Heinemann BIOLOGY 1

5TH EDITION

VCE Units 1 & 2
Written for the VCE Biology Study Design 2016–2021

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ALWAYS LEARNING

PEARSON

CHAPTER

01 Biology keystones — Foundation concepts and skills

The development of a set of key science skills is a core component of the study of VCE Biology and applies across Units 1 to 4 in all areas of study. Chapter 1 scaffolds the development of these skills. The opportunity to develop, use and demonstrate these skills in a variety of contexts is important ahead of undertaking investigations and when evaluating the research of others.

Although this chapter can be done as a whole, it is best to refer to it and use it when the need arises as you work through other chapters. For example, you may need a refresher on the structure of organic molecules or the process of the scientific method. It also contains useful checklists to assist when drawing scientific diagrams, graphing and completing aspects of your report. Similarly, when performing a first-hand investigation, refer to this chapter to make sure your investigation is valid, reliable and accurate.

Key skills

Develop aims and questions, formulate hypotheses and make predictions

- determine aims, hypotheses, questions and predictions that can be tested
- identify independent, dependent and controlled variables

Plan and undertake investigations

- determine appropriate type of investigation: conduct experiments (including use of controls); solve a scientific or technological problem; use of databases; simulations; access secondary data, including data sourced through the internet that would otherwise be difficult to source as raw or primary data through fieldwork, a laboratory or a classroom
- select and use equipment, materials and procedures appropriate to the investigation, taking into account potential sources of error and uncertainty

Comply with safety and ethical guidelines

- apply ethical principles when undertaking and reporting investigations
- apply relevant occupational health and safety guidelines while undertaking practical investigations, including following relevant bioethical guidelines when handling live materials

Conduct investigations to collect and record data

- work independently and collaboratively as appropriate and within identified research constraints
- systematically generate, collect, record and summarise both qualitative and quantitative data

KEY SKILLS CONTINUED

Analyse and evaluate data, methods and scientific models

- process quantitative data using appropriate mathematical relationships and units
- organise, present and interpret data using schematic diagrams and flow charts, tables, bar charts, line graphs, ratios, percentages and calculations of mean
- take a qualitative approach when identifying and analysing experimental data with reference to accuracy, precision, reliability, validity, uncertainty and errors (random and systematic)
- explain the merit of replicating procedures and the effects of sample sizes in obtaining reliable data
- evaluate investigative procedures and possible sources of bias, and suggest improvements
- explain how models are used to organise and understand observed phenomena and concepts related to biology, identifying limitations of the models

Draw evidence-based conclusions

- determine to what extent evidence from an investigation supports the purpose of the investigation, and make recommendations, as appropriate, for modifying or extending the investigation
- draw conclusions consistent with evidence and relevant to the question under investigation
- identify, describe and explain the limitations of conclusions, including identification of further evidence required
- critically evaluate various types of information related to biology from journal articles, mass media and opinions presented in the public domain
- discuss the implications of research findings and proposals

Communicate and explain scientific ideas

- use appropriate biological terminology, representations and conventions, including standard abbreviations, graphing conventions and units of measurement
- discuss relevant biological information, ideas, concepts, theories and models and the connections between them
- identify and explain formal biological terminology about investigations and concepts
- use clear, coherent and concise expression
- acknowledge sources of information and use standard scientific referencing conventions

1.1 Important principles in biology

Biology is a science, and our current understanding of life is based on the results of careful observations and experiments. In biology, some ideas or theories are supported by overwhelming amounts of evidence from such a wide variety of sources that it seems very unlikely they will be found to be untrue in the future. They are accepted as biological principles. Other theories are less strongly supported. Many are being modified or overturned even as you read this book.

Some biological principles and processes are relevant to the ways that almost all living **organisms** function. For example, living organisms are composed of cells, organisms have common characteristics and requirements, evolution explains the diversity of organisms, and organisms are adapted to their environments.

FIGURE 1.1.1 An example of living organisms: a common wombat (*Vombatus ursinus*) mother with her young joey.

BIOFILE

Popular theories overturned

Scientific theories often change or are discarded when new information is obtained. Some popular theories that have been recently modified or overturned include:

- sugar causes tooth decay (bacteria are the real cause; they use the sugar and release acid which attacks teeth)
- stress causes ulcers (the bacterium *Helicobacter pylori* is the cause)
- fibre in the diet reduces the risk of colon cancer (a huge study showed no correlation).

ORGANISMS ARE LIVING THINGS

There are usually obvious differences between a living organism and a non-living object, such as a wombat and a rock. A wombat (Figure 1.1.1) is able to move, eat and respond to sounds; the young animal in the picture is evidence that the wombat is able to reproduce. A tree cannot move about, but we can observe it grow new leaves and reproduce at a certain time of the year by flowering and producing seeds, which can germinate and develop into new plants. We can observe that a tree obtains materials and energy from its surroundings, since without sunlight, soil, nutrients and water a tree will cease to grow.

We can also see when an organism is no longer living. In a tree the signs of death may be yellowing and loss of leaves, and branches that become dry and brittle. It is perhaps more difficult to tell whether or not mould on rotting fruit or vegetables is living (Figure 1.1.2). But if we carefully observe a patch of mould over a few days we can see it grow in size and eventually produce dark spores that disperse in air currents.

We can also apply the terms 'living' and 'dead' to parts of organisms, but this is not always straightforward. A fruit that has dropped from an apple tree encloses seeds, each of which contains and protects a living embryonic plant. In contrast, the outer corky part of the bark of the tree consists of dead tissue, just as the outer layer of your skin is dead. An organ such as a kidney that has been removed from a donor must be kept alive artificially if it is to be transplanted successfully into a recipient patient. If the organ died it could not maintain its structure and functions.

FIGURE 1.1.2 Moulds are also living organisms. This image shows mould (pale grey) growing in a compost bin on decaying fruit and vegetables.

ORGANISMS CONSIST OF CELLS

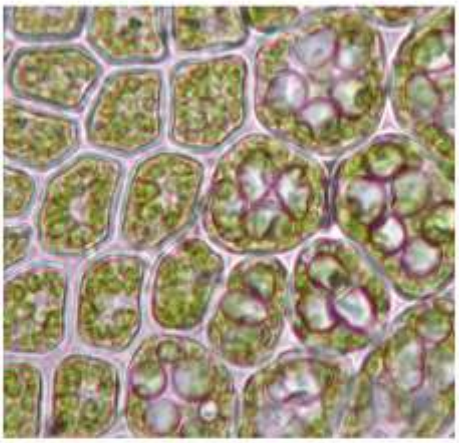


FIGURE 1.1.3 Living cells of the leafy liverwort *Bazzania subtilis*, which grows in rainforests from Borneo to northern Queensland.

The **cell theory** is one of the fundamental principles of biology. It is based on microscopic and experimental studies of tissues, from all types of organisms, carried out over the last 300 years.

The cell theory states:

- all organisms are made up of cells (and the products of cells)
- all cells come from pre-existing cells
- the cell is the smallest living organisational unit.

There is really no such thing as a typical cell, but some features are common to all or most cells. All cells have an outer p**lasma membrane** (cell membrane) that encloses the fluid contents of the cell, the **cytoplasm**, and all cells have DNA as their genetic material. There are many different types of cells in animals and plants, and they have very different appearances and functions.

Modern techniques allow us to examine the smallest structures within cells, to visualise the surfaces of cell organelles (Figure 1.1.3), to grow and study single cells in culture, and to grow cells and use them as tiny factories to produce medically and commercially important molecules in huge quantities. In the following chapters of this unit we will consider the similarities and differences in the structure, activities and needs of various types of cells.

● *You will now be able to answer Key Questions 1 and 2.*

EVOLUTION EXPLAINS DIVERSITY

Evolution is another fundamental principle of biology. Scientists have concluded that organisms have changed through time and that evolution is a fact. Observations which led them to this conclusion include:

- the diversity of living organisms
- their similarities and differences (Figure 1.1.4)
- the richness of the fossil record
- the geographic distribution of organisms
- the discovery of DNA and the genetic code.

Also techniques such as the ability to sequence and compare the DNA of different species support this conclusion. But how evolution occurs is still debated by biologists.

i In phylogeny, a branching diagram (tree) shows how organisms are related to one another through evolution.

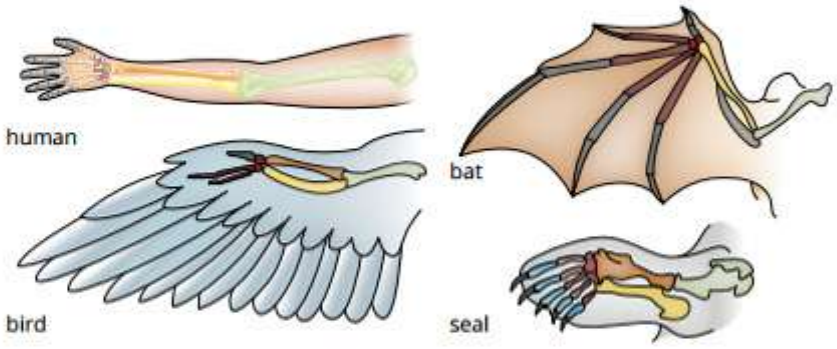


FIGURE 1.1.4 Humans stand upright, bats and birds fly, and seals swim, but the skeletons of their forearms have the same pattern of bones. Only the shapes of the bones are different.

Taxonomists are biologists who draw together information from a wide variety of sources to discover how closely organisms are related to each other. Organisms can be grouped or classified in many ways (see Chapter 6). Scientific classification, which involves a hierarchy of names for all organisms, ensures that communication between scientists is accurate and efficient.

CHARACTERISTICS OF ORGANISMS

In later chapters you will examine particular aspects of different organisms in much more detail. But there are certain features and requirements that characterise all living organisms (Figure 1.1.5). You are probably familiar with many of these from your earlier studies in science, and from your own reading and observations.

FIGURE 1.1.5 (a) Rounded noonflower (*Disphyma crassifolium*). (b) An intermediate egret (*Ardea intermedia*) and its offspring. The rounded noonflower and the intermediate egret both show complexity, energy exchange, sensing and responding to the environment, growth and reproduction, and adaptive change over generations—all features that characterise living things.

All living organisms have the following features:

- movement—to find food, shelter and avoid predators; plants move more slowly as they grow, with leaves and stems moving as they grow towards sunlight to capture solar energy and roots moving down into the soil
- reproduction—the ability to produce offspring to keep the species in existence
- sensitivity—awareness of changes in the environment, and the ability to respond to those changes if necessary
- growth—animals grow to adulthood; plants grow throughout their life; even when growth stops, there is still growth and replication of cells to replace old or damaged cells and for repair
- respiration—extracting energy from food to support all other processes
- excretion—getting rid of wastes and toxic substances
- nutrition—animals eat plants and other animals for their nutrition; plants are able to make their own food by photosynthesis.

Additionally, all living organisms:

- are made of cells
- are chemically complex and highly organised
- show changes that are often adaptive over succeeding generations.

These features are common to all organisms: plants, animals, fungi, protists and bacteria. No non-living thing possesses all of these attributes.

● *You will now be able to answer Key Question 3.*

COMMON REQUIREMENTS FOR LIFE

To carry out their various activities, organisms have certain requirements. All life requires a source of energy. The amount of energy required depends on the type of organism, its stage of growth, its level of activity and its reproductive state. Organisms also require nutrients and water for growth, maintenance and repair. The nutrients are organic compounds (including proteins, carbohydrates, lipids and vitamins) and minerals. These materials, or simpler substances from which they can be made, must be obtained from the surrounding environment. Organisms also require environmental conditions in which they can survive and reproduce.

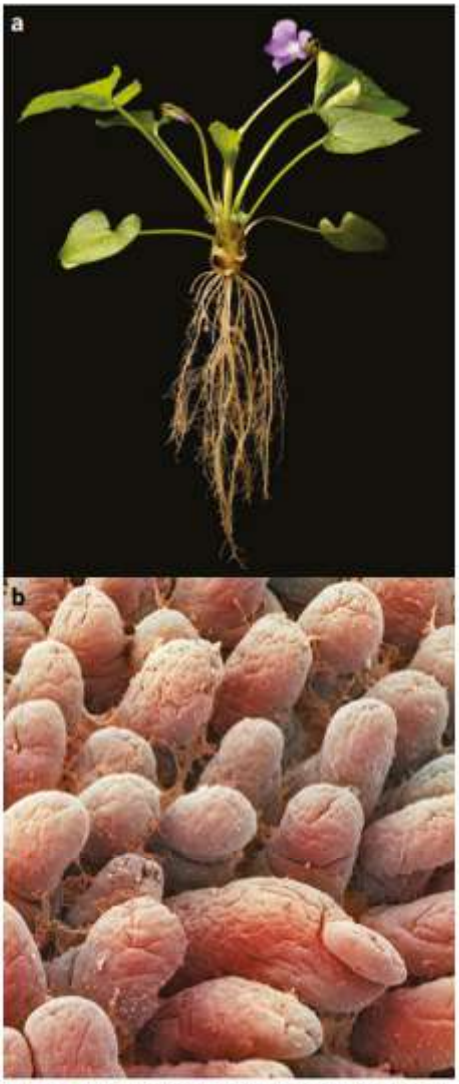


FIGURE 1.1.6 Two examples of highly increased surface areas that are especially adapted for the uptake of nutrients: (a) the root system of a plant and (b) the internal surface of a human gut.

FIGURE 1.1.7 To the males of a certain wasp species, the flying duck orchid (*Caleana major*) looks and smells like a female wasp.

In using energy and carrying out the processes of growth, maintenance and repair, an organism produces substances that are of no use to them, and some of these substances may be harmful to the organism. These waste substances are often removed by releasing them into the environment.

The ways that organisms carry out exchanges with their environment depend partly on the size of the organism and partly on the amount of material that needs to be exchanged. For small organisms with moderate needs, the processes are relatively simple; exchange and distribution within the organism occurs by diffusion. Larger organisms, and smaller organisms with very high nutritional requirements, have evolved large or complex systems for transport and exchange, such as the leaves and root systems of plants and the circulatory, digestive and excretory systems of animals (Figure 1.1.6). Organisms must also be able to sense and respond to changes in their internal and external environments.

● *You will now be able to answer Key Questions 4 and 5.*

ORGANISMS ARE ADAPTED TO THEIR ENVIRONMENTS

When studying the ways that different organisms function, the advantages of some features are often very clear. For example, the blood of Antarctic icefishes contains a substance that lowers the freezing point of their blood, allowing them to live at temperatures that would freeze the blood of other fishes. Banksia cones are woody and hard, and seeds are protected in the cone until they are released into the nutrient rich ash following a fire. (Banksia seedlings have a greater chance of surviving if there has been a fire.) The native orchid *Caleana major* is commonly called the flying duck orchid because to us it looks like a tiny flying duck (Figure 1.1.7). To the male of a certain wasp species, however, it looks and smells like a female wasp. The wasp attempts to mate with the orchid, and in doing so transfers pollen from one orchid flower to another. In each of these examples the feature makes the organism better able to succeed in its environment.

Any study of the ways that organisms function is enhanced by an understanding of the principle of **adaptation**. Over time, species accumulate genetic changes that make them structurally, physiologically and behaviourally adapted to the particular environment in which they live. This adaptation is the result of **natural selection**. Individuals with features most suited to their environment are likely to survive and produce more offspring than those with less favourable features. So the next generation will have more individuals who have inherited the favourable feature and fewer individuals who lack it. Over many generations, favoured features become more frequent in the **population** and undesirable features become less frequent.

Adaptation means that the inherited structures, functions and behaviours of organisms make the individuals well suited to their environments and life styles.

● *You will now be able to answer Key Questions 6 and 7.*

1.1 Review

SUMMARY

- The cell theory is a fundamental principle of biology, and is based on evidence collected over the last 300 years.
- Evolution and adaptation are fundamental principles of biology that are underpinned by a vast amount of experimental and observational evidence.
- Living organisms have common characteristics and requirements. They are made of cells, are chemically complex and highly organised, exchange energy and materials with their environment, grow and reproduce, sense and respond to their environment, and show changes that are often adaptive.

KEY QUESTIONS

1 Which of the following statements about cells is true?
   - **A** Cells are made of organelles, which are the smallest organisational units of life.
   - **B** All cells have a plasma membrane, cytoplasm and nucleus.
   - **C** All cells are composed mainly of inorganic material such as carbohydrates, proteins, nucleic acids and lipids.
   - **D** Cells and their products are the components of all living things.

2 Name three components that all cells possess.

3 List the features shared by plants and animals that enable scientists to classify them all as 'living things'.

4 Decide whether each of the items listed is living, dead, or inorganic. Give reasons for your decision in each case.

grass	timber chair
bee	dry fallen twig
honey	ripening peach on a tree
gravel	sleeping possum
hair	hibernating bat
spider web	growing crystals

5 Define the term 'adaptation'.

6 Give two examples of adaptations mentioned in the text.

7 The idea of adaptation is a key component of which biological principles?

1.2 The molecular composition of organisms

There are 92 different types of naturally occurring atoms on Earth, and each type is known as an element. Some of these elements, such as carbon, aluminium, silicon, iron, oxygen and hydrogen, are very common, while others such as osmium, thallium and tellurium are very rare. The same elements can be found in rocks, soil, air, plants and animals. But there is a difference in the way that these atoms are organised into larger compounds (compounds are molecules containing different elements) in living organisms. Organisms produce characteristic complex compounds that contain carbon and hydrogen (Figure 1.2.1). These are called **organic compounds** because the first ones discovered were produced by organisms or found in them. Most large organic molecules are composed of many smaller organic molecules linked together.

All other compounds, whether in living or non-living things, are called **inorganic compounds**. Inorganic compounds that are important for living organisms include water, oxygen, carbon dioxide, nitrogen and minerals.

- *You will now be able to answer Key Questions 1 and 2.*

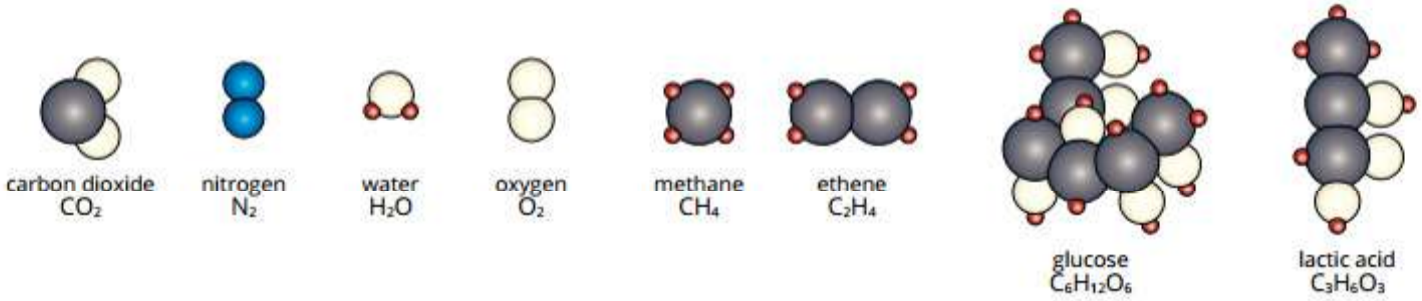


FIGURE 1.2.1 Some common molecules in organisms. Carbon atoms are coloured black, oxygen white, hydrogen red and nitrogen blue.

INORGANIC COMPONENTS

Water

FIGURE 1.2.2 A wingless water strider walking over the surface of a lake.

Life evolved in water. Most organisms are 70–90% water, and the chemical reactions that take place in cells take place in a watery medium. This is why the properties of water, such as pH, cohesiveness and heat capacity, are important in many biological processes. Water molecules are very **cohesive**, which means they have a strong tendency to stick together. This property allows thin columns of water to be pulled up tree trunks without breaking. Bonds between surface molecules also cause **surface tension**, which allows small insects to walk across the surface of water without breaking into the water molecules and sinking (Figure 1.2.2).

Water has a high **heat capacity**; that is, it can absorb a great deal of heat with very little increase in temperature. This is important for temperature regulation. When you exercise, the chemical reactions taking place in your cells produce heat. Much of this heat can be absorbed by water in your body, without the cells heating up significantly. Because water has a high heat of vapourisation, the evaporation of even small amounts of water will be effective in cooling that part of the body surface.

- *You will now be able to answer Key Question 3.*

Oxygen and carbon dioxide

In most cells, oxygen is needed to release energy from food molecules in processes known collectively as **cellular respiration**. A constant supply of oxygen is therefore necessary to maintain the activity of these cells. This is usually easy for organisms that get their oxygen from air, because the atmosphere is 21% oxygen. However, oxygen is not very soluble in water (Figure 1.2.3), so organisms that get their oxygen from water are either small, flat and relatively inactive, or have very efficient ventilation systems, such as fish gills.

Carbon is the key atom in organic molecules. Carbon dioxide (CO_2) is taken from the atmosphere (which contains approximately 0.033% by volume of carbon dioxide) by plants, some bacteria and some protists. It is used in the process of photosynthesis to make sugars, some of which are eaten by animals. Carbon dioxide is returned to the atmosphere mainly by the decay of organic material and as an end-product of cellular respiration. This cycling of carbon through organisms and the atmosphere is critical to the survival of all organisms.

FIGURE 1.2.3 Carbon dioxide is a byproduct of cellular respiration, and is expelled from your lungs when you breathe out.

Nitrogen

Nitrogen is required by organisms in relatively large amounts because it is a key component of all proteins. There is plenty of nitrogen around because the atmosphere is about 78% nitrogen gas (N_2). Atmospheric nitrogen is trapped by certain bacteria and converted into compounds that can be used by plants in a process known as **nitrogen fixation**. Symbiotic bacteria in the roots of some plants, such as legumes, she-oaks and acacias, are by far the most important for this (Figure 1.2.4).

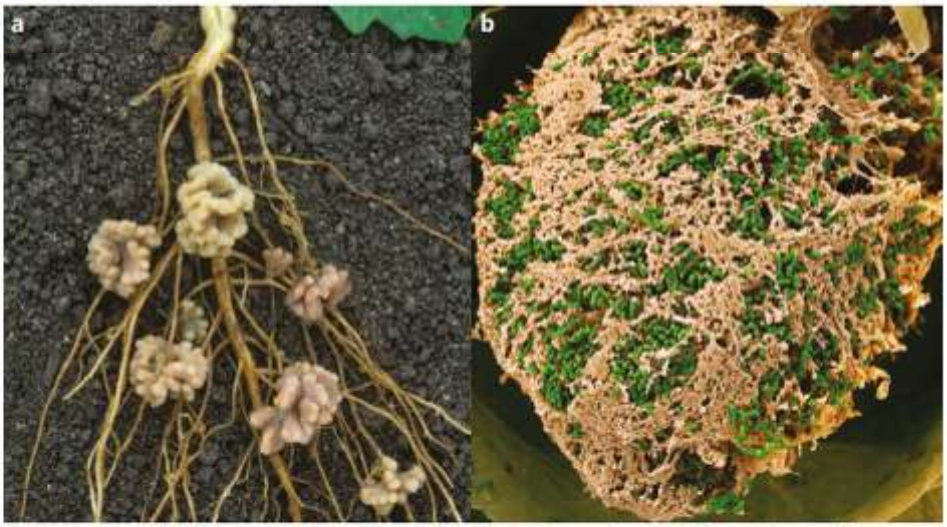


FIGURE 1.2.4 (a) Nodules containing nitrogen-fixing bacteria on the roots of a garden pea (*Pisum sativum*). b) Nitrogen-fixing bacteria. Coloured scanning electron micrograph (SEM) of nitrogen-fixing soil bacteria (*Rhizobium* species) in a root nodule of a bean plant. These bacteria (green) have a symbiotic relationship with the plant.

Minerals

Biologically important minerals include phosphorus, potassium, calcium, magnesium, iron, sodium, iodine and sulfur. Many others are needed in small (trace) amounts. Mineral salts are produced by the weathering of rocks and are absorbed in solution by the roots of plants (Figure 1.2.5). Mineral ions are found in the cytosol of cells, in structural components (such as bone) and in the molecules of many enzymes and vitamins. They may also be incorporated into other important organic compounds in cells. Humans require more than 20 minerals, some in only minute quantities.

FIGURE 1.2.5 A soil profile showing the horizons (layers) which vary in colour depending on the mineral content in the soil. Plants absorb these minerals when they draw water out of the soil.

ORGANIC MOLECULES

The photosynthetic parts of plants and algae—usually coloured green—are able to trap carbon dioxide from the air and convert it into the simple carbohydrate glucose by a process known as photosynthesis (see Chapter 3). In this way, plants and algae are the ultimate sources of organic molecules. The more complex organic molecules needed for growth are made by linking simple molecules together or by attaching other chemical groups such as amines (containing NH^{2-}) or phosphates (containing PO_4^{2-}).

The four main types of organic molecules are carbohydrates, lipids, proteins and nucleic acids (Figures 1.2.6 to 1.2.9). In mammals these can be converted from one form into another within cells. Units may be linked together to form larger molecules, and other chemical groups may be attached to form molecules such as glycoproteins (proteins with sugars attached) and phospholipids (lipids with phosphate attached). When food is plentiful, carbohydrates are converted into fats for storage; when it is scarce the reverse will occur and even proteins can be converted into small molecules to use for energy.

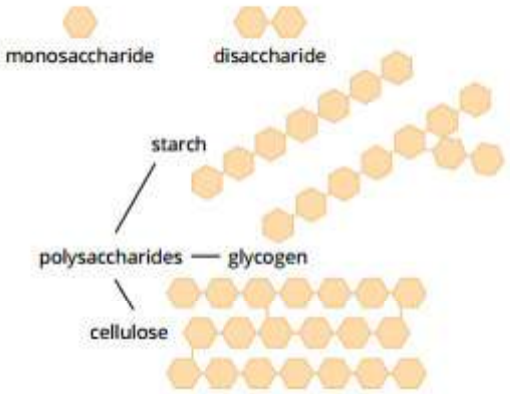


FIGURE 1.2.6 The structures of some carbohydrates.

Carbohydrates

Carbohydrates are the most abundant organic compounds in nature. They are an important source of energy for living organisms. In plants, starch is a carbohydrate used for energy storage and cellulose is a carbohydrate used for structural support. In animals, glycogen is a carbohydrate used for energy storage.

Carbohydrates are compounds made of carbon, hydrogen and oxygen. The basic subunits of carbohydrates are simple sugars called **monosaccharides** (meaning 'single sugars'). For example, glucose is a monosaccharide formed during photosynthesis. In simple carbohydrates the hydrogen and oxygen are present in the same proportions as in water: there are two hydrogens for each oxygen atom. The general formula is $C_nH_{2n}O_n$.

When two sugars are joined together they form a **disaccharide** (meaning 'two sugars'), and a molecule of water is removed. When many are joined together they form long chains called **polysaccharides** ('many sugars') (Figure 1.2.6).

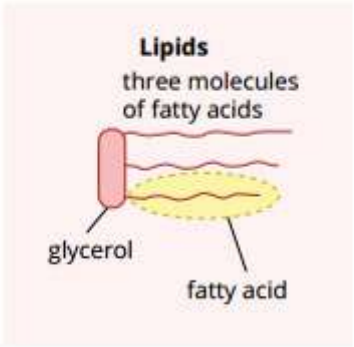


FIGURE 1.2.7 The structure of lipids.

Lipids

Lipids are fatty substances. They include fats and oils, which are important as energy-storing molecules (Figure 1.2.7). Phospholipids are an important component of cell membranes, which contain the cell's contents and subdivide it into many sub-cellular compartments. Steroids are lipids that act as membrane components, hormones and vitamins.

Lipids are composed of carbon, hydrogen and oxygen, but in different proportions to carbohydrates. Lipids contain a much smaller proportion of oxygen, and they can contain other elements such as phosphorus and nitrogen.

Proteins

Proteins are more complex than carbohydrates or lipids. There are thousands of different kinds of proteins, and their functions vary widely. While carbohydrates and lipids are similar in all plants and animals, each kind of organism has its own unique proteins. Some proteins form structural components of cells; others are enzymes, hormones or carrier molecules. For example, haemoglobin is a protein that carries oxygen in the blood.

All proteins contain carbon, hydrogen, oxygen and nitrogen; many also contain sulfur, and often phosphorus and other elements. Proteins are composed of chains of smaller subunits called **amino acids** (Figure 1.2.8). Amino acids in proteins are linked by a particular kind of chemical bond called a peptide bond, and proteins are called polypeptides or polypeptide chains. There are 20 different amino acids commonly found in proteins.

The study of all the proteins of an organism is known as proteomics. In medicine, 99% of all drugs are proteins, or act by binding to proteins. A better understanding of proteins and proteomes (all the proteins produced by organisms) will aid the development of new pharmaceuticals, clarify the relationships between genes and diseases (e.g. by identifying marker proteins for diseases), and lead to better treatments.

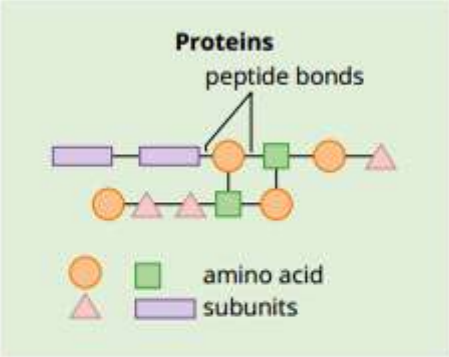


FIGURE 1.2.8 The structures of proteins.

Nucleic acids

Nucleic acids are the genetic material of all organisms, and they determine many of the features of an organism. There are two types of nucleic acid: **DNA** (deoxyribonucleic acid) and **RNA** (ribonucleic acid). Both are made of long chains of subunits called nucleotides (Figure 1.2.9).

DNA carries the information needed to assemble proteins from amino acid subunits. It is accurately passed from cell to cell during cell division. RNA plays a major role in the manufacture of proteins within cells.

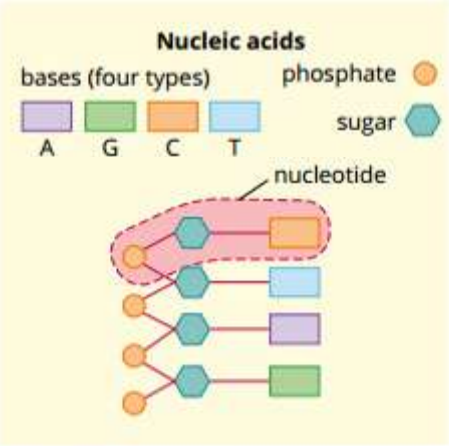


FIGURE 1.2.9 The structures of nucleic acids.

Vitamins

Vitamins are organic molecules required by animals in small amounts for normal functioning. Animals may be able to synthesise some vitamins, but others must be obtained in their diet. For example, most mammals can synthesise vitamin C, but humans must obtain it in their diet. Vitamins may be water-soluble (such as vitamins B and C) or lipid-soluble (such as vitamins A, D, E and K). Water-soluble vitamins must be consumed regularly in the diet because they cannot be stored in body tissues. Lipid-soluble vitamins can be stored. Many vitamins are important because they are needed to make particular enzymes.

● *You will now be able to answer Key Questions 4–6.*

1.2 Review

SUMMARY

- Inorganic components of living organisms include water, oxygen, carbon dioxide, nitrogen and minerals.
- Organic components include carbohydrates, lipids, proteins and nucleic acids.
- Important properties of water include cohesiveness, surface tension, heat capacity and pH.
- Oxygen is needed for efficient energy supply in organisms.
- Carbon dioxide is the ultimate source of carbon for organic molecules, and nitrogen is a key molecule of proteins.
- Carbohydrates are important as energy sources and for structural components of organisms.
- Lipids play an important role in cell membranes.
- Proteins are composed of amino acids and their functions vary. Organisms have their own unique proteins.
- Minerals are important for building many enzymes.
- Structural organic molecules and vitamins are small organic molecules that are vital for normal cell function.
- Nucleic acids carry the genetic information of cells.

KEY QUESTIONS

1 **a** Define the terms 'organic compound' and 'inorganic compound'.

b Is carbon dioxide organic or inorganic? Explain.

2 Which of the following statements is true?

A All organic compounds contain carbon and nitrogen.

B All organic compounds contain carbon and hydrogen.

C All organic compounds contain carbon, hydrogen and oxygen.

D All organic compounds contain carbon and oxygen.

3 Copy and complete the following table, which should list the four main types of organic compounds that make up organisms, the elements of which each is composed, and the main function of each compound.

Organic compound	Elements	Main function
1		
2		
3		
4	carbon, hydrogen, oxygen, phosphorus, nitrogen	

4 Match each of the following terms to the correct statement about it.

carbohydrate	byproduct of cellular respiration
carbon dioxide	composed of amino acids
lipid	compound of carbon, hydrogen and oxygen
mineral	examples are phosphorus, calcium and potassium
nucleic acid	fatty substance stored in tissues
oxygen	made of subunits called nucleotides
protein	may be water-soluble or lipid-soluble
vitamin	needed for cellular respiration

5 Name the units that make up the following compounds.

a nucleic acids

b proteins

c carbohydrates

6 Are minerals and vitamins inorganic or organic? Explain your answer.

1.3 The scientific method

Biology is the study of living organisms. As scientists, biologists extend their understanding using the scientific method, which involves investigations that are carefully designed, carried out and reported. Well-designed research is based on a sound knowledge of what is already understood about a subject, as well as careful preparation and observation (Figure 1.3.1).

FIGURE 1.3.1 An entomologist (a scientist who studies insects) collecting insects from the top of a tropical rainforest tree.

OBSERVATION

Observation includes using all your senses and the wide variety of instruments available to allow closer observation. Through careful inquiry and observation you can learn a lot about organisms, the ways they function, and their interactions with each other and the environment. For example, animals clearly function very differently from plants. Animals usually move around, take in nutrients and water, and often interact with each other in groups. We find them in water, on land, and flying in the air. Some are fast, efficient predators (Figure 1.3.2). Some maintain high body temperatures. They may mate to reproduce, and some care for their offspring as they grow. On the other hand, plants are green, stationary, turn their leaves towards the light and grow. Sometimes they lose all their leaves then grow new ones. Many develop flowers and fruit for reproduction. All of these things can be learned from simple observation. Observational studies are a common research method you'll learn more about in the next section.

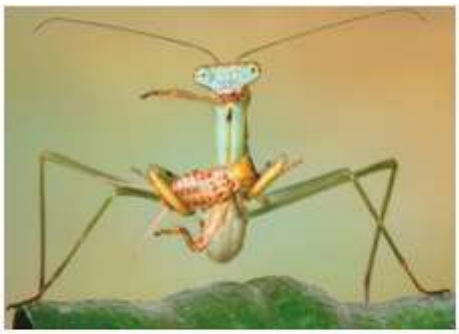


FIGURE 1.3.2 The praying mantis is a fast, efficient predator. Its green colouration and leaf-like shape give it the deadly advantage of camouflage.

The idea for a first-hand investigation of a complex problem arises from prior learning and observations. This tells us there are questions to be answered. For example, indoor plants do not grow well in the long term without artificial lighting, which suggests light is required for photosynthesis in plants. This aspect of photosynthesis can be researched.

How observations are interpreted depends on past experiences and knowledge, but to enquiring minds they will usually provoke further questions such as:

- How is a grassland ecosystem different from a forest?
- What are the basic differences between plants, animals, bacteria, fungi and protists?
- How do organisms grow?
- What materials and conditions do they need to grow?
- What do particular structures do?
- How do these structures work?

Many of these questions cannot be answered by observation alone, but they can be answered through scientific investigations. For example from his careful observations, Lazzaro Spallanzani was able to suggest an explanation for the night vision of bats (see the Biology in Action below). However, he did not know whether he was likely to be correct until he performed certain experiments.

● *You will now be able to answer Key Question 1.*

BIOFILE

Large bats do not use echolocation

Small bats use echolocation to catch insects or other small animals. However, larger bats such as flying-foxes (fruit bats) do not use echolocation, because their main diet is fruits and other plant matter. Instead they have large eyes for better night vision.

FIGURE 1.3.4 Fruit bats do not use echolocation, but they have large eyes for better night vision.

BIOLOGY IN ACTION

Flying blind

In 1793, Italian scientist Lazzaro Spallanzani observed that owls could not fly in complete darkness, or with their eyes covered, but that bats could. Bats could not only 'fly blind', but they were apparently just as efficient at catching insects for food when their eyes were covered as they were when they could see. He wondered how they did this. He found that if he plugged their ears, the bats had no sense of direction and collided randomly into obstacles, but if the plugs had a central hole then they flew normally. He concluded that bats used their ears to detect obstacles and prey at night (Figure 1.3.3). This suggestion was ridiculed and then virtually forgotten. Everyone thought bats must use a sense of touch to avoid obstacles.

FIGURE 1.3.3 The large nose of this microbat is adapted to send ultrasonic signals, and its ears are adapted to pick up the faint returning echoes.

Over 100 years later, during the First World War, sonar (also known as echolocation) was developed for detecting submarines under water. By sending out a sound signal and analysing the returning echoes, the position and size of any object that reflects the sound could be determined.

Soon after the war, when a bat inadvertently flew into his room at Cambridge, English physiologist Hamilton Hartridge realised bats might rely on ultrasonic echolocation to orientate themselves at night (ultrasonic sounds are too high in frequency to be heard by humans). Finally, in 1938, the ultrasonic signals made by bats were detected with a receiver designed to hear the high-pitched signals emitted by insects. Spallanzani's original prediction that bats used hearing to navigate at night had been validated by an independent researcher's supporting evidence.

LEARNING BY EXPERIMENTATION

Scientists observe, study what is already known, and then ask questions. Using their knowledge and experience, scientists suggest possible explanations for the things they observe. A possible explanation is called a **hypothesis**. A hypothesis can be used to make certain predictions. Often these predictions can be tested experimentally. This is the basis of the scientific method (Figure 1.3.5).

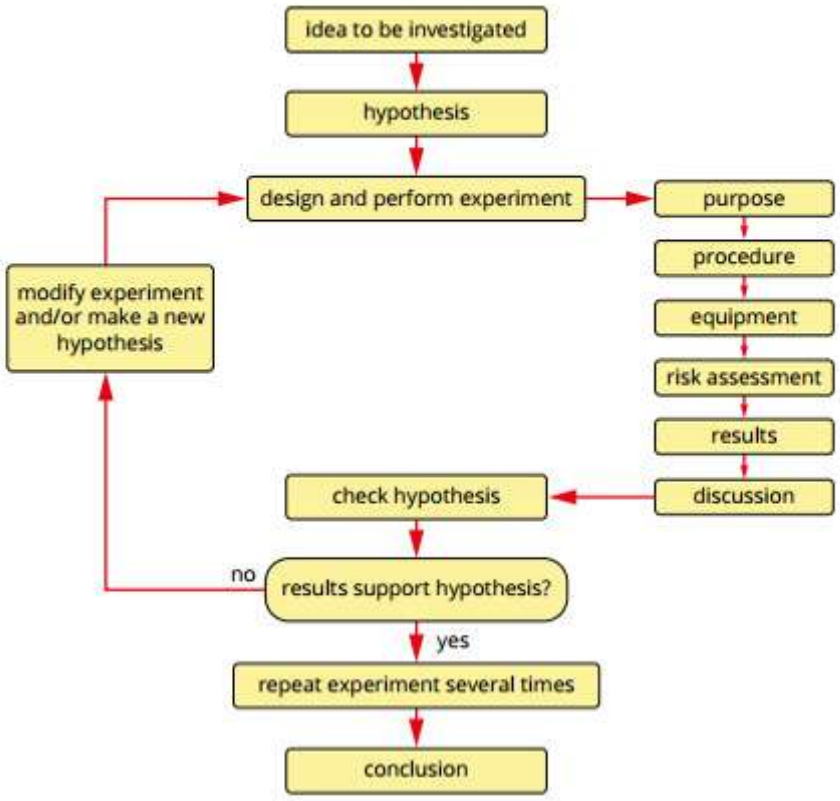


FIGURE 1.3.5 The scientific method.

Carefully designed experiments are carried out to determine whether the predictions are accurate or not. If the results of an experiment do not fall within an acceptable range, the hypothesis is rejected. If the predictions are found to be accurate, the hypothesis is supported. If, after many different experiments, one hypothesis is supported by all the results obtained so far, then this explanation can be given the status of a **theory** or **principle**.

There is nothing mysterious about the experimental approach to the study of science that is called the **scientific method**. You might use the same process to find out how an unfamiliar machine works if you had no instructions. Careful observation is usually the first step.

● *You will now be able to answer Key Question 2.*

ASKING THE RIGHT QUESTIONS

In science, there is little value in asking questions that cannot be answered. An experimental hypothesis must be testable, but your inability to test a particular hypothesis does not mean that the hypothesis cannot be correct. If you asked the question, 'How do bats navigate at night?', there would be no point in your hypothesis being 'Bats use thought waves to navigate', because it is not possible to test this.

You must also ask the right questions to get answers that are relevant to the problem you are examining. There is no point in asking how long bats live when you are studying their navigation, as the information you obtain will not help to test the hypothesis. Spallanzani had two hypotheses that were both testable and relevant:

- Hypothesis 1: Bats do not depend on their eyes to navigate at night.
- Hypothesis 2: Bats use their ears to navigate at night.

● *You will now be able to answer Key Question 3.*

CHOOSING THE RIGHT METHOD

To conduct a scientific experiment correctly, the methods used must be reliable. Methods must be described clearly and in sufficient detail to allow other scientists to repeat the experiment. If other scientists cannot obtain similar results when an experiment is repeated, then the experiment is considered unreliable. It is also important to avoid personal bias that might affect the collection of data or the analysis of results. A good scientist works hard to be objective (free of personal bias) rather than subjective (influenced by personal views). The results of an experiment must be clearly stated and must be separate from any discussion of the conclusions that are drawn from the results.

