: acid; breakdown product of fat metabolism
keys: means for identification of organisms based on a series of questions
keystone species: species whose presence in an ecosystem is essential for the maintenance of that ecosystem
kidney disease: disease of the excretory organs that filter wastes, mainly nitrogenous, from the blood and form urine
kinetochore: a special attachment site of a chromatid by which it links to a spindle fibre
kingdom: level of classification above phylum
Kreb's cycle: second stage of aerobic respiration, occurring mainly in mitochondria, in which pyruvate is broken down to carbon dioxide

L

leucocytes: white blood cells
lignin: a complex insoluble cross-linked polymer

limiting factor: environmental condition that restricts the types of organism that can survive in a given habitat
linked genes: describes genes whose loci are located on a given chromosome
lipids: general term for fats, oils and waxes
littoral (intertidal) zone: intertidal zone along a coast between high- and low-water marks
locus: (plural = loci) position of a gene on a chromosome
loop of Henle: section of tubule in a nephron where urine becomes concentrated by removal of water
lumbar puncture: process used to take a sample of cerebrospinal fluid (CSF)
lysosome: a sac which destroys bacteria
lysosome storage disease: a disruption of normal cell function due to defective enzymes; examples include Tay-Sachs disease, Hurler syndrome, Pompe disease

M

M checkpoint: connection between chromatid and spindle fibres is checked and, if it is not correct, the cell cycle is delayed until the arrangement is corrected
macroscopic: of a size that is visible to the unaided eye
meiosis: process of cell division that results in the production of new cells, each containing half the number of chromosomes of the original cell
melanoma: cancer derived from the pigment-producing cells (melanocytes)
Mendel's factors: term that identifies the name given by Gregor Mendel to entities in his postulated model of inheritance in peas
meninges: membranous tissue surrounding the brain and spinal cord and separated from them by a thin layer of fluid
meningitis: disease that results if the bacteria *N. meningitidis* cross the blood–brain barrier and reach the cerebrospinal fluid that bathes the brain and spinal cord
menstrual age: gestational age of pregnancy
meristem: plant tissue found in tips of roots and shoots and made of unspecialised cells that can reproduce by mitosis
meristematic tissues: the source of the cells that grow into plantlets
metaphase: stage of mitosis during which chromosomes align around the equator of a spindle
metastasis: a process where malignant tumours spread throughout the body
methanogens: microbes within the Archaea domain that gain their energy for living from chemical reactions that produce methane
microbial mat: composed of multilayers of a community of microbial species that can form on moist or submerged surfaces including lakebeds, on sediments such as mud or sand, on tidal flats, in hypersaline (very salty) pools, in fissures, around hot springs and even around deep ocean vents
microscopes: instruments used for viewing cells and other small objects to give an increase in both magnification and resolution
microtubules: part of the supporting structure or cytoskeleton of a cell, made of sub-units of the protein tubulin
mid-ocean ridges: series of ridges and mounts located on the ocean floor
mimicry: a situation in which one species has an appearance similar to that of a different but distasteful species where that similarity apparently gives protection against predators
mitochondria: (singular = mitochondrion) in eukaryotic cells, organelles that are the major site of ATP production
mitosis: process involved in the production of new cells genetically identical with the original cell; an essential process in asexual reproduction
monogenic: refers to traits that are under the control of single genes
monohybrid cross: a cross in which alleles of only one gene are involved
monosomy: condition in which a cell or organism has only one copy of a particular chromosome that is normally present as a homologous pair
mulgara: a small native marsupial mammal
multiple fission: process of division in which multiple cells are produced from a single starting cell
multipotent: refers to a cell that can differentiate into a number of closely related cell types
mutagen: environmental factor that causes gene mutations
mutualism: an association between two different species in a community in which both gain some benefit
mycorrhiza: fine threads formed by a fungus that form a large surface area for uptake of nutrients

N

nephron: functional units of a kidney
nervous cells: neurons, each generally consisting of a cell body, dendrites and an axon and specialised to initiate, receive and transmit electrical signals
nitrogen-fixing bacteria: bacteria able to convert nitrogen from the atmosphere into ammonium ions
noncoding DNA: DNA that is not transcribed into proteins

nondisjunction: failure of normal separation of homologous chromosomes during meiosis or failure of normal separation of the two strands of a double-stranded chromosome during meiosis or mitosis
nonhomologous: nonmatching chromosomes
nuclear envelope: membrane surrounding the nucleus of a eukaryote cell
nuclear pore complex: protein-lined channel that perforates the nuclear envelope
nucleic acid: compound, such as DNA or RNA, built from nucleotide sub-units
nucleoli: (singular = nucleolus) structure present in the nucleus and which is a store of ribosomal RNA (rRNA)
nucleosome: super coil of DNA coiled around histones
nucleotides: basic building blocks or sub-units of DNA and RNA and consisting of a phosphate group, a base and a sugar; the sugar in DNA is deoxyribose and that in RNA is ribose
nucleus: in eukaryotic cells, membrane-bound organelle containing the genetic material DNA