Experiments and their results must be able to be repeated by other scientists to be validated.

In science, doing an experiment once is not usually sufficient. You can have little confidence in a single result because you cannot be sure that the result was not due to some unusual circumstance that occurred at the time. The same experiment is usually repeated a number of times over a period of time and the combined results are then analysed statistically. If the statistics show that there is a low probability (usually less than 5%, referred to as $P < 0.05$) that the results could have occurred as a result of chance, then the result is accepted as being significant.

Spallanzani tested his first hypothesis by using a number of blindfolded bats. They were still able to fly and catch insects for food. He tested his second hypothesis by blocking their ears. Bats with tightly blocked ears were unable to navigate at night or catch insects.

- *You will now be able to answer Key Question 4.*

THE NEED FOR EXPERIMENTAL CONTROLS

The experimental conditions of the control group are identical to the experimental group, except that the variable of interest (the independent variable) is also kept constant.

It is difficult—sometimes impossible—to eliminate all **variables** that might affect the outcome of an experiment. In biology, time of day, temperature, amount of light, season, and level of noise are examples of such variables. A way to eliminate the possibility that random factors affect results is to set up a second group within the experiment (called a **control group**) that is identical in every way to the first group (the **experimental group**) except for the single experimental variable that is being tested. This is a controlled experiment. Because it allows us to examine one variable at a time, it is an important way of testing a hypothesis.

In an experiment, controlled (fixed) variables are kept constant; only one variable (the independent variable) is changed, and the dependent variable is measured to determine any effect of the change.

The variable that the experimenter is testing is the **independent variable**. In our example, Spallanzani separately tested two independent variables—the abilities to see and to hear. The **dependent variable** is what is measured when the independent variable changes. In this example the dependent variable that Spallanzani measured in each case was the number of insects caught.

- *You will now be able to answer Key Question 5.*

What experimental controls were needed in Spallanzani's experiments? Did blindfolded bats catch the same number of insects as normal bats? Measuring the number of insects caught by normal bats was a necessary control. Did the earplugs interfere in some other way with the bat's behaviour? Spallanzani made a device to place in the bats' ears that was similar to the one used to block their hearing, but allowed sound through. With this device in their ears bats flew perfectly well, indicating that it was the loss of hearing not the presence of the plugs in their ears that prevented navigation. More detail on setting up an investigation with controls and variables is included in section 1.4.

BIOFILE

The simplest hypothesis

The idea that the simplest hypothesis should be accepted was first put forward by the Greek philosopher Aristotle. It is sometimes called Ockham's Razor, because a 14th century English philosopher named William of Ockham accepted it as a fundamental principle of philosophy.

MAKING VALID CONCLUSIONS

Conclusions are based on results and other knowledge. Making valid conclusions depends on the reliability of results and whether they are correctly interpreted. Speculation involves going beyond the results to make suggestions about what might be occurring. Conclusions are necessary, but speculation is interesting and thought-provoking. Both concluding and speculating are worthwhile, but you must be careful to keep them separate. It is also the usual practice of scientists to accept the simplest hypothesis that accounts for all the evidence available.

BIOFILE

Moths can hear bats

Some moths (Figure 1.3.6) can tune their hearing organs (which are on the sides of their thorax) to the frequency of the echolocation signals of bats, and then respond appropriately. This has been demonstrated experimentally (Figure 1.3.7).

FIGURE 1.3.6 This eyed hawk-moth, (*Smerinthus ocellatus*) is capable of tuning its hearing organs so that it can hear bats.

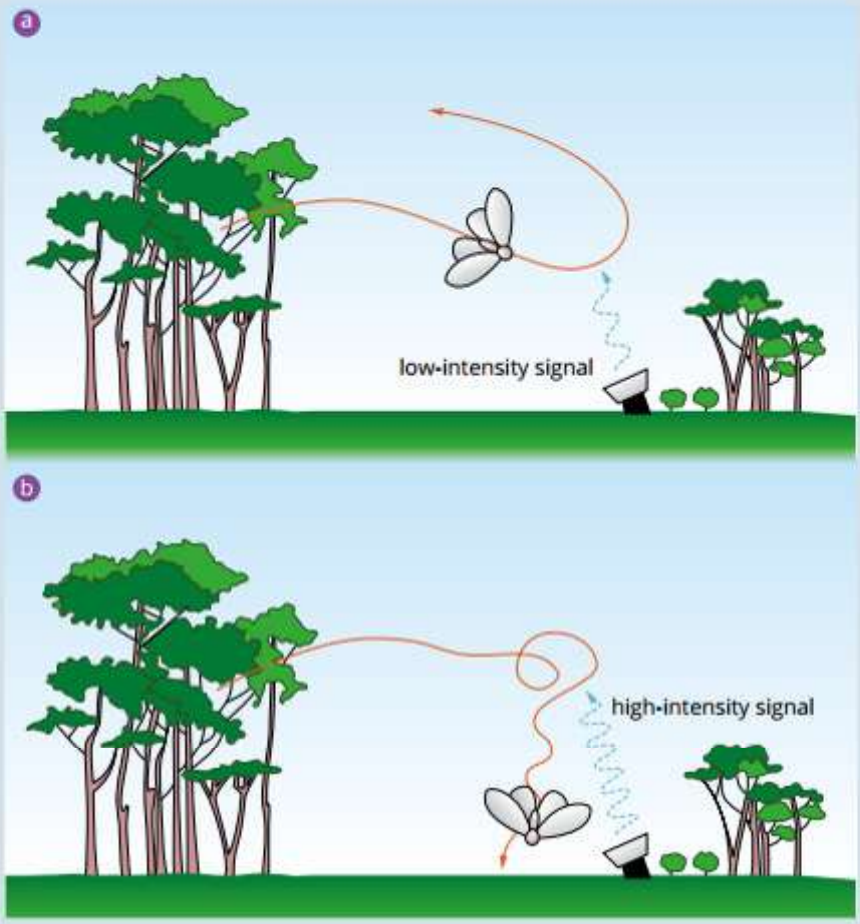


FIGURE 1.3.7 A loudspeaker was set up in a field and the experimenter was able to see moths as they came into the clearing. (a) When a low-intensity bat echolocation call was played (simulating a bat that was some distance away) the moths simply flew away again. (b) When a high-intensity call was played (simulating a bat that was very close) the moths quickly went into a downward spiral, dropping out of the echolocation range.

The conclusions made by Spallanzani were valid. He concluded that the bats he studied did not need to see to navigate at night, but that they did need to hear. Even so, he was not believed for a long time.

Imagine you are Spallanzani and that you are going to write a report about your bat experiments. What type of information should be included in your report? What headings could you use? What would you include under each heading? What other information might be useful to other scientists?

LIMITATIONS OF THE SCIENTIFIC METHOD

The scientific method is not perfect; however, it remains the best way to understand our surroundings, and to constantly improve on that understanding. Even when the scientific method is strictly adhered to, there is still an element of chance in scientific discovery. Many great discoveries have been made when a scientist has been busy investigating another problem. Good scientists have acute powers of observation and enquiring minds, and they make the most of these chance opportunities (Figure 1.3.8, page 18).

FIGURE 1.3.8A Scottish biologist Alexander Fleming discovered penicillin when one of his agar plates containing *Staphylococcus* bacteria was contaminated with a fungus (*Penicillium notatum*). He noticed that bacterial colonies were unable to grow in the zone around the fungus, as if it were secreting something that inhibited their growth. That something would later be called penicillin, the first antibiotic.

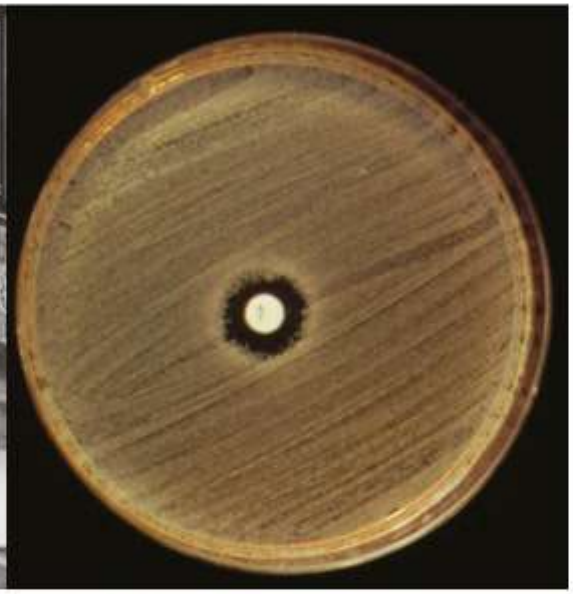


FIGURE 1.3.8B A culture of *Staphylococcus aureus* bacteria with a white disc containing penicillin placed at the centre. *Staphylococcus aureus* has not been able to grow near the penicillin disc.

The scientific method can be applied only to hypotheses that can be tested, and to questions that can be answered. A hypothesis that is not testable can be neither supported nor disproved by the scientific method. Such hypotheses therefore remain as possible explanations. For example, we cannot use scientific experiments to determine whether there is 'life after death', because we cannot do suitable experiments. It is also important to understand, that while science can prove a particular hypothesis wrong, it cannot prove that hypothesis to be true in all circumstances—only under the conditions that have been tested.

Science and the scientific method also cannot be used to test morality or ethics. These judgements belong to the fields of philosophy, history, politics and law. Science can, however, provide valuable information that people can take into account when making these judgements. For example, science can be used to predict the environmental consequences of pollution and the medical consequences of chemical weapons, but it cannot itself make value or moral judgements about either.

EXPERIMENTATION

Once you have a testable hypothesis, you are ready to conduct an experiment to test it. Every experiment has to be designed and planned carefully. You need to be sure that somebody else can repeat your experiment exactly the way you did it and get similar results. In the next section, you will learn how to formulate your hypothesis and design an experiment to test it.

● *You will now be able to answer Key Questions 6 and 7.*

BIOLOGY IN ACTION

Intertidal molluscs

If you wander along rocky seashores when the tide is out, you will see many different species of molluscs on the rocks (soft-bodied animals which often have shells). Limpets, mussels, periwinkles, and tiny blue littorinids are some of the molluscs commonly found along the Victorian coastline.

We can learn something about the dependence of the different mollusc species on water, and their ability to withstand drying out when the water recedes to the low tide mark, by observing the pattern of distribution of the molluscs along the shoreline (Figure 1.3.9).

Rocky shorelines can be divided into a subtidal zone (always covered with water), an intertidal zone (between low and high tide marks), a spray zone (splashed by water at high tide) and a supratidal zone (out of range of sea water).

Few molluscs are found in the subtidal and supratidal zones. In the intertidal region, limpets are scattered randomly, mussels are clumped together, and periwinkles are often found under rocks and in crevices. Littorinids are found mainly in the spray zone.

Some possible explanations for these observations are as follows:

- Each of these molluscs needs some contact with sea water.
- Limpets can tolerate a wide range of environmental conditions.
- Periwinkles cannot withstand long periods out of water.
- Mussels maintain higher moisture levels by clumping together.
- Littorinids need very little water.
- Periwinkles are eaten by predatory birds and only survive where they are hidden from view.

These explanations lead to further questions. How do molluscs protect themselves from drying out when they are out of water? Do different molluscs have different levels of resistance to drying out? Water is not likely to be the only factor affecting distribution. What other factors might be involved? You should think about whether your observations tell you anything about the importance of food sources, predation, temperature variation, the ability of the mollusc to withstand wave action, and how tightly each species of mollusc can hold onto rocks.

FIGURE 1.3.9A Black mussels clump together along rock crevices in the intertidal region of the shoreline.

FIGURE 1.3.9B Limpets distributed randomly over an exposed rock surface in the intertidal zone.

FIGURE 1.3.9C In the spray zone, tiny blue littorinids can be seen among the larger cream-coloured barnacles (which are small crustaceans in shells) and striped siphon-limpets.

You will now be able to answer Key Question 8.

FIGURE 1.3.10 The glass in this greenhouse behaves like greenhouse gases such as carbon dioxide and methane in the Earth's atmosphere. Like greenhouse gases, the glass lets the sunlight in but prevents the reflected heat from escaping back out into space.

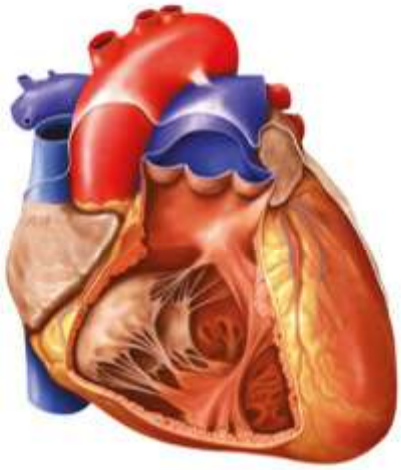


FIGURE 1.3.11 A visual model of the human heart showing the external structure and internal structure of the right ventricle.

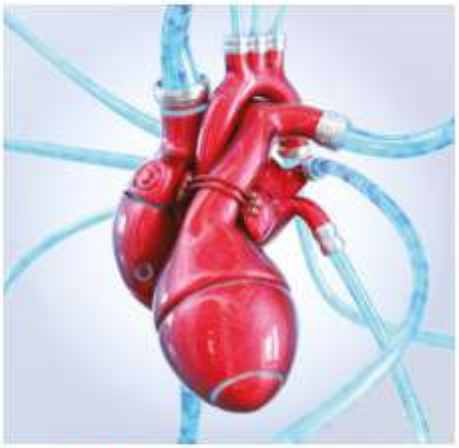


FIGURE 1.3.12 An artificial heart model made from metal (red) and plastic tubes (blue) is useful for showing the movement of blood into and out of the heart. However, it is not useful for showing the rhythmic contractions of the heart muscles, or for showing the internal structure of the heart.

MODELS

Scientific models are used to create and test theories and explain concepts. Different types of models can be used to study systems such as parts of the body or particular environments. However, each model has limitations on the type of information it can provide.

Modelling concepts

Models are created to answer specific questions. How a model is designed will depend on the questions you want to answer. The two most familiar types of models are visual models and physical models, but mathematical models and computational models are also common. Models help to make sense of ideas by visualising:

- objects that are difficult to see because of their size (too big or too small) or position, such as an ecosystem, a cell, and a heart
- processes that cannot easily be seen directly, such as digestion and feedback loops
- abstract ideas such as energy transfer and the particulate nature of matter
- complex ideas such as climate change.

For example, the greenhouse effect on Earth can be modelled using a real greenhouse (Figure 1.3.10).

Using digital modelling software to develop physical or mathematical models has enhanced our understanding in many areas. For example, flight simulators have enabled pilots to learn how to fly new aircraft, and dissection and surgery simulations can replace the practice of dissecting living organisms.

A deeper understanding of concepts can be developed through models. However, you need to identify the benefits and limitations of using a particular model to represent a concept.

Visual models

Visual models are used to represent concepts. They are two-dimensional representations of concepts. Diagrams and flow charts are examples of visual models. A picture of the human heart with red and blue colouring to represent oxygenated and deoxygenated blood is an example of a visual model (Figure 1.3.11). It is difficult for us to see this phenomenon, so models can be used to represent it. The introduction of computer technology, including two-dimensional and three-dimensional animations, has helped to create more detailed and realistic representations of biological processes.

Physical models

Physical models can be scaled-up or scaled-down three-dimensional versions of reality. You have probably already used physical models many times in the classroom without being aware of it. The human skeleton is a physical model often seen in classrooms.

Although models help us to understand concepts, they are limited in how well they can represent what they are modelling. For example, although a plastic model of a lung does inflate and deflate, it does not take in oxygen and release carbon dioxide, and it is hard and solid instead of soft and flexible.

When making physical models (Figure 1.3.12), it is important to consider what materials are used to represent reality, so that the model has fewer limitations. The materials you use to construct your model should relate to what you are modelling.

● *You will now be able to answer Key Questions 9–13.*

1.3 Review

SUMMARY

- Well-designed experiments are based on a sound knowledge of what is already understood or 'known' and careful observation.
- The scientific method is an accepted procedure for conducting experiments.
- A hypothesis is a possible explanation for a set of observations that can be used to make predictions, which can then be tested experimentally.
- Controlled experiments allow us to examine one factor at a time; they are the major means of testing hypotheses.
- Science can prove that a particular hypothesis is wrong, but it cannot prove it to be true in all circumstances.
- Science cannot be used to evaluate hypotheses that are not testable, nor can it make value or moral judgments.
- Models are useful tools that can be created and used to assist in a deeper understanding of concepts.

KEY QUESTIONS

1 What is the scientific method based on?
- **A** observation
- **B** subjective decisions
- **C** manipulation of results
- **D** generalisations

2 Name the key components of the scientific method.

3 Scientists make observations from which a hypothesis is stated and this is then experimentally tested.
- **a** Define 'hypothesis'.
- **b** How are theories and principles different from a hypothesis?

4
- **a** What do 'objective' and 'subjective' mean?
- **b** Why must experiments be carried out objectively?

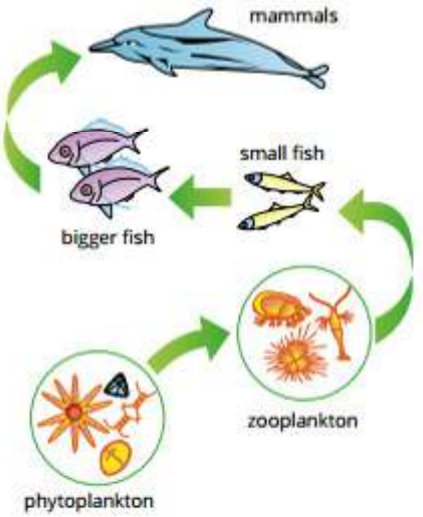
5 Which of the following is an important part of conducting an experiment?
- **A** disregarding results which do not fit the hypothesis
- **B** making sure the experiment can be repeated by others
- **C** producing results that are identical to each other
- **D** changing the results to match the hypothesis

6
- **a** Explain what is meant by the term 'controlled experiment'.
- **b** Using an example, distinguish between independent and dependent variables.

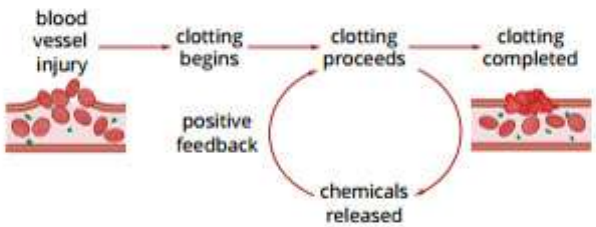
7 A scientist carries out a set of experiments, analyses the results and publishes them in a scientific journal. Other scientists in different laboratories repeat the experiment, but do not get the same results as the original scientist. Suggest several reasons that could explain this.

8 Design an experiment to test whether temperature is an important factor in the distribution of a mollusc species on a rocky coast. Clearly state the hypothesis that your experiment will test. Explain the methods that you would use. Do not forget to include experimental controls.

9 Explain what is represented by the visual model below.



10 Discuss the benefits and limitations of using the feedback loop model shown below.



11 Explain the benefits of using a torso model to learn about the parts and relative positions of the organs in the human body.

12 Explain two limitations of using models. Include an example.

13 Discuss how computer modelling could assist in representing and learning scientific concepts.

1.4 Planning investigations

First-hand investigations are those where you gather the raw data for yourself. These often take the form of experiments, activities, field trips or surveys (Figure 1.4.1). There are many elements to this type of practical investigation. A step-by-step approach will help you through the process and assist you in completing a solid and worthwhile investigation.

FIGURE 1.4.1 A microbiologist in the field collecting soil samples to test for bacteria in the East Kimberley, Western Australia.

Taking the time to carefully plan and design an investigation before you begin will help you maintain a clear and concise focus throughout. Preparation is essential. Ensure you have both a solid understanding of the theory behind your investigation and a detailed plan for the practical components of your investigation.

In this section you will learn about some of the key steps to take when planning and designing investigations:

- choosing a topic
- defining the key terms
- sourcing information
- research techniques
- ethics approval
- occupational health and safety.

CHOOSING A TOPIC

Throughout the course of your studies, you will be required to conduct two major investigations. One will relate to the survival of an individual or species (your practical investigation), and the other will focus on applications of genetics knowledge and reproductive science in society (your investigation of an issue). The following sections in this chapter will provide you with the information you need to complete both.

Practical investigation

In your practical investigation you will need to:

- develop a question and plan a course of action to answer the question
- undertake an experimental investigation to collect the appropriate primary qualitative and/or quantitative data; in the next section you will learn about how this data can be collected from laboratory work, fieldwork and/or observational studies
- organise and interpret the data and reach a conclusion in response to the question.

The question for your investigation must be related to the survival of an organism or a species. Some examples of things you might study include:

- how cellular structure or cellular organisation in an organism functions to sustain life
- how a structural, physiological or behavioural adaptation enhances the survival of an organism or enables it to exist in a wide range of environments.

Investigation of an issue

In your investigation of an issue relating to genetic and reproductive science you will need to:

- explain the scientific concepts behind the genetic or reproductive technology or application chosen
- describe the technology or application
- discuss the impacts of this technology or application on individuals and society including the related social, economic, legal and ethical issues, which can be complex and controversial
- gather information from laboratory work, literature searches, global databases and/or interviews with experts.

When choosing a topic, choose one that you are interested in, including both the scientific theory and the implications for society. You must be willing to research different points of view in relation to your topic and discuss them.

Another thing to consider is the scope of your investigation. Remember you will need to keep to your word count, so you need to be concise, while still being accurate and complete. Choosing a specific focus rather than a general one will help ensure you are able to cover it thoroughly. For example, the specific topic 'Gene modification in plants or crops' can be covered more thoroughly in a limited format than the broader topic 'Gene modification', which would include gene modification in all organisms.

DEFINING KEY TERMS

When beginning a research investigation, you first have to develop and evaluate a research question, and determine the associated variables, hypothesis, and aims. It is important to understand that each of these can be refined as the planning of your investigation continues.

The research question is a statement defining what is being investigated. For example: Is the rate of transpiration in plants dependent on temperature?

The variables are the factors that change during your experiment. For example: temperature is a variable.

The hypothesis is a suggested outcome of the experiment based on previous knowledge and evidence or observations that attempts to answer the research question. For example: If the temperature increases from 20 °C to 40 °C then the rate of transpiration in plants will increase.

The aim is a statement describing in detail what will be investigated. For example: To investigate the effect of temperature on the rate of transpiration in plants at 20 °C, 30 °C and 40 °C.

Determining your research question

Before conducting an experimental investigation you need a research question to address. You may come up with a topic or idea of interest, so the first thing you need to do is conduct a literature review; that is, reading scientific reports and other articles on the topic, to find out what is already known, and what is not known or not yet agreed upon. The literature also gives you important information for the introduction to your report and ideas for experimental methods.

A literature review is an analysis of second-hand information. When conducting a literature review you should write down questions or correlations you find. Compile a list of possible ideas. Do not reject ideas that initially may seem impossible. Use these ideas to generate questions.

When you have defined the question, you are able to formulate a hypothesis, identify the measurable variables, proceed with designing your investigation and suggest a possible outcome of the experiment.

Stop to evaluate the question before you progress; it may need further refinement or even further investigation before it is suitable as a basis for an achievable and worthwhile investigation. Consider the following checklist:

- ☐ relevance—Your question must be related to your chosen topic. For your practical investigation decide whether your question will relate to cellular structure or organisation, or to structural, physiological or behavioural adaptations of an organism to an environment.
- ☐ clarity and measurability—Your question must be able to be framed as a clear hypothesis. If the question cannot be stated as a specific hypothesis, then it is going to be very difficult to complete your research.
- ☐ time frame—Make sure your question can be answered within a reasonable period of time. Ensure your question isn't too broad.
- ☐ knowledge and skills—Make sure you have a level of knowledge and a level of laboratory skills that will allow you to explore the question. Keep the question simple and achievable.
- ☐ practicality—Check the resources you require, like reagents and laboratory equipment, are going to be available. You may need to consult your teacher. Keep things simple. Avoid investigations that require sophisticated or rare equipment. More readily available equipment may include thermometers, photometers, light microscopes and other common laboratory equipment.
- ☐ safety and ethics—Consider the safety and ethical issues associated with the question you will be investigating. If there are issues determine if these need to be addressed.
- ☐ advice—Seek advice from your teacher on your question. Their input may prove very useful. Their experience may lead them to consider aspects of the question that you have not thought about.

Defining your variables

The factors that can change during your experiment or investigation are called the variables. An experiment or investigation determines the relationship between variables, measuring the results. There are three categories of variables:

- independent—a variable that is controlled by the researcher (the one that is selected and changed)
- dependent—a variable that may change in response to a change in the independent variable, and is measured or observed
- controlled variables—the variables that are kept constant during the investigation.

You should have only one independent variable. Otherwise you could not be sure which independent variable was responsible for changes in the dependent variable.

Constructing your hypothesis

The hypothesis is an educated guess (based on evidence and prior knowledge) to answer your research question. It defines a proposed relationship between two variables. To do this, you will need to identify the dependent and independent variables.

A good hypothesis is written in terms of the dependent and independent variables:

If *x* happens, then *y* will happen.

For example:

If *I bake potatoes, pumpkin and sweet potatoes at the same temperature,*
then *the pumpkin will cook the fastest.*

The 'if' part of the hypothesis refers to the independent variable—the variable you alter in the experiment. The 'then' part relates to the dependent variable, which is the variable you measure or observe.

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

Pumpkin will cook faster than potatoes and sweet potatoes
when *they are cooked at the same temperature.*

A good hypothesis can be tested to determine whether it is true (verified), or false (falsified) by investigation. To be testable, your hypothesis should include variables that are measurable.

Writing a hypothesis from an inference

Scientists often develop a hypothesis by **inference** (reasoning) based on preliminary observations. For example, in summer the colour of grasses usually changes from green to brown or yellow. One observation is that grass growing near the edges of a concrete path stays green for longer than grass farther from the edges (Figure 1.4.2).

FIGURE 1.4.2 The grass closer to the concrete and in between the cracks in the concrete is green.

A valid inference is one that explains all the observations. Some inferences that may explain why grass growing near the edge of the concrete path remains green in summer are as follows:

- Inference 1: This grass receives the rain runoff from the path when it rains.
- Inference 2: The concrete path insulates the grass roots from the heat and cold.
- Inference 3: People do not walk on this part of the grass.

For Inference 2 the hypothesis might be: 'The temperature of the soil around the grass roots under the path is less than the temperature of the soil around the grass roots beside the path.'

Creating a table like Table 1.4.1 will assist in evaluating your research question, the variables to be considered, and different hypotheses to be considered.

Research question	Independent variable	Dependent variable	Controlled variables	Potential hypothesis
Does fertiliser make plants grow bigger?	fertiliser	plant height	type of plant, soil, temperature, water, and sunlight	If fertiliser is added to the soil, plant X will grow taller.

TABLE 1.4.1 Summary table of research question, variables and potential hypothesis

● *You will now be able to answer Key Questions 1 and 2.*

Determining your aims

The aims are the key steps required to test your hypothesis. Each aim should directly relate to the variables in the hypothesis, describing how each will be studied or measured. The aims do not need to include the details of the method.

Example 1

- Hypothesis: If the temperature is increased, then the rate of transpiration in plants will also increase.
- Aim: To compare the rate of transpiration of corn seedlings in air temperatures of 15 °C, 25 °C, 35 °C and 45 °C over 24 hours.
- Variables: temperature (independent) and transpiration rate (dependent).

Example 2

- Hypothesis: Red flowers attract more bees than blue flowers.
- Aim: To compare the number of visits by bees to red flowers with the number of visits by bees to blue flowers over a set period.
- Variables: number of visits by bees (dependent) and level of contrast of the colour of flowers with their background (independent).

● *You will now be able to answer Key Questions 3–6.*

SOURCING INFORMATION

When sourcing information for the literature review, researching experimental methods and investigating a broader issue, consider whether that information is from primary or secondary sources. You should also consider the advantages and disadvantages of using resources like books or the internet.

Primary and secondary sources

Primary and secondary sources provide valuable information for research. Sometimes the same type of resource may be classified as both a primary and a secondary source, depending on when and by whom it was written. For example, a scientist's journal article on a clinical trial of treatments for teenage obesity is a **primary source**, while a general magazine article about teenage obesity written by a journalist and referring to the scientific study is a **secondary source**. Table 1.4.2 compares primary and secondary sources.

	Primary sources	Secondary sources
Characteristics	• first-hand records of events or experiences • written at the time the event happened • original documents	• interpretations of primary sources • written by people who did not see or experience the event • use information from original documents but rework it
Examples	• results of experiments • scientific journal/magazine articles • reports of scientific discoveries • photographs, specimens, maps and artefacts • interviews with experts • websites (if they meet the criteria above)	• textbooks • biographies • newspaper articles • magazine articles • documentaries • websites that interpret the scientific work of others

TABLE 1.4.2 Summary of primary and secondary sources.

Secondary sources of information include books, journals, magazines, newspapers, interviews, television programs and the internet. You should aim to use a wide range of data sources when performing your second-hand data investigations. Secondary sources of information may have a bias, so you need to determine if they are accurate, reliable and valid sources of information. You will learn about assessing the accuracy, reliability and validity of second-hand data in section 1.5.

Using books and the internet

The resources you use affect the quality of your research. Peer-reviewed scientific journals are the best sources of information, but you are unlikely to have access to them. Books, magazines and internet searches will be your most commonly used resources for information. However, you should be aware of the limitations of these resources (Table 1.4.3). Reputable science magazines you might find in your school library include *New Scientist*, *Cosmos*, *Scientific American* and *Helix* (Figure 1.4.3).

FIGURE 1.4.3 You will find reputable science magazines in your school library.

	Book resources	Internet resources
Advantages	• written by experts • authoritative information • proofread, so information is accurate • logical, organised layout • content is relevant to the topic • contain a table of contents and index to help find relevant information	• quick and easy to access • allow access to hard-to-find information • access to the whole world; millions of websites • up-to-date information
Disadvantages	• may not have been published recently • usable by only one person at a time	• time-consuming looking for relevant information • a lot of 'junk' sites and biased material • search engines may not display the most useful sites • cannot always tell how up-to-date information is • difficult to tell if information is accurate • hard to tell who has responsibility for authorship • information is not ordered • less than 10% of sites are educational

TABLE 1.4.3 Advantages and disadvantages of book and Internet resources.

Evaluating websites

Remember that anyone can publish anything on the Internet, so it is important to evaluate the credibility, currency and content of online information:

- ☐ credibility—Consider who the author is, their qualifications and expertise; check for their contact information and for a trusted abbreviation in the web address, such as .gov or .edu; websites using .com may have a bias towards selling a product, and .org sites might have a bias towards one point of view.
- ☐ currency—Check the date the information you are using was last revised.
- ☐ content—Consider whether the information presented is fact or opinion; check for properly referenced sources; compare to other reputable sources, including books and science journals.

Evaluating books and journals

Your textbook should be your first source of reliable information. Other information should agree with this. Articles published in journals can often present findings of new research, which may or may not be confirmed later, so be careful not to treat such sources of information as established fact. Scientific journals are peer-reviewed (critically reviewed by other specialist scientists), which gives them more credibility than other sources.

● *You will now be able to answer Key Questions 7 and 8.*

RESEARCH METHODS

Many research methods are used in scientific investigations. In your studies you are required to undertake investigations through a combination of laboratory work and fieldwork.

Laboratory work

In an investigation into the survival of an organism or species, laboratory work will likely involve light microscopy. For example, you might choose to investigate and observe a microscopic organism, or investigate the role of microscopic features in the survival of a larger organism. While researching the topic, look for methods that can be used in your school laboratory.

Types of things you might investigate in a lab include factors affecting the survival and growth of organisms. Check that you can:

- obtain and grow (or culture) the organism (might be plants, bacteria, protists or invertebrates)
- obtain the equipment and any reagents needed to perform the experiments; get trained in their use
- order any materials needed
- access the school laboratory when you need to.

Protocol and schedule

Write a protocol (detailed description) of how to conduct the experiment so that your teacher can check that it is appropriate, and so that others can repeat it exactly.

Test the protocol and evaluate and modify it if necessary. You need to be able to do it independently and in the time available in the school lab and with minimum support from your teachers and school laboratory staff.

Make a work schedule (including sufficient time to repeat experiments if necessary) and give this to your teacher and laboratory technician.

Microscope lenses and magnification

The eyepiece (or ocular lens) of a microscope is the lens closest to the eye, and usually magnifies objects by 10 times their actual size (×10). The other lens is the objective lens and is located on the rotating part of the microscope barrel. There are usually three or four objective lenses, each allowing for a different degree of magnification.

Start off with the lowest magnification lens (usually ×4) and rotate through each lens until you have the view of the specimen that you want. Other lenses are usually a ×10 medium power lens, a ×40 high power lens, and sometimes a ×100 oil immersion lens designed for use with a special oil.

The magnification of the microscope is determined by multiplying the magnification on the ocular lens by the magnification on the objective lens being used. For example, using a ×10 ocular lens and a ×40 objective gives a total magnification of ×400.

Field of view and size of specimens

Being able to calculate the field of view is essential in order to estimate the size of specimens you are looking at under the microscope. Also, all biological drawings require a scale. To calculate the field of view you use a minigrid. This is a 1 mm × 1 mm grid with a smaller microgrid of 100 µm × 100 µm in the centre (used with the ×40 objective). If you do not have a minigrid, you can use a clear ruler marked in mm or a 1 mm × 1 mm grid on clear plastic film.

To calculate the field of view:

- ☐ place the minigrid on the microscope stage.
- ☐ focus using the ×4 objective lens so that you can see the grid clearly.
- ☐ adjust the slide position so that one line is on the edge of the field of view (Figure 1.4.4).

Typical magnifications and fields of view with a ×10 eyepiece:

Objective lens	Field of view
×4	4.5 mm
×10	1.5 mm
×40	450 µm
×100	150 µm

- ☐ count the grid lines across and estimate the diameter of the circle you see (on extra low power, it should be about 4.5 mm or 4500 µm).
- ☐ now change to the ×10 objective lens and estimate the size again (it should be about 1.5 mm or 1500 µm). You should be able to use the microgrid to measure the exact distance across the field of view.
- ☐ move the microgrid to the centre of the field of view.
- ☐ focus on the microgrid using the ×40 objective lens (remembering that the microgrid lines are 100 µm apart). The field of view on high power should be about 450 µm.

It is important that you measure the field of view every time you use a different microscope, because there are differences between microscopes and this will affect your estimates of the size of specimens.

Now that you have calculated your field of view for each lens, it is possible to estimate the size of a whole specimen or the size of individual features such as cells.

Place the slide with your specimen on the microscope stage and focus your microscope. Knowing the field of view, you can estimate the size of the specimen. For example, if you are looking at a transverse section of a leaf and you can see exactly half of the leaf under extra low power, then you can estimate that the leaf is 2 × 4.5 mm = 9 mm long.

If you wish to calculate the size of the individual cells in the leaf, then you can count the number of cells across the high power field of view, as shown in Figure 1.4.5.

Microscopy is covered in more detail in Chapter 2.

Field work

Your investigation may look at the population of a particular species in two different areas. When studying ecology, it may be necessary to determine the type and number of living organisms in an area. There are many different ways to do this, including quadrats and transects. Whatever way you use, it is important to always leave the environment the way you found it (Figure 1.4.6).

● *You will now be able to answer Key Questions 9 and 10.*

FIGURE 1.4.6 When working in the field, a good principle to work by is to take only photographs, leave only footprints.

In natural environments it is usually impossible to count all the individuals of a species. Even just counting the living things in your school would take a very long time. Sampling gives us a good idea of the organisms in an ecosystem without needing to count each one. Table 1.4.4 on page 32 outlines some sampling techniques and when they are best used.

When sampling in the field you should always consider the time and equipment available, the organisms involved and the impact the sampling may have on the environment.

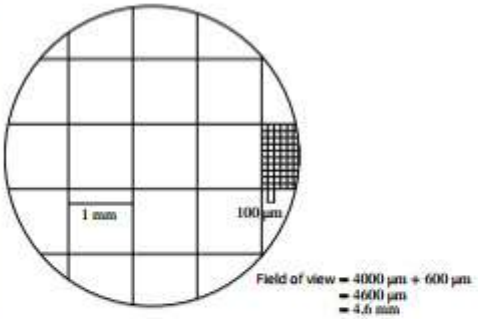


FIGURE 1.4.4 The field of view of this microscope using the ×4 lens is 4.6 mm (or 4600 µm). You can work this out using the minigrid.

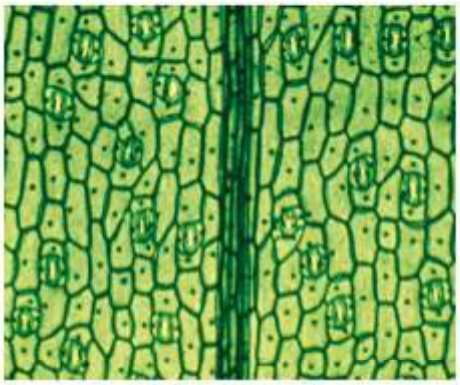


FIGURE 1.4.5 Leaf epidermis cells under a high power lens (×40). The field of view is 450 µm. There are about 30 cells across the field of view, so the average width of a leaf epidermis cell is 450/30 = 15 µm.

Point sampling

Point sampling involves counting organisms only at selected points (Figure 1.4.7). These points might be selected randomly or regularly, depending on the type of sampling being done. It can be used to determine the range of organisms that live in an area and how common they are. Point sampling is quick, but you might miss rare organisms.

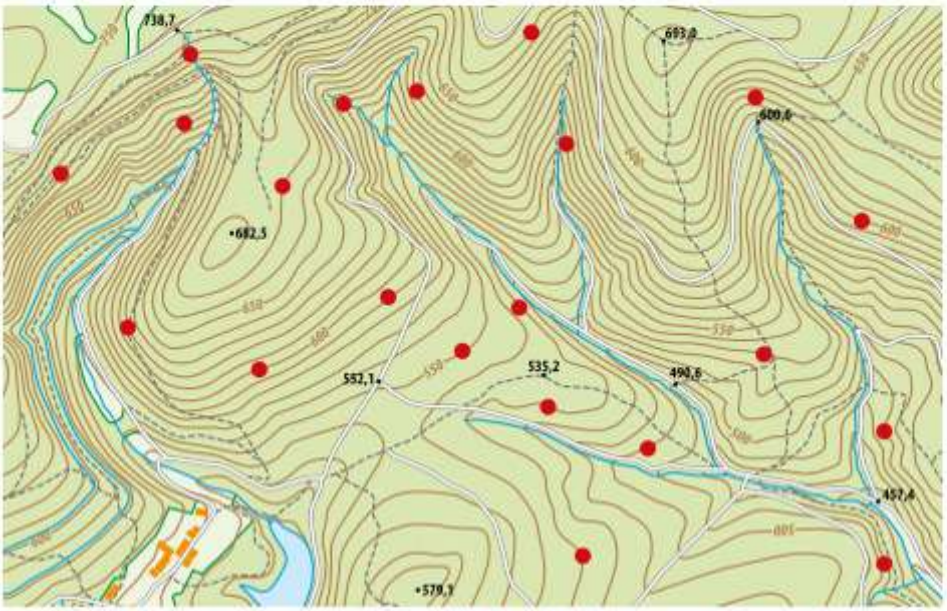


FIGURE 1.4.7 Randomly selected points for sampling marked on a topographical map. Sampling sites are indicated by the red dots.

Quadrats

A **quadrat** is a sampling method that allows you to estimate the number and variety of organisms in a large area by counting in a small area (Figure 1.4.8). A quadrat is usually square, rectangular or circular. Keep the following points in mind when planning to use quadrats:

- Quadrats are most useful in sampling immobile organisms such as plants or corals.
- Determine the size of the quadrat based on the size and abundance of the organism that you are sampling.
- The more quadrats you use, the more accurate your results will be.
- Very abundant organisms can be measured as a percentage of the area covered, rather than as a number of organisms.
- Photographing the quadrat can be a useful way of record-keeping.

FIGURE 1.4.8 A botanist using a quadrat frame to monitor a threatened species of aquatic moss. The quadrat frame is a 50 cm square divided into 10 cm squares. The presence or absence of the moss is recorded for each 10 cm square, over a large area marked out by string lines.

Transects

A **transect** is a straight line along which vegetation is sampled (Figure 1.4.9). Transects are useful for investigating the distribution of a population of plants, animals or insects across different zones (with different abiotic factors) or in a linear pattern. For example, Figure 1.4.9 shows how a transect that was used to sample and describe the change from eucalypt forest to heathland. A transect running from the sea to the land can also be used to describe the change from seagrass (closest to the sea) to mangrove to saltmarsh communities (inland) associated with the build-up of sediment along a coastline.

Physical aspects of the environment, such as soil type and pH, salinity, amount of light, slope angle and height can also be measured along a transect to see if they correlate with changes in biological communities.

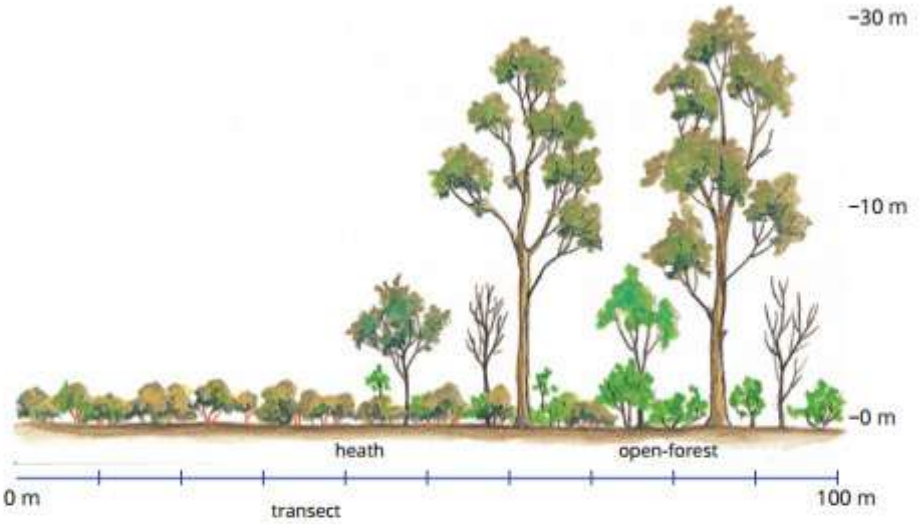


FIGURE 1.4.9 A transect is a straight line along which vegetation is sampled.