O

obligate anerobe: microbe that lives only in anoxic conditions to which oxygen is toxic
omnivore: organism that eat both plants and animals
oncogene: gene that signals cells to continue dividing
open reading frame: in a computer scan, a long sequence before a stop signal is reached that indicates possible genes
operculum: in fish, the flaps covering the gills; in molluscs, a hard impermeable lid that closes the shell, making a watertight compartment for the animal inside
order: taxonomic grouping consisting of members of related families
organ: structure consisting of several tissues that is specialised to carry out a particular biological function, for example, liver, kidney
osmoregulation: maintenance of constant internal salt and water concentrations in internal fluids (homeostasis) in spite of different concentrations in the external environment
osmosis: net movement of water across a partially permeable membrane without an input of energy and down a concentration gradient
ovary: egg-producing organ
ovulation: release of an egg from the ovary
oxygenic: (oxygen-producing) the type of photosynthesis carried out by plants and algae

P

palynology: the branch of biology concerned with the study and identification of pollen
pancreas: organ that secretes digestive enzymes into the duodenum and hormones into the bloodstream
parasite: organism that lives on or in another organism and feeds from it usually without killing it
parasite–host relationships: form of interaction within a community that involves one species, the parasite, living on or in another species, the host, typically without killing the host
parasitoids: adult females of some wasp and fly species that are like parasites but that slowly kill their hosts
parthenogenesis: one form of asexual reproduction in which new individuals are produced from unfertilised eggs
parthenote: potential source of embryonic stem cells, derived from unfertilised human eggs that are artificially stimulated to begin development
paternal inheritance: where DNA of Y-linked genes is transmitted exclusively from males to their sons only
pedigree: graphic representation using standard symbols showing the pattern of occurrence of an inherited trait in a family
peripheral proteins: are either anchored to the exterior of the plasma membrane through bonding with lipids or are indirectly associated with the plasma membrane through interactions with integral proteins in the membrane.
peripheral surface temperature: temperature of cells on the outside of the body; may be many degrees cooler than core temperature
peritubular capillaries: capillary network around the tubules in the kidney formed by the arteriole that leaves the capillaries of the glomerulus
permanent tissue: tissues that are made of cells that can no longer divide; include ground tissue, vascular tissue and dermal tissue
peroxisome: small membrane-bound organelle rich in the enzymes that detoxify various toxic materials that enter the bloodstream
phase contrast microscope: modified light microscope which enables transparent or unstained specimens, including living organisms, to be seen in more detail than can be obtained with a light microscope
phenotype: expression of an organism's genotype in its structural, biochemical and physiological characteristics
phloem: kind of vascular tissue in plants that transports sugar (mainly sucrose) and other organic compounds
phospholipids: major type of lipid found in plasma membranes
photosynthesis: process by which plants use the radiant energy of sunlight trapped by chlorophyll to build carbohydrates from carbon dioxide and water