Techniques for sampling aquatic habitats

Marine and freshwater habitats can be sampled in many ways. Open water habitats are sampled by pulling a net through the water to collect swimming and floating organisms. Reefs and other underwater habitats are sampled using techniques similar to those used on land, such as quadrats and transects.

You are most likely to sample a freshwater habitat during your studies (Figure 1.4.10). Water is collected in a bucket and tipped into a white tray so that free-floating organisms can be easily spotted. Loose rocks are also collected to search for organisms such as stoneflies. Mud might also be collected and sampled to search for organisms such as nematodes and snails. Larger animals such as fish and yabbies can be collected using a net, then quickly identified and returned to the water.

FIGURE 1.4.10 Sampling organisms in a freshwater stream. The researchers have placed a sample of water and rocks in a white tray and are searching for different types of organisms. After sampling, the water and rocks are returned to the stream.

Mark–recapture

In a mark–recapture study, animals are captured, marked and then released. When they are recaptured or observed again, their mark is used to identify them (Figure 1.4.11). Mark and recapture is used to determine the total population of a mobile species such as birds and turtles. It can also be used to track the movements of individual animals. However, it is very time-consuming and requires a lot of expertise to be done properly.

FIGURE 1.4.11 Bird banding is a common mark–recapture technique. The leg bands on these pied currawongs (*Strepera graculina*) uniquely identify each individual, and include information about where and when the birds were captured.

Summary

Table 1.4.4 summarises the common fieldwork techniques.

Method	Procedure	Uses	Considerations
Point sampling	Individual points are chosen on a map and the organisms at those points are counted.	Determining the range of organisms that live in an area and how common they are.	Time efficient, disturbance to the environment is minimised. Rare organisms may be missed.
Transect sampling	Lines are drawn across a map. Organisms occurring along the line are sampled.	Determining how the community changes in an area and how common organisms are.	Time efficient, disturbance to the environment is minimised. Rare organisms may be missed. Only suitable for sampling stationary or slow-moving organisms.
Quadrat sampling	Sampling squares (quadrats) are placed in a grid pattern on the sample area and the occurrence of organisms in each quadrat is noted.	Determining the range of organisms that live in an area and how common they are. Gives very good data over a large area.	Time-consuming to do well and only suits slow-moving or stationary organisms. Disturbance to the environment is minimised.
Mark and recapture	Animals are captured, marked and then released. After a suitable time period, the population is resampled using the same method.	Determining the total population of highly mobile species like birds or possums. Movements of individuals can be tracked.	Time-consuming to do well and not suitable for slow-moving or stationary organisms. The marking of animals should not affect their behaviour or movement.

TABLE 1.4.4 Summary table of common fieldwork techniques.

● *You will now be able to answer Key Questions 11–13.*

Observational studies

An observational study involves observing the behaviour of organisms. They are often used to identify characteristic behaviours of a species, the functions of those behaviours, and the conditions that trigger them. This branch of science is called **ethology**. Observational studies can take place in a laboratory (e.g. with mice in a maze), an artificial environment (e.g. seals in a zoo) or a natural environment (e.g. birds in a forest).

In natural environments you might need a field guide to enable you to identify the species correctly. Make sure you select a field guide that is appropriate for your environment and investigation.

A list of specific behaviours of a species is called an **ethogram**. For example, the ethogram of a mouse includes behaviours such as exploratory, sexual, maternal and maintenance (drinking, feeding etc.).

Making casual observations of the behaviours of organisms is not scientific, but it can provide important information when planning a scientific study. For example, knowing where and when a species feeds will help when planning research on the amount or type of food they eat.

In more formal observational studies you should have a measurable question in mind. For example, 'How much time do possums spend in their nest each day?' Other ways in which you could limit your investigation to a quantifiable behaviour might include:

- recording the behaviours of just one individual organism
- recording one particular behaviour of a group of organisms
- recording continuously or discontinuously at determined time intervals (for example, 1 minute every 10 minutes)
- measuring the frequency of a clearly defined set of behaviours (an ethogram), the sequence of the behaviours or both
- inferring the occurrence of a behaviour by observing traces left behind as a result of the behaviour, rather than directly observing the behaviour itself
- mapping a single behaviour in an environment or space
- using internet databases of ethograms to obtain results.

ETHICS APPROVAL

Ethics is a set of moral principles by which your actions can be judged as right or wrong. Every society or group of people has its own principles or rules of conduct. Scientists have to obtain approval from an ethics committee and follow ethical guidelines when conducting research that involves animals including, and especially, humans.

If you work with animals as part of your studies, your school should have already obtained a special licence to cover this, and should be following the Victorian Government's guidelines for the care and use of animals in schools. These guidelines recommend that schools consider the '3Rs rule':

- replacing the use of animals with other methods where possible
- reducing the number of animals used
- refining techniques to reduce the impact on animals.

You should treat animals with respect and care. The welfare of the animal must be the most important factor to consider when determining the use of animals in experiments. If at any time the animal being used in your experiment is distressed or injured, the experiment must stop.

● *You will now be able to answer Key Question 14.*

OCCUPATIONAL HEALTH AND SAFETY

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

Everything we do has some risk involved. **Risk assessments** are performed to identify, assess and control hazards. A risk assessment should be performed for any situation, whether in the laboratory or out in the field, which could cause harm to people or animals. Always identify the risks and control them to keep everyone safe.

To identify risks, think about the following:

- the activity that you will be carrying out
- where in the environment you will be working, e.g. in a laboratory, school grounds, or a natural environment
- how you will use equipment, chemicals, organisms or parts of organisms that you will be handling
- what clothing you should wear.

The following hierarchy of risk controls (see Figure 1.4.12) is organised from most effective to least effective:

- elimination—Eliminate dangerous equipment, procedures or substances.
- substitution—Find different equipment, procedures or substances to use that will achieve the same result, but have less risk associated.
- isolation—Ensure there is a barrier between the person and the hazard. Examples include physical barriers such as guards in machines or fume hoods to work with volatile substances.
- engineering controls—Modify equipment to reduce risks.

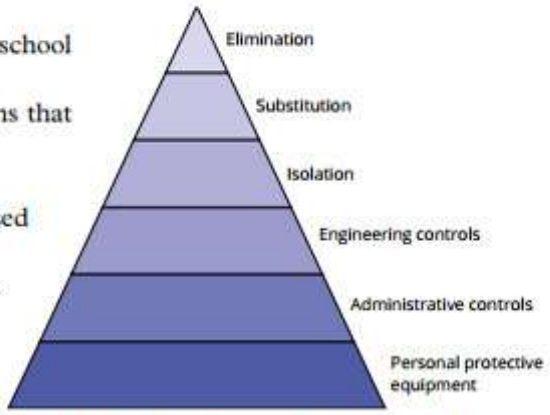


FIGURE 1.4.12 The hierarchy for hazard control is shown in this pyramid, marked from top to bottom in order of importance.

FIGURE 1.4.13 A lab coat, gloves and safety glasses are essential items of personal protective equipment in the laboratory.

- administrative controls—Provide guidelines, special procedures, warning signs and safe behaviours for any participants.
- personal protective equipment—Wear safety glasses, lab coats, gloves, respirators and any other necessary safety equipment where appropriate, and provide these to other participants.

Personal protective equipment

Everyone who works in a laboratory wears clothing and equipment to improve safety (Figure 1.4.13). This is called personal protective equipment (PPE) and includes:

- safety glasses
- shoes with covered tops
- disposable gloves when handling chemicals or organisms
- an apron or a lab coat to prevent spills from coming into contact with your clothes and skin
- ear protection if there is risk to your hearing.

Science outdoors

Scientific research often involves outdoor field work in potentially hazardous situations (Figure 1.4.14). All the potential risks, and ways to minimise them, must be considered when planning field work. Table 1.4.5 shows some common risks and measures that can be taken to minimise them.

FIGURE 1.4.14 These botanists are well prepared for the hazards of working in the Victorian Alps. They are wearing warm clothing, waterproof jackets, long pants and stout boots. They are carrying food, water and everything they might need in an emergency in their backpacks, and they are working in a group rather than alone.

Risk	Measures to minimise risk
sunburn	wear a hat, sunglasses and long-sleeve top; apply sunscreen regularly
hot weather	wear light, loose-fitting clothing; drink water regularly to avoid dehydration
cold weather	wear warm clothing such as a polar fleece jacket and woollen hat
insect and animal bites	apply insect repellent; watch where you walk, and do not put your hand in a hole or hollow without checking first; bring a first aid kit
sprained ankle, blisters	wear stout, well-fitted boots with thick socks
wet weather	carry waterproof clothing
getting lost	work in a group, never alone; carry a map, compass, torch, GPS, and mobile phone or two-way radio
bushfire	check fire conditions before you leave; do not do field work when danger is rated high or more; carry a radio to listen for bushfire warnings

TABLE 1.4.5 Some common risks associated with field work.

Chemical safety

Some chemicals used in laboratories are harmful. When you are working with chemicals in the laboratory or at home, it is important you keep them away from your body. Laboratory chemicals can enter the body in three ways:

- ingestion: Chemicals that have been ingested (eaten) may be absorbed across cell lining the mouth or enter the stomach, and may then be absorbed into the bloodstream
- inhalation: Chemicals that are breathed in (inhaled) can cross the thin cell layer of the alveoli in the lungs and enter the bloodstream
- absorption: Some chemicals are able to pass through the skin in a process called absorption.

When working with any type of chemical you should:

- identify the chemical codes and be aware of the dangers they are warning about
- become familiar with the **Material Safety Data Sheets** (MSDS)
- use personal protective equipment (PPE)
- wipe up any spills
- wash your hands thoroughly after use.

Chemical codes

The chemicals in laboratories, supermarkets, pharmacies and hardware shops have a warning symbol on the label. These are a chemical code indicating the nature of the contents (Table 1.4.6).

Symbol	Meaning	Symbol	Meaning
	can dissolve or eat away at substances, including tissues such as your skin or airways		can cause injury or death if ingested, inhaled or absorbed
	causes discomfort, pain or itchiness		is a flammable liquid

TABLE 1.4.6 Some different warning labels you might see on chemicals.

Material safety data sheets

Every chemical substance used in a laboratory has a **material safety data sheet** (MSDS). This contains important information about the possible hazards in using the substance and how it should be handled and stored. An MSDS states:

- the name of the hazardous substance
- the chemical and generic names of certain ingredients
- the chemical and physical properties of the hazardous substance
- health hazard information
- how to store the chemical safely
- precautions for safe use and handling
- how to dispose of the chemical safely
- the name of the manufacturer or importer, including an Australian address and telephone number.

An MSDS contains important safety and first aid information for teachers and technicians about each chemical you commonly use in the laboratory.

The MSDS provides employers, workers and emergency crews with the necessary information to safely manage the risk of hazardous substance exposure.

First aid

Minimising the risk of injury reduces the chance of requiring first aid assistance. However, it is still important to have someone with first aid training with you during practical investigations. Always tell your teacher or laboratory technician if an injury or accident happens.

● *You will now be able to answer Key Questions 15–17.*

1.4 Review

SUMMARY

- A research question is a statement that broadly defines what is being investigated.
- A hypothesis:
  - is a possible outcome based on previous knowledge and evidence or observations, and addresses the research question
  - often takes the form of a proposed relationship between two or more variables in a cause and effect relationship
  - must be testable; that is, able to be supported (verified) or refuted (falsified) by investigation.
- A practical investigation determines the relationship between variables, measuring the results.
- The three types of variables are:
  - independent—a variable that is controlled by the researcher (the one that is selected and changed)
  - dependent—a variable that may change in response to a change in the independent variable, and is measured or observed
  - controlled variables—the variables that are kept constant during the investigation.
- An aim is a statement describing in detail what will be investigated.
- Laboratory research techniques include microscopy:
  - the magnification of the microscope is determined by multiplying the magnification on the ocular lens by the magnification on the objective lens
  - to calculate the field of view you use a minigrid, which you can then use to estimate the size of your specimen.
- Field research techniques include:
  - point sampling: choosing points on a map to count organisms
  - quadrats: a sampling method that allows you to estimate the number and range of organisms in a large area by counting in a small area, and which is usually square or rectangular
  - transects: quadrats placed at regular or random intervals along a line or area, which are useful for investigating the distribution of organisms across different zones or in a linear pattern
  - mark and recapture: capturing, marking and recapturing animals is a way of determining the total population of a highly mobile species, as well as tracking the movements of individuals
  - observational studies are often used to observe the behaviour of organisms
- Observational studies involve the observation of the behaviour of organisms in their natural environment.
- Ethical and safety considerations must be of the highest priority at all times during a practical investigation.

KEY QUESTIONS

1 Write each of the five numbered inferences below as an, 'if... then...' hypothesis that could be tested in an experiment.

a This grass receives the rain runoff from the path when it rains.

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

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

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

e More earthworms live under the path than under the open grass.

2 Write a hypothesis for each of the following purposes:

a to test whether carrot seeds or tomato seeds germinate quicker

b to test whether sourdough, multigrain or white bread goes mouldy the quickest

c to test whether Trigg the dog likes dry food or fresh food better

3 Select the best hypothesis, and explain why the other options are not good hypotheses.

A if light and temperature increase, the rate of photosynthesis increases

B transpiration is affected by temperature

C light is related to the rate of photosynthesis

D multigrain bread gets mouldy faster than white bread

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

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

Independent variable	Controlled variables	Dependent variable

5 Identify the independent, dependent, and controlled variables that would be needed to investigate each of the following hypotheses:

a Hypothesis: An increase in temperature will lead to an increase in the rate of transpiration in plants.

b Hypothesis: If there is no light, there will be no photosynthesis in the leaves of a plant.

c Hypothesis: If a cup of hot chocolate has a lid on it, then it will stay hot for a longer period of time.

d Hypothesis: Because thin candles have less wax to burn, they will burn faster than thick candles.

6 Consider the seedling growth investigation below:

Purpose
To investigate the effect of pH on seedling growth.

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

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

a State the independent variable for the experiment.

b State the dependent variable for the experiment.

c List the controlled variables stated in the procedure.

d Explain the importance of controlling all variables except the dependent variable.

7 Decide whether each of the following is a primary or a secondary source.

a a newspaper article about global warming

b an experiment to investigate chemical changes when mixing combinations of chemicals

c an interview with a forensic scientist about using science in tracking criminals

d a website with information about genetic engineering

8 You are learning about genetically inherited diseases and are searching for facts about cystic fibrosis. From the list below, which would be the best resource to use? Explain your answer.

A the book *Cystic Fibrosis*, published in 1997

B the article 'Living with cystic fibrosis' published in the *Daily Mail* on 23 February 2008

C the website www.cysticfibrosis.org.au, accessed on 30 October 2015

9 **a** Complete the following table.

Ocular lens	Objective lens	Total magnification	Field of view (μm)
10×	4×		
	10×		
	40×		
	100× (oil)		

b Which magnification and field of view would be best for viewing:

i protists about 20 μm long?

ii yeast cells about 7 μm in size?

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

11 What is the difference between a quadrat and transect?

12 Why is it important for quadrats to be located randomly across the area being studied?

13 Describe a sampling technique that would be suitable for each of the following investigations:

a the changes in a coastal community over sand dunes

b the number of turtles in a pond population

c the number of clover plants in a lawn

14 What three things (the 3Rs rule) should be considered in the care and use of animals in schools?

15 Explain the difference between ingestion, inhalation and absorption.

16 Explain the reasons for having MSDS for the chemicals used in the laboratory.

17 If you spilled a chemical substance with the following label on yourself, what would be the appropriate thing to do?

1.5 Conducting investigations

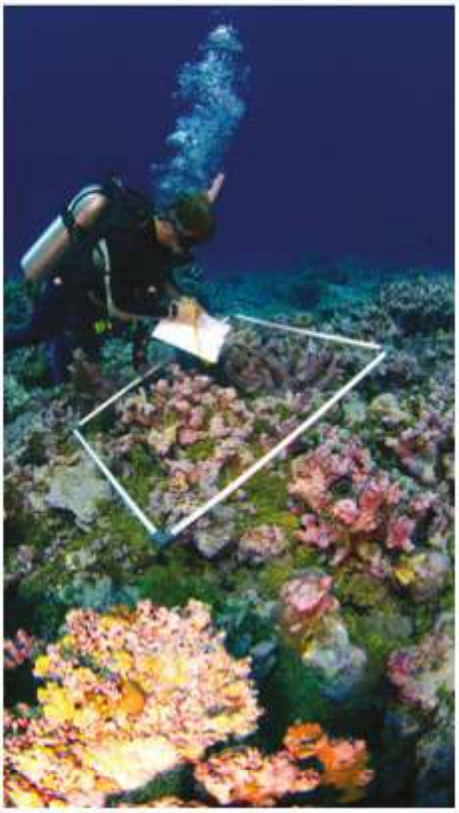


FIGURE 1.5.1 This marine biologist is keeping a logbook, recording observations as he assesses corals.

Once the planning and design of your practical investigation is complete, the next step is to undertake your investigation and record the results. As with the planning stages, there are key steps and skills to keep in mind to maintain high standards and minimise potential errors throughout your investigation.

For an investigation to be scientific, you must be objective, ensure you are familiar with your methodology and protocols before you begin, and identify potential sources of error.

In this section you will learn about collecting and analysing different types of data, and identifying and reducing sources of error that can affect data quality.

DATA COLLECTION

The measurements or observations that *you* collect during *your* investigation are your first-hand **data** (Figure 1.5.1). During your investigation you must keep a log book that includes every detail of your research. The following checklist will help you to remember what to record:

- ☐ your ideas when planning the research
- ☐ clear protocols for each stage of the research (e.g. what standard procedures you will use)
- ☐ records of all materials, methods, experiments and raw data
- ☐ instructions/table noting exactly what needs to be recorded
- ☐ the experimental/observation protocol that you will follow exactly each time
- ☐ tables you draw up ready for data entry (see Table 1.5.1)
- ☐ all notes, sketches, photographs and results should be recorded directly into log book – not on loose paper
- ☐ records of any incidents or errors that may influence results

First-hand data is data that you collect yourself.
Second-hand data is data that someone else has collected.

Keep in mind there are different types of data that can be collected in a scientific investigation, so when planning your investigation, consider the type of data you will collect and how best to record it. Data can be raw or processed, and qualitative or quantitative.

Raw and processed data

The data you record in your logbook is **raw data**. This data often needs to be processed or analysed before it can be presented. If an error occurs in processing the data, or you decide to present the data in a different format, you will always have the recorded raw data to refer back to.

Raw data is unlikely to be used directly to validate your hypothesis. However, it is essential to your investigation, and plans for collecting your raw data should be made carefully. Consider the formulas or graphs you will be using to analyse your data at the end of your investigation. This will help you to determine the type of raw data you need to collect in order to test your hypothesis.

For example, you might want to study the effect of nutrient concentration on tomato production in a hydroponic garden. To do this you might collect two sets of raw data: the concentration of nutrient solution applied to each plant, and the total mass of tomatoes harvested from each plant.

● *You will now be able to answer Key Question 1.*

Once you have determined the data you need to collect, you can prepare a table to record your data. An example for the experiment described above is shown in Table 1.5.1.

You can then process this data further. For example, the nutrient might be very expensive, so you might be interested in the ratio of tomato mass to nutrient concentration. This value (shown in the last column in Table 1.5.1) is processed data. **Processed data** is data obtained by applying a calculation or formula to raw data.

Plant tray no.	Total tomato mass (kg)	Nutrient concentration (g/L)	Mass per unit concentration (kg per g/L)
1	1.25	5.0	0.250
2	2.81	10.0	0.281
3	4.64	15.0	0.309
4	5.02	20.0	0.251
5	5.84	25.0	0.234

TABLE 1.5.1 This is an example of the kind of table that you might include in your logbook for first-hand data collection.

Qualitative data

Data collected about categorical variables is known as **qualitative data**. Categorical variables can be counted but not measured, and relate to a type or category such colour or gender, or states such as on/off or wet/dry. Categorical variables can be nominal or ordinal:

- **Nominal** (or unordered) variables are categorical variables in which there is no inherent order; they can be counted but not ordered. Examples are flower colour, gender, number of children, and dog breed.
- **Ordinal** (or ordered) variables are categorical variables in which there is an inherent order. They have a ranking or level, so they can be counted and also ordered. Examples are age group, position in a DNA sequence, and trophic level.

Recording qualitative data

Qualitative data can be represented by names, symbols or numbers. Observations of categorical variables can be descriptions or images. For example, dog breeds can be shown in a diagram, and textures of materials can be described using words such as brittle, coarse, crumbly, dense, flexible, rocky, rough, silky, slimy, smooth, spongy or velvety.

When you have to record qualitative data, think carefully about how each categorical variable will be defined. For example, if you are recording colours, a set of reference colours are a good way of clearly showing what each colour represents (Figure 1.5.2).

FIGURE 1.5.2 When recording the colour of leaves, a reference image like this one helps to record good qualitative data.

Creating a referencing system, such as assigning codes to different colours, allows you to quickly and easily record your data. For example, for the different colours in Figure 1.5.2 codes you could use G1, G2 and G3 for different shades of green, Y1, Y2 and Y3 for different shades of yellow, and O1, O2 and O3 for different shades of orange. You might find that someone has already have created a coding system for the data you want to collect, so it is a good idea to check before making your own. Whatever system you choose, make sure you apply it consistently.

Quantitative data

Data collected about numeric variables is **quantitative data**. Like categorical variables, numeric variables can be counted. Unlike categorical variables, numeric variables can also be measured, because they have a measurable quantity, like length, mass or time. Numeric variables can be discrete or continuous:

- **Discrete variables** are values that can be counted or measured, but which can only have certain values. Examples are number of fish in a pond, number of red blood cells on a slide, number of times a lever is pulled.
- **Continuous variables** may be any number value within a given range that can be measured. Examples are age, temperature, length, mass and wavelength.

Recording quantitative data

When you record quantitative data, remember to use scientific measuring units such as grams, centimetres, millimetres or degrees Celsius. Table 1.5.2 summarises the different types of data and variables.

Data type	Variable	Variable types	Examples
qualitative	categorical	nominal (no inherent category order)	object colour, gender
		ordinal (inherent category order)	age group, light intensity, house number
quantitative	numeric	discrete (distinct and separate values)	number of stars in the galaxy, number of flowers in the garden
		continuous (any number value in a range)	temperature, time, height, age

TABLE 1.5.2 Summary table of types of data and variables.

● *You will now be able to answer Key Questions 2–4.*

IDENTIFYING AND REDUCING ERRORS

When an instrument is used to measure a physical quantity and obtain a numerical value, the aim is to determine the true value. However, for a number of reasons the measured value is often not the true value. The difference between the true value and the measured value is called the **error**. This error in the measured value is the result of errors in the experiment. The two types of experimental errors are systematic errors and random errors.

Systematic errors

A systematic error (or bias) is a consistent error that occurs every time you take a measurement. Systematic errors are not easy to spot, because they do not appear as a single difference in the data set. Instead, repeated measurements give results that differ by the same amount from the true value. There are many different types of systematic errors, but the most common types are selection bias and measurement bias.

Selection bias

Selection bias occurs when your sample is not representative of the population being studied. This can have a number of different causes, including sampling bias, which is when your sample has not been selected randomly, and time-interval bias, which is when you stop your study too early because the results support your hypothesis.

Measurement bias

Measurement bias is usually a result of instruments that are faulty or not calibrated, or incorrect use of instruments, which produces inaccurate results. For example, if a scale under-reads by 1%, a measurement of 99 mm will actually be 100 mm. Another example would be if you repeatedly used a piece of equipment incorrectly throughout your investigation, such as reading from the top of the meniscus instead of the bottom when using a measuring cylinder (Figure 1.5.3).

A meniscus is the curved upper surface of liquid in a tube.

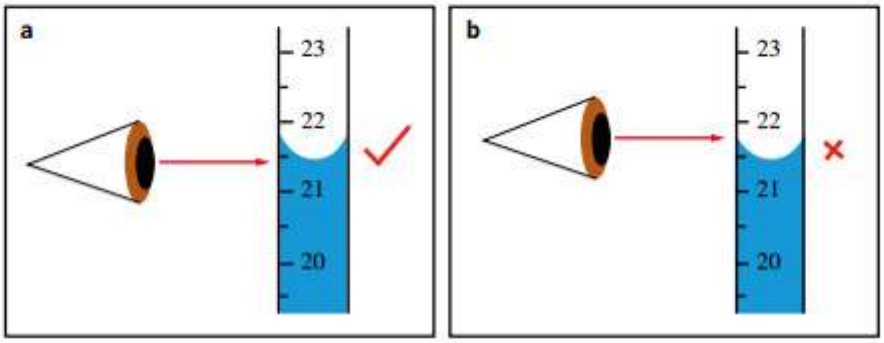


FIGURE 1.5.3 When measuring liquid levels in cylinders, measure the value at the bottom of the meniscus of the liquid as in (a), not at the top as in (b).

Reducing systematic errors

The appropriate selection and correct use of calibrated equipment will help you reduce systematic errors. Because systematic errors are difficult to identify, it is also a good idea (if you have time) to repeat your measurements using different equipment.

Appropriate equipment

Use the equipment best suited to the data you need to collect. Determining the units of the data you are collecting, and at what scale, will help you to select the correct equipment. For example, if you need to measure 10 mL of a liquid, using a 20 mL measuring cylinder will give more accurate readings than a 200 mL measuring cylinder would, because the 20 mL cylinder will have a finer scale. Accurate measurement also requires properly calibrated equipment. A laboratory measuring cylinder is calibrated for precise volume measurements and will be more accurate that a kitchen jug with a 200 mL mark.

Calibrated equipment

Before you carry out your investigation, make sure your instruments or measuring devices are properly calibrated and functioning correctly (Figure 1.5.4). Your school laboratory should have a set of standard masses that can be used to calibrate a balance or scale. A pH meter should have a set of standard pH solutions, e.g. at pH 4, pH 7 and pH 9, to check the meter readings and adjust the meter if necessary.

FIGURE 1.5.4 Measuring the pH level of tartaric acid with a pH meter. To ensure an accurate reading, the student would first have calibrated the meter using a solution of known pH.

Correct use of equipment

Use your equipment properly. Ensure you have been trained to use the equipment, write the instructions in detail so you can follow them exactly each time, and practise using it before you start your investigation. Improper use of equipment can result in inaccurate, imprecise data with large errors, and the validity of the data can be compromised. An example of incorrect use of equipment would be if a scale was not placed on a level surface, or was used in a room with air currents or vibrations.

Random errors

Random errors (also called variability) are unpredictable variations that can occur with each measurement. Random errors can occur because instruments are affected by small variations in their surroundings, such as changes in temperature. All instruments have a limited precision, so the results they produce will always fall within a range of values.

Another cause of random errors is natural variation in the things being measured. For example, if you measure the air temperature in a room at several different points, small natural variations in the air temperature will result in slightly different readings.

Reducing random errors

To reduce random errors you need to make more measurements or increase your sample size. You can then calculate the average (or mean), which should be close to the true value.

More measurements

The impact of random errors can be minimised by taking more measurements and then calculating the average value. In general, more measurements will improve the accuracy of the measured value. The minimum number of measurements you should make is three. If one reading differs greatly from the rest, mention this in your results and discuss possible reasons for the difference. If you think it is the result of an error, do not include it in your results because it will skew (bias) the result.

Sample size

Increasing the sample size reduces the effect of random errors, which in turn makes your data more reliable. For example, if you are conducting an investigation into the effects of sunlight on plant growth, do not test your hypothesis on just one plant; test it on several plants (minimum three). Using a large number of plants will reduce the likelihood of your results being skewed by (for example) plants that are diseased or have a poor root system.

● *You will now be able to answer Key Questions 5 and 6.*

ACCURACY, PRECISION AND ERRORS IN FIRST-HAND DATA

The results of your data analysis will only be as good as the quality of the data. A well-designed scientific experiment should produce accurate, precise, reliable and valid results. You should consider all of these factors when collecting first-hand data in your practical investigations, and also when you assess the quality of second-hand data (data from other sources).

Accuracy and precision

In normal language accuracy and precision have more or less the same meaning. But in science and statistics they have very specific and different meanings:

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

To understand more clearly the difference between accuracy and precision, think about firing arrows at an archery target (Figure 1.5.5). Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot. If you hit the bullseye every time you shoot, you are both accurate and precise. If you hit the same area of the target every time but not the bullseye, you are precise but not accurate. If you hit the area around the bullseye each time but don't always hit the bullseye, you are accurate but not precise. If you hit a different part of the target every time you shoot, you are neither accurate nor precise.

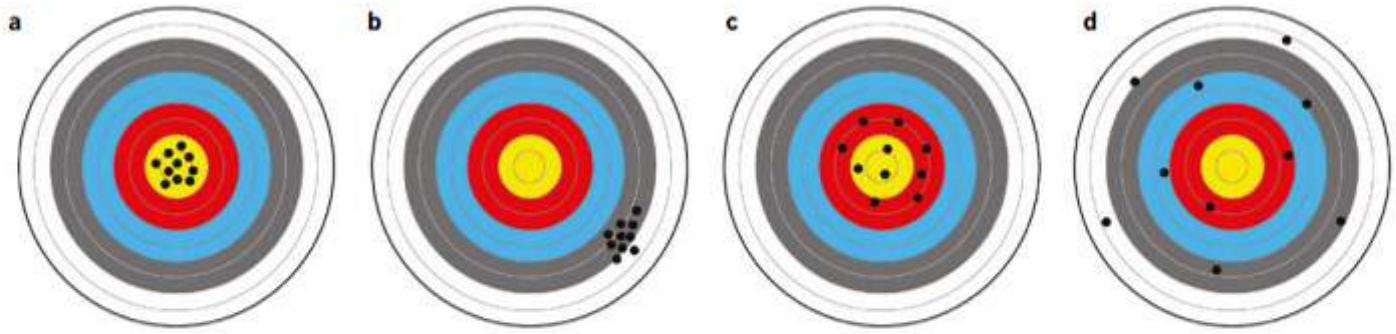


FIGURE 1.5.5 Examples of accuracy and precision: (a) both accurate and precise, (b) precise but not accurate, (c) accurate but not precise, and (d) neither accurate nor precise.

Significant figures

When using measuring instruments, the number of significant figures (or digits) you use determines how precise your measurements are. When determining the number of significant figures, remember that:

- non-zero numbers are always significant
- zeros in the middle of non-zero numbers are always significant
- zeros at the beginning of a number aren't significant, even when they are after the decimal point
- zeros at the end of a number are only significant if they are before or after a decimal point

Some examples of numbers and their significant figures are: 15 (2 significant figures), 3.5 (2 significant figures), 3.50 (3 significant figures), 0.037 (2 significant figures), 1401 (4 significant figures), 150 (2 or 3 significant figures), 150.00 (5 significant figures).

The number of significant figures you can use depends on the scale of the instrument you are using (Figure 1.5.6).

It is important to record your data to the number of significant figures available from your equipment or observation. Using either a greater or smaller number of significant figures can be misleading.

FIGURE 1.5.6 A biologist measuring the nape-to-bill length of a fairy-wren with a vernier caliper, which can measure distances to an accuracy of one tenth of a millimetre.

Reliability

Reliability (sometimes called repeatability) is the ability to obtain the same results if an experiment is repeated (Figure 1.5.7). Because a single measurement or experimental result could be affected by errors, **replication** and **repeat trials** are key components of reliability. To improve reliability you should:

- specify the materials and methods in detail
- include replicate (several) samples within each experiment
- take repeat readings of each sample
- run the experiment or trial more than once.

● *You will now be able to answer Key Questions 7 and 8.*

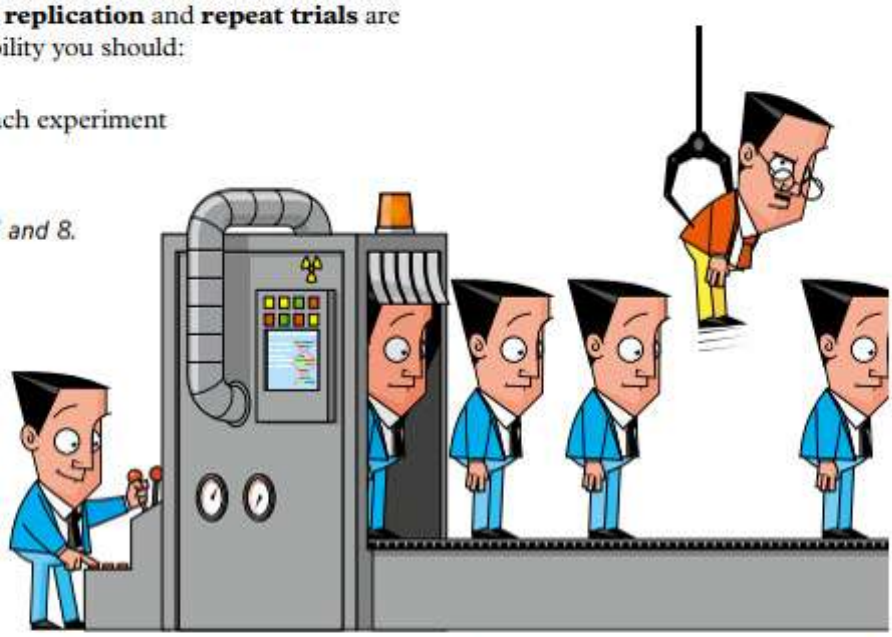


FIGURE 1.5.7 If you can reproduce your results, they are reliable.

Validity

Validity refers to whether your results are real results and whether they apply to all situations. Results are invalid, for example, if you think you have measured a variable but have actually measured something else. Factors influencing validity include:

- whether your experiment measures what it claims to measure. In other words, your experiment should test your hypothesis.
- the certainty that something observed in your experiment was the result of your experimental conditions and not some other cause that you did not consider. In other words, whether the independent variable influenced the dependent variable in the way you have concluded.
- the degree to which your findings can be generalised to the wider population your sample is taken from, or to a different population, place or time.

Randomisation

Random selection of your sample reduces selection bias and improves validity. Selection bias is when your sample doesn't reflect the wider population you wish to generalise your results to. For example, if you were conducting a survey of insects in the local area, a study design in which you chose locations at random would have better validity than one in which you chose only your own backyard.

Controls

To ensure an investigation is valid, it should be designed so only one variable is being changed at a time. The remaining variables must be kept constant (or controlled) so that meaningful conclusions can be drawn about the effect of each variable in turn. To ensure validity, carefully determine:

- the independent variable (the variable that you will change) and how you will change it
- the dependent variable (the variable that you will measure)
- the controlled variables (the variables that must remain constant) and how you will maintain them.

A control group is a comparison group. This means you need to conduct two groups side by side within an experiment. Both groups are the same, except for the variable you are testing. This is the independent variable in the hypothesis, and is applied to your experimental group but not your control group. All the other variables have to stay the same. We do not want them to change, as these may affect the result of our experiment. For example, when testing a new medication (the variable being tested), two groups of patients are involved. The control group of patients is given a placebo (a blank capsule). The other group is given the actual medication, and the data collected from this group is compared to data from the control group to see the medication's effects.

BIOFILE

The Biodiversity Heritage Library

The Biodiversity Heritage Library (http://www.biodiversitylibrary.org) is an international project that aims to provide historical and modern scientific literature freely to everyone. It is based at the Missouri Botanical Garden's Peter H. Raven Library and involves organisations throughout the world, including Australia.

The library contains around 100 000 different titles with almost 50 million pages of information. The content ranges from rare books published in the 16th century to journals published this year. You can search for a title, an author, a scientific name or a subject, or just browse through the collection.

FINDING AND EVALUATING SECOND-HAND DATA

Finding second-hand data

In order to use second-hand data you must first decide whether it is good enough to use. The best second-hand data is found in peer-reviewed scientific journals (including online journals) and books. However, this information can become out of date quickly as scientific knowledge is advanced by new research. As a rule of thumb it is not advisable to rely on information from publications over 10 years old.

You can use second-hand data from other sources too, but this data is usually less reliable than peer-reviewed sources. Whatever sources you use, you still need to check that the data is precise, accurate, reliable and valid. You also need to make sure you acknowledge that you have used these sources by referencing them in the text, and cite the sources accurately in the reference list.

Evaluating precision

To evaluate the precision of second-hand data, check in the methods section that steps were taken to identify random errors. If the data has been analysed, check that the type of analysis was appropriate.

Evaluating reliability

To evaluate the reliability of second-hand data, check whether the experimental method was statistically valid. For example:

- Are the materials and methods clearly stated?
- Were enough replicates used?
- Was the population size large enough?

The results should be able to be repeated, and ideally will have already been reproduced by other researchers. When reviewing the scientific literature, it is important to review several articles to see if the results support or contradict each other.

Peer-reviewed means that other scientists have checked the information and have agreed that it is appropriate for publication.

Evaluating validity

To evaluate the validity of second-hand data, check whether the research tested the stated hypothesis and covered the stated aims. An investigation should obtain data that is relevant to the hypothesis. If it does not then the study is invalid. You should also check whether there was appropriate randomisation and that one or more controls were included.

Summary

Table 1.5.3 summarises factors to consider when evaluating and using second-hand data. Make sure you consider all the factors that might affect the quality of the data when you are deciding whether to use it in your research.

	First-hand data	Second-hand data
Accuracy	• Use appropriate and calibrated instruments. • Address systematic errors.	• Use reputable sources such as peer-reviewed journals and books. • Check that systematic errors were addressed.
Precision	• Use an appropriate number of significant figures. • Address random errors.	• Check that random errors were addressed. • Check that any data analysis was appropriate.
Reliability	• Perform repeat readings. • If possible repeat your experiment.	• Check that the experimental method was statistically valid. • Check that information is consistent with other reputable sources.
Validity	• Ensure your experiment tests your hypothesis. • Randomise your sample and use one or more controls.	• Check that the results relate to the hypothesis and aims. • Check that samples have been randomised, and one or more controls have been used.

TABLE 1.5.3 Summary of factors impacting quality of first- and second-hand data.

OTHER ISSUES TO CONSIDER IN SCIENTIFIC RESEARCH

Scientific research is part of human society and often has social, economic, legal and ethical implications. These implications therefore need to be addressed when planning research.

Social issues

Social issues relate to implications for individuals, communities and society. People often fear what they do not understand, so they tend to fear new scientific advances and technology.

When considering social issues, it is important to think about how technology will affect different groups of people. For example, in vitro fertilisation allows couples that cannot biologically reproduce to have children, however, it remains very expensive, meaning couples from a lower socio-economic background cannot afford it.

Economic issues

Economic issues relate to costs and benefits. No scientific research is immune from economic considerations, because all research requires money and some research might have important implications for local, national or global economies.

It is important to consider who is paying for the research. For example, a company funding research into the benefits of its products will be more interested in positive results than negative results. This could result in a bias in reporting the results, especially if the company rather than the researcher reports the results.

An important economic issue for scientific research relates to costs and benefits. Valuable scientific research might never be funded because it is unlikely to make a large enough profit, or any profit at all. For example, rare diseases usually receive less research funding because they affect fewer and often poorer people, so the return on an investment in research is likely to be small.

Legal issues

The most common legal issue that researchers face is the need to obtain permits under relevant legislation. For example, in Victoria a legal permit is required to collect plants, trap animals, or conduct any other sort of research on public land. In some parts of Australia, permission is also required from the traditional owners or custodians of land. Legal issues might also be relevant if there are risks involved in using the results of research, or when new research could lead to conflict between stakeholders.

Ethical considerations

Scientific research involving humans or animals must be approved by an ethics committee before it can commence. All research involving animals in Australia must comply with the *Australian Code of Practice for the Care and Use of Animals for Scientific Purposes*. However, there might still be public concern about some types of research. For example, many people have raised concerns about the prospect of being able to genetically modify humans before birth, leading to 'designer babies', in which parents could choose things like the gender of their child or colour of their eyes. The use of live animals in research (for example, for testing the safety of pharmaceutical products) is also an issue for many people.

● *You will now be able to answer Key Question 9.*

BIOLOGY IN ACTION

Genetically modified crops

There are a range of social, economic, legal and ethical issues to consider when thinking about genetically modified (GM) organisms (Figure 1.5.8). Genetically modified crops are more disease and drought resistant, so crop yields are better and ultimately there is more food to feed people. This might be the difference between people eating or going hungry in developing countries that do not have ready access to a large food supply, so there are real benefits to GM crops. An increased supply of food can also reduce its cost, making it more affordable.

Crops can also be genetically modified to contain higher levels of important vitamins that are deficient in the diets of people in some countries. For example, hundred of thousands of young children, mainly in Africa an India, die each year from a deficiency of vitamin A in their diet. A genetically modified rice called golden rice has higher levels of beta carotene (which the body uses to synthesise vitamin A) and was designed to help address this deficiency.

Despite their benefits, and research showing that existing genetically modified crops are not harmful to human health, people are still concerned about potential impacts of genetically modified organisms on humans, and the effects on the social fabric of communities and the environment. These concerns have led some to lobby policymakers to get GM labels on GM food products. They argue that consumers have a right to know what they are buying.

If such labelling did come into effect, policymakers would have to consider just what makes something genetically modified in the first place. Humans have been genetically modifying plants and animals for thousands of years by selectively cultivating and breeding those with the desired traits. However, advances in technology make that process much faster, and in ways that are not possible by simple selective breeding. For example, genes that code for venom production in scorpions have been inserted into cabbage DNA to produce a cabbage that kills caterpillars that eat cabbage leaves, while being harmless to humans.

To meet the demand for food that is not genetically modified using technology, farmers have started growing crops that are marketed as being 'GM free'. However, because genetically modified crops can spread to farms that produce GM free crops, they can 'contaminate' these crops, meaning the farmers could suffer a financial loss. This raises legal considerations, as some farmers may consider suing for damages.

FIGURE 1.5.8 Golden rice was developed to address a deficiency in vitamin A that kills hundreds of thousands of children in poor countries each year.

1.5 Review

SUMMARY

- Record all information objectively in your logbook including your data and method of investigation.
- Raw data is the data you collect in your logbook.
- Processed data is raw data that has been mathematically manipulated.
- Beware of potential errors when conducting an investigation, including:
  - systematic errors—consistent errors that reduce accuracy
  - random errors—unpredictable errors that reduce precision.
- Reduce random errors by:
  - having a large sample size
  - repeating measurements.
- Reduce systematic errors by:
  - selecting appropriate equipment
  - properly calibrating equipment
  - using equipment correctly
  - repeating experiments.
- Accuracy is the ability to obtain a correct measurement.
- Precision is the ability to consistently obtain the same measurement.
- Reliability is the ability to reproduce your results.
- Validity refers to whether your results are real results and whether they apply to all situations.
- The social, economic, legal and ethical implications of scientific research must be considered when planning research.

KEY QUESTIONS

1 What is the difference between raw and processed data?

2 What is the difference between quantitative and qualitative data?

3 Identify which of the following pieces of information about a cup of coffee are qualitative, and which are quantitative. Place a tick in the appropriate column.

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

4 Using a Venn diagram, present the differences and similarities between discrete and continuous data.

5 Both sets of data below contain errors. Identify which set is more likely to contain systematic error and which is more likely to contain random error.
Data set A: 11.4, 10.9, 11.8, 10.6, 1.5, 11.1
Data set B: 25, 27, 22, 26, 28, 23, 25, 27

6 What type of error is associated with:
a inaccurate measurements?
b imprecise measurements?

7 Describe the difference between repeat trials and replication.

8 Explain why repeat trials and replication are necessary.

9 Consider the following experiment.

Hypothesis
If seedlings are watered with mineral water, then they will grow more leaves than seedlings watered with tap water.

Experiment
Set up two identical trays of seedlings. They should have the same type of plant, age of plant, type of potting mix, drainage and amount of sunlight and water. Everything should be the same except the type of water given to the plants.

Variables
Anything that could be different in the experiments must be kept the same. This includes everything listed above and even the height of the plants, the depth of potting mix and the intensity of the sunlight. These variables are kept the same—they are the controlled variables.

Only one variable is changed—the type of water. It is the effect of this variable that we are measuring. It is the independent variable. Its measurement should be **objective** (be able to be measured **quantitatively**).

The independent variable—the type of water—may change the number of leaves. The number of leaves is the dependent variable. The number of leaves depends on the type of water.

Results
Measure or count the number of leaves on each plant. This will give you objective results. Your friends could replicate the experiment at their houses. When you and your peers have repeated the experiment many times on different plants, the results can become a **generalisation**.

a What is the sample size?
b Identify the controlled variables.
c Identify the independent and dependent variables.
d Will the results be objective or subjective? Explain.
e Will the results be valid for all plants? Explain.

1.6 Data analysis and presentation

In section 1.5 you learned about different types of data and factors that affect data quality. In this section you will learn how the nature of the data being collected, such as whether the variables are qualitative or quantitative, influences the type of method or tool you can use to analyse your data.

DESCRIPTIVE STATISTICS

Descriptive statistics can be used for both quantitative and qualitative data. An important type of descriptive statistic is the measure of central tendency. It is good practice to use a measure of central tendency to provide a clearer understanding of the data.

Measures of central tendency

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

The **mean** (or average) is the sum of the values divided by the number of values. For example, the mean of 3, 7, 9, 10 and 11 is (3 + 7 + 9 + 10 + 11) ÷ 5, which is 8.

The **median** is the 'middle' value in an ordered list of values. For example, the median of the seven values 5, 5, 8, 8, 9, 10, 20 is the fourth value, which is 8.

The **mode** is the value that occurs most often in a list of values. This measure is particularly useful for describing qualitative or discrete data. For example, the mode of the values 0.01, 0.01, 0.02, 0.02, 0.02, 0.03, 0.04 is 0.02

The appropriate measure of central tendency to use depends on the type of data you are working with (Table 1.6.1).

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

TABLE 1.6.1 When to use the different measures of central tendency.

SUMMARISING DATA

Most of the time you will want to summarise your data to allow you to generalise your sample results to a population. For example, if you were testing the effects of fertiliser on the growth of bean plants, you would probably want to generalise your results to the growth of bean plants generally, not just the bean plants you used in your experiment. To provide a bigger picture, you can do some further calculations on the data.

Percentage change

Calculating the change in a variable is a helpful statistic because it provides a general trend or pattern rather than a specific value, which will vary depending on size or shape for example. Table 1.6.2 shows the data collected over 5 days for three plants. One was a control, the second was exposed to intense light and the third plant was in low light.

Plant	Mass on Day 1 (g)	Mass on Day 2 (g)	% change	Mass on Day 3 (g)	% change	Mass on Day 4 (g)	% change	Mass on Day 5 (g)	% change
Plant 1 (control)	12.3	12.5	1.63	12.7	1.60	12.8	0.79	13.0	1.56
Plant 2 (intense light)	12.4	12.7	2.42	13.0	2.36	13.4	3.08	13.7	2.24
Plant 3 (low light)	12.1	12.0	−0.83	11.8	−1.67	11.9	0.85	11.8	−0.84

TABLE 1.6.2 Percentage change in plant mass for different light intensities over a 5-day period.

The mass of each plant was measured at the same time each day. The percentage change in mass was calculated from Day 2.

$$\text{percentage change} = \frac{\text{Day 1 mass} \times \text{Day 2 mass} \times 100}{\text{Day 1 mass}}$$

The percentage change (loss or gain) values can then be graphed for each plant.

Percentage difference

The percentage difference (also often expressed as a fraction) is a measure of the precision of two measurements. It is calculated by working out the difference between the two measurements and dividing by the average of the two measurements:

$$\text{percentage difference} = \left(\frac{\text{measurement 1} - \text{measurement 2}}{\text{average of measurements}}\right)$$

For example, if your two measurements were 25 cm and 24 cm, you would calculate percentage difference as follows:

$$\text{percentage difference} = \frac{(25 - 24)}{(25 + 24) \div 2} = \frac{1}{24.5} = 0.041 \times 100 = 4.1\%$$

Calculating uncertainty in measurement

When averaging repeat measurements, the **uncertainty** should be reported alongside your average. Uncertainty results from errors and represents a realistic range within which the true value is likely to be. A simple way to calculate the uncertainty is:

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

For example, if an experiment were conducted to measure the length of time it takes to convert a substrate to a product in an enzymatic reaction, and three replications of the experiment produced the times 2.50, 3.47 and 2.81 seconds, the average time taken would be 2.93 seconds. The uncertainty would be calculated as follows:

$$\text{uncertainty} = \pm (3.47 - 2.50) \div 2 = \pm 0.49$$

Therefore the results showing the mean and uncertainty would be $2.93 = \pm 0.49$.

● *You will now be able to answer Key Questions 1–3.*

Calculating the range of measurements

The **range** is simply the difference between the highest and lowest values in your data set. Table 1.6.3 shows the measurements taken for eight different white bolly gum leaves.

Leaf no.	1	2	3	4	5	6	7	8
Width (cm)	7.6	9.1	9.3	10.1	5.6	10.3	9.4	8.5

TABLE 1.6.3 Width of white bolly gum leaves.

To determine the **range** for values in Table 1.6.3 you would subtract the smallest value (5.6 cm) from the largest value (10.3 cm), which equals 4.7 cm. Notice how a very large or small value in the data set makes the variability appear high. For example, if the small leaf with a width of 5.6 cm had not been included, the range would have only been 2.7 cm. This illustrates the importance of having a sample size that is large enough to limit the impact of anomalies in the data set.

PRESENTING DATA

After you have completed your experiment, the data need to be organised and displayed. This makes it much easier to identify trends or patterns in the data. It also helps to identify any relationships that result from cause and effect between the independent and dependent variables. This can also help you see if one variable has had any effect on another variable.

There are a number of ways to present data, including tables, graphs, flow charts or diagrams. The best way of visualising your data depends on its nature. Try several formats before you make a final decision to create the best possible presentation.

PRESENTING DATA IN TABLES

Tables record number values and allow you to organise your data.

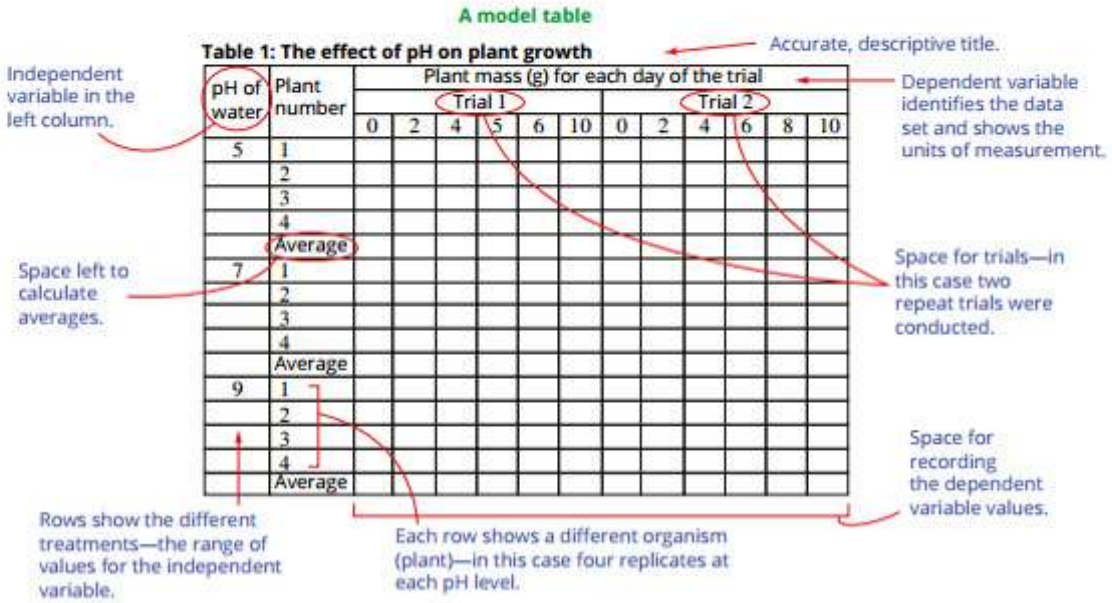
Presenting raw data in tables

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

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

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

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



pH of water	Plant number	Plant mass (g) for each day of the trial											
		Trial 1						Trial 2					
		0	2	4	5	6	10	0	2	4	6	8	10
5	1												
	2												
	3												
	4												
	Average												
7	1												
	2												
	3												
	4												
	Average												
9	1												
	2												
	3												
	4												
	Average												

FIGURE 1.6.1 Features of a good table.

Presenting processed data in tables

Table 1.6.4 shows the relationship between temperature and mean transpiration rate. It displays transpiration data in a processed format, because several values have been averaged to calculate the mean.

Temperature (°C)	Mean transpiration rate (mL/g/h)
15	0.038
25	0.043
35	0.059
45	0.074

TABLE 1.6.4 Effect of temperature on mean transpiration rate.

Table 1.6.5 is an improved version of the data in Table 1.6.4, because it includes the uncertainty in the processed data.

Temperature (°C)	Mean transpiration rate (mL/g/h)
15	0.038 ± 0.002
25	0.043 ± 0.001
35	0.059 ± 0.001
45	0.074 ± 0.0015

TABLE 1.6.5 Effect of temperature on mean transpiration rate, including uncertainty.

PRESENTING DATA IN GRAPHS

In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data in graph form than in table form. Graphs are used when two variables are being considered and one variable is dependent on the other (Figure 1.6.2).

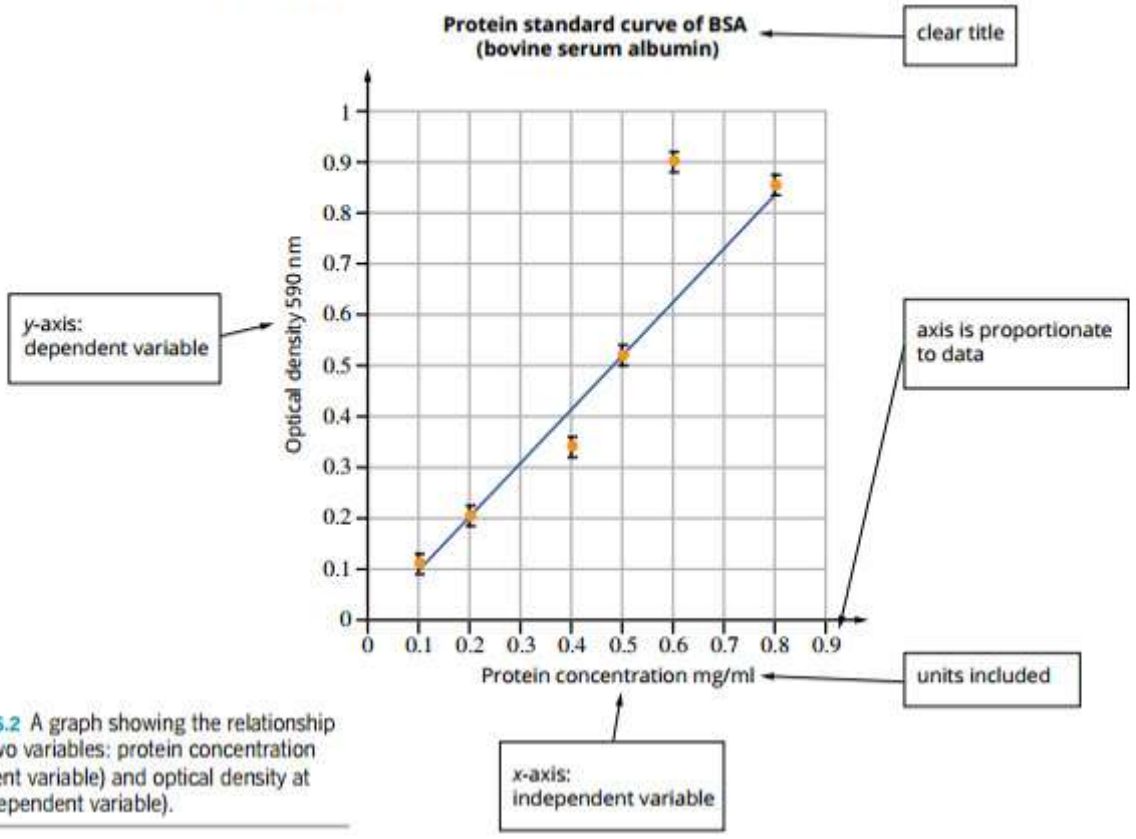


FIGURE 1.6.2 A graph showing the relationship between two variables: protein concentration (independent variable) and optical density at 590 nm (dependent variable).

There are several types of graphs, including line graphs, bar graphs and pie charts. The best one to use will depend on the nature of the data.

General rules to follow when making a graph include the following:

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

● *You will now be able to answer Key Questions 4 and 5.*

Scatterplots and line graphs

Scatterplots and are commonly used to display data in the form of a graph. They are used to show the relationship between two variables when one variable is dependent on the other.

The independent variable, which is set by the experimenter, is always shown on the *x*-axis. The dependent variable, which is the variable measured in the experiment, is always shown on the *y*-axis. The data is plotted on the graph as a series of points. Each point should be drawn in pencil as a small circle or cross. Alternatively you can use a computer program to generate your graphs.

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

Alternatively, a single straight or curved line can be drawn, as shown in Figure 1.6.4. This line is called a trend line or a line of best fit. It is used to show the overall trend in the data, and can be used to predict values between the data points. A line of best fit usually does not pass through every data point. Its position can be estimated by eye, but in serious research it is always calculated mathematically from the data.

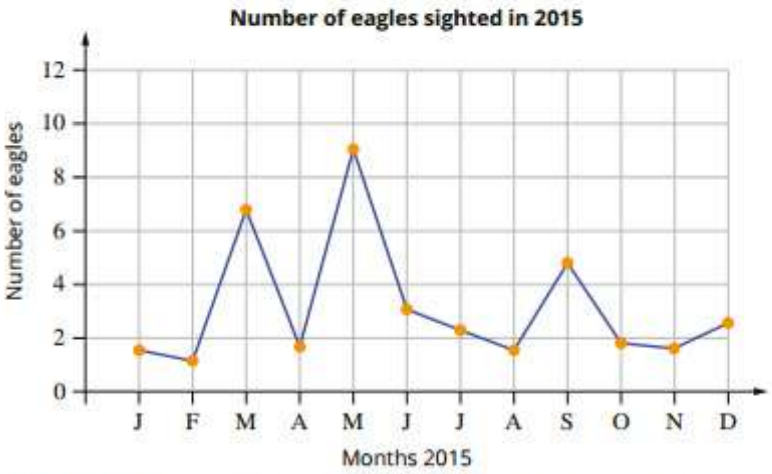


FIGURE 1.6.3 A line graph showing the number of eagle sightings in 2015, with lines ruled from each point to the next.

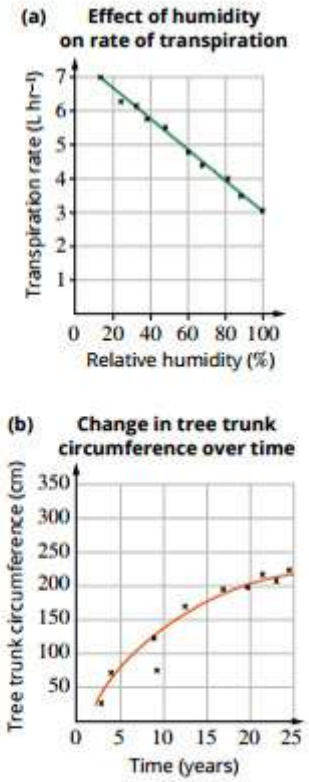


FIGURE 1.6.4 Graphs showing straight (a) and curved (b) trend lines.

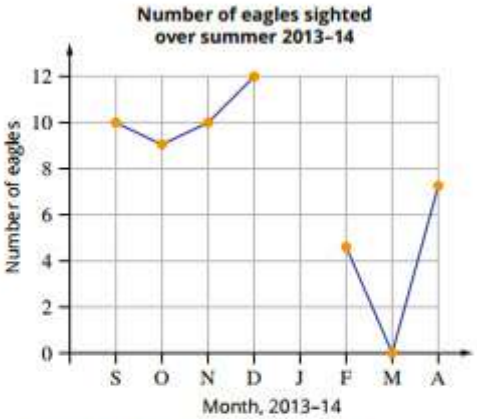


FIGURE 1.6.5 A line graph with missing data.

Missing data

When you have missing data, leave a gap for it, as shown in Figure 1.6.5. Ensure that the axes are complete (do not skip values) and do not join the data points that have missing data points between them.

Outliers

Sometimes when you collect data, there may be one point that does not fit the trend and is clearly an error. This is called an **outlier**. An outlier is often caused by a mistake made in measuring or recording data, or from a random error in the measuring equipment. If you have an outlier you should include it in your graph but ignore it when drawing the line of best fit (Figure 1.6.6).

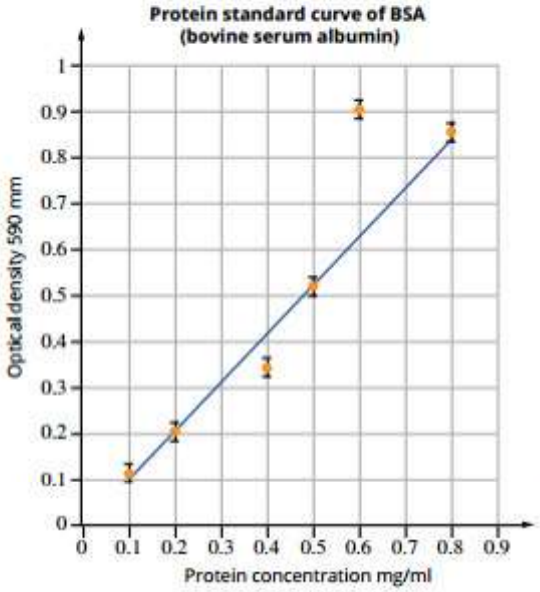


FIGURE 1.6.6 A line graph showing an outlier, which has been ignored when adding the line of best fit.

● *You will now be able to answer Key Questions 6 and 7.*

Bar graphs

Bar and column graphs are used to show categories of data that have been counted.

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

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

Bar and column graphs are very useful for graphing qualitative and discontinuous data (Figure 1.6.7). When the labels of the variables are long, horizontal bar graphs can be used (Figure 1.6.8).

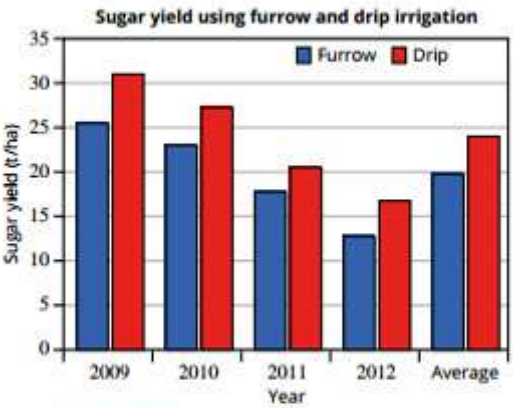


FIGURE 1.6.7 A bar graph comparing two types of irrigation systems in relation to sugar yield.

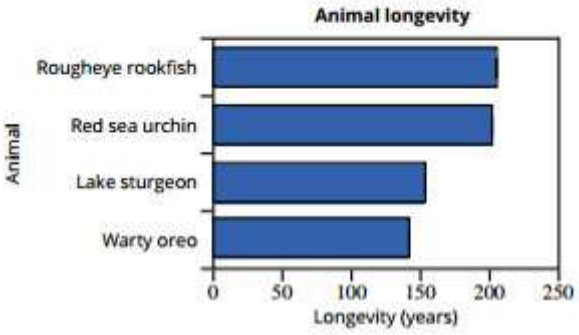


FIGURE 1.6.8 A horizontal bar graph comparing longevity of different animal species.

Pie charts

A **pie chart** is a way of presenting qualitative data. It shows each category of data as a proportion of the total data. The chart is a circle divided into sections according to the proportions of each category, like slices of a pie (Figure 1.6.9). Each category is coloured or shaded differently so that it can be distinguished clearly from the other categories. Pie charts should only be used when there are few categories.

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

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

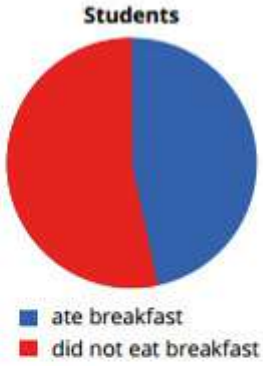


FIGURE 1.6.9 A pie chart presenting data on the breakfast habits of students.

Distorting the truth

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

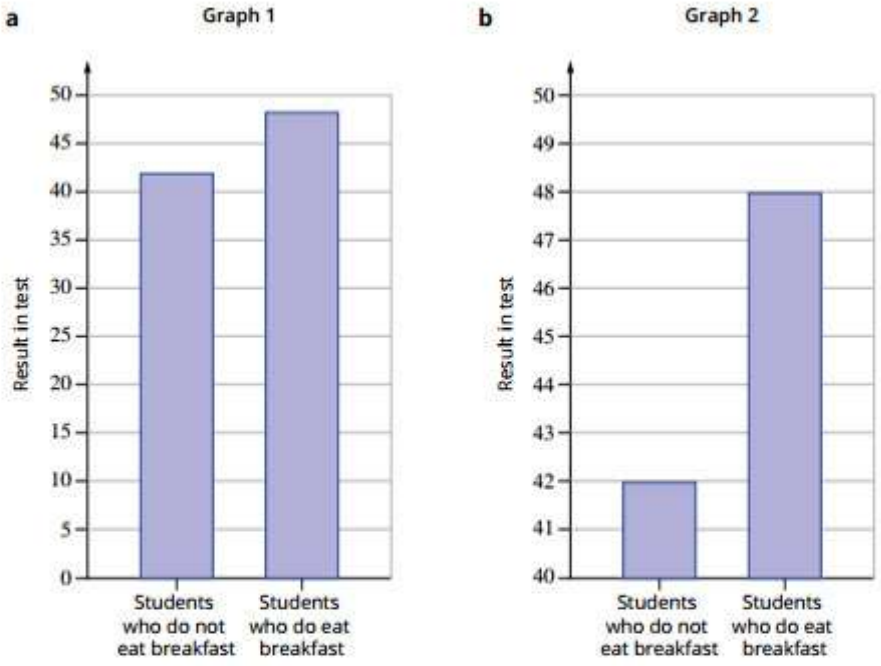


FIGURE 1.6.10 (a) A graph showing the difference between two groups of students out of the total 50 marks on the Y-axis. (b) A graph showing the difference between the two groups within only a narrow range of marks on the Y-axis, which distorts the difference and makes it appear larger than it really is.

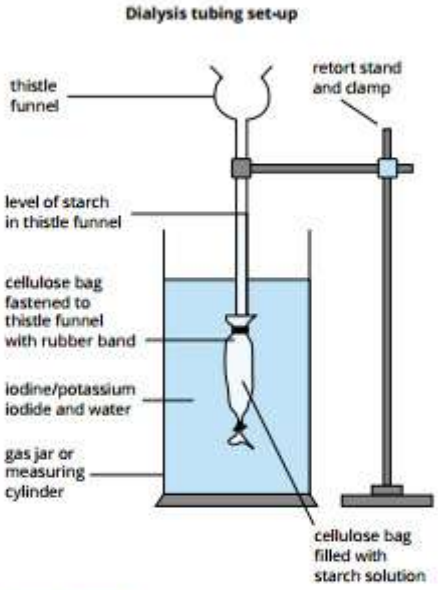


FIGURE 1.6.11 Diagram showing a dialysis tubing arrangement. Note the straight lines for labels that are horizontal where possible, and the realistic proportions of different parts in relation to each other.

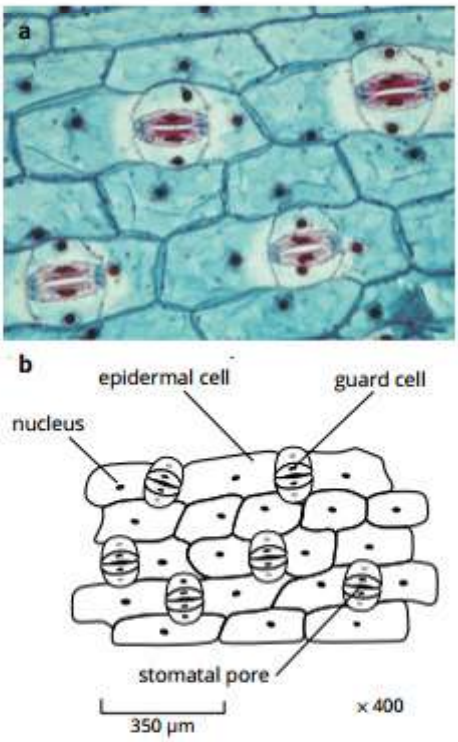


FIGURE 1.6.12 A photomicrograph (a) and a scientific diagram (b) showing leaf epidermis.

PREPARING DIAGRAMS

It is important to learn how to draw and label diagrams of equipment and biological specimens in your studies of biology. There are certain rules you must follow in order to produce a diagram that will be acceptable in your reports and exams.

When drawing scientific equipment, diagrams should:

- ☐ be large, simple, two-dimensional pencil drawings
- ☐ have ruled lines where possible
- ☐ keep proportions realistic (Figure 1.6.11).

Here are some guidelines for drawing biological specimens:

- ☐ Draw the whole diagram (including labels, lines, magnification, heading and scale) in pencil.
- ☐ Do not draw the diagram in a circle representing the field of view.
- ☐ Draw your diagram with simple and clear lines (do not sketch).
- ☐ Do not shade your drawing.
- ☐ Make your diagram as large as possible (at least 10 × 10 cm).
- ☐ Do not draw structures that cannot be seen, e.g. mitochondria (Figure 1.6.12).
- ☐ Include clear labels for the features you want to highlight.
- ☐ Place labels outside the drawing.
- ☐ Make sure label pointers do not cross over each other.
- ☐ Labels should line up on either side of the diagram.
- ☐ Do not use arrowheads on lines pointing to features.
- ☐ Include a scale bar or scale (e.g. 1: 100) in the diagram, or state the magnification (e.g. ×400) in the caption.

If there are lots of features to show, a supporting diagram is useful. This is where you show the general structures in a photo and pair it with a diagram showing cellular detail, as shown in Figure 1.6.13.

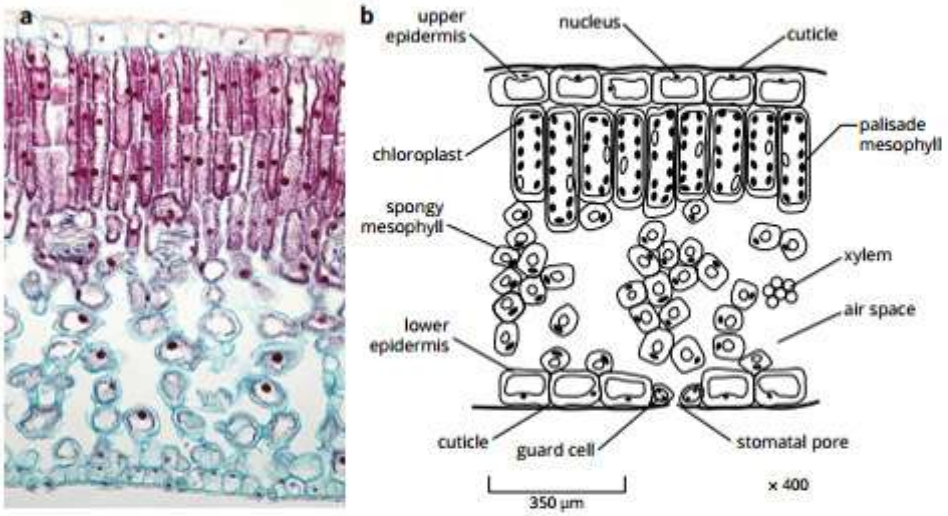


FIGURE 1.6.13 A photomicrograph (a) and diagram (b) of a transverse section through a leaf.

EXTENSION

Inferential statistics

Descriptive statistics are used to draw conclusions about individuals or objects you have measured in your sample population. However, descriptive statistics do not allow you to use your data to generalise about other individuals or objects. In other words, you cannot use your data to draw inferences about a wider population. To do that you need to use inferential statistics.

Inferential statistics can only be used for quantitative data. They test statistical hypotheses, which are different from your experimental hypothesis. The two types of statistical hypotheses are the null hypothesis (H0) and the alternative hypothesis (H1). In general, the null hypothesis is the opposite of the experimental hypothesis. For example, if the experimental hypothesis is that the mean values of two different groups are different, the null hypothesis is that the mean values are the same. The alternative hypothesis would state that there is a difference between the mean values of the groups.

For example, if you grew 15 bean plants with a nitrogen fertiliser and 15 without, your null hypothesis would be that there is no difference between the average heights of the plants in the different groups, and that any observed differences happened by chance. Your alternative hypothesis would be that there is a difference in height between the two groups not explained by chance. These statistical hypotheses are different to your experimental hypothesis, which would be that nitrogen-based fertilisers promote plant growth. As you can see, your statistical alternative hypothesis is the one that supports your experimental hypothesis.

1.6 Review

SUMMARY

- Descriptive statistics can be used for qualitative and quantitative data.
- Descriptive statistics include three measures of central tendency: mean, median and mode.
- To present data properly, the mean and its uncertainty should be included. Other statistical measures such as mode and median may also be useful for analysing and presenting data.
- Tables are used to record raw and processed data.
- Tables allow the presentation of more detail, while graphs allow trends to be shown more clearly.
- When presenting the results of an investigation, do not distort the truth—this includes selecting appropriate scales on graph axes, including outliers in graphs and including and explaining all errors.

KEY QUESTIONS

1 State the median of the following data: 21, 28, 19, 19, 25, 24, 20

2 State the mode of the following data: 21, 28, 19, 19, 25, 24

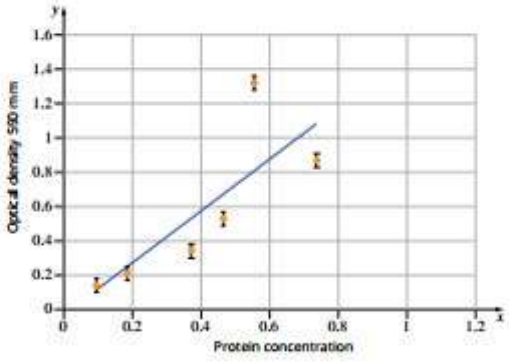
3 State the average and uncertainty for the following data: 21, 28, 19, 19, 25, 24

4 Using the student results below, draw an appropriate table and graph.

Mining temperatures

Mine A				
Depth	Surface	300 m	700 m	1.0 km
Temp	15 °C	28 °C	49 °C	62 °C
Mine B				
Depth	Surface	600 m	1.5 km	3.5 km
Temp	20 °C	25 °C	37 °C	55 °C

5 Describe at least four ways the graph below could be improved.



6 Distinguish between the times when a line of best fit graph should be used and the times when a ruled graph line from point to point is more appropriate.

7 What are outliers, and what is the statistical measurement most affected by them?

1.7 Reporting investigations

Now that you have thoroughly researched your topic, formulated a research question and hypothesis, conducted experiments, and collected data, it is time to bring it all together. The final part of an investigation involves summarising the findings in an objective, clear and concise manner for your audience.

In this section you will learn how about each presentation format, to write and present your findings effectively, structure a report, discuss the investigation, and draw evidence-based conclusions in relation to your hypothesis and research question.

SELECTING THE PRESENTATION FORMAT

Although all presentations on research work will have the same elements, there are many different ways of presenting the information. The format you choose will depend on the type of research, whether the research has been completed, and who the audience is. Table 1.7.1 provides some options and hints for different formats.

Format	Characteristics	Things you should include or remember
poster presentation	• visual display of information • suitable for presenting information to many people • summary of ideas	• title that attracts attention • large headings that stand out • subheadings of a smaller size • attractive presentation • balance of written material and visual material such as diagrams, sketches, photographs, tables or graphs • writing large enough to read from a distance
research report	• presents clear and detailed information on a topic • suitable for providing detailed information to individuals	• include an introduction and sections covering materials and methods, results, discussion and conclusions • use subheadings • mainly text but can include diagrams, sketches, photographs, tables or graphs
oral communication with supporting slides or handouts e.g. on-screen presentation	• easy-to-follow format • good for presenting to a large audience • best if combined with an oral presentation • can summarise information covered in an oral presentation • can be printed as a set of notes to be given to the audience	• mostly visual with small amount of text • use the same background, format and colours throughout • not too much text on each slide • use palm cards to glance at if needed • rehearse the presentation so you do not have to read the slides or palm cards word for word • maintain eye contact with the audience • speak clearly and at a volume that can be heard • don't fidget or wriggle round • stand up straight and look confident • stand to one side of the screen, not in front of it
online presentation e.g. website, blog	• can present visual and written information • accessible to a worldwide audience • easy to follow • easy to update with new information	• include hyperlinks to related information • include multimedia, such as video clips and audio, if appropriate • use the same background, format and colours throughout • use headings that stand out • list all the site hyperlinked contents on the main page • include your name and credentials, and the date of publication

TABLE 1.7.1 Characteristics and advantages of the main formats for presenting research work.

EFFECTIVE SCIENCE WRITING

Effective science writing is objective, clear and concise, and has a consistent narrative and visual support. If you have time, it is a good idea to put your finished writing aside for a few days and then go back and read it over again, fixing anything that is incorrect or poorly written. Checking the spelling is also an essential part of editing your writing. Do not rely only on computer programs to check spelling; they can make mistakes too, and often do not recognise scientific words. Make sure the spell-checker is set to Australian English; the default setting is usually American English.

Objective writing

Scientific reports should be written in an objective (unbiased) style. This is in contrast to literary writing, which often uses subjective (biased) techniques of persuasion (Table 1.7.2).

Unscientific writing examples	Scientific writing examples
Examples of biased and subjective language: • The results were weird/bad/atrocious/ wonderful... • This produced a disgusting odour... • This is a major health crisis... • This breathtakingly beautiful golden bowerbird...	Examples of unbiased and objective language: • The results showed... • This produced a pungent odour... • This is a serious health issue... • The golden bowerbird...
Examples of exaggeration: • The object weighed a colossal amount... • No one has ever seen this phenomenon... • The magnesium exploded into flames... • Millions of ants swarmed over the next...	Examples of accurate language: • The object weighed about 250 kg... • This phenomenon has not been reported previously... • The magnesium burnt vigorously... • Ants swarmed over the next...
Examples of everyday language: • The bacteria passed away... • The results don't... • We had a sneaking suspicion... • Previous researchers were slack and missed...	Examples of formal language: • The bacteria died... • The results do not... • We predicted / hypothesised / theorised... • Previous researchers did not notice that...

TABLE 1.7.2 Examples of unscientific and scientific writing.

Qualified writing

It is best to avoid words that are absolute, such as always, never, shall, will, or proven. Instead qualify your writing using words such as may, might, possible, probably, likely, suggests, indicates, appears, tends, can and could.

Concise writing

To be concise use short sentences with a simple structure. The opposite of being concise is being verbose (wordy). When editing your writing consider how you could say the same thing using fewer words (Table 1.7.3).

Verbose	Concise
due to the fact that	because
Carlos undertook an investigation into...	Carlos investigated...
It is possible that the cause could be...	The cause may be...
a total of five experiments	five experiments
end result	result
in the event that	if
at the time of writing	today
is well known to be	is
on an annual basis	yearly
until such time as	until
in the vicinity of	near
while in the process preparation	while preparing
I am of the opinion that	I think

TABLE 1.7.3 Examples of verbose writing and concise alternatives.

Voice

Voice means whether the subject of the sentence is the 'doer' or 'receiver' of the action. In the active voice the subject is the doer; for example, 'We added 20 mL of sodium chloride to the beaker.' In the passive voice the subject is the receiver; for example, '20 mL of water was added to the solution.' Choose the voice that helps you communicate your ideas clearly. This will usually be the active voice rather than the passive voice. Using the passive voice all the time can result in awkward, confusing and sometimes silly sentences (Table 1.7.4). However, you will often find that a mixture of active and passive voice is best.

Active voice	Passive voice
A thermostat controlled the temperature.	The temperature was controlled by a thermostat.
We placed 50 g of marble chips in a conical flask and then slowly added 10 mL of 2M hydrochloric acid.	Fifty grams of marble chips were placed in a conical flask, then 10 mL of 2M hydrochloric acid was slowly added.
The observers checked the tree hollows every morning.	The tree hollows were checked every morning by the observers.
We used night-vision goggles to see the owls.	The owls were seen using night-vision goggles.

TABLE 1.7.4 Examples of active and passive voice.

Tense

Use the past tense when describing your research, including the planning, the experiments and the results, as well as the work of previous researchers. For everything else (including describing facts and theories) you should use the present tense. Avoid using the conditional tense (could or would) and the future tense (unless you are talking about something that has not yet happened). Table 1.7.5 shows some examples of the correct and incorrect use of tenses in scientific writing.

Correct tense	Incorrect tense
Zhu (2013) described a similar phenomenon.	Zhu (2013) describes a similar phenomenon.
The fish were then fed for five days on protein A.	The fish are then fed for five days on protein A.
The results suggest that killer whales are not disoriented by low-frequency sonar emissions.	The results suggested that killer whales were not disoriented by low-frequency sonar emissions.
The crayfish burrow deeper if the water level falls.	The crayfish will burrow deeper if the water level falls.
This suggests that parrots can transmit the virus directly to humans.	This would suggest that parrots could transmit the virus directly to humans.

TABLE 1.7.5 Examples of correct and incorrect use of tense.

Visual support

Use graphs or diagrams to present complex concepts or information. This will reduce the number of words you need, and also make your research more accessible for your audience.

WRITING A SCIENTIFIC REPORT

Scientific reports are usually structured in the following way:

- Title—This should give a clear idea of what the report is about, without being too long.
- Introduction—The introduction is a short statement of what you intended to find out (the hypothesis, or the research aim if it did not involve a hypothesis) and a discussion of any relevant biological concepts.
- Materials and method—This lists all materials required and all the steps involved in the research.
- Results—This section presents the data obtained in the research. Results sections often include graphs, tables or figures.
- Discussion—In this section the results (and sometimes the materials and methods) are interpreted and evaluated.
- Conclusion—This is the section where the outcomes of the research are stated. It states how the results relate to the hypothesis, and might suggest what future research should be conducted.
- References—All the scientific papers and other sources that are mentioned in the report are listed here. This helps to demonstrate that you have not claimed other people's ideas or words as your own (which is called plagiarism).
- Acknowledgements—Here you should thank all the people and organisations who helped you conduct the research.

Introduction

The introduction sets the context of your report. It should outline relevant biological ideas, concepts, theories and models, and use the context they establish as the basis for the explanation of your hypothesis. For example, if you were studying the effect of temperature on plant transpiration, your introduction might include:

- the definition of plant transpiration
- the functions of plant transpiration
- the relationship between plant transpiration and photosynthesis, gas exchange and transport of minerals and nutrients
- the known mechanisms of plant transpiration
- the environmental factors known to affect plant transpiration (Figure 1.7.1)
- existing knowledge on the role of temperature in plant transpiration
- the ranges of temperatures investigated and the reason these temperatures were chosen
- the species of plant studied and the reasons for this choice
- methods of measuring the rate of transpiration
- known rates of plant transpiration.