phyllodes: leaf-like structures derived from a petiole (stem of a leaf)
phylum: (plural = phyla) taxonomic grouping consisting of members of related classes
pituitary gland: endocrine gland attached to the hypothalamus; influences the production of thyroxin by the thyroid
plant tissue culture: technique used to clone plants in large numbers
plasma: the fluid portion of blood in which blood cells are suspended
plasma membrane: partially permeable boundary of a cell separating it from its physical surroundings; boundary controlling entry to and exit of substances from a cell
pluripotent: a cell that can differentiate into many different cell types
polygene: genes that have a small, but cumulative effect on the phenotype and control polygenic traits
polygenic: traits controlled by the action of two or more polygenes
polynomial system: early system of naming organisms using long Latin descriptions; now superseded by the binomial system
polysaccharides: carbohydrates made of many monosaccharide units
population: members of one species living in one region at a particular time
positron emission tomography (PET): non-invasive technique that provides images of metabolic activity of tissues
predator: an animal that actively seeks out other animals as its source of food
predator–prey relationship: a form of interaction within a community that involves the eating of one species, the prey, by another species, the predator
prey: living animal that is captured and eaten by a predator
primary cell wall: the first layer of cellulose and other polysaccharides forming the cell wall outside a newly formed plant cell
primitive characters: features that were present in the common ancestor of a group of organisms
producers: photosynthetic organisms and chemosynthetic bacteria that, given a source of energy, can build organic matter from simple inorganic substances
prokaryotes: any cells or organisms without a membrane-bound nucleus
promoters: part of the upstream flanking region of a gene containing base sequences that control the activity of that gene
prophase: stage of mitosis in which the chromosomes contract and become visible, the nuclear membrane begins to disintegrate and the spindle forms
proteins: macromolecules built of amino acid sub-units and linked by peptide bonds to form a chain, sometimes termed a polypeptide; usual product of gene translation; some proteins consist of a single polypeptide while other proteins consist of two or more polypeptides
proteomics: the study of the proteome, the complete array of proteins produced by an organism
proto-cell: one of the earliest cells on Earth
psoriasis: chronic autoimmune condition in which skin cells are overproduced, resulting in raised patches of red inflamed skin, often covered in a crust of small silvery scales
pulmonary artery: major artery that carries deoxygenated blood from the heart to the lungs
pulmonary veins: major veins that return oxygenated blood from the lungs to the heart
pumps: special transport proteins embedded across the plasma membrane that carry out the process of active transport

R

radiant energy: kind of wave energy which includes X-rays, ultraviolet rays and, most importantly, visible sunlight
raptors: birds of prey, such as eagles, hawks, owls
re-association: pairing again of single strands of DNA during cooling after the two strands of a DNA double helix have been dissociated by heating
receptors: chemical structures, often on the surface of cells, that receive signals from hormones, neurons or cytokines
recessive: refers to a trait that is not expressed but remains hidden in a heterozygous organism
recombination: process of generating new combinations of alleles of various genes both by crossing over and by independent assortment during meiosis reduction division; a starting cell with 46 chromosomes gives rise to gametes, either egg or sperm, that have only 23 chromosomes.
reference collection: collections of plant or animal species held in herbaria and museums respectively
regenerative medicine: still at an experimental stage but it raises promises for the treatment of degenerative conditions and severe trauma injuries.
resolution: measure of the ability of a microscope to distinguish fine detail in a specimen; higher resolution means finer detail can be seen.
resolving power: refers to the minimum distance apart that two points must be in order for them to be seen as two discrete points
retrovirus: viruses whose genetic material is RNA; the RNA is changed into a molecule of DNA that is inserted into a host's DNA when the retrovirus enters the host cell.

rhizoids: fine root-like structures present in some plants such as mosses
rhizomes: horizontal underground stems
ribonucleic acid (RNA): type of nucleic acid consisting of a single chain of nucleotide sub-units which contain the sugar, ribose and the bases A, U, C and G; RNA includes messenger RNA (mRNA), transfer RNA(tRNA) and ribosomal RNA (rRNA).
ribosome: organelle containing RNA that is the major site of protein production in cells
rough endoplasmic reticulum: endoplasmic reticulum with ribosomes attached