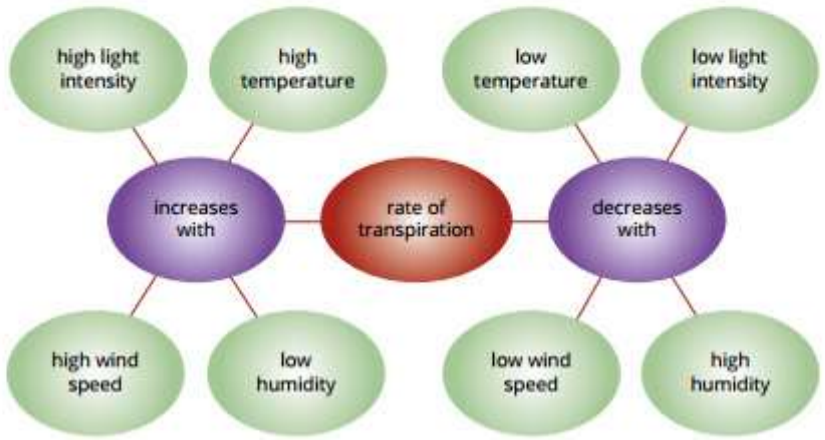


FIGURE 1.7.1 Factors that affect the rate of plant transpiration.

Materials and method

FIGURE 1.7.2 Celery in a beaker of water coloured with red dye.

The materials and method section lists all the material that were used in the research, and describes in detail all the steps that were undertaken. The style for this section differs from the way you write instructions for a procedure, where starting each instruction with a verb is acceptable as you are telling the reader what should be done. For example, 'Cut the base off a stick of celery and place the stem into a beaker containing dye solution'. Here is an example of a materials and method section for the experiment shown in Figures 1.7.2 and 1.7.3.

Materials and method

For this experiment we used a 250 mL beaker, red food dye, a wooden stirrer, a fresh celery stick with leaves still attached, a sharp knife, tap water, absorbent paper, and a 10× hand lens.

We put 100 mL of tap water in the beaker, then added 8 drops of the dye and stirred thoroughly. We then used the knife to cut about 2 cm off the base of the celery stick to give a clean, straight cut, and immediately placed the celery stick upright in the dye solution, as shown in photo 1.

This was left to stand overnight on the laboratory bench. In the morning we observed the leaves and stem of the celery stalk and photographed them. We used the hand lens to look more closely at the leaves. We then cut the celery stalk cross-ways at several points along its length and observed the cross-sections, which we also photographed. After removing the celery stick from the beaker we recorded the volume of dye solution remaining in the beaker.

If you have written your materials and method section well, someone else should be able to repeat your investigation exactly as you did it, and get the same or similar results. Therefore, your method needs to be in the correct sequence, and include how you observed, measured, recorded and analysed the results. If you are testing a hypothesis, this section should also identify the independent, dependent and controlled variables (see Section 1.4).

Results

FIGURE 1.7.3 Cross-section of celery stalk after removing from beaker.

The results section is a record of your observations. It is where you present your data using graphs, diagrams, tables or photographs. Do not interpret your results in the results section; as the appropriate place to interpret results is in the discussion. For the experiment shown in Figures 1.7.2 and 1.7.3, the results section might be like the following:

Results

In the morning we observed that the stalk of the celery stick had turned pink, and the stem was also slightly pink (photo 2). In the leaves we observed that the red colour was concentrated in the veins of the leaf.

When we made the cross-sections of the stalk we observed that the holes in the stalk were filled with red dye solution (photo 3). The amount of water in the beaker when the celery stalk was removed was 63 mL.

Discussion

In the discussion you should interpret your results, and discuss how your findings relate to your initial research, the research of others, and the biological concepts outlined in your introduction.

Interpret the results

When you interpret your results, you need to clearly state whether a pattern, trend or relationship was observed between the independent and dependent variables, describe what kind of pattern it was, and specify under what conditions it was observed.

The main types of relationships between variables you are likely to encounter are:

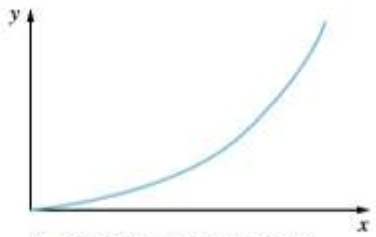
- **linear**—variables that change in linear or direct proportion to each other produce a straight trend line (Figure 1.7.4a)
- **exponential**—variables that change exponentially in proportion to each other produce a curved trend line (Figure 1.7.4b, c)
- **inverse**—when there is an inverse relationship, one variable increases as the other variable decreases; this relationship may be linear or exponential (Figure 1.7.4d, e)
- none—when there is no relationship between two variables, one variable will not change even if the other does (Figure 1.7.4f).

More complex relationships might have to be evaluated mathematically to obtain a formula that describes the trend line.

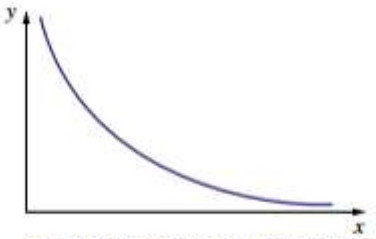
● *You will now be able to answer Key Question 1.*

a. Direct or linear proportional relationship
- Variables change at the same rate (graph line is straight, slope is constant)
- Positive relationship—as *x* increases, *y* increases

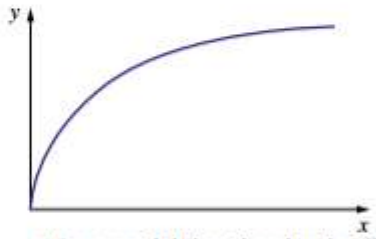
d. Inverse direct or linear proportional relationship
- Variables change at the same rate (graph line is straight, slope is constant)
- Negative relationship—as *x* increases, *y* decreases



b. Exponential relationship
- As *x* increases, *y* increases slowly, then more rapidly



e. Inverse exponential relationship
- As *x* increases, *y* decreases rapidly, then more slowly, until a minimum *y* value is reached



c. Exponential rise, then levels off or plateaus (stops rising)
- As *x* increases, *y* increases rapidly at first, then slows, then finally does not increase at all—*y* reaches a maximum value

f. No relationship between *x* and *y*
- As *x* increases, *y* remains the same

FIGURE 1.7.4 Line graphs illustrating common relationships between variables: (a) direct linear relationship, (b,c) exponential relationships, (d,e) inverse relationships, (f) no relationship.

Evaluate investigative methods

Your discussion should evaluate your investigative methods and identify any issues that could have affected the validity, reliability, accuracy or precision of the data. Any possible sources of error in your experiment should be stated. Remember that controls are important to the reliability of your investigation, so if you have overlooked or were unable to control a variable that should have been controlled, this may explain unexpected results.

After you have identified any limitations in the data you have collected, discuss how things could be done differently to improve on these limitations. For example, perhaps using a larger sample size or controlling other variables could lead to a stronger conclusion.

● *You will now be able to answer Key Question 2.*

Relate findings to biological concepts

In your introduction you established a context. Now you have a framework to discuss whether your data supported or refuted your hypothesis in your discussion. Providing context also enables you to compare your results with existing research and knowledge. After identifying the major findings of your investigation, you should discuss:

- whether your data contradicts the literature
- how your findings fill a gap in the literature
- how your findings might lead to further questions
- further research that might be needed
- any practical applications that your research might have.

BIOLOGY IN ACTION

Testing the POLS hypothesis

FIGURE 1.7.5 A female superb fairy-wren (*Malurus cyaneus*). Coloured bands are attached around the legs to identify individual birds.

The pace of life syndrome (POLS) hypothesis relates to animal personality, and suggests variation in an individual animal's life-history strategies is associated with consistent differences in its behaviour.

To test this hypothesis, a group of researchers from the University of Melbourne, the Max Planck Institute for Ornithology and the University of Munich studied the superb fairy-wren (*Malurus cyaneus*) in a wetland near Melbourne (Figure 1.7.5).

Their study was titled 'Animal personality and pace-of-life syndromes: do fast-exploring fairy-wrens die young?' The report on the research, which investigated long-term risk-related behaviours and also looked at the impact of these behaviours on survival, was published in the journal *Frontiers in Ecology and Evolution* in 2015.

In their introduction, the authors explained their hypothesis and the relevant biological concepts. In their methods section they detailed the experimental design, including the number of fairy-wrens that were studied, how they were trapped and handled, the exact location of the population being studied, and the ethics approvals

Conclusion

Your conclusion should be one or two paragraphs that link your evidence to your hypothesis. It should provide a carefully considered response to your research question based on your results and discussion. You should clearly state whether your hypothesis was supported or not. Draw your conclusions by identifying trends, patterns and relationships in the data. It is also important to acknowledge contradictions in data and information.

Base your conclusions only on evidence, not wishful thinking or speculation. In order for your conclusion to be based on good evidence, you must have designed your method to obtain accurate, precise, reliable and valid results, and ensured that any second-hand information you have referred to is of a suitable quality.

It is important to appreciate your limitations and the limitations of the scientific method. For example, do not write that you 'proved' something is true, as you can only ever provide evidence that indicates the probability of something being true.

Do not provide irrelevant information or introduce new information in your conclusion. Refer to the specifics of your hypothesis and research question, and do not make generalisations.

References and acknowledgements

It is important to cite any information you have obtained from secondary sources in the text of your report, and provide a list of references at the end of your report. This demonstrates that you are aware of previous work in the area, and allows readers to locate sources of information if they want to study them further. The usual way of doing this is to give a short reference in the text, such as 'Meagher (2015)', and give the full reference in the reference list.

FIGURE 1.7.6 A superb fairy-wren in the personality assay room.

that permitted them to conduct their research. They also described how they quantified the behaviour of adult fairy-wrens, by exposing them to a new environment test in which the birds were temporarily removed from the wild and placed in a room with a water dispenser, perches, and a tray with 10 mealworms (Figure 1.7.6).

The variables they quantified were the time it took for the bird to emerge from its cage into the room once the door was raised (emergence), the number of different areas the bird perched in the 5 minutes after entering the room (exploration), the total number of areas the bird perched in the 2 minutes starting from 6 minutes after entering the room and becoming familiar with it (activity), and how they responded to a mirror (mirror responsiveness). To test mirror responsiveness, after the bird had been in the room for 8 minutes a mirror was revealed that could only be seen to birds on the upper perches. The researchers scored their response to the mirror on a scale of 1 to 3, where 1 was swooping at the mirror, 2 was perching in front of the mirror, and 3 was pecking at the mirror. Based on their recapture rates, the same individuals were retested in this way up to five times.

The results, which included uncertainties, found the behaviour of individual fairy wrens was consistent over several years and that risky individuals, like those with greater exploratory behaviour, were less likely to be in the population 12 months later. These results support the POLS hypothesis that consistent individual differences in risk-related behaviours are associated with variation in survival.

It is also important to acknowledge the work of anyone who has assisted you in your research. Everyone from your fellow researchers if you are working in a group, to people who helped you edit your report, to artists who helped produce any images you may be using, all need to be acknowledged.

If you are stating factual information from another source, you can either quote in word-for-word or rewrite it in your own words. However, if you rewrite it you must make it clear that the information is not your own. Plagiarism (claiming that another person's work is your own) is not tolerated in scientific research.

Table 1.7.6 shows examples of ways to reference the three most common sources of information: journal articles, books and web pages. Whichever style you use, make sure the references have a consistent format. For example, if you decide not to put parentheses around the date, make sure this style is used for every reference.

Source, information and example of reference in text	Example of the reference written out in the reference list
Article in a scientific journal: • Author(s), date, article title, journal, volume number, page numbers. • Meagher & Cairns (2014) discovered this genus recently in remote rainforest in tropical Queensland.	Meagher D. & Cairns A. (2014) *Entodontopsis* (Bryophyta: Stereophyllaceae) new to the Australian flora. *Telopea* 17: 295–301.
Book: • Author(s), date (and page number if necessary), title of book, publisher, publisher's location. • Insects comprise more than 50% of the 1.4 million species described so far (Wilson 1992, page 126).	Wilson E.O. (1992) *The Diversity of Life*. Harvard University Press: Cambridge MA, USA.
Online article or page: • Author(s), title of article, URL address, date accessed • Scientists believe they may have found a cure for white-nose syndrome that is wiping out bats in the United States (Lee 2015).	Lee J.J. (2015) Killer fungus that's devastating bats may have met its match. http://news.nationalgeographic.com/2015/05/150527-bats-white-nose-syndrome-treatment-conservation-animals-science/ (accessed 4 September 2015).

TABLE 1.7.6 Examples of references for three common information sources.

1.7 Review

SUMMARY

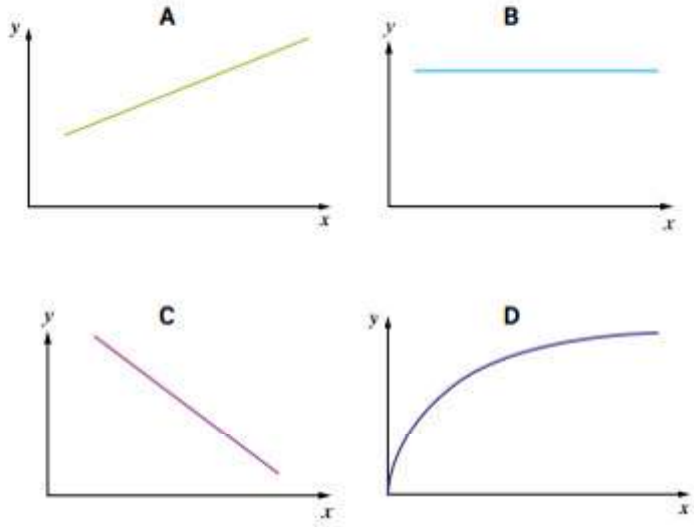
- Your reports should include the following sections:
  - title
  - introduction
  - materials and methods
  - results
  - discussion
  - conclusion
  - references
  - acknowledgements
- A materials and methods sections should:
  - clearly state the materials required and the method used to conduct your study
  - be presented in a clear, logical order that accurately reflects how you conducted your study
- A results section should state your results and display them using graphs, figures and tables, but not interpret results.
- A discussion should:
  - interpret data (identifying patterns, discrepancies and limitations)
  - evaluate the investigative method (identifying any issues that may have affected validity, reliability, accuracy or precision), make recommendations for improving the method
  - explain the link between investigation findings and relevant biological concepts (defining concepts and investigation variables, discussing the investigation results in relation to the hypothesis, linking the investigation's findings to existing knowledge and literature, and discussing the implications and possible applications of the investigation's findings)
- A conclusion should succinctly link the evidence collected to the hypothesis and research question, indicating whether the hypothesis was supported or refuted.
- References and acknowledgements should be presented in an appropriate format.

KEY QUESTIONS

1 **a** Which of the graphs below shows that the rate of transpiration increases as temperature increases?

b Which of the graphs below describes the following observation?

You are growing yeast in a low concentration of glucose, and observe that the yeast cells multiply exponentially, then slow down. You interpret this to mean that the energy source has become depleted.



2 A scientist designed and conducted an experiment to test the following hypothesis: An increased consumption of fast food causes a decrease in the function of the liver.

a The discussion section of the scientist's report included comments on the accuracy, precision, reliability, and validity of the investigation. Read each of the following statements and determine whether they relate to precision, reliability or validity.

i Only teenage boys were tested.

ii Six boys were tested.

b The scientist then conducted the fast food study with 50 people in the experimental group and 50 people in the control group. In the experimental group, all 50 people gained weight. The scientist concluded all the subjects gained weight as a result of the experiment. Is this conclusion valid? Explain why or why not.

c What recommendations would you make to the scientist to improve the investigation?

01

KEY TERMS

accuracy
adaptation
amino acid
bar graph
carbohydrate
cell theory
cellular respiration
cohesive
column graph
continuous variable
control group
cytoplasm
data
dependent variable
disaccharide
discrete variable
DNA (deoxyribonucleic acid)
ethogram
ethology
error
evolution
experimental group
exponential relationship
heat capacity
hypothesis
inference
independent variable
inorganic compound
inverse relationship
line graph
lipid
linear relationship
Materials Safety Data Sheet (MSDS)
mean
median
meniscus
mode
monosaccharide
natural selection
nitrogen fixation
nominal variable
nucleic acid
observation
ordinal variable
organic compound
organism
outlier
pie chart
plasma membrane
polysaccharide
population
precision
primary source
principle
processed data
protein
quadrat
qualitative data
quantitative data
random selection
range
raw data
reliability
repeat trial
replication
risk assessment
RNA (ribonucleic acid)
scatterplot
scientific method
secondary sources
surface tension
theory
transect
uncertainty
validity
variable

UNIT 1 How do living things stay alive?

AREA OF STUDY 1

How do organisms function?

Outcome 1: After completing this unit you should be able to investigate and explain how cellular structures and systems function to sustain life.

AREA OF STUDY 2

How do living systems sustain life?

Outcome 2: After completing this unit you should be able explain how various adaptations enhance the survival of an individual organism, investigate the relationships between organisms that form a living community and their habitat, and analyse the impacts of factors that affect population growth.

AREA OF STUDY 3

Practical investigation

Outcome 3: After completing this unit you should be able to design and undertake an investigation related to the survival of an organism or species, and draw conclusions based on evidence from collected data. To achieve this outcome you will draw on key knowledge outlined in Area of Study 3 and the related key science skills contained in Chapter 1.

CHAPTER

02 Cells

By the end of this chapter you will understand the importance of cells as the basic structural and functional units of life on Earth. You will learn about the components of different types of cells and how the structures and systems of cells function to sustain life.

Key knowledge

- cells as the basic structural feature of life on Earth, including the distinction between prokaryotic and eukaryotic cells
- surface area to volume ratio as an important factor in explaining the limitations of cell size and the need for internal compartments (organelles) with specific cellular functions
- the ultrastructure of plant and animal cells in terms of their organelles and identification of these organelles using the light microscope and electron micrographs
- the characteristics of the plasma membrane as a semi-permeable boundary between the internal and external environments of a cell
- modes of transport of soluble substances across the plasma membrane including simple diffusion, facilitated diffusion, osmosis and active transport.

2.1 Cell theory, types and microscopy

Cells are the basic structural units of all living things. The cell theory is one of the fundamental principles of biology. It is based on microscopic and experimental studies of tissues, from all types of organisms, carried out over the last 300 years.

In this section you will learn about cell theory, the differences between prokaryotic and eukaryotic cells, and the microscopy techniques that are used to view cells and their components.

CELL THEORY

Cells are the basic structural units of living organisms. The cell theory states that:

- all organisms are composed of cells
- all cells come from pre-existing cells
- the cell is the smallest living organisational unit.

Biogenesis

The cell theory states that all cells arise from pre-existing cells. This is known as **biogenesis**.

Until the 1850s, the idea of spontaneous generation was accepted as the origin of small organisms such as maggots. In other words, maggots could suddenly be formed from anything, even a grain of sand.

Experiments by Francesco Redi on maggots in the 17th century and Lazzaro Spallanzani on microorganisms in the 18th century suggested that 'spontaneous generation' was caused by contamination.

BIOLOGY IN ACTION

History of cell theory

Hooke: the discovery of cells

The first description of cells was made by Robert Hooke in his book *Micrographia*, published in 1665. Hooke made a thin slice of cork from the bark of a tree and examined it under a microscope he had made himself (Figure 2.1.1). He saw that the bark was made up of hundreds of little 'empty boxes' that gave it a honeycomb appearance. He called the boxes 'cells'.

Hooke was actually looking at empty dead cells. When he later looked at fresh plant tissue, he noted the cells appeared to contain water. A few years later, Marcello Malpighi produced more detailed descriptions of plant cells.

Leeuwenhoek: first observations of living cells

In 1676 Anton van Leeuwenhoek observed many living cells under the microscope, including bacteria, blood cells and sperm. He was the first to describe the reproduction of unicellular organisms, which he called 'animalcules'.

FIGURE 2.1.1 Robert Hooke's drawing of his light microscope in *Micrographia*, published in 1665.

In 1859 Louis Pasteur finally disproved the theory of spontaneous generation. He did so by boiling beef broth in two flasks. Each flask had a glass 'goose neck' to prevent contaminants in the air from reaching the broth (Figure 2.1.2). At this point no microorganisms grew in either of the flasks. When the goose neck was broken on one flask and the broth was exposed to the air, microorganisms began to grow in the broth. But the unbroken flask remained free of microorganisms. Pasteur had finally disproved the theory of spontaneous generation.

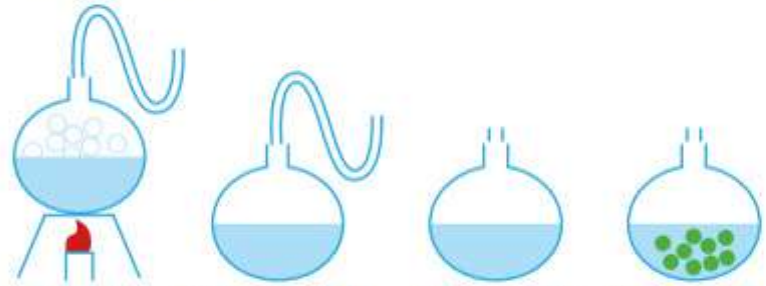


FIGURE 2.1.2 Pasteur's experiment disproved the theory of spontaneous generation.

Pasteur also showed that boiling and cooling wine or milk killed any microorganisms in them. This process was named after him and is called pasteurisation.

An important implication of Pasteur's experiment is that it provided the scientific basis for the germ theory of infection. This theory states that germs are widely present in the environment and are the cause of many diseases. Understanding germ theory eventually led to the development of antiseptic procedures in medicine.

Lamarck and Dutrochet: all living things are composed of cells

By the early 19th century the microscope had become a standard tool of biologists, and living animal and plant cells were easy to observe. In the early 19th century Jean Lamarck stated that all living things are a mass of cells, and that complex solutions move in and out of cells. René Dutrochet supported this idea, stating: 'plants are composed entirely of cells, or of organs that are obviously derived from cells...the same is true for animals'.

Schleiden and Schwann: cells are organised into tissues

By the middle of the 19th century the fundamental principle that entire organisms are composed of highly organised groups of cells was broadly accepted. This was largely because of the work of Matthias Schleiden on plant tissues, and Theodor Schwann on animal tissues.

Remak and Virchow: the theory of biogenesis

Until the 1840s most biologists still believed that cells formed spontaneously from body fluids or from the

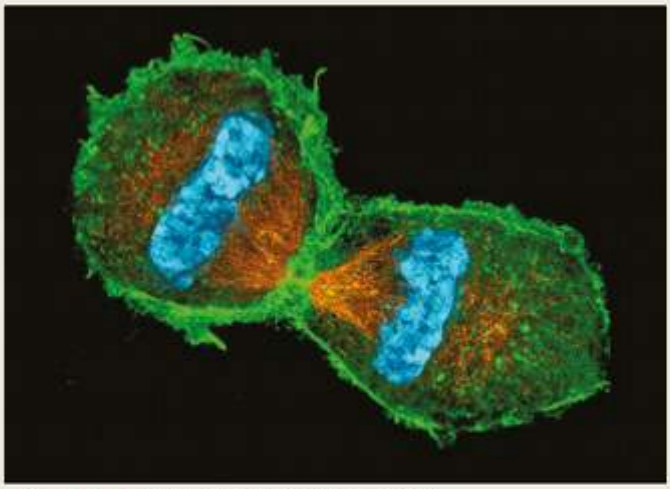


FIGURE 2.1.3 A cell dividing to form a new cell.

nucleus, which they thought was the embryo of a new cell. Then Robert Remak discovered that new cells were formed by a single cell dividing in two, with the nucleus dividing at the same time (Figure 2.1.3). In the 1850s Rudolph Virchow used Remak's discovery to popularise the theory of biogenesis: that all cells come from pre-existing cells. Because of Virchow's great popularity this theory was quickly accepted in Europe, and then the rest of the world.

Proteins are large molecules composed of one or more polypeptides. Polypeptides are long, chain-like molecules consisting of many amino acids linked together.

COMMON CELL FEATURES

Cells are the basic structural unit of all living things. Although there are different types of cells, the cells of plants animals and bacteria share a number of common features (Figure 2.1.4). These common features include:

- a **plasma membrane** (also called a cell membrane)—separates the interior of the cell from the outside environment
- **cytoplasm**—consists of the **cytosol** and, in eukaryotes, the organelles. Cytosol is a gel-like substance. It is made up of more than 80% water and contains ions, salts and organic molecules
- **DNA**—carries hereditary information, directs the cell's activities and is passed accurately from generation to generation
- **ribosomes**—organelles responsible for the synthesis of **proteins**.

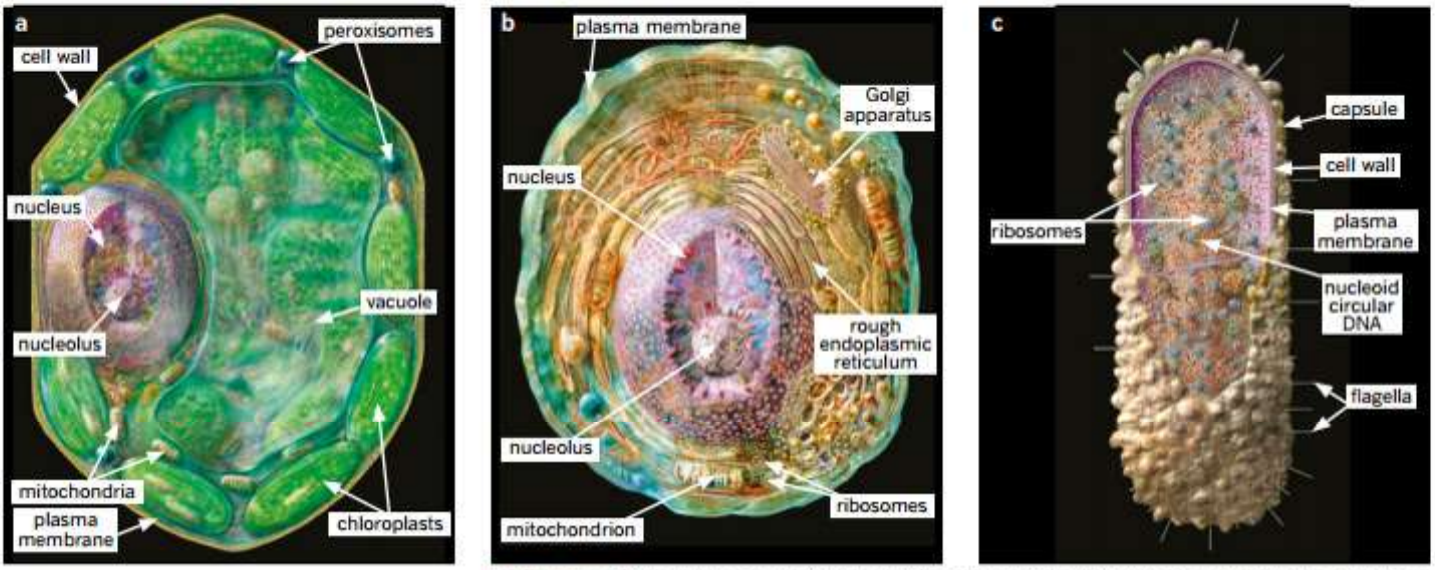


FIGURE 2.1.4 The cells in a plant (a), animal (b) and bacterium (c) share common features, including a plasma membrane, cytoplasm, DNA and ribosomes. Note: Not all features are visible here.

CELL TYPES

The two fundamentally different cell types are **prokaryotic cells** and **eukaryotic cells**. Organisms are classified according to which cell type they have. Protists, fungi, plants and animals are composed of eukaryotic cells and are classified as **eukaryotes**. Bacteria and archaea are composed of prokaryotic cells and are classified as **prokaryotes**. Prokaryotic cells are small and lack membrane-bound organelles, but they still have a number of features in common with eukaryotic cells (Figure 2.1.5).

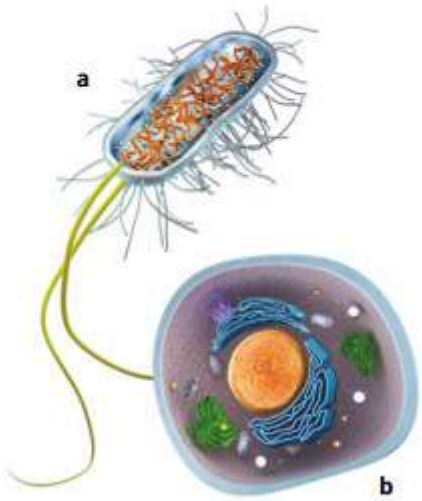


FIGURE 2.1.5 A typical prokaryotic cell (a) and eukaryotic cell (b). Note the different membrane-bound organelles in the eukaryotic cell and the lack of such organelles in the prokaryotic cell.

CLASSIFICATION

In older classification systems all organisms were divided into five ranks, called kingdoms. Prokaryotic organisms were placed in the kingdom Monera and eukaryotic organisms were placed in the kingdoms Protista, Plantae, Fungi and Animalia. These systems were based on the morphology (appearance and structure) of organisms.

However, in the late 1970s the use of DNA techniques in the emerging field of the evolutionary genetics led to the discovery of two different types of prokaryotic cells. This resulted in the development of a system with three domains and six kingdoms (Figure 2.1.6). Domains are now the highest rank in **taxonomy**, instead of kingdoms. Prokaryotes are divided into two domains: Bacteria and Archaea. All eukaryotic organisms are placed in a third domain called Eukarya. The four kingdoms within the Eukarya domain remain the same: Protista, Plantae, Fungi and Animalia (Figure 2.1.6).

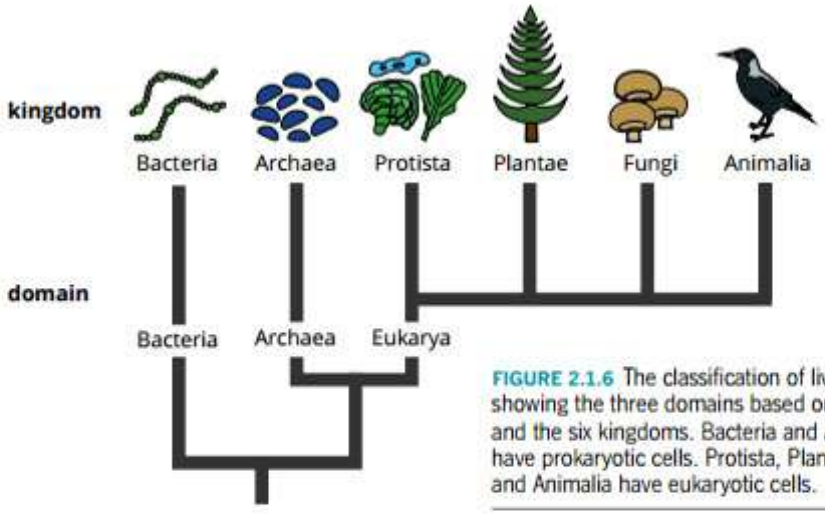


FIGURE 2.1.6 The classification of living things, showing the three domains based on cell types, and the six kingdoms. Bacteria and Archaea have prokaryotic cells. Protista, Plantae, Fungi and Animalia have eukaryotic cells.

PROKARYOTES

Prokaryotic organisms are unicellular and have a simple cell structure. Bacteria, cyanobacteria (photosynthetic bacteria), and archaea such as methanogens are examples of prokaryotes. Prokaryotic organisms can be found everywhere, even in extreme environments such as volcanoes.

Most prokaryotic cells are small and therefore have a large surface area relative to their volume (see Section 2.3 for discussion of surface are to volume ratio). This allows the cells to take in and release materials efficiently and replicate quickly.

The structure of a typical prokaryotic cell is shown in Figure 2.1.7. Prokaryote cells lack membrane-bound organelles, and their cytoplasm contains scattered ribosomes that are involved in the synthesis of proteins. The genetic material of prokaryotic cells is usually a single, circular DNA **chromosome** called the **genophore**, which is contained in an irregularly shaped region called the nucleoid. The nucleoid does not have a nuclear membrane like the nucleus of eukaryotes.

This chromosomal DNA is attached to the plasma membrane by a region of the chromosome called the origin. In addition to this chromosomal DNA, many prokaryotic cells also contain small rings of double-stranded DNA called plasmids.

The plasma membrane of prokaryotic cells is surrounded by an outer cell wall. Many bacteria also have a capsule outside the cell wall, which protects the cell from damage and dehydration. Many prokaryotes also have flagella that enables them to move freely.

Many prokaryotes also have small hair-like projections called pili, which are involved in the transfer of DNA between organisms and can also help generate movement. Specialised pili that can attach to surfaces are called fimbriae.

Carbohydrates are organic compounds of carbon, hydrogen and oxygen, with the number of hydrogen and oxygen atoms in the ratio 2:1. This ratio of 2:1 is the same ratio of hydrogen to oxygen for water. Sugars and starches are examples of carbohydrates.

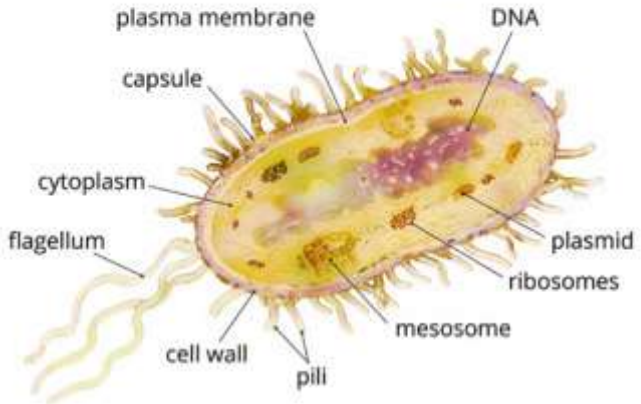


FIGURE 2.1.7 A typical prokaryotic bacterial cell.

Bacteria

Most prokaryotes in the domain Bacteria are microscopic single-celled organisms. Fossil evidence dated at 3.5 billion years old confirms that bacteria were the first type of living organism on Earth. Today they are still the most numerous type of organism in the biosphere.

Bacteria have very diverse metabolisms, and they can survive in a great range of habitats and conditions. They are common in environments of moderate temperature that are moist and low in salt, where sunlight or **organic compounds** are plentiful, and in or on plants and animals.

Bacteria need little oxygen to survive, as they have many ways of extracting energy and fixing carbon. Bacteria are able to obtain energy from sunlight (photosynthesis) by reducing **inorganic compounds** such as sulfides or ferrous ions (chemosynthesis).

Bacteria play an important role in ecosystems because they break down many kinds of substances, including plant and animal remains and wastes. Bacteria are also widely used in industry to manufacture foods, such as cheeses and yoghurt, and in medicine, to produce antibiotics, drugs and even human insulin. Some bacteria can break down oils and plastics, which makes them useful for pollution control.

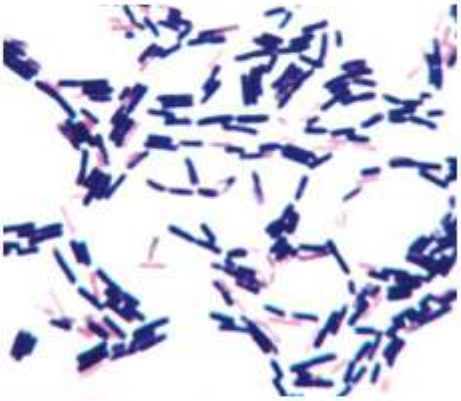


FIGURE 2.1.8 Light micrograph (LM) showing Gram-positive (stained purple) and Gram-negative (stained pink) bacteria.

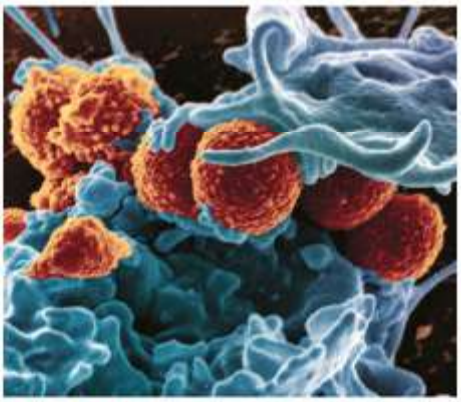


FIGURE 2.1.9 A scanning electron micrograph (SEM) of *Staphylococcus aureus* (commonly called 'golden staph') being engulfed by a white blood cell. The cocci are coloured orange in this image to represent their actual colour.

Gram-positive and Gram-negative bacteria

The cell walls of prokaryotes are distinctive for containing murein (also known as peptidoglycan), which is a giant molecule consisting of sugars linked by amino acids. In most bacteria the murein forms a cell wall in a mesh-like layer outside the plasma membrane. Prokaryotic bacteria are commonly identified as either Gram-negative or Gram-positive. A purple stain called crystal violet is used for this purpose.

Gram-positive bacteria have a thicker layer of murein that absorbs and holds the stain, so they give a purple or 'positive' result. Gram-negative bacteria have a much thinner layer of murein that does not retain the stain as well, so they give a pink or 'negative' result (Figure 2.1.8).

There are numerous types of Gram-negative and Gram-positive bacteria. For example, Gram-positive cocci are spherical bacteria and include *Staphylococcus* and *Streptococcus*, which can cause serious diseases or death in humans (Figure 2.1.9).

An example of a Gram-negative bacterium is a cyanobacterium (Figure 2.1.10). Cyanobacteria were once called blue-green algae because they contain chlorophyll, but they were found to be actually prokaryotes and placed in the Bacteria domain. They often form dense colonies in shallow estuaries or fresh water. Some species can form large colonies ('blooms') that produce toxins capable of killing fish and other aquatic life and cause illness in humans.

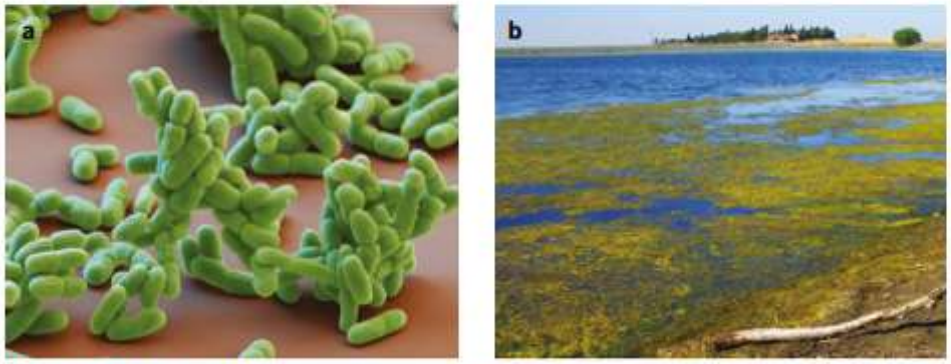


FIGURE 2.1.10 (a) An SEM of a *Synechococcus* cyanobacterium. (b) A colony of *Synechococcus* cyanobacteria in a lake.

Archaea

The prokaryotes in the domain Archaea include **extremophiles**. These are organisms that can live in extreme conditions, such as:

- areas of high temperatures (thermophiles)
- areas of low temperatures
- the upper atmosphere
- very alkaline environments
- very acidic environments (acidophiles)
- very salty environments (halophiles)
- environments with little or no oxygen
- areas without light
- petroleum deposits deep underground.

Archaea hold records for living in the hottest places (121 °C), the most acidic environments (pH 0), and the saltiest water (about 30% salt). However, some archaea live in less extreme environments such as the open seas.

The unique place of archaea among living organisms was not recognised for a long time. The main reason for this is that the extreme habitats where they live has made them difficult to find and also culture in a laboratory. Another reason is that most archaea look very similar to bacteria, even though they are as different from bacteria as humans are.

The ability of archaea to live in extreme environments is due in part to their unique membranes. Like other living organisms, archaea possess a membrane composed mainly of **lipids**. Cell membranes need to be fluid to respond to external deformations and damage and allow proteins to move around.

The lipids in eukaryotic cell membranes have fluidity and selective permeability, but only in a narrow range of temperatures. The lipids that compose archaean membranes are different. They form a unique cell membrane structure that remains fluid and permeable over a wide range of temperatures, from freezing cold to boiling hot.

There are many different types of extremophiles. Hyperthermophiles like *Pyrococcus furiosus* are extremophiles that can survive in very hot environments such as undersea vents, where temperatures are often above 100 °C (Figure 2.1.11). They can also withstand extremely high pressures. Sulfolobus bacteria, which live in volcanic springs are thermophiles as well as acidophiles: they can survive both high temperatures and high acidity (Figure 2.1.12).

Lipids are 'fatty' organic compounds, including fats and oils, composed mainly of carbon, hydrogen and oxygen. Lipids have proportionally less oxygen than carbohydrates, and may contain other elements.

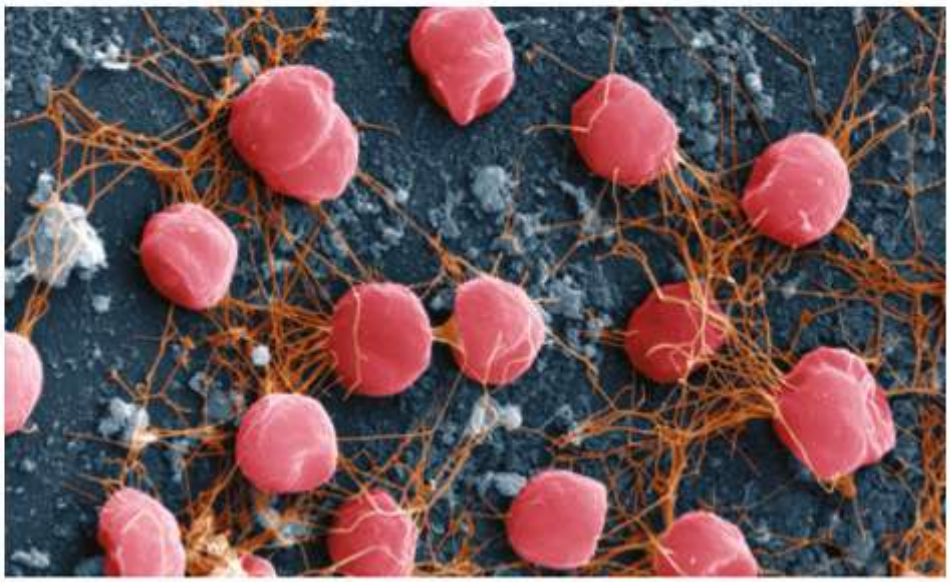


FIGURE 2.1.11 An SEM of hyperthermophile *Pyrococcus furiosus*. These bacteria can only exist in very hot environments such as hot undersea vents.

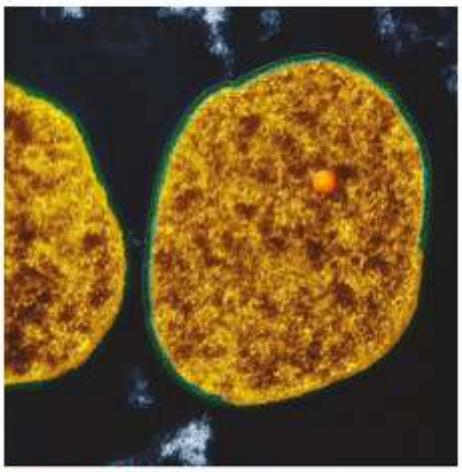


FIGURE 2.1.12 *Sulfolobus* bacteria are thermophiles as well as acidophiles. They thrive in hot, acidic environments.

Differences between bacteria and archaea

Despite their name, archaea are not the most ancient group of organisms. DNA studies have shown that bacteria are the most ancient group, and that archaea evolved from eukaryotic cells at a later time.

The cells of bacteria and archaea are different in a number of ways:

- archaea have a different type of lipid structure in the plasma membrane
- the cell wall in bacteria contains murein, but the cell wall in archaea does not (although there is a similar compound in some archaea)
- both have diverse metabolic systems, but methanogenesis (in which methane is produced) is unique to archaea.

COMPARISON OF PROKARYOTIC AND EUKARYOTIC CELLS

There are a number of differences between prokaryotic and eukaryotic cells (Table 2.1.1). Eukaryotic cells have their DNA in the nucleus, in the form of linear chromosomes. Their cytoplasm contains many different membrane-bound organelles, which are specialised structures that have specific functions. Some eukaryotic cells are surrounded by a cell wall composed of carbohydrates. You can identify the nucleus, cytoplasm and organelles in the diagram of a typical eukaryotic cell (Figure 2.1.13).

Feature	Prokaryotic cells	Eukaryotic cells
Size	• very small	• larger, with large variation in size
Surface area to volume ratio (SA:V)	• large SA:V ratio • allows materials to diffuse in and out of the cell rapidly	• smaller SA:V ratio • results in slower diffusion
Membrane-bound organelles	• absent, no membrane-bound organelles	• many organelles bound by membranes, forming an organised internal structure
Chromosomal DNA	• DNA chromosome in the form of a single-stranded loop • located in a region of cytoplasm called the nucleoid, lacking a membrane	• DNA in the form of linear, thread-like chromosomes • • located in the nucleus, which is separated from the cytoplasm by a double-layered membrane
Ribosomes	• many tiny ribosomes scattered in the cytoplasm	• many ribosomes, either attached to the endoplasmic reticulum (ER), or free in the cytoplasm
Cell membrane	• bilayer of phospholipid molecules enclosing the cytoplasm in bacteria • phospholipids are different and sometimes fuse into a monolayer in archaea	• bilayer of phospholipid molecules enclosing the cytoplasm
Cell wall	• in bacteria, consists of protein/carbohydrate compound called murein	• present in fungi, plants and some protists • consists mainly of carbohydrates: chitin in fungi and cellulose in plants
Flagella	• may have flagella to provide movement • consists of three protein fibrils coiled in a helix and protruding through the cell membrane and wall	• may have flagella or cilia for motility (but not in fungi) • consists of a highly organised array of microtubules (hollow protein tubes) enclosed by extended cell membrane

TABLE 2.1.1 Comparison of prokaryotic and eukaryotic cells.

CELL SIZE

Cells vary greatly in size (Figure 2.1.13). Most cells are only visible under a light microscope, and their size is usually measured in micrometres. There are 1000 micrometres (μm) in 1 millimetre (mm). There are exceptions though; the egg cell of some bird species can be many centimetres in diameter. Some typical cell sizes are as follows:

- bacterium: 0.1–1.5 μm long
- human: 8–60 μm long
- paramecium (a single-celled eukaryote): about 150 μm long.

The thickness of plasma membranes also differs between cells, and can be between 0.004 and 0.1 μm thick.

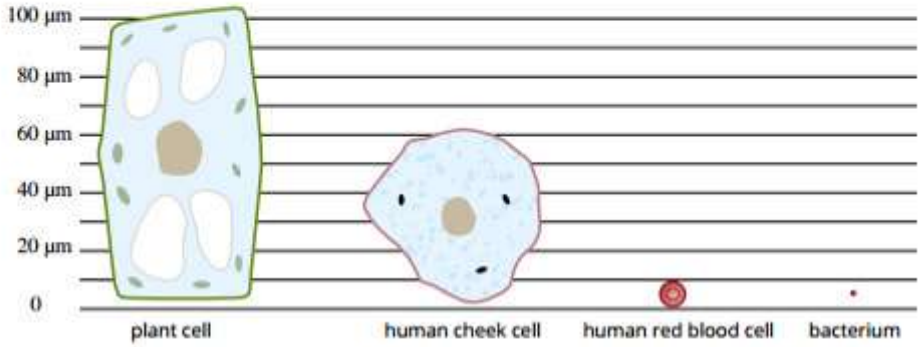


FIGURE 2.1.13 A typical plant cell, human cheek cell, human red blood cell and a bacterium. Note the great difference in size between the eukaryotic cells and the prokaryotic cell (bacterium).

INVESTIGATING CELLS

Cytology is the study of cells. Cytologists use a variety of tools and techniques to study cells, including several microscopy techniques. Modern microscopy techniques, including light and electron microscopy (see Figure 2.1.16), have greatly advanced our understanding of the structure and function of cells.

Light microscopy

Most cells are so small that they can only be seen with a microscope (Figure 2.1.16). The light microscope uses light and a system of lenses to magnify the image. One lens is called the objective and the other is the eyepiece or ocular lens. The total magnification of a microscope is calculated by multiplying the magnifying powers of the objective and the eyepiece. For example, a 10 times (10×) objective used with a 4× eyepiece gives a total magnification of 40×.

One of the main advantages of light microscopy is that it can be used to view living cells in colour.

Preparation time is usually quick and simple. Stains can be used to highlight different components of cells in colour. A thin specimen is mounted on a glass slide and placed on the stage under the lenses. Light travels through the specimen and into the lens system, and the image is viewed by eye or with a digital camera.

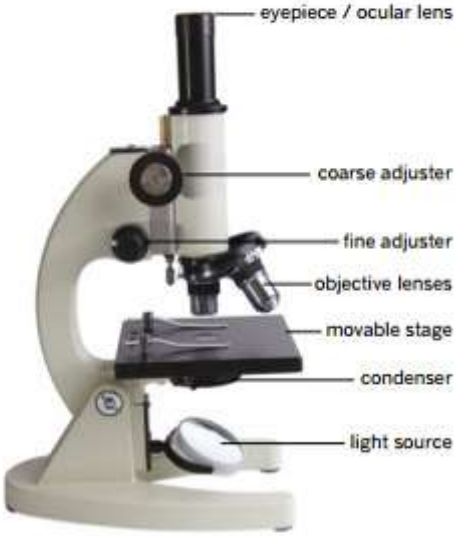


FIGURE 2.1.16 A light microscope and its parts.

BIOFILE

Giant bacteria

In 1985 a huge single-celled organism was found in the gut of a surgeonfish (Figure 2.1.14) caught in the Red Sea. It measured up to 600 μm (0.06 cm) long and 80 μm (0.008 cm) wide, making it visible to the naked eye. It was first thought to be a protist, but further examination showed it to be a giant bacterium, now called *Epulopiscium fishelsoni* (Figure 2.1.15). The largest bacterium known is *Thiomargarita namibiensis*, which grows up to 750 μm long.

Largest cells

Although the ostrich egg is probably the largest eukaryotic cell in terms of volume, it is not the longest. For example, the giant squid has nerve cells up to 12 metres long, and in humans the nerve that runs from the base of the spine to the big toe can be over 1 metre long.

FIGURE 2.1.14 The brown surgeonfish (*Acanthurus nigrodfuscus*), the species in which *Epulopiscium fishelsoni* was discovered.

FIGURE 2.1.15 The genus *Epulopiscium* is an unusual group of cigar-shaped Gram-positive organisms which live in the guts of fish. The bacteria grow up to nearly a millimetre in length, big enough to see with the naked eye.

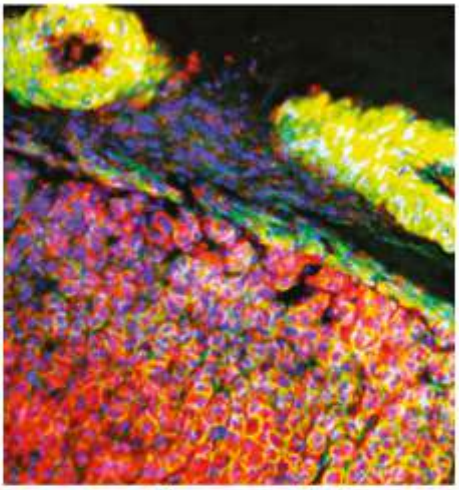


FIGURE 2.1.17 A fluorescence LM of a stained section through an adrenal gland. The endothelial nitric oxide synthase enzymes are red, cell nuclei are blue, and smooth muscle actin proteins of blood vessels are green/yellow.

The condenser lens beneath the movable stage is used to concentrate light from the light source onto the specimen, and the image is focused using the coarse and fine adjusters. Different parts of the specimen can be viewed by moving the specimen on the stage.

Light microscopy techniques used in cytology include histology, autoradiography, fluorescence and confocal microscopy. Each of these uses visible light to examine cells and tissues.

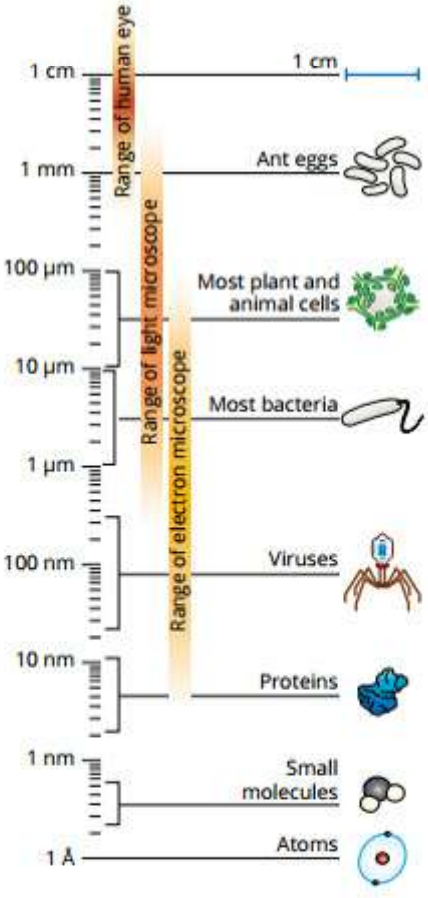
Fluorescence microscopy

The fluorescent microscope is used to examine cells that are naturally or artificially fluorescent. That is, they contain molecules that absorb light of one wavelength (called the exciting wavelength, which is usually ultraviolet) and emit it at another wavelength (and therefore with a different colour). By using filters to block out the exciting wavelength, the light emitted by the fluorescing molecules can then be seen against a black background (Figure 2.1.17). If the cells do not contain fluorescent molecules, fluorescent dyes (called markers) can be added that attach to the structures being investigated, such as DNA, particular proteins or cell wall components (Figure 2.1.17).

Immunofluorescence involves using a fluorescent tag that is linked to an antibody, which then attaches to its particular target antigen in the cell.

Confocal microscopy

Confocal microscopy allows scientists to obtain 'optical sections' of a cell or tissue, stained with fluorescent markers, without actually sectioning or slicing the cells. Confocal microscopy is a relatively new technique that permits high-resolution images of very thin sections of a specimen (Figure 2.1.18). It involves passing laser light through a pinhole and lens, which provides highly focused light onto only a tiny part of the specimen. This eliminates light reflecting from adjacent parts of the section, which normally blur the image. Slowly scanning the object in this way, together with a suitable computer, allows you to view an 'optical section' of the sample. Thicker samples can be imaged in thin sections and then reconstructed in three dimensions using image analysis software. At present confocal microscopes and the computer software required are very expensive, and the production of images is slow. However they can produce startling three-dimensional views of living structures.



$1\ cm = 10\ mm = 10^4\ \mu m = 10^7\ nm = 10^8\ Å$

FIGURE 2.1.19 A comparison of the ranges of the light and electron microscopes. (Note that the scale is logarithmic.)

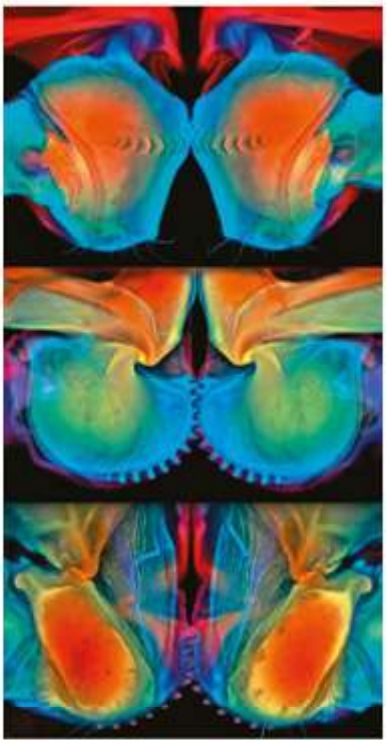


FIGURE 2.1.18 A confocal laser scanning micrograph of the green cone-headed planthopper (*Acanalonia conica*). The image (top to bottom: posterior, dorsal and ventral views) shows cog or gear-like structures of the structure at the top of each hind leg, which allows the hind legs to interlock and move together in perfect synchrony. Confocal microscopes create optical slices of specimens. Laser light from the microscope causes the stained specimen to fluoresce and reveal variations in the chitin (the main component in the exoskeleton) structures.

Electron microscopy

In electron microscopy, an object is viewed using an electron beam instead of light. This allows us to see structures in far more detail than is possible using light microscopy (see Figure 2.1.19 on previous page). An electron microscope produces a narrow beam of electrons that is maintained by electromagnetic lenses, which are coils that surround the tube and emit an electromagnetic field. Electrons striking the specimen are absorbed or scattered, or pass through it.

The image obtained with an electron microscope has a much higher resolution and a greater depth of field than an image from a light microscope. Electron microscopy produces only black and white images, but these are often coloured later to highlight important features.

Transmission electron microscopy

In transmission electron microscopy (TEM) the electron beam travels through an ultrathin section (less than 100 nanometres thick) of a specimen. This allows very fine details of cellular structures to be seen (Figure 2.1.20).

Because the specimen must be in a vacuum in the TEM, it is first chemically fixed to stop the structures from collapsing and then dehydrated with alcohol. It is then embedded in a plastic resin, sectioned with a diamond cutter called an ultramicrotome, and stained.

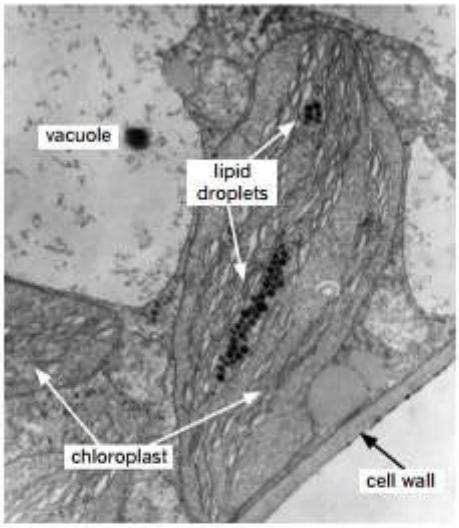


FIGURE 2.1.20 A TEM of a plant leaf, showing chloroplasts, with lipid droplets showing in one. The pale area to the upper left is a vacuole and the cell wall is also visible at the lower right.

Scanning electron microscopy

In scanning electron microscopy (SEM) the electrons are bounced off a specimen that has been coated with an extremely thin layer of gold. This gives a high-resolution picture of the surface features but cannot show internal details (Figure 2.1.21).

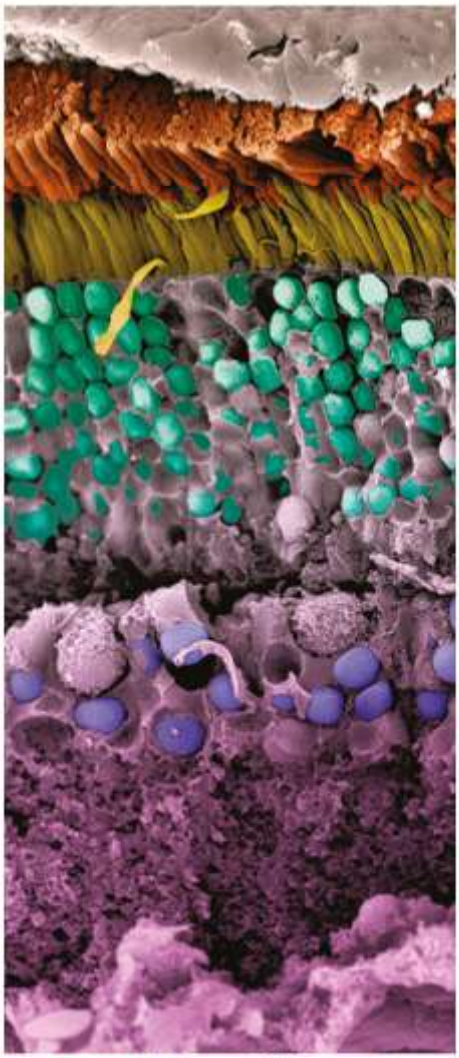


FIGURE 2.1.21 A coloured SEM of a section through the retina of an eye, showing cone and rod cells.

Autoradiography

Autoradiography is a method that allows you to identify specific organelles or the location of molecules within a cell or tissue. In autoradiography the tissue is first treated with a radioactively labelled substance that is taken up into the part of the cell that is being investigated (Figure 2.1.22). The tissue is then sliced into very thin sections which are then placed against a very thin high-resolution photographic film. The radioactive substance emits beta particles that produce an image on the film. The tissue sections are then stained so that the photographic image can be located in relation to cellular structures. This technique can be used to indicate which organelles are active under particular circumstances.

Although autoradiography is still sometimes used with light microscopy, it is more commonly used today with electron microscopy.

FIGURE 2.1.22 An autoradiograph of a slice through nerve tissue from the visual centre of the brain, showing how visual messages from one eye are received by the brain. Rows of neuron (nerve cell) cubes are laid out in columns on the outside of the brain tissue, and the active areas of the brain have absorbed a radioactive chemical. The glow is developed onto photographic paper and produces an autoradiograph.

BIOLOGY IN ACTION

The synchrotron and its use in biology

A synchrotron is a machine in which a beam of electrons is accelerated almost to the speed of light. Powerful magnets are used to guide the beam into a particular path, usually a circle. The first synchrotron was built in 1945 and was the size of a small room. The largest synchrotron today is the Large Hadron Collider in Switzerland, which has a circumference of 27 km. The Australian Synchrotron in Melbourne (Figure 2.1.23) is one of the most advanced synchrotrons, and can produce an extremely intense beam of radiation in a wide range of wavelengths. Most biological investigations using synchrotrons involve visible light.

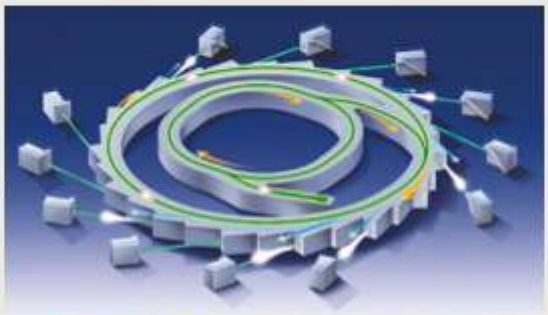
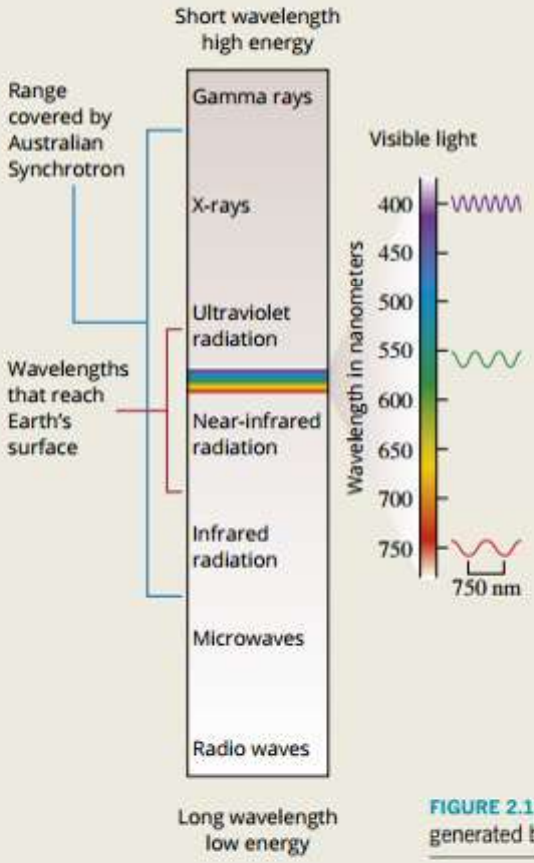


FIGURE 2.1.23 The Australian Synchrotron is almost the size of the MCG. The large diameter is needed to accelerate particles to almost the speed of light. Synchrotron light of different wavelengths can be obtained from several points around the circumference.



The special nature of synchrotron light

Visible light is a small part of the electromagnetic wavelengths that can be generated by a synchrotron. It lies between the longer wavelengths (radio waves, microwaves and infrared) and the shorter wavelengths of ultraviolet light, X-rays and gamma rays (Figure 2.1.24).

Synchrotron light allows matter to be seen at the atomic scale, including the nanosecond-by-nanosecond behaviour of protein molecules such as antibodies. It enables scientists to collect, in hours, data on the structure of proteins that would once have taken weeks or months. While structural biology is their most important application, synchrotrons are useful in many other areas, such as nanotechnology and materials science.

A synchrotron allows complex protein structures to be determined quickly and is central to drug design and development. It allows further development of medical imaging technologies and the analysis of biological samples to potentially help diagnose diseases.

FIGURE 2.1.24 The electromagnetic spectrum, showing the range generated by the Australian Synchrotron and the range of visible light.

2.1 Review

SUMMARY

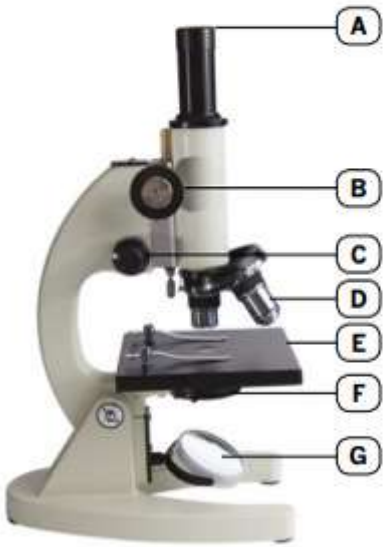
- The cell theory states that:
  - all organisms are composed of cells
  - all cells come from pre-existing cells
  - the cell is the smallest living organisational unit.
- All cells have a plasma membrane, cytoplasm, genetic material in the form of DNA, and ribosomes.
- There are two fundamentally different types of cells—prokaryote and eukaryote.
- Organisms with prokaryote cells are called prokaryotes. They are classified into two domains: Bacteria and Archaea.
- Prokaryotic cells are small, with simple structure and lack membrane-bound organelles.
- Organisms with eukaryote cells are called eukaryotes. They are classified into the domain Eukarya, which is divided into four kingdoms: Protista, Fungi, Plantae and Animalia.
- Prokaryotic cells have a simple structure, with a nucleoid lacking a membrane, scattered ribosomes, and DNA mainly in a single-stranded loop in the nucleoid.
- Eukaryotic cells have a complex structure, membrane-bound nucleus, many organelles in the cell cytoplasm, and DNA mainly in chromosomes in the nucleus.
- Archaea (the extremophiles) are often found in very harsh environments where their unique cell membrane structure protects them.
- Cells vary greatly in size, and a microscope is needed to see most cells.
- Light microscopes use visible light and a system of lenses to magnify images.
- Electron microscopes use an electron beam focused by electromagnets to view objects. They have a much higher magnification and resolution than a light microscope.

KEY QUESTIONS

1 State the cell theory.

2 Describe the main differences between prokaryotic and eukaryotic cells.

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

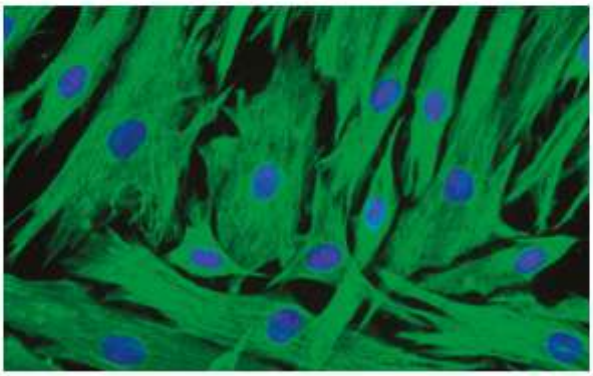


4 What is the main difference between light microscopy and electron microscopy?

5 What is the difference between transmission electron microscopy and scanning electron microscopy?

6 How might fluorescence microscopy be used to visualise the bacterial capsule?

7 The figure below shows an image of hair follicle cells. Which type of microscope was used to take the image? Explain your answer.



8 What advantages in structural biology are gained by a synchrotron?

9 What advances have been made in science with the help of synchrotron technology?

2.2 Cell ultrastructure

FIGURE 2.2.1 Plants are eukaryotes and so their cells have membrane-bound structures, some of which can be seen in this SEM. The cell is encased in a cellulose, hemicellulose and pectin cell wall. Inside the cell wall are chloroplasts (dark green), the nucleus (orange) and a large vacuole in the centre of the cell.

In the previous section you learned that the two fundamentally different types of cells are prokaryotic and eukaryotic cells, and that organisms are classified into one of three domains (Bacteria, Archaea or Eukarya) according to the type of cell they have.

Bacteria and archaea are prokaryotes. their cells do not contain membrane-bound organelles. Animals, plants, fungi and protists are eukaryotes. Each represents a kingdom in taxonomy: Animalia, Plantae, Fungi and Protista. There are many different types of cells within the four eukaryotic kingdoms. These cells have very different appearances and functions, but they all contain membrane-bound organelles (Figure 2.2.1).

In this section you will learn about the importance of cell compartmentalisation and membrane-bound structures in eukaryotes. You will also learn more about the structure and function of organelles and the differences between plant and animal cells.

COMPARTMENTALISATION IN EUKARYOTIC CELLS

As you learned in the previous section, the two main types of cells are prokaryotic and eukaryotic cells:

- prokaryotic cells—are relatively small and lack membrane-bound organelles. Bacteria and archaea are called prokaryotes.
- eukaryotic cells—are relatively large and more complex. They possess membrane-bound organelles such as a nucleus and mitochondria. Protists, fungi, plants and animals are called eukaryotes because they are composed of eukaryotic cells.

As well as a plasma membrane surrounding the cytoplasm, eukaryotes have internal membranes that form specialised membrane-bound compartments within the cell. This is known as **cell compartmentalisation**. The membrane-bound compartments are **organelles**. However, not all organelles have membranes (Figure 2.2.2).

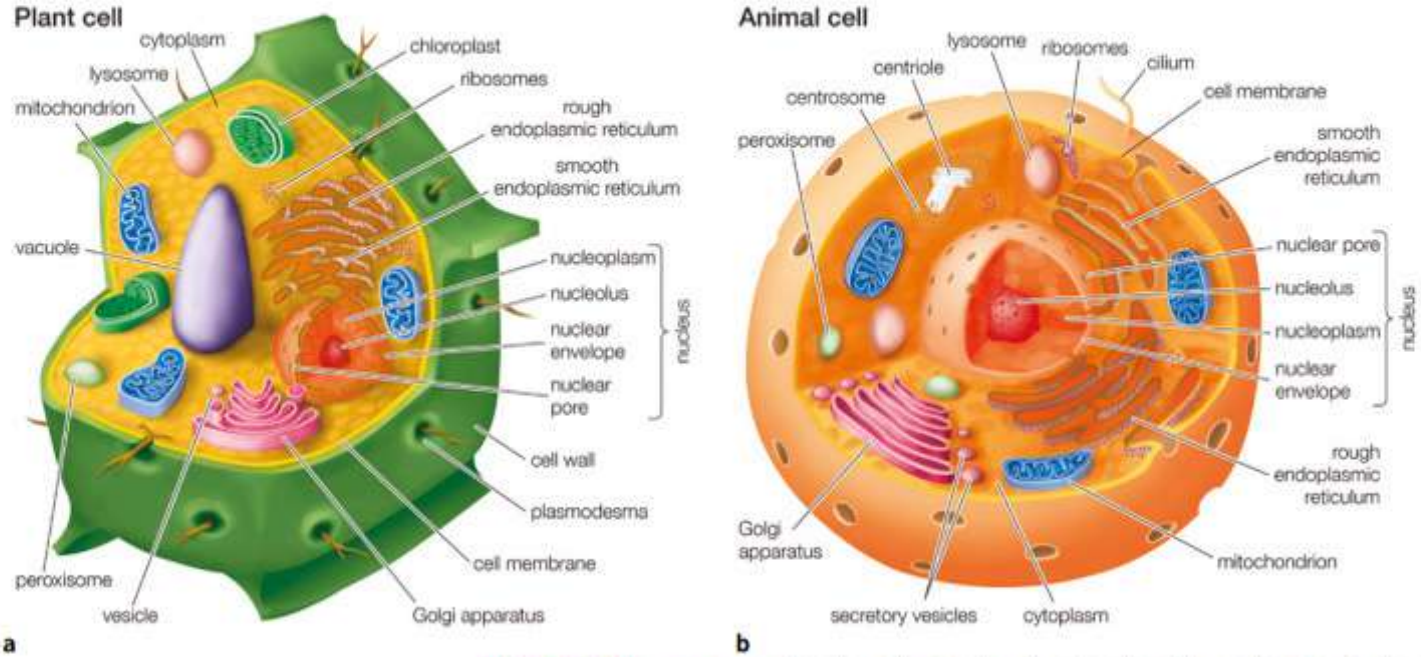


FIGURE 2.2.2 The many membrane-bound organelles of eukaryotic cells can be seen in these illustrations of (a) a plant and (b) an animal cell.

Each membrane-bound organelle has a different function. For this reason, each organelle requires a different internal composition, including a high concentration of **enzymes** and reactants that are needed for the organelle's particular function.

Role of organelle membranes

The membranes surrounding organelles control the movement of substances between the organelle and the cell's cytosol. Just as the plasma membrane of a cell enables the cytosol to have a different composition from the cell's surrounding environment, the membranes of membrane-bound organelles enable each organelle to have a different composition from the surrounding cytosol and other organelles.

Benefits of compartmentalisation

Cellular compartmentalisation benefits the cell in several ways:

- it allows enzymes and reactants for a particular function to be close together in high concentrations and at the right conditions, such as at optimum pH levels, so that the processes within the organelles are very efficient
- it allows processes that require different environments to occur at the same time, in the same cell
- it makes the cell less vulnerable to changes to its external environment, because changes will affect the cytosol much more than the membrane-bound organelles.

Enzymes are proteins that act as biological catalysts. Enzymes speed up rates of biochemical reactions that would otherwise take place much more slowly. Their action is specific: they catalyse (cause or accelerate) only one type of reaction.

BIOLOGY IN ACTION

An artificial cell with working organelles

Cells are the basic building blocks of all life on Earth. These microscopic structures are responsible for carrying out all the processes that make life possible—everything from transporting oxygen, nutrients and waste to synthesising proteins and producing new life.

Cells are extremely complex, yet incredibly efficient, processing multiple reactions simultaneously in a very small space. The efficiency of eukaryotic cells is largely a result of compartmentalisation. Compartmentalisation allows processes that require different environments to occur at the same time, in the same cell. Chemical signals send messages between the compartments to ensure that the cell is functioning optimally as a unit.

Biochemists are interested in understanding how a cell can carry out such efficient chemistry on such a small scale, but the complexity of cells makes it extremely difficult for scientists to mimic these structures and their functions in the laboratory. If scientists can create functioning cell-like structures in the laboratory, they can learn more about the inner workings of cells and better understand how life evolved from chemical reactions to functioning life forms.

In 2014 a team of researchers from the University of Bordeaux in France and Radboud University in the Netherlands built the world's first artificial eukaryotic cell. The scientists created the cell's organelles from tiny enzyme-filled spheres. The organelles were placed inside a droplet of water, which was then coated with a polymer layer to create a cell membrane (Figure 2.2.3). Using this method, the researchers had built a compartmentalised structure that mimicked a eukaryotic cell. To test whether the cell was functional, the researchers used fluorescent dyes to observe the series of chemical reactions within it. Just like the cells in our bodies, chemical reactions took place in the organelles and moved into the plasma membrane for processing elsewhere. The scientists had successfully created an artificial cell with working organelles! In the future, researchers hope to create cells that can produce their own energy.

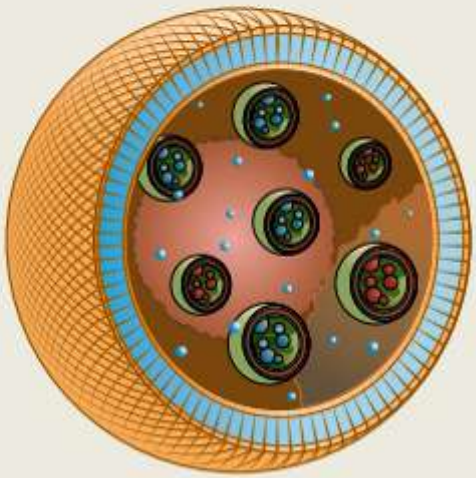


FIGURE 2.2.3 A cutaway diagram of an artificial cell. The cell consists of a polymer membrane surrounding a water droplet containing enzyme-filled spheres that function as organelles.

MEMBRANE-BOUND AND NON-MEMBRANE-BOUND ORGANELLES

Organelles are subcellular structures that have a specific function (Table 2.2.1). Some organelles, as mentioned earlier, are membrane-bound compartments within the cytoplasm. Membrane-bound organelles are only present in eukaryotic cells.

Organelle	Structure	Function
Nucleus	• Membrane-bound: double membrane • Contains DNA	Contains hereditary information
Rough endoplasmic reticulum	• Membrane-bound: network of cisternae • Ribosomes bind to its membranes	Processes and modifies proteins
Ribosome	• Made of proteins and rRNA	Synthesises proteins
Golgi apparatus	• Membrane-bound: stack of cisternae that are not connected to each other	Processes and packages proteins
Lysosome	• Membrane-bound: vesicle containing digestive enzymes	Digests cellular waste material and foreign matter
Smooth endoplasmic reticulum	• Membrane-bound: network of cisternae	Synthesises lipids
Mitochondrion	• Membrane-bound: double membrane. The inner membrane is highly folded • Contains DNA	Obtains energy from organic compounds
Chloroplast	• Spherical or ellipsoidal, with double membrane • Contains DNA and thylakoid sacs	Uses light energy, carbon dioxide and water to produce glucose
Centriole	• Small structure in the cytoplasm, consisting of microtubules	Involved in cell division and the formation of cell structures such as flagella and cilia
Cilium or flagellum	• External structure consisting of microtubules	Motility; movement of substances across cell surface
Vacuole	• Membrane-bound, fluid-filled vesicle	Stores substances; also involved in cell structure in plant cells
Plastid	• Small, with double membrane • Contains DNA	Synthesises and stores various organic molecules
Cell wall	• External structure surrounding plasma membrane • Composition depends on type of cell	Cell structure and protection

TABLE 2.2.1 Organelle structure and function

Prokaryotic cells have some non-membrane bound organelles, such as ribosomes a cell wall and sometimes flagella, although the structure and composition of these are usually different to those of eukaryotic cells.

FUNCTION AND ULTRASTRUCTURE OF ORGANELLES

Cellular organelles are involved in a number of different functions (Table 2.2.2). Their functions include the synthesis and processing of proteins and lipids, energy transformations, storage, and maintaining the structure of the cell.

Function	Organelle	Present in plants	Present in animals
Involved in synthesis and processing of proteins and lipids	nucleus	✔	✔
	ribosome	✔	✔
	rough endoplasmic reticulum	✔	✔
	Golgi apparatus	✔	✔
	lysosome	✔✘	✔
	smooth endoplasmic reticulum	✔	✔
Involved in energy transformations	mitochondrion	✔	✔
	chloroplast	✔	✘
Involved in storage and cell structure	centriole	sometimes	✔
	flagellum or cilium	✔	✔
	vacuole	✔	small
	cell wall	✔	✘

TABLE 2.2.2 Organelles and their functions

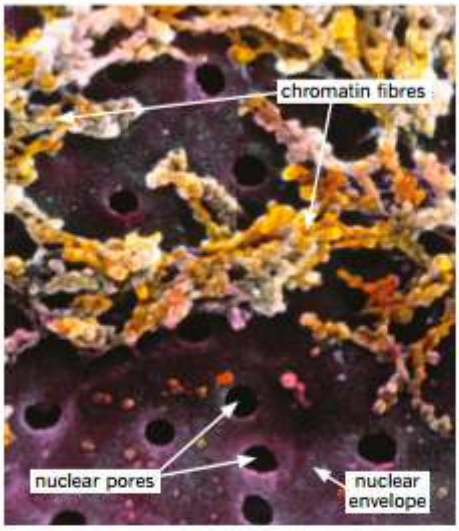


FIGURE 2.2.4 An SEM of the external surface of a nuclear envelope in an onion root tip cell. The envelope consists of a double membrane (purple) which encloses the nuclear DNA. The nuclear pores (black circles) are pathways for the transport of larger molecules between the nucleus and the cytoplasm. Contained within the nucleus are the chromatin fibres (yellow and orange) which contains the chromosomes.

Synthesis and processing of proteins and lipids

The following organelles are involved in the synthesis and processing of proteins and lipids in eukaryotic cells:

Nucleus

In eukaryotes most of the DNA (genetic material) is contained in the nucleus, which is a large organelle surrounded by a double-layered nuclear membrane. The genetic material in the nucleus takes the form of linear chromosomes composed of DNA and proteins. Chromosomes are usually not clearly visible, except during cell division. The nuclear membrane contains pores that link it with the cytoplasm (Figure 2.2.4).

The information for the synthesis of new proteins is present in the DNA. Genes in the DNA are transcribed (copied) into messenger RNA (**mRNA**). The mRNA leaves the nucleus and moves into the cytoplasm. The most visible structure inside the nucleus of a non-dividing cell is the **nucleolus**. The nucleolus is composed of proteins, DNA and RNA, and is where ribosomes are assembled.

Ribosomes

Cells contain many thousands of ribosomes, which are only about 30 nanometres in diameter and therefore only visible using an electron microscope. Ribosomes are composed of proteins and ribosomal RNA (**rRNA**), and are sites of protein synthesis. They consist of two subunits joined together (Figure 2.2.5). The subunits in eukaryote ribosomes are different to those in prokaryote ribosomes. Ribosomes are either free in the cytoplasm or bound to rough endoplasmic reticulum.

Ribosomes translate mRNA into proteins. The mRNA specifies the sequence of amino acids in the protein. Proteins produced in free ribosomes will function in the cell's cytoplasm, while proteins synthesised in ribosomes bound to the rough endoplasmic reticulum are secreted out of the cell, packaged into organelles or inserted in cell membranes.

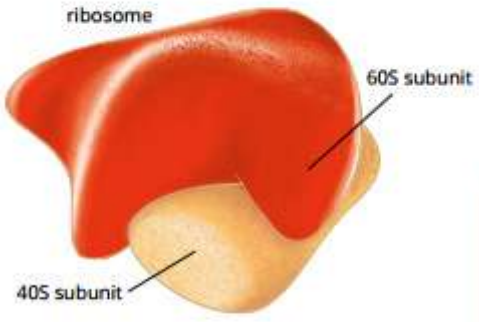


FIGURE 2.2.5 A single eukaryote ribosome consists of a larger 60S subunit and a smaller 40S subunit, which together form an 80S unit.