S

S stage of interphase: the stage where the parent cell replicates its DNA; at the end of the S stages the parent cell contains two identical copies of its original DNA.
scanning electron microscope (SEM): type of microscope that enables observation of cell and tissue surfaces
scats: animal faeces or droppings
secondary cell wall: walls of lignin and cellulose deposited on the primary cell wall of some plant cells after cell growth has ceased
selectively permeable (semipermeable): allows some substances to cross but precludes the passage of others
sequential hermaphrodite: organism that can change sex
sessile: fixed to one spot
sex chromosomes: the pair of chromosomes that differ in males and females of a species
sexual reproduction: method of producing offspring in which an egg and a sperm fuse to form a zygote
shunt vessel: directly connects arteries and veins
simple diffusion: the movement of substances across the phospholipid bilayer from a region of higher concentration to one of lower concentration of that substance; that is, *down* its concentration gradient
simultaneous (synchronous) hermaphrodism: when both sperm-producing and egg-producing organs are active at the same time in one organism; occurs in snails and earthworms
smooth endoplasmic reticulum: involved in transporting different materials *within* cells, but they are not passive channels like pipes
sodium–potassium pump: protein that transports sodium and potassium ions against their concentration gradients to maintain the differences in their concentrations inside and outside cells
somatic (adult) stem cells: undifferentiated cells obtained from various sources and capable of differentiating into related cell types; also known as adult stem cells
somatic cells: refers to cells of the body other than germline cells
species: taxonomic unit consisting of organisms capable of mating and producing viable and fertile offspring
species diversity: the number of different species, that is, different populations, in a community
specific name: second part of the scientific name of a species, such as *sapiens* (in *Homo sapiens*)
sperm: male gametes produced in the testes
spindle: fine protein fibres that form between the poles of a cell during mitosis and to which chromosomes become attached
spindle fibres: clusters of microtubules, composed of the contractile protein actin, that grow out from the centrioles at opposite ends of a spindle; at anaphase the contraction of these fibres pull sister chromatids to the opposite poles of the spindle
sporangium: plane aerial structures where spores are formed by mitosis
spore: in bacteria, reproductive structure that is resistant to heat and desiccation; also formed by fungi and some plants
starch: complex carbohydrate (polysaccharide), polymer of glucose units; main storage carbohydrate in many plant cells
stem cells: cells with the capacity to reproduce themselves and then differentiate into either one or different kinds of cells; in bone marrow, a type of cell that reproduces and differentiates into the different kinds of blood cells
stomata: (singular = stoma) openings, typically on a leaf surface, through which water vapour and carbon dioxide can move
stroma: in chloroplasts, the semi-fluid substance between the grana which contains enzymes for some of the reactions of photosynthesis
sulfur-oxidising bacteria: one group of bacteria that gain their energy by oxidising sulfur compounds
surface-area-to-volume ratio: measure that identifies the number of units of surface area available to 'serve' each unit of internal volume of a cell, tissues or organism
symbiosis: prolonged association between different species in a community in which at least one partner benefits; includes parasitism, mutualism and commensalism
systematics: area of study concerned with identifying relationships between organisms and making inferences about their evolutionary history

T

taxon: (plural = taxa) any taxonomic group; for example, class, family, genus
taxonomist: biologists who specialise in the study of the classification of living things
taxonomy: area of study concerned with the describing, naming and classification of organisms

telomeres: normal terminal regions of a chromosome
telophase: stage of mitosis in which new nuclear membranes form around the separated groups of chromosomes
test cross: cross of an organism (uncertain genotype ***A***–) with a homozygous recessive organism (genotype ***aa***) to determine whether that organism is homozygous (***AA***) or heterozygous (***Aa***); cross of a double heterozygote (***AaBb***) with a homozygous recessive (***aabb***) to determine whether or not the two genes concerned are linked, and, if they are linked, to obtain an estimate of the distance between the two loci
testis: (plural = testes) male gonad that produces both sperm and male sex hormones
therapeutic cloning: cloning carried out to create an embryo from which stem cells can be harvested
thymine (T): one of the pyrimidine bases (T) found in the nucleotides that are the building blocks of DNA
thyroid gland: endocrine gland located on the ventral surface of the trachea
thyroxine: hormone produced by the thyroid gland that acts to increase the rate of cell metabolism
tolerance range: extent of variation in an environmental factor within which a particular species can survive
totipotent: refers to a cell that can differentiate into all different cell types
translocation: transport of organic material, including sugars, through the phloem of a vascular plant
transmission electron microscope (TEM): type of microscope that enables observation of very highly magnified images of cell sections; often abbreviated to TEM
transpiration: loss of water from the surfaces of a plant
trisomic: describes a cell or organism with three copies of a particular chromosome that is normally present as an homologous pair
trophic level: feeding level of an organism within a community
type 1 diabetes: a condition that results when the homeostatic mechanisms that regulate blood glucose levels fail when insulin production fails, characterised by a blood glucose level that is higher than normal
type 2 diabetes: a condition that results when insulin is produced but the homeostatic mechanisms that regulate blood glucose levels fail

V

vacuoles: structures within plant cells that are filled with fluid containing materials in solution, including plant pigments
vascular plants: plants that have xylem and phloem tissue
vascular tissue: plant tissue specialised for transport of nutrients, water and minerals, and which provides a plant with support
vegetative reproduction: asexual reproduction in plants
ventricle: heart chamber that pumps blood out of the heart
vesicle: membrane-bound sac found within a cell, typically fluid-filled; for example, lysosome

W

water tappers: refers to trees that have a single main root extending to depths near the water table before forming lateral branches

X

X-linked gene: gene with its locus on the X chromosome; also refers to a trait that is controlled by such a gene
xylem: the part of vascular tissue that transports water and minerals throughout a plant and provides a plant with support

Y

Y-linked gene: gene with its locus on the Y chromosome; also refers to a trait that is controlled by such a gene

Z

zygote: fertilised egg that results from the fusion of haploid gametes

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