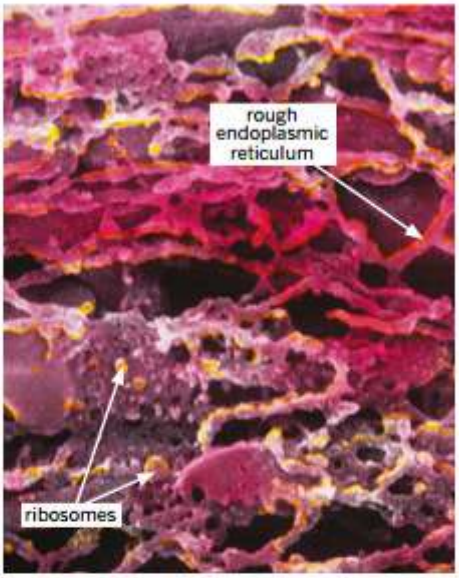


FIGURE 2.2.6 An SEM of endoplasmic reticulum (ER) in an olfactory epithelium supporting cell. ER is a network of folded membranes forming sheets, tubes or flattened sacs in the cell cytoplasm. On the surface of some of the ER membranes are ribosomes (yellow spheres).

Endoplasmic reticulum

Endoplasmic reticulum is a network of intracellular membranous sacs (cisternae) and tubules that link with the plasma membrane and other membranous organelles, including the nucleus. The endoplasmic reticulum can be rough or smooth.

Rough endoplasmic reticulum has ribosomes attached, which synthesise proteins. These ribosomes are bound to the membrane of the rough endoplasmic reticulum (Figure 2.2.6). After the proteins are made, they pass into the ER cavity containing enzymes. The enzymes add sugar molecules to the proteins to form glycoproteins.

Rough endoplasmic reticulum is abundant in cells that actively produce and export proteins, such as pancreatic cells that secrete digestive enzymes. From the rough endoplasmic reticulum, proteins move into the Golgi apparatus for export from the cell.

Smooth endoplasmic reticulum contains the enzymes involved in the synthesis of molecules other than proteins, such as **phospholipids** and steroids. It is abundant in steroid-secreting cells in the testes, ovaries, kidneys adrenal glands (Figure 2.2.7).

Golgi apparatus

The **Golgi apparatus** (also called the Golgi body or Golgi complex) is a stack of flattened smooth membrane sacs called cisternae (Figure 2.2.8). Unlike the rough endoplasmic reticulum, the cisternae in the Golgi apparatus are not connected. When proteins formed in the rough endoplasmic reticulum reach the Golgi apparatus, vesicles are formed from each cisternae to transport the proteins from one cisternae to the next, where they are modified for use by the cell, or for transport out of the cell. The cisternae then form transport vesicles to move these materials into the cytosol or out of the cell, such as secreted hormones. Vesicles budding from the Golgi apparatus also carry membrane-bound proteins to the plasma membrane and digestive enzymes into lysosomes.

The Golgi apparatus has two faces: the cis face and the trans face (Figure 2.2.9). The cisternae of the cis face are connected to the endoplasmic reticulum, either directly or by small transport vesicles. This allows the proteins made in the rough endoplasmic reticulum to enter the Golgi apparatus. The cisternae of the trans face are connected to the plasma membrane by large secretory vesicles, which contain proteins to be secreted outside the cell. The membranes of the cis face more closely resemble the membranes of the endoplasmic reticulum, and the membranes of the trans face more closely resemble the plasma membrane in their composition.

Secretory cells have a well-developed Golgi apparatus, but in other cells the Golgi apparatus is small. Some products packaged by the Golgi apparatus, such as the enzymes found in lysosomes, are not released from the cell.

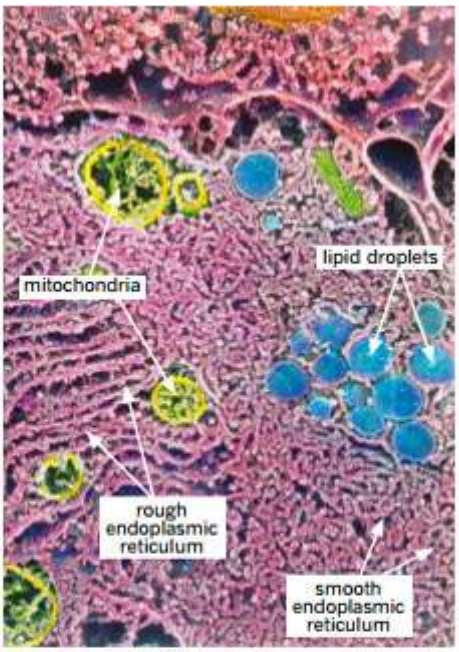


FIGURE 2.2.7 An SEM showing smooth (right) and rough (left) endoplasmic reticulum (light pink) inside a Leydig cell of a 14-week-old human foetus. Leydig cells synthesise steroid hormones in the male testis. Lipid droplets (round blue structures) supply the cholesterol needed for the biosynthesis of steroids. Mitochondria (yellow) produce chemical energy for the cell.

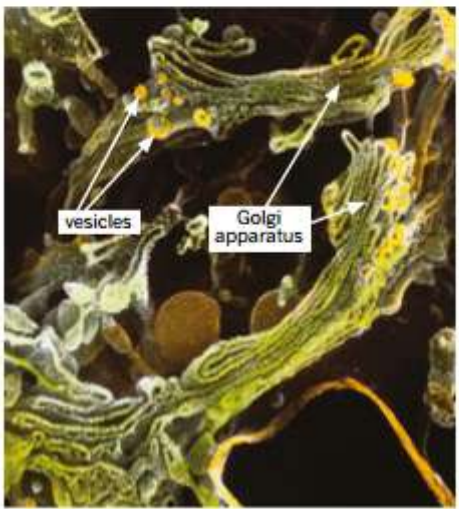


FIGURE 2.2.8 An SEM of the Golgi apparatus of an olfactory bulb cell. The Golgi apparatus consists of a stack of flattened interconnecting membranous sacs (centre right and upper centre). It is the site in the cell of synthesis of biochemicals that are packaged into swellings at the margins of the sacs and become pinched off as vesicles (small yellow spheres).

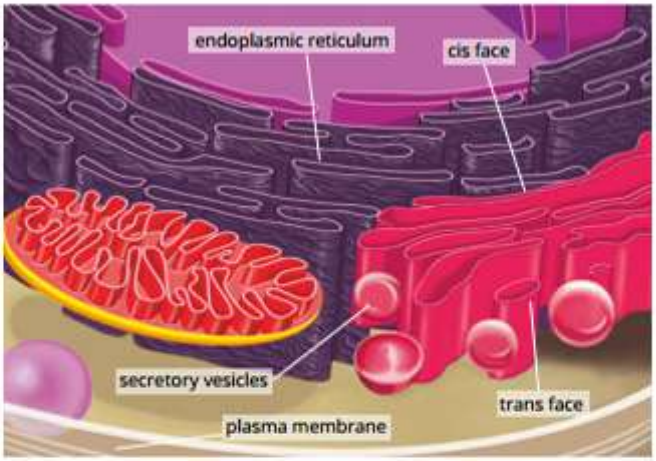


FIGURE 2.2.9 The Golgi apparatus has a cis face, which faces the endoplasmic reticulum, and a trans face, which faces the plasma membrane.

Lysosomes

Lysosomes are specialised vesicles that digest (break down) unwanted matter (Figure 2.2.11). They are the recycling units of the cells. They are found only in animal cells. Lysosomes are formed when a transport vesicle containing enzymes is released from the Golgi apparatus and fuses with another vesicle called an endosome. The endosome contains molecules brought into the cell by **endocytosis**.

Lysosomes fuse with vesicles containing unwanted matter such as damaged organelles or foreign matter. The enzymes in the lysosome then digest the unwanted matter. Small molecules that the cell can re-use may diffuse back into the cytoplasm, but the rest are retained in the lysosome or released from the cell by **exocytosis**.

Summary: Synthesis and processing proteins and lipids

Protein and lipid synthesis and processing is shown in Figure 2.2.12. DNA is transcribed inside the nucleus into RNA. RNA moves out of the nucleus and binds to ribosomes. Ribosomes synthesise proteins using the information on the RNA. Proteins that will be secreted out of the cell are made in the ribosomes bound to the rough endoplasmic reticulum. These proteins are modified and packaged in the Golgi apparatus. Vesicles arising from the Golgi apparatus fuse with the plasma membrane, releasing their contents from the cell. They also insert membrane-bound proteins into the plasma membrane. Lipids are synthesised and processed in the smooth endoplasmic reticulum.

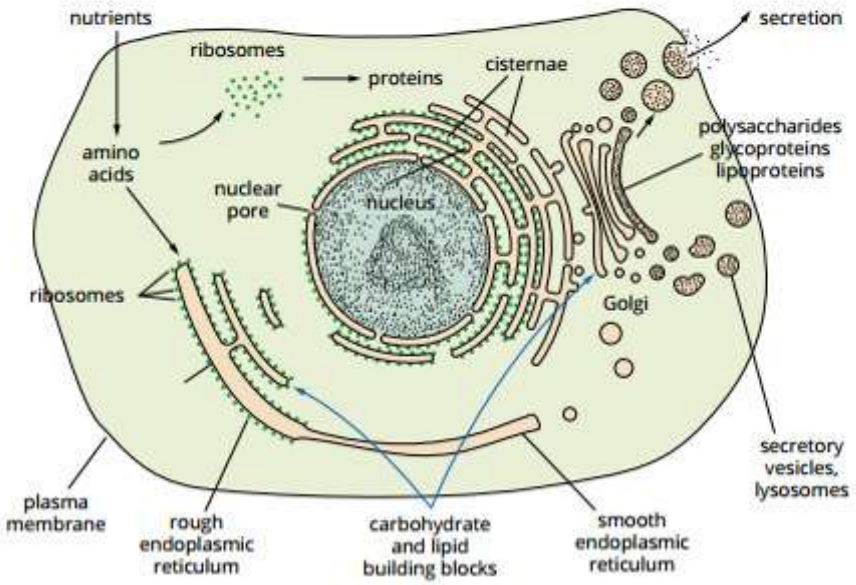


FIGURE 2.2.12 A typical animal cell, showing the organelles involved in synthesising and processing proteins and lipids.

BIOFILE

Camillo Golgi (1844–1926)

FIGURE 2.2.10 Camillo Golgi

Camillo Golgi was an Italian physician, anatomist and histologist. Golgi developed a method of staining tissues with silver nitrate, which he called the 'black reaction'. He was the first person to describe the membranous structure in the cell that is now known as the Golgi apparatus or Golgi complex.

Golgi won the Nobel Prize in Physiology and Medicine in 1906, but it was for his work on the structure of the nervous system, not his discovery of the Golgi apparatus. In fact, many biologists did not think the Golgi apparatus existed, and it was not until the 1950s that its existence was confirmed using electron microscopy. Today scientists are increasingly referring to the Golgi apparatus as simply 'the Golgi'.

Exocytosis is the fusion of a vesicle with the cell membrane, expelling its contents outside the cell.

FIGURE 2.2.11 An SEM of two lysosomes in a pancreatic cell. Lysosomes (green) are small spherical vesicles bound by a single membrane (clearest on lower lysosome). Material probably representing partially digested cell organelles can be seen in each lysosome.

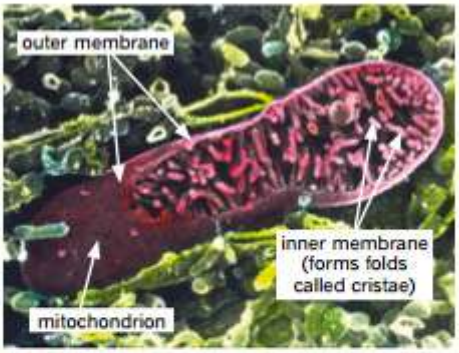


FIGURE 2.2.13 An SEM of a single mitochondrion in the cytoplasm of an intestinal epithelial cell. The cylindrical mitochondrion (pink, centre) has a highly folded internal membrane, which provides a large surface area for aerobic respiration.

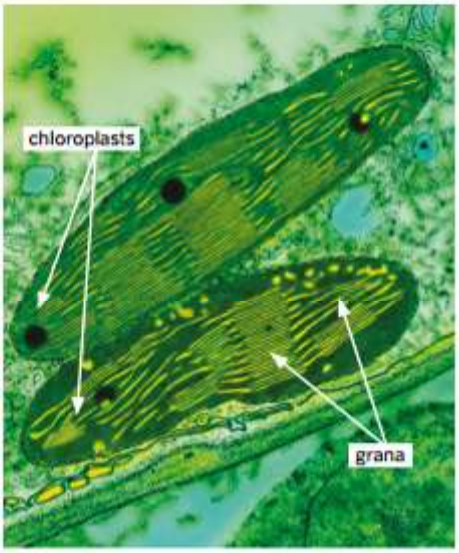


FIGURE 2.2.14 A TEM of two chloroplasts seen in the leaf of a pea plant *Pisum sativum*. Each chloroplast is seen cut lengthways and contains stacks of flattened membranes (yellow) known as grana. The chloroplasts contain chlorophyll and are surrounded by an external double membrane.

Energy transformations

Mitochondria and chloroplasts are the organelles involved in energy transformations within eukaryotic cells.

Mitochondria

Mitochondria (singular mitochondrion) are organelles composed of two membranes. The inner membrane of the mitochondria has folds called cristae (Figure 2.2.13). There are two different compartments inside mitochondria: an intermembrane space and the matrix. The matrix is the fluid filled space enclosed by the inner membrane and contains a double-stranded DNA molecule. Different enzymes are found inside each compartment and on each membrane.

Mitochondria are involved in the energy transformations that release energy from organic molecules for use by the cell. The number of mitochondria in a cell is related to the cell's energy requirements. Very active cells, such as heart muscle cells, have many of thousands of mitochondria.

Chloroplasts

Chloroplasts are organelles involved with photosynthesis. They possess a double stranded DNA molecule are green because of the large amounts of chlorophyll (a green pigment) they contain (Figure 2.2.14). They are present in plants and many protists, but never in animals or fungi.

Chloroplasts are composed of a system of three membranes: the outer membrane, the inner membrane and the thylakoid system. Thylakoids are disc-shaped sacs. This system of membranes forms compartments within the chloroplast that contain different enzymes.

Chloroplasts trap light energy, which is used to split water molecules into hydrogen and oxygen. The hydrogen then combines with carbon dioxide to make glucose, and the oxygen is released into the atmosphere as a waste product.

BIOLOGY IN ACTION

The endosymbiotic theory

Endosymbiosis is a type of **symbiosis** in which one organism lives inside the other. The endosymbiotic theory suggests that it is possible for a large cell to ingest a smaller bacterial cell and for the two to become dependent on each other. It was first suggested as the origin of large, complex cells by Constantin Mereschkowsky in 1910, but he was ridiculed for the idea and it was largely forgotten.

Then in 1967 American biologist Lynn Margulis (Figure 2.2.15) published a paper titled 'On the origin of mitosing cells'. In this paper she argued that mitochondria and chloroplasts were both once free-living prokaryotic cells that came to live inside larger cells, eventually becoming the specialised organelles that cannot survive outside the cell today.

FIGURE 2.2.15 Lynn Margulis, earlier in her career.

Although most biologists were extremely sceptical when she first put forward her hypothesis, it is now widely accepted. Evidence supporting the theory includes the fact mitochondria and chloroplasts have double membranes and their own DNA, which you would expect if they were once free-living prokaryotes (Figure 2.2.16).

Storage and cell structure

The following organelles are involved in storage and also support the cell structure in eukaryotic cells.

Vacuoles

Vacuoles are membrane-bound, liquid-filled spaces that store enzymes and other organic and inorganic molecules. They occur in most cells, but the number varies. Vacuoles in animal cells and plant cells are different (Figure 2.2.17). Animal cells contain many small temporary vacuoles, but most plant cells contain a single large permanent vacuole surrounded by a membrane called the **tonoplast**. In plants the vacuole provides structural support by helping to maintain **turgor** and it seems that lysosome function also occurs here in the plant vacuole.

Plastids

Plastids are organelles involved in the synthesis and storage of different chemical compounds. They contain a double-stranded DNA molecule and possess a double membrane. Plastids develop from simple organelles called proplasts. Animal cells lack plastids. Plastids can be:

- chloroplasts, which are involved in photosynthesis and are fond only in plants and some protists
- leucoplasts, which are involved in storage
- chromoplasts, which contain colour pigments and occur in petals and fruit.

Amyloplasts are a type of leucoplast in plants (Figure 2.2.18). They are commonly responsible for synthesising and storing starch, but can also convert the starch back to sugar when the plant requires energy.

Cell wall

The cell wall is a rigid structure outside the plasma membrane of plant cells, fungal cells and some prokaryote cells (Figure 2.2.19). In plants the cell wall is composed mainly of cellulose. The fungal cell wall is made of chitin.

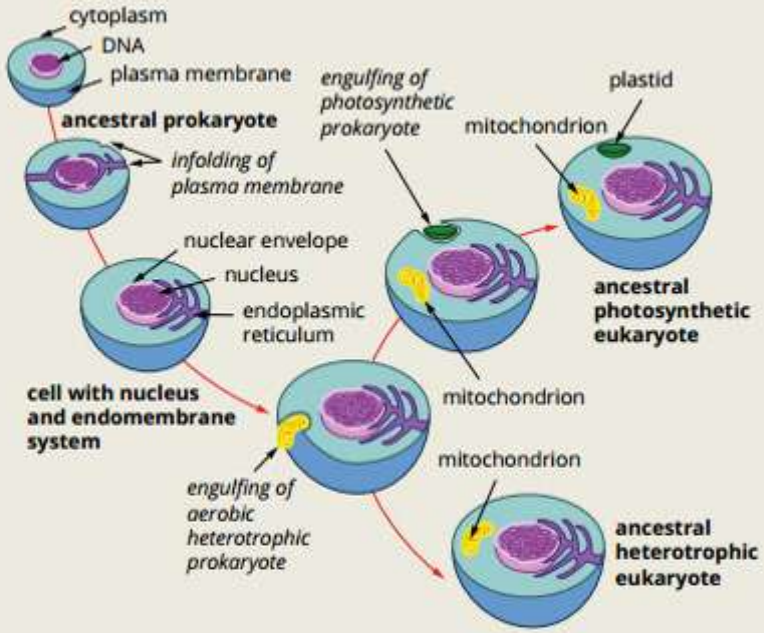


FIGURE 2.2.16 The theory of endosymbiosis explains how eukaryotes originated from the symbiosis of prokaryotic ancestors.

It is now thought that mitochondria came from aerobic bacteria (bacteria that can survive in the presence of oxygen) and that chloroplasts came from cyanobacteria (bacteria that obtain their energy by photosynthesis).

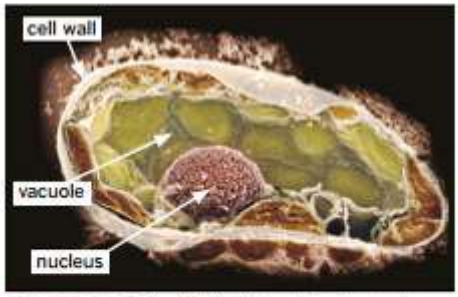


FIGURE 2.2.17 An SEM of a section through a plant cell, revealing its internal structure. At the centre of the cell is a large vacuole, which maintains the cell's shape, stores useful materials and digests the cell's waste products.

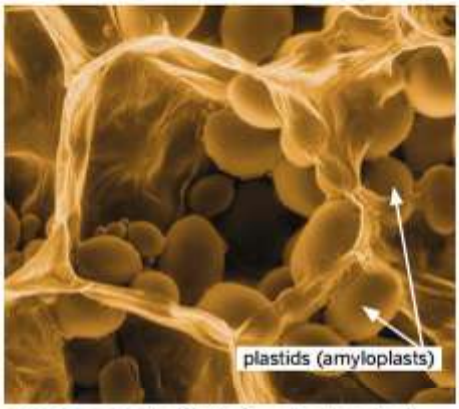


FIGURE 2.2.18 An SEM of amyloplasts (oval) in the sectioned cells of a potato (*Solanum tuberosum*). Amyloplasts are starch-storing plastids, or plant organelles.

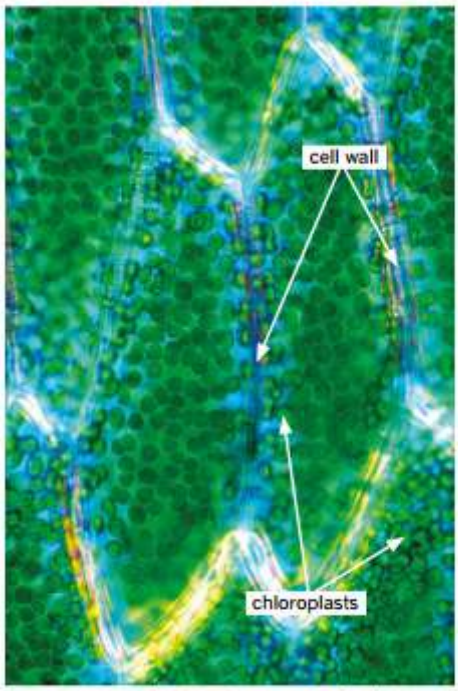


FIGURE 2.2.19 A light micrograph of cells in a leaf of shining Hookeria moss (*Hookeria lucens*). The leaf is made up of a single layer of cells. A cell wall (blue) encloses each cell, and numerous chloroplasts containing the pigment chlorophyll (green, round) are seen in each cell.

Xylem is the tissue in vascular plants that transports water and nutrients upwards from the roots.

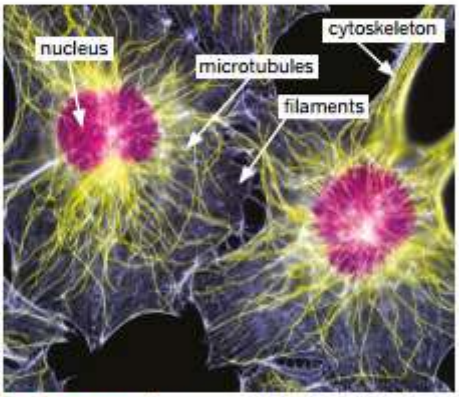


FIGURE 2.2.20 Fluorescent LM of two fibroblast cells, showing their nuclei (purple) and cytoskeleton.

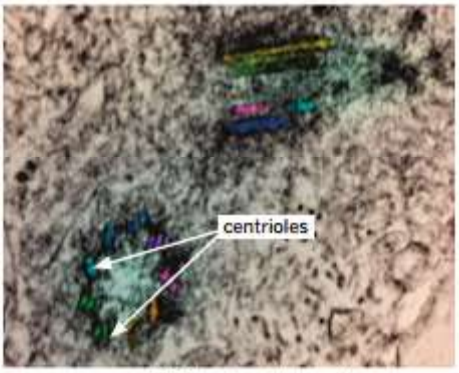


FIGURE 2.2.21 A TEM of centrioles, the organelles that help the cell to divide. These cylindrical structures are mainly composed of the protein tubulin and are involved in assembling the spindle that pulls cells apart during mitosis.

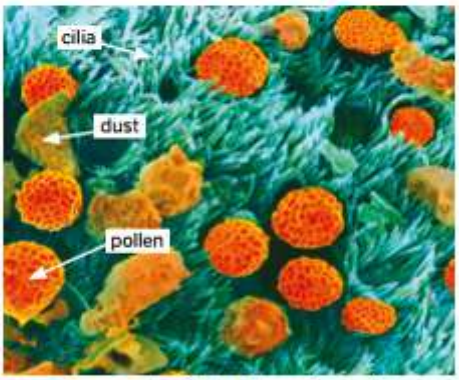


FIGURE 2.2.22 An SEM of the surface of the trachea (windpipe) with breathed in pollen (orange) and dust (brown). The surface of the trachea is made up of cells with hair-like cilia (green) which, together with mucus, trap airborne particles and remove foreign matter from the air tubes and lungs.

The cell wall provides support, prevents expansion of the cell, and allows water and dissolved substances to pass freely through it. Lignin in the cell walls of woody plants, especially in the **xylem**, gives them additional strength.

Cytoskeleton

The cytoskeleton consists of microtubules of the protein tubulin and filaments of the protein actin (Figure 2.2.20). The cytoskeleton supports the cell's structure, allows the cell to move and assists in the transport of organelles and vesicles within the cell.

Centrioles

Centrioles are a pair of small cylindrical structures composed of microtubules (Figure 2.2.21). They are present in most eukaryotic cells, but many plant cells do not have centrioles. Centrioles are involved in cell division and in the formation of cell structures such as cilia and flagella.

Cilia and flagella

Cilia and flagella (singular cilium and flagellum) are hair-like structures on the surface of cells (Figures 2.2.22 and 2.2.23). They consist of an arrangement of microtubules enclosed by an extension of the cell membrane. Cilia move with an oar-like motion and are usually shorter and more numerous than flagella. Both structures are involved in the movement of the cell or things around the cell.

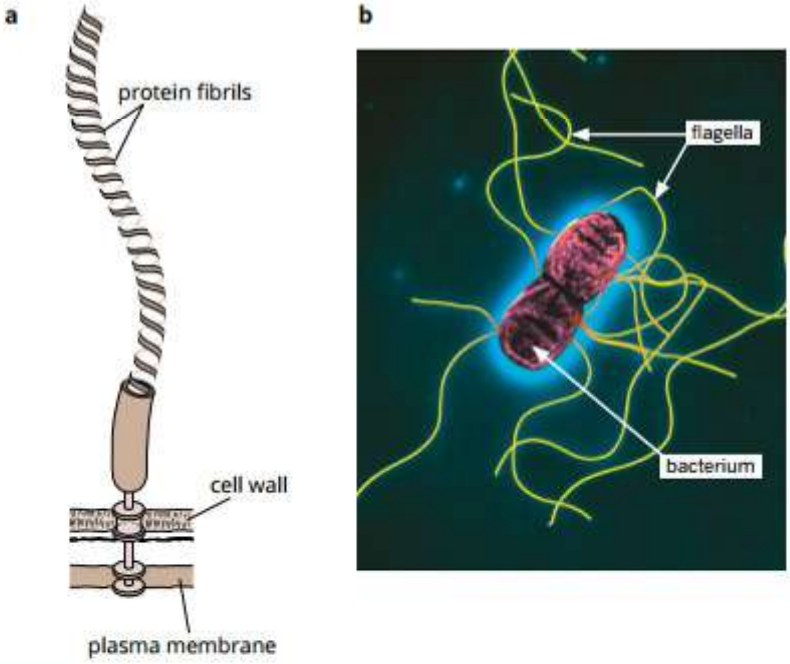


FIGURE 2.2.23 (a) Bacterial flagella consist of three protein fibrils coiled in a helical pattern. (b) An SEM of a *Salmonella typhimurium* bacterium. This rodshaped, Gram-negative bacterium moves by using its long, hair-like flagella (yellow).

ANIMAL AND PLANT CELLS

There are cellular differences not only between prokaryotes and eukaryotes but also between different groups of eukaryotic organisms, and even between tissues in one organism. Organelles are involved in specific functions, so their presence depends on the needs of the cells. A good way to understand this is to compare animal and plant cells.

Animal and plant cells are very similar. They both contain a nucleus with cytoplasm around it, all enclosed by the plasma membrane. They have mitochondria for cell respiration and organelles such as the endoplasmic reticulum and Golgi apparatus where the synthesis and processing of organic molecules occurs. However, there are a number of differences between plant and animal cells (Figure 2.2.24).

The main differences between plant and animal cells are as follows:

- Plant cells have cell walls made from cellulose outside the plasma membrane, which provides structural support and results in a fixed shape. Animal cells do not have cell walls.
- Plant cells have a large permanent vacuole that stores minerals and nutrients in a solution called cell sap. The vacuole also provides structure to plant cells by maintaining turgor pressure against the cell wall. Animal cells have many small temporary fluid-filled vacuoles called vesicles which do not provide structural support.
- Plant cells have chloroplasts in their cytoplasm. Chloroplasts are the site of photosynthesis. Animal cells do not contain chloroplasts and do not perform photosynthesis.

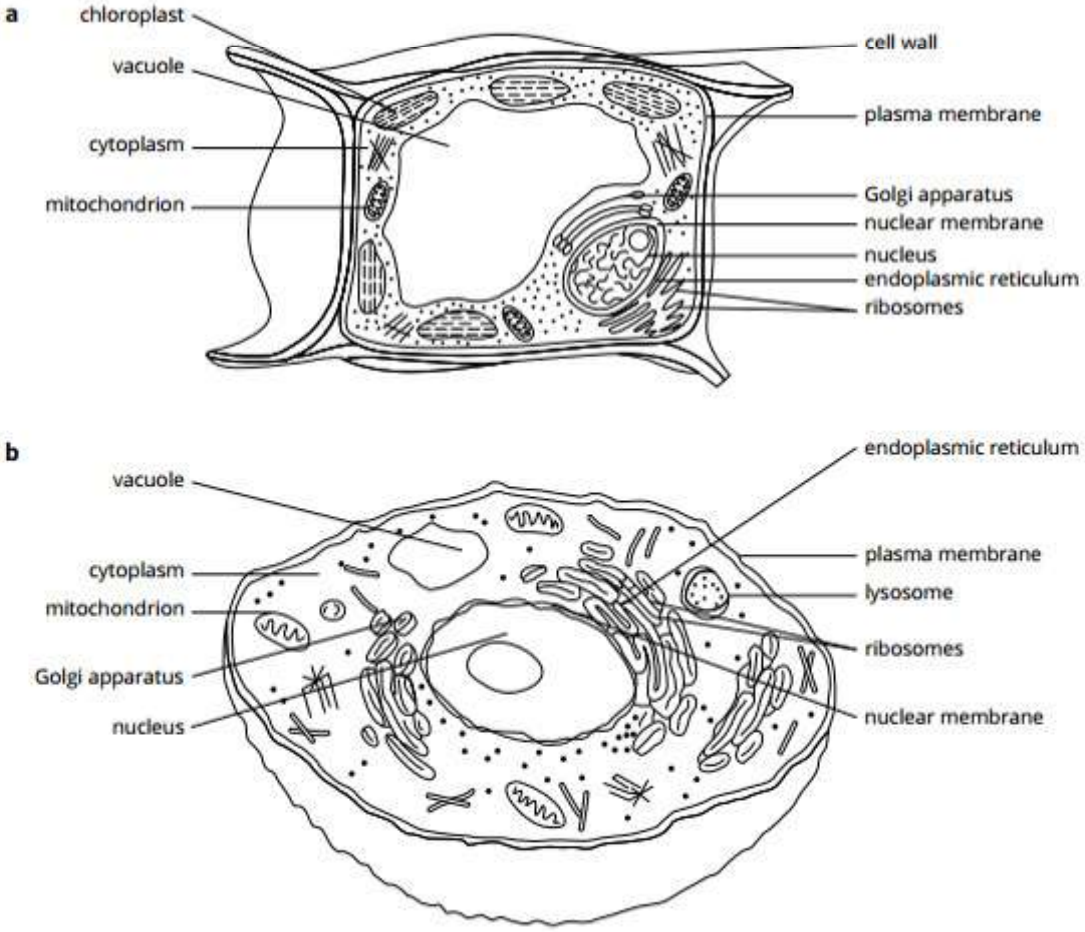


FIGURE 2.2.24 Diagram of typical (a) plant and (b) animal cells, showing major organelles.

2.2 Review

SUMMARY

- There are two fundamentally different types of cells:
  - prokaryotic cells—these are generally small and lack membrane-bound organelles. Prokaryotes include bacteria and archaea.
  - eukaryotic cells—these are relatively larger and contain specialised membrane-bound organelles. Eukaryotes include animals, plants, protists and fungi.
- Compartmentalisation in eukaryotic cells allows for: concentrations of enzymes and reactants in particular organelles of the cell and maintenance of the right conditions for their function; performance of incompatible chemical reactions simultaneously within the cell; and reduced vulnerability of the cell to environmental changes.
- The main structures in a plant cell include the nucleus, tonoplast, vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum, ribosomes, plastids, mitochondria and cell wall.
- The main structures in an animal cell include the nucleus, ribosomes, Golgi apparatus, rough and smooth endoplasmic reticulum, vacuoles, mitochondria, lysosomes, vesicles and centrioles.

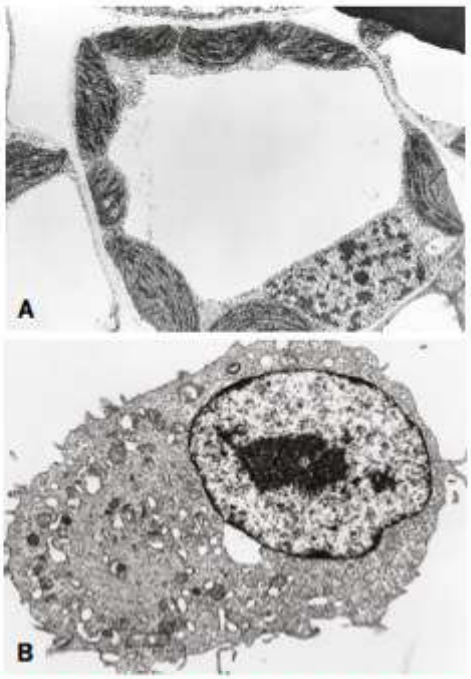
KEY QUESTIONS

1 What function is shared by mitochondria and chloroplasts?

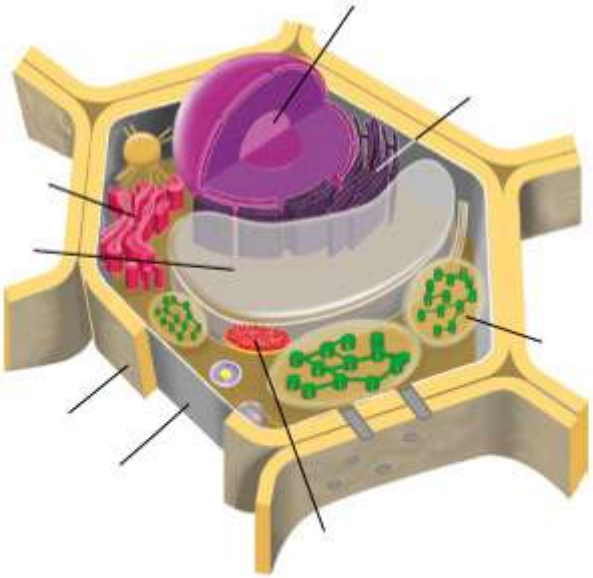
2 Which one of the following options lists only membrane-bound organelles?

A nuclei, mitochondria, vacuoles, ribosomes
B nuclei, mitochondria, centrioles, ribosomes
C nuclei, mitochondria, vacuoles, chloroplasts
D nuclei, mitochondria, vacuoles, cell walls

3 Which of the images in the following figure is a plant cell? Explain your answer.



4 Label the parts of the plant cell in the following diagram.



5 List the main differences between plant and animal cells.

2.3 Plasma membrane: composition and surface area

Cells exist in a watery environment of **extracellular fluid**, which can be a large amount of fluid or a thin surface layer of fluid. In plants the cell wall is porous and has little effect on the movement of molecules. So for all cells the environment of living cells is a layer of fluid in contact with the outer plasma membrane. The composition of this fluid is critical to the stability of cells because it is from this environment that cells get the nutrients they need. The plasma membrane controls the movement of substances between the extracellular fluid outside and the **intracellular fluid** (or cytosol) inside the cell (Figure 2.3.1).

In this section you will learn about the composition and characteristics of the plasma membrane. You will also study the ways cells can increase the surface area of plasma membrane available for the exchange of substances.

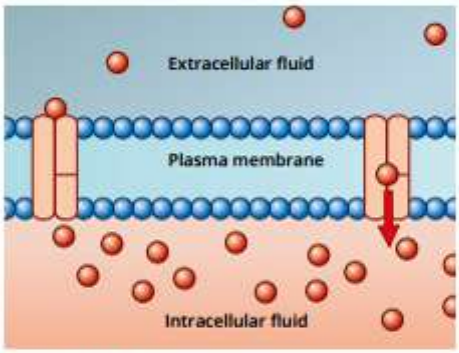


FIGURE 2.3.1 The plasma membrane regulates the movement of substances between the extracellular fluid and intracellular fluid.

Extracellular fluid – body fluid outside the cell membranes; includes blood plasma and interstitial fluid.

EXTRACELLULAR FLUID IN UNICELLULAR ORGANISMS

For unicellular organisms the extracellular fluid is simply the watery external environment in which they live. Unicellular organisms can do little to control their environment and may die if it changes significantly.

However, some unicellular organisms such as yeasts can become dormant until their environment returns to normal again. Others can move slowly to a place where conditions are more suitable to their needs. For example, unicellular algae are able to move towards light, and some bacteria can detect and move towards nutrients or away from toxic substances.

EXTRACELLULAR FLUID IN MULTICELLULAR ORGANISMS

Conditions for cells in multicellular organisms are better than those of unicellular organisms. The more complex the organism, the more control it will have over the environment in which its cells exist, and the more independent it will be from the external environment. Whether they live in water or on land, multicellular organisms have an outer layer that acts as a protective barrier (Figure 2.3.2). This outer layer creates an **internal environment** for the organism that is different from their external environment. Therefore, in multicellular organisms, the environment of the cells is the extracellular fluid that surrounds them.

FIGURE 2.3.2 Crabs have an external skeleton (carapace) that protects them from water loss when on land.

Most multicellular organisms can regulate the conditions of their internal environment, often very precisely. This allows them to provide the specific environments needed by specialised cells and tissues, and for their cells to function more efficiently. Commonly regulated aspects of the internal environment are:

- temperature
- concentration of oxygen
- concentration of carbon dioxide
- pH (acidity or alkalinity)
- osmotic pressure (concentrations of salts or ions)
- concentration of nitrogen wastes
- concentration of glucose.

Importantly, the way cells interact with the extracellular fluid of the internal environment is regulated by the plasma membrane.

Plasma membranes are phospholipid bilayers that enclose the cytoplasm and subdivide the cell into compartments (organelles).

PLASMA MEMBRANE COMPOSITION

This fluid mosaic model that describes the structure of the plasma membrane was first proposed by Jonathan Singer and Garth Nicholson in 1972. It is now widely accepted as the basic model of all biological membranes. According to this model, plasma membranes consist of two layers of **phospholipid** molecules, with other molecules including proteins, carbohydrates and cholesterol scattered throughout the membrane (Figure 2.3.3).

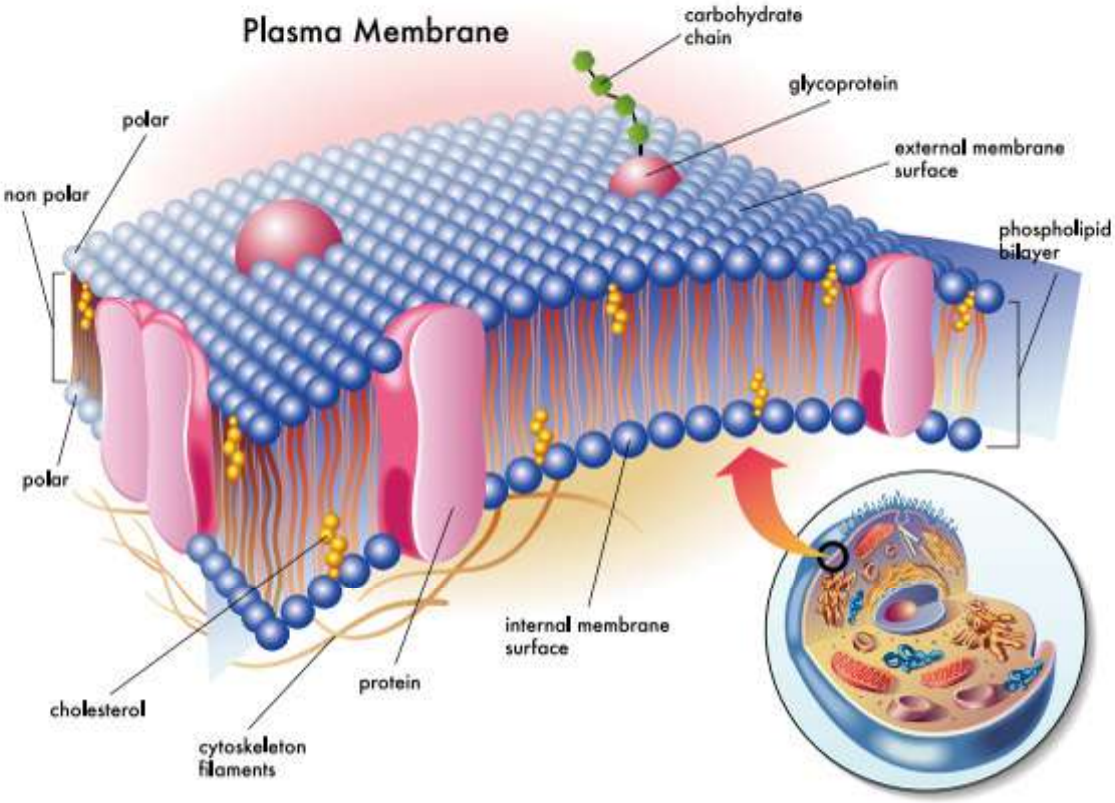


FIGURE 2.3.3 The fluid mosaic model of a plasma membrane, showing the phospholipid bilayer in which large protein molecules are embedded.

Plasma membranes have the same basic structure in all organisms, which serves to separate the interior of the cell (the cytoplasm) from its external environment. Most membranes are also asymmetrical, meaning one layer has different properties from the other. For example, the pattern of proteins and carbohydrate molecules in the external surface is different from the pattern in its internal surface.

The composition and characteristics of the plasma membrane are related to the needs and function of the cell. In addition to transporting molecules into and out of the cell, the plasma membrane performs other important functions, such as cell recognition and communication with other cells (Figure 2.3.6).

Phospholipids

Phospholipid molecules have a hydrophobic (water-repelling) 'tail' and a hydrophilic (water-attracting) 'head'. The phospholipid bilayer of the plasma membrane is called a bilayer because it has two layers of phospholipids. The hydrophilic heads form the outside and inside lining of the plasma membrane, and the hydrophobic tails of the two layers of phospholipids meet in the middle (Figure 2.3.4).

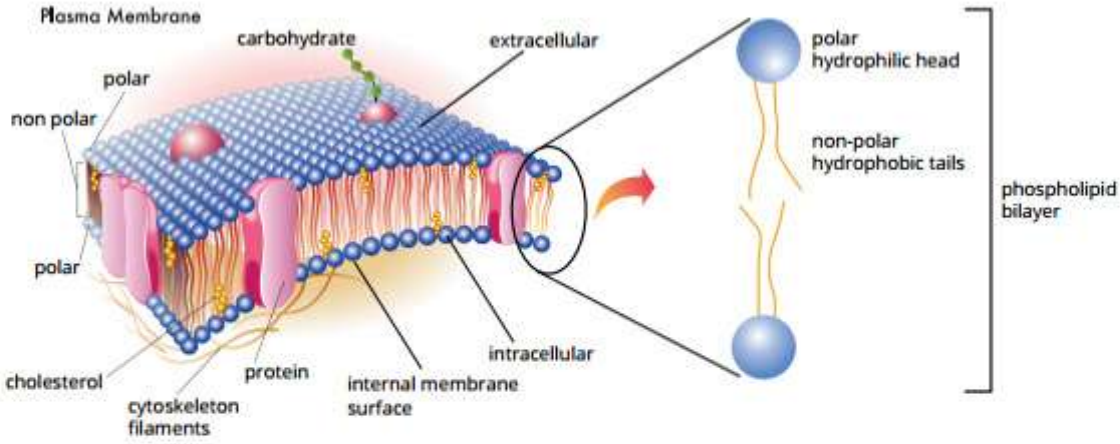


FIGURE 2.3.4 A phospholipid has a hydrophobic 'tail' and a hydrophilic 'head'.

The phospholipid – a molecule consists of long-chain fatty acids (which are hydrophobic) and a phosphate (which is hydrophillic). It is the major component of plasma membranes.

The phospholipid nature of plasma membranes makes them impermeable to water-soluble particles, ions and polar molecules. The movement of these molecules across the membrane is controlled by protein channels, which allow the cell to regulate the exchange of molecules with the environment. Controlling the movement of substances into and out of the cell is central to important processes that keep the cell alive, such as cell respiration, digestion, and elimination of wastes. You will learn more about transport across plasma membranes later in this section and in section 2.4.

Plasma membranes are fluid structures, which means that individual phospholipid molecules (and some proteins) are free to move about within the layers. However, they rarely cross from one side of the membrane to the other. The level of fluidity depends on the percentage of unsaturated fatty acids in the phospholipid molecules—the greater the percentage, the more fluid the membrane.

Figure 2.3.5 shows the components of the plasma membrane that are discussed below.

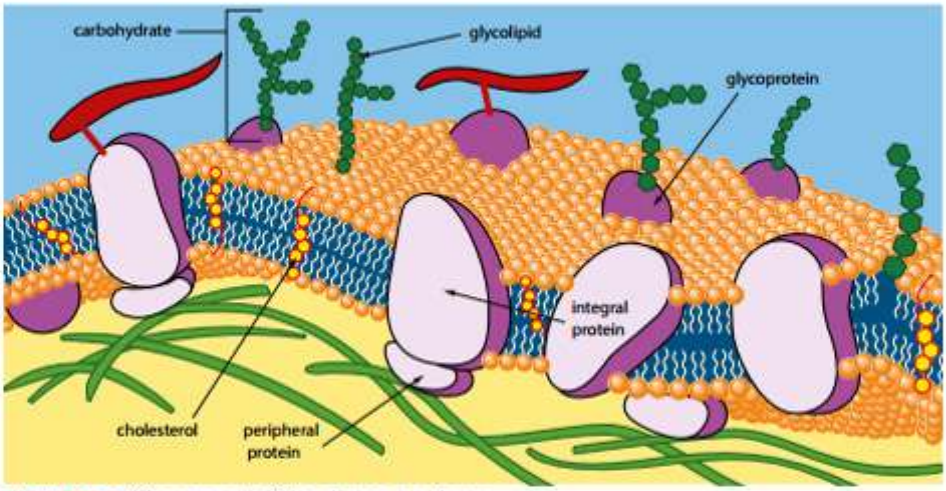


FIGURE 2.3.5 Components of the plasma membrane.

Cholesterol

Membranes contain many fatty molecules, including **cholesterol** molecules, between the phospholipid molecules (Figure 2.3.5). The plasma membranes of eukaryotes contain cholesterol, a type of fatty molecule that gives stability to the membrane without affecting its fluidity, and reduces the permeability of the membrane to small water-soluble molecules.

Proteins

Like phospholipid molecules, proteins in the plasma membrane are able to move about to some extent, but this movement may be limited to particular regions of the cell membrane.

Proteins that are a permanent part of the plasma membrane are called **integral proteins**. Proteins that are a temporary part of the plasma membrane are called **peripheral proteins**. Peripheral proteins bind to integral proteins or penetrate into one surface of the plasma membrane (Figure 2.3.5). When integral proteins span both phospholipid layers they are also called **transmembrane proteins**. Transmembrane proteins are involved in a number of important cellular and intercellular activities (Figure 2.3.6).

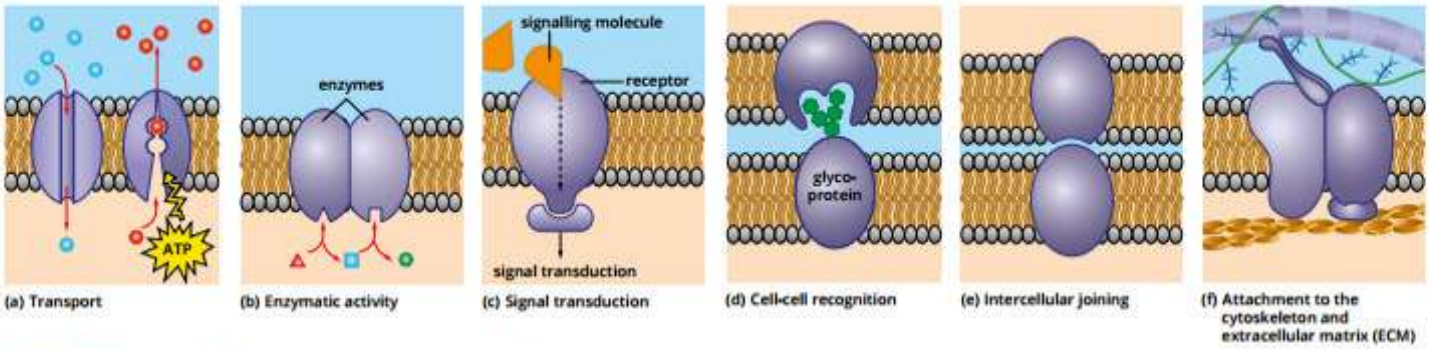
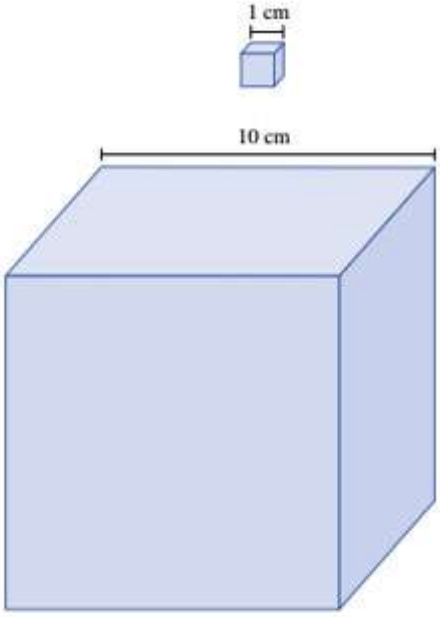


FIGURE 2.3.6 Different functions of plasma membrane proteins.



Side length	1 cm	10 cm
Surface area	6 cm^2	600 cm^2
Volume	1 cm^3	1000 cm^3
Surface area to volume ratio	6	0.6

FIGURE 2.3.7 Two cubes, showing the relationship between surface area and volume.

Carbohydrates

Carbohydrates associated with plasma membranes are usually linked to protruding proteins (forming **glycoproteins**) or to lipids (forming **glycolipids**) on the outer surface of the membrane (Figure 2.3.5). They play a role in recognition and adhesion between cells, and in the recognition of antibodies, hormones and viruses by cells.

SURFACE AREA TO VOLUME RATIO AND CELL SIZE

All cells must exchange nutrients and wastes with their environment via the plasma membrane. In addition, enzymes that are bound to the plasma membrane catalyse many important cellular processes.

The surface area of the plasma membrane around a cell affects the rate of exchange that is possible between the cell and its environment, and can affect certain processes catalysed by membrane-bound enzymes.

Larger cells have greater metabolic needs, so they need to exchange more nutrients and waste with their environment. However, because of the surface area to volume relationship they do not have a proportionally larger surface area of plasma membrane for this exchange to take place. So being small helps cells to maximise their efficiency in exchanging matter with their environment.

Surface area vs volume

The relationship between surface area and volume can be explained using cubes (Figure 2.3.7). A cube with a side length of 1 cm has a surface area of 6 cm^2, a volume of 1 cm^3 and a surface area to volume ratio of 6. A cube with a side length of 10 cm has a surface area of 600 cm^2, a volume of 1000 cm^3, and a surface area to volume ratio of 0.6. Comparing these two cubes, it can be observed that, while the volume of the bigger cube is 1000 times larger than the volume of the smaller cube, its surface area is only 100 times larger.

Increasing the cell surface area to volume ratio

Three ways of increasing the membrane surface area of cells without changing cell volume are:

- cell compartmentalisation
- a flattened shape
- plasma membrane extensions.

Cell compartmentalisation

In section 2.2 you learned that cell compartmentalisation allows organelles to have the right conditions and concentration of enzymes and reactants for a particular function, making the processes in the organelles, and in turn the whole cell, highly efficient.

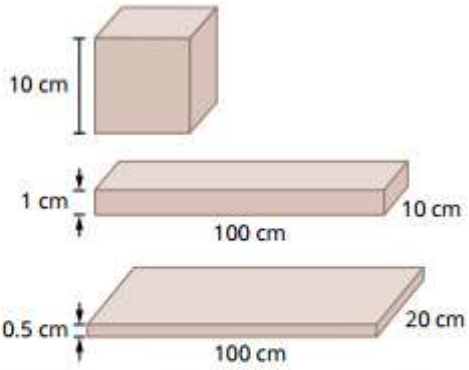
Cell compartmentalisation also allows eukaryotic cells to be much bigger than prokaryotic cells, because:

- it reduces the amount of exchange that needs to occur across the plasma membrane to maintain an environment suitable for all cell functions
- it creates more space for membrane-bound enzymes, allowing increased activity in the cell.

A flattened shape

As a cell increases in volume, the distance from the centre of the cell to the plasma membrane also increases. The rate of chemical exchange (or rate of diffusion) from the centre of the cell to the surrounding environment may then become too low to maintain the cell.

One way to counteract this effect is to be flatter. For example, flattening a cube while keeping the volume constant results in a larger surface area, and therefore a larger surface area to volume ratio (Figure 2.3.8). This larger surface area to volume ratio allows a higher rate of exchange through the plasma membrane, and also reduces the distance that substances need to be transported to and from the plasma membrane.



Surface area (SA)	Volume (V)	SA : V ratio
60 cm^2	1000 cm^3	0.06
2220 cm^2	1000 cm^3	2.22
4120 cm^2	1000 cm^3	4.12

FIGURE 2.3.8 The effect of changing shape on the surface area to volume ratio.

The flattened shape solution is observed in nature in many types of cells, especially those involved in the rapid transport of substances, such as red blood cells and lung epithelium. These cells usually do not have a high metabolism and so do not contain many organelles.

BIOFILE

Red blood cells

Red blood cells are small and flexible so they can travel through thin blood vessels (capillaries). But because of their role in gas exchange they need a large surface area to volume ratio to maximise the diffusion rate in and out of the cell. To achieve this, mammalian red blood cells are shaped like biconcave discs, which increases their surface area. This increases diffusion rate and thus maximises their capacity to transport gases. Red blood cells adopt this shape because mature mammalian red blood cells lack a nucleus and other organelles.

FIGURE 2.3.9 Red blood cells have a biconcave, slightly disc-like shape and no nucleus.

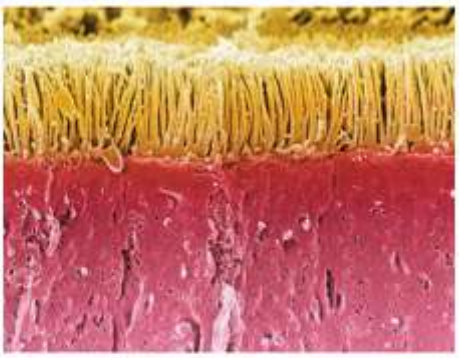


FIGURE 2.3.10 Scanning electron micrograph of microvilli in the small intestine, where digested food is absorbed.

Plasma membrane extensions

Instead of being larger or flatter, cells involved in absorbing nutrients or secreting wastes counteract the surface area to volume ratio problem by extending the surface area of their plasma membranes. For example, some animal cells have finger-like extensions of the plasma membrane called microvilli (singular microvillus) which increase the surface area (Figure 2.3.10). Another example is root hairs in plants (lateral extensions of root cells), which increase the surface area of the root to allow the plant to absorb more water and nutrients from the soil.

A flattened shape would not be useful for these cells because they require an increased surface area in particular regions of the cell. For example, in cells of the small intestine an increased surface for exchange is only required on the inside of the intestinal tube from which the cells absorb nutrients. In addition, these cells have a high metabolism and possess many organelles. If they were flattened, the distance between the different organelles of the cell would affect the movement of substances within the cell and reduce its functionality.

EXTENSION

Surface area to volume ratio in organs

The important effect of surface area to volume ratio is not exclusive to cells. Organs and organisms must also exchange substances with their environment. To increase the amount of surface area available for exchanges, some organisms have highly specialised organs with a large surface area to volume ratio. This is often the case with organs involved in gas or nutrient exchanges, such as plant roots and animal gills, lungs and guts. Cells in these organs often show structural adaptations that increase their exchange efficiency. For example, microvilli create a folded surface and increase the surface area.

To increase the surface area further, the epithelial cells in the small intestine are arranged together forming finger-like projections called **villi** (singular villus) (Figure 2.3.11). This creates a very large surface area and allows the intestine to absorb nutrients more efficiently. The human intestine is about 7 m long and has a surface area of about 2000 m² for absorption.

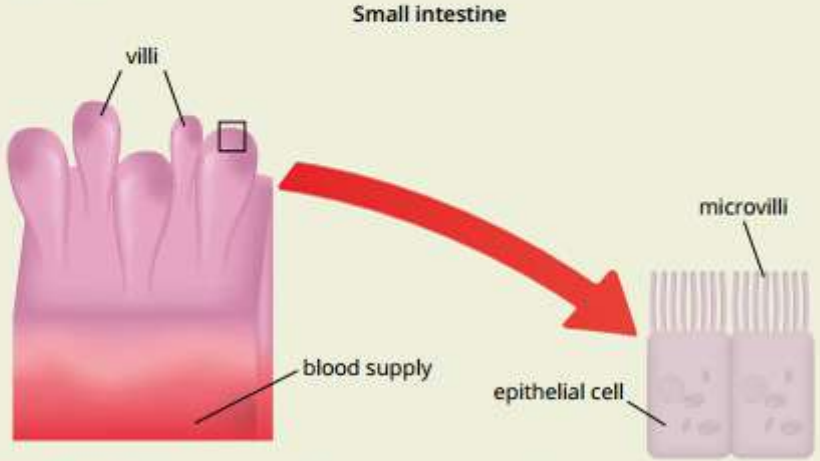


FIGURE 2.3.11 The villi at tissue level and microvilli at cell level in the small intestine.

2.3 Review

SUMMARY

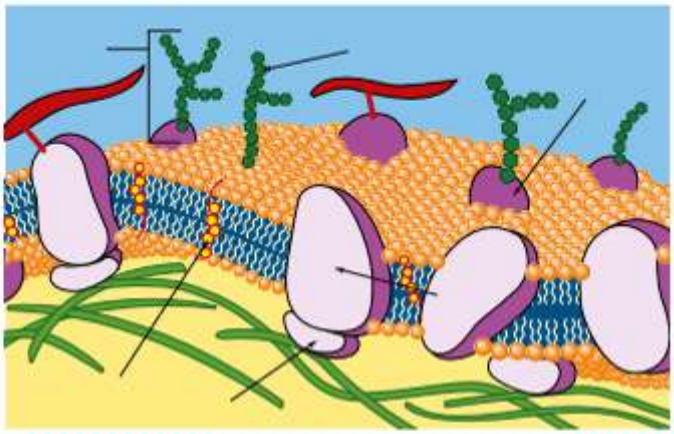
- The external environment of living cells is the layer of extracellular fluid that is in direct contact with the plasma membrane.
- For unicellular organisms, the extracellular fluid is the watery environment in which they live and that they can do little to control.
- Multicellular organisms have an internal environment that is more or less independent from the external environment. The external environment of the cells is therefore the extracellular fluid that surrounds them.
- Most multicellular organisms can regulate aspects of their internal environment, including: concentrations of particular salts (ions); temperature; concentrations of nutrients, water and wastes; and pH (acidity or alkalinity).
- Plasma membranes separate the interior of the cell, the cytoplasm, from the external environment and control the movement of substances between the two.
- Plasma membranes consist of a double layer of phospholipid molecules. They contain protein molecules of various sizes as well as fatty molecules such as cholesterol. They are also associated with other molecules, including carbohydrates.
- The phospholipid nature of the plasma membrane makes it impermeable to water-soluble particles, ions and polar molecules.
- Plasma membrane proteins:
  - provide selective channels that enable water-soluble particles and ions to travel through the plasma membrane
  - catalyse reactions associated with the plasma membrane
  - communicate with the external environment and other cells
  - bind with other cells.
- Cells exchange nutrients and waste with their environment across the plasma membrane through channel proteins. Membrane-bound enzymes catalyse reactions. The rate of exchange is related to the volume of the cell and its metabolic needs or function (such as the transport or absorption of substances).
- A large object has a smaller surface area to volume ratio than a small object with the same shape.
- The cell surface area (plasma membrane area) can be increased without varying the cell volume in three ways:
  - compartmentalisation
  - a flattened shape (e.g. red blood cells)
  - plasma membrane extensions (e.g. microvilli and root hairs in plants).

KEY QUESTIONS

1 List three functions of the plasma membrane.

2 Membrane-bound proteins may have carbohydrates attached. What are these proteins and what is their function?

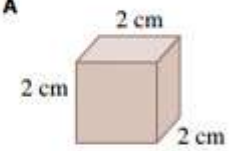
3 Label the key components of the plasma membrane shown in the following diagram.



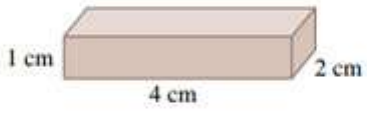
4 **a** Explain what is meant by 'surface area to volume ratio'.

b Consider the two objects shown which have the same volume of 8 cm². Which shape has the greatest surface area?

A



B



5 With reference to a cell, where is the extracellular fluid found?

6 **a** What is the main structural component of a plasma membrane, and what other molecules are associated with it?

b What role do (i) proteins and (ii) cholesterol play in the functioning of the membrane?

2.4 Transport across the plasma membrane

In the previous section you learned about the composition of the plasma membrane, and that one of its main characteristics is exchanges of molecules between the cytoplasm and the external environment of the cell. In this section you will learn about the semi-permeability of the plasma membrane. You will also explore the various methods employed to control the exchange of molecules, including diffusion, osmosis, active transport, facilitated diffusion, endocytosis and exocytosis.

PLASMA MEMBRANE PERMEABILITY

Many different types of molecules can move across plasma membranes (Figure 2.4.1), and they do so in different ways, depending on their properties, such as size and charge, and whether or not the phospholipid bilayer is permeable to the substance (Table 2.4.1).

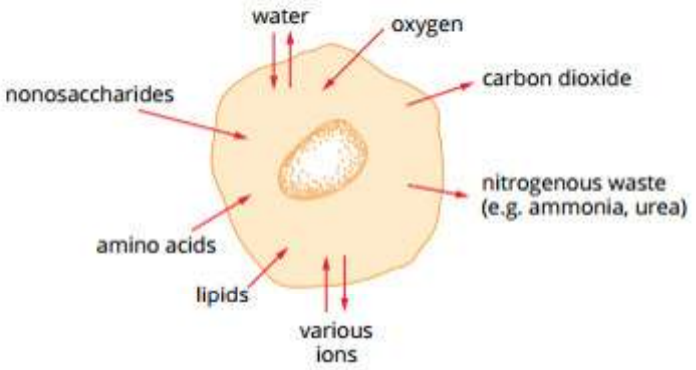


FIGURE 2.4.1 Cells exchange many substances with their environment across the plasma membrane.

Molecule/Ion	Examples	Permeability of membrane to the molecule/ion
small uncharged molecule	oxygen, carbon dioxide	permeable
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	permeable
small polar molecule	water, urea	permeable or semi-permeable
small ion	potassium ion (K^+) sodium ion (Na^+), chloride ion (Cl^-)	non-permeable (molecule passes through protein channels)
large, polar, water-soluble molecule	amino acid, glucose	non-permeable (molecule passes through protein channels)

TABLE 2.4.1 The plasma membrane's permeability to different molecules.

Because of their lipid nature, plasma membranes are permeable to small molecules and lipid-soluble molecules that can move freely through the phospholipid bilayer. However, their lipid nature also makes plasma membranes impermeable to:

- most water-soluble molecules
- ions (atoms or groups of atoms with an overall positive or negative charge)
- polar molecules (molecules with charged regions but no overall charge).

These substances must therefore pass through specific protein channels in the plasma membrane (Figure 2.4.2).

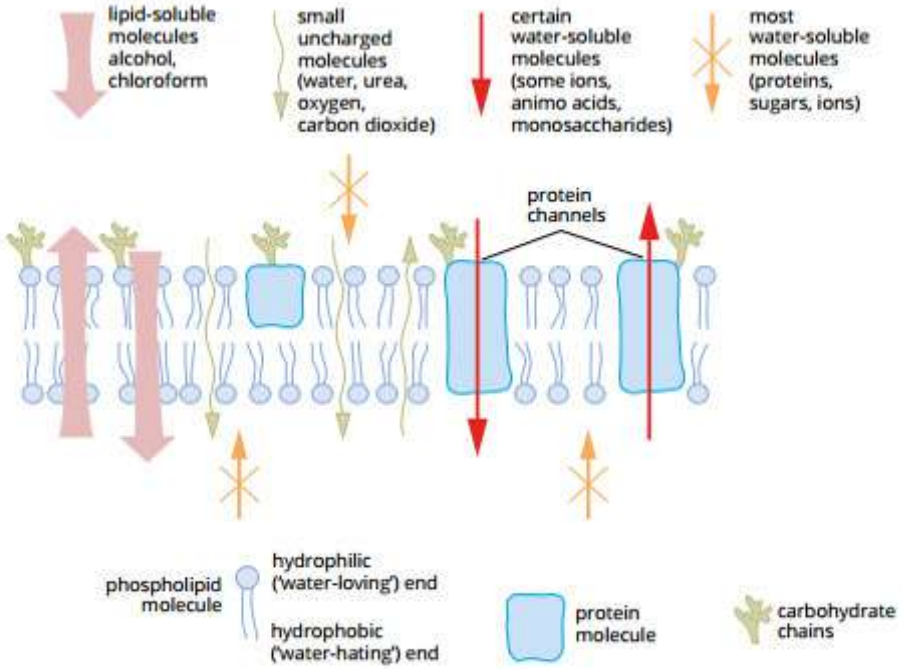


FIGURE 2.4.2 If the plasma membrane is not permeable to molecules, protein channels must assist the molecules to cross the membrane.

DIFFUSION

Particles in a solution move from an area of high concentration to an area of low concentration. This process is called **diffusion** (Figure 2.4.3). As there are many particles colliding with each other during this process, the overall movement of particles is very slow.

Diffusion can be seen when a drop of ink (the **solute**), is placed in a jar of still water (the **solvent**). The dye particles in the ink move randomly through the water until the colour is homogenous (evenly spread). In other words, the solute particles move from an area of high solute concentration (the drop of ink) to the areas of low solute concentration (the rest of the jar). The solute particles are said to have moved along the **concentration gradient**.

Diffusion is called a passive process because it does not require energy. It occurs only because there is a concentration gradient.

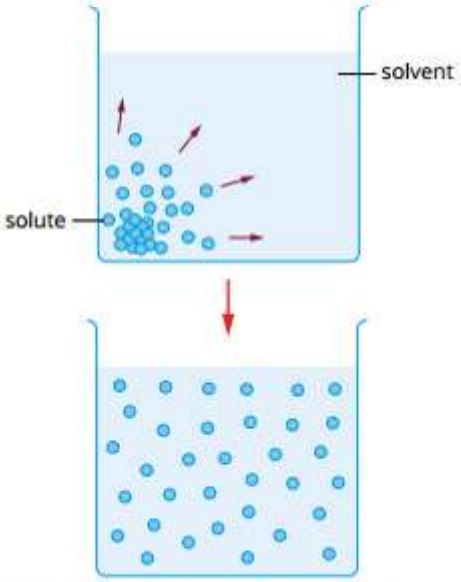


FIGURE 2.4.3 Diffusion results in the random dispersal of solute molecules throughout a solvent.

DIFFUSION ACROSS MEMBRANES

The two types of diffusion across membranes are simple diffusion and facilitated diffusion. These are both passive types of diffusion, and both move molecules along the concentration gradient.

Simple diffusion

Solute molecules can diffuse across a membrane only if the membrane is permeable to them. There is a constant movement of solute molecules backwards and forwards across the membrane. If the concentration of solute molecules is the same on both sides of the membrane, there will always be about the same number moving across in either direction. That is, there will be no net movement from one side to the other.

However, if the concentration of the solute molecule is higher on one side of the membrane than the other, more molecules will cross from the area of higher concentration to the area of lower concentration (i.e. down its concentration gradient), as you can see on the left side of Figure 2.4.4.

BIOFILE

Fast molecules

At body temperature, water molecules travel at about 2500 km/h. Glucose, a larger molecule, travels more slowly at only about 850 km/h!

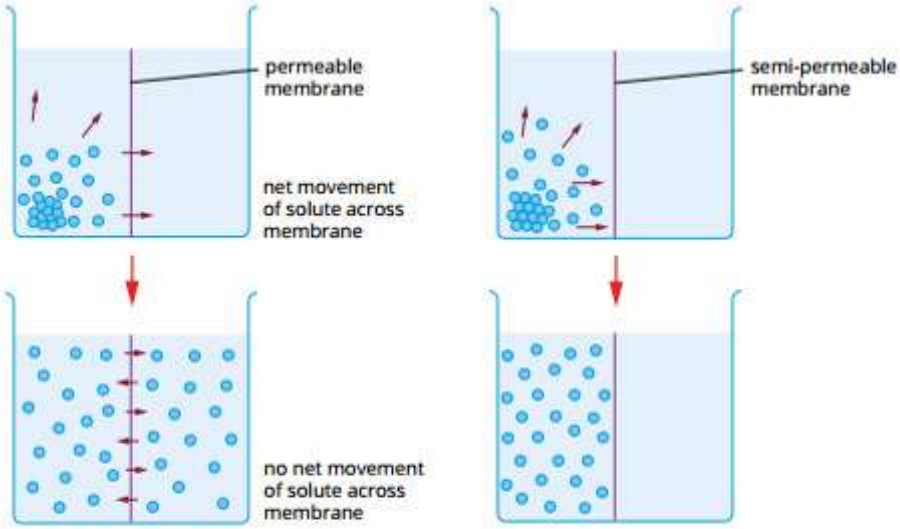


FIGURE 2.4.4 If a membrane that is permeable to both the solute and the solvent is inserted in the liquid it does not affect the pattern of diffusion (left). A membrane that allows the solvent molecules to pass through, but not the solute molecules, stops the solute from diffusing through the membrane (right).

If the membrane is semi-permeable—that is, it is impermeable to some molecules—there will be no movement of those molecules from the area of higher concentration to the area of lower concentration, as you can see on the right side of Figure 2.4.4.

Factors affecting rate of diffusion

The three main factors that affect the rate of diffusion across a membrane are:

- concentration—the greater the difference in concentration gradient, the faster the rate of diffusion. When the concentration is equal on both sides of the membrane the net diffusion is zero, even at high temperatures
- temperature—the higher the temperature, the higher the rate of diffusion. Increasing temperature increases the speed at which molecules move
- particle size—the smaller the particles, the faster the rate of diffusion through a membrane.

Facilitated diffusion

You have seen that the phospholipid bilayer of the membrane is impermeable to certain particles (ions or molecules). However, channel proteins in the membrane allow for the movement of these particles. When movement is down the concentration gradient, the process is called **facilitated diffusion**.

In facilitated diffusion:

- the membrane transport proteins are specific for particular particles, so transport is selective; some particles are transported and others are not
- transport is more rapid than by simple diffusion
- the transport proteins can become saturated (fully occupied) as the concentration of the transported substances increases
- the transport of one particle may be inhibited by the presence of another particle that uses the same transport protein
- no energy is required; the particles move down their own concentration gradient.

The two main types of membrane transport proteins in facilitated diffusion are **channel proteins** and **carrier proteins**. Membrane proteins provide channels for the passage of water-soluble (polar) molecules and ions across the phospholipid bilayer. The channel proteins are specific for a substance. **Channel proteins** do not usually bind with the molecules being transported. They function like pores that open and close to allow the passage of specific molecules. Channel proteins are mainly involved in the passage of water-soluble polar particles such as ions.

Carrier proteins bind the molecules being transported, causing the protein to undergo changes in shape (conformation) that allow specific molecules to be transported across the membrane. After the molecule has crossed the membrane the original shape of the protein is restored.

OSMOSIS

Osmosis refers to the net diffusion of water molecules across a semi-permeable membrane.

If a diluted and a concentrated solution are separated by a semi-permeable membrane that allows the movement of free water molecules across the membrane, but not the movement of the solute molecules, the free water molecules will move across the membrane from the diluted to the concentrated solution.

In osmosis, net diffusion of water occurs through a semi-permeable membrane from a diluted to a concentrated solution along its own concentration gradient, which is known as the **osmotic gradient** (Figure 2.4.5). The pressure causing the water to move along this gradient is called **osmotic pressure**.

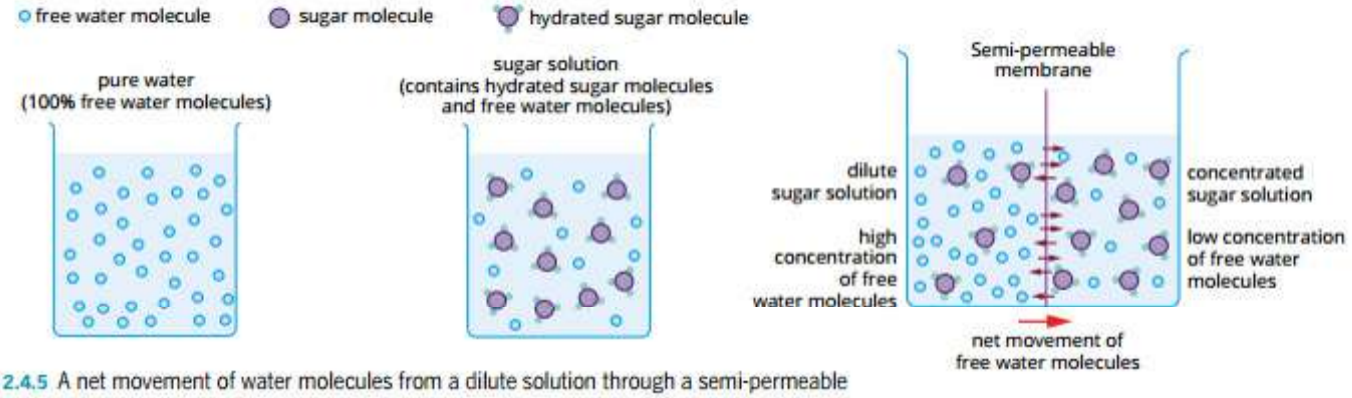


FIGURE 2.4.5 A net movement of water molecules from a dilute solution through a semi-permeable membrane into a concentrated solution is osmosis.

The plasma membrane is permeable to water, so when cells are placed in fresh water an osmotic gradient will draw water into the cells. This is because the cytosol is a concentrated solution containing many dissolved substances. For example, if red blood cells are placed in fresh water, the cells absorb so much water by osmosis that they swell and may eventually burst, releasing red pigment into the water (Figure 2.4.6). Conversely, if red blood cells are placed in a solution that is more concentrated than their cytosol, water leaves the red blood cells by osmosis and causes them to shrink.

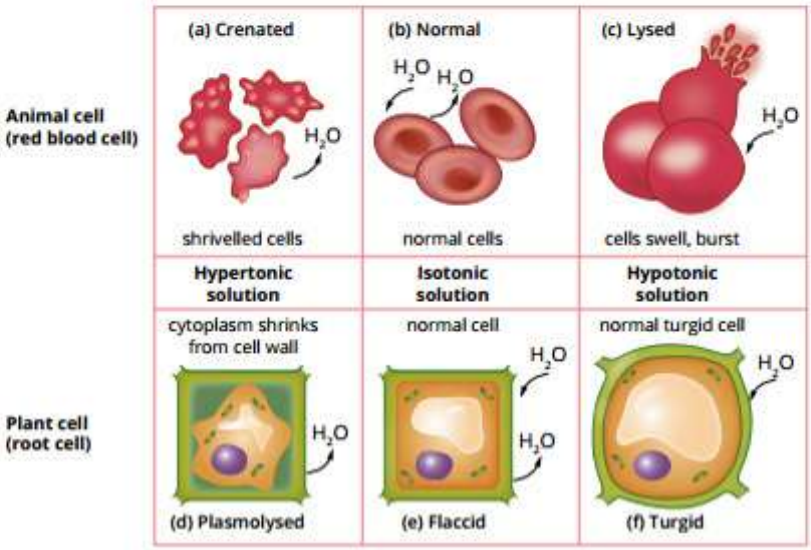


FIGURE 2.4.6 The effect of three different solution concentrations on an animal cell and plant cell.

BIOFILE

Osmosis in salty environments

There is no biological mechanism for actively transporting water molecules across cell membranes. Net movement of water across membranes occurs only by osmosis. Bacteria that are adapted to extremely salty environments survive by retaining much higher ion concentrations within their cells. They also produce small, osmotically active but otherwise inert molecules to reduce the osmotic gradient. This prevents the loss of water to their salty surroundings. Their proteins are also specialised to function normally despite the high concentration of salts in the cytosol. Organisms such as these are called halophiles.

FIGURE 2.4.7 The pink salt lakes of Murray–Sunset National Park in Victoria owe their pink colour to the presence of red algae (domain Archaea, family Halobacteriaceae) that, along with the solid salt bed of the lakes, create this distinctive pinkish red colour of the lake.

If a plant cell absorbs water it swells to some extent, but the cell wall prevents the cell from bursting (Figure 2.4.6). Water will continue to enter the cell along an osmotic gradient until the internal fluid pressure equals the osmotic pressure drawing water in, at which point no more water will enter. Plant cells with high internal fluid pressures have a high turgor.

In osmosis, we are always comparing solute concentration between two solutions. The terms isotonic, hypertonic and hypotonic solution are often being used to describe the differences:

- Isotonic solutions: The solutions being compared have equal concentration of solutes
- Hypertonic solution: The solution with a higher concentration of solute (hence lower concentration of free water molecules)
- Hypotonic solution: The solution with a lower concentration of solute (hence higher concentration of free water molecules)

ACTIVE TRANSPORT

Diffusion, facilitated diffusion and osmosis are examples of passive transport, because they do not require energy to move particles across the plasma membrane. **Active transport** involves the use of energy by the cell to transport particles across membranes (see Figure 2.4.9 on next page).

Active transport and facilitated diffusion compared

Active transport has the same properties of selectivity, saturation and competitive inhibition as facilitated diffusion, because it also occurs through transport proteins (Figure 2.4.10). Selectivity means that some substances are transported but others are not. Saturation means that there is no increase in the rate of transfer when all transport proteins are open. Competitive inhibition means that one substance can inhibit the transport of another substance by using the same transport protein.

But unlike facilitated diffusion, which can occur through either channel or carrier proteins, active transport only occurs through carrier proteins. Because active transport uses energy, it can move substances against a concentration gradient (from low concentrations to high concentrations). In comparison, facilitated diffusion uses no energy, so it can only move substances down a concentration gradient.

In different situations, either facilitated diffusion or active transport may be used to transport a particular molecule. Whether a cell uses facilitated diffusion or active transport depends on the specific needs of the cell.

BIOLOGY IN ACTION

Ilya Mechnikov (1845–1916)

FIGURE 2.4.8 Ilya Mechnikov.

Ilya Mechnikov (Figure 2.4.8) was a Russian scientist who first described phagocytosis. In 1882 he noticed free-moving cells (which he called 'wandering cells') in transparent sea star larvae. It occurred to him that these cells take in nutrients, and so perhaps they take in other microbes too. And if they did then the same might be true for humans, and perhaps our 'wandering cells' (white blood cells) also protect us from germs.

To test his hypothesis Mechnikov inserted thorns from garden plants into sea star larvae. The next day he found the free-moving cells were not moving around aimlessly, but rather they had surrounded the thorns as if attempting to drive them out. In that moment Mechnikov knew he was right about what he would later term phagocytosis, from the Greek words *phag* (eat) and *kytos* (vessel or cell), with the ending *–osis* (a process). In other words, the process of eating cells.

Mechnikov also laid the foundation for the science of immunology with his concept of cell-mediated immunity, for which he won the Nobel Prize in 1908.

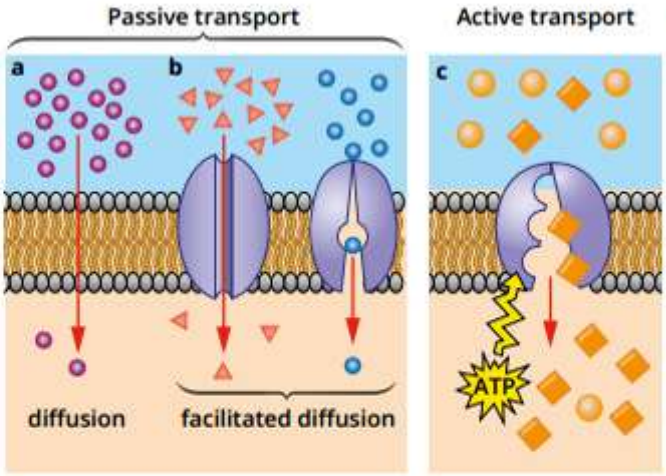


FIGURE 2.4.9 Cell transport must occur to maintain homeostasis between cells within the body. Passive transport does not require an energy source. There are three types of passive transport. Diffusion (a) where substances move from high to low concentrations. Facilitated diffusion (b) where substances move from high to low concentrations with help from a carrier protein. Active transport (c) requires an energy source. As a result, it usually moves substances from low to high concentrations. This shows a protein pump that assists the movement of substances. Note that osmosis is only the movement of water from high to low concentrations.

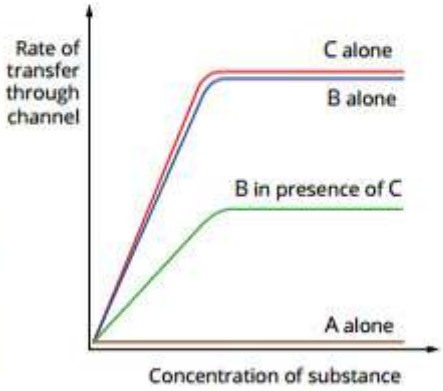


FIGURE 2.4.10 Theoretical transport rate vs concentration graph for the movement of three substances through a channel protein. Substances B and C are transported, but not substance A, demonstrating selectivity. The rate of transfer of substances B and C flattens out when their concentrations reach a certain level, demonstrating saturation. The rate of transport of B is less when C is present, demonstrating competitive inhibition.

For example, glucose is actively transported from the gut into epithelial cells lining the gut so it can enter the bloodstream. The regulation of this process is controlled by hormones, principally insulin and glucagon. If gut glucose levels are high, blood glucose levels will increase. If gut glucose levels are low, active transport makes sure that the little glucose that is in the gut gets pumped into the epithelium from where it can move to blood via facilitated diffusion.

In contrast, red blood cells move glucose by facilitated diffusion. This makes sense because glucose concentration in the blood is usually maintained within a narrow range. In addition, cells convert glucose into other chemicals as soon as it enters the cell, keeping the intracellular concentration of glucose lower than the blood concentration of glucose.

Endocytosis and exocytosis

Some large molecules and other particles and fluids are moved into or out of the cell by exocytosis and endocytosis (Figure 2.4.11). These are both forms of active transport because they require energy.

Exocytosis is the movement of substances out of the cell, from the cytoplasm to the extracellular fluid. A transport vesicle, which may contain wastes or substances needed for secretion (e.g. digestive enzymes), fuses with the plasma membrane and the junction then breaks down, releasing the enclosed materials. Unicellular heterotrophs such as amoebas remove digestive wastes in this way.

Endocytosis is the movement of substances into the cell, from the extracellular fluid into the cytoplasm. Particles near the plasma membrane are enclosed by the membrane, which then pinches off to form a vesicle enclosing the particle. In eukaryotes this vesicle may then become fused with a lysosome so that its contents can be digested for use by the cell. The two forms of endocytosis are pinocytosis and phagocytosis. **Pinocytosis** is the entry of extracellular fluid and substances such as proteins and sugars that are carried in it. **Phagocytosis** is the entry of large particles such as bacteria and cell debris.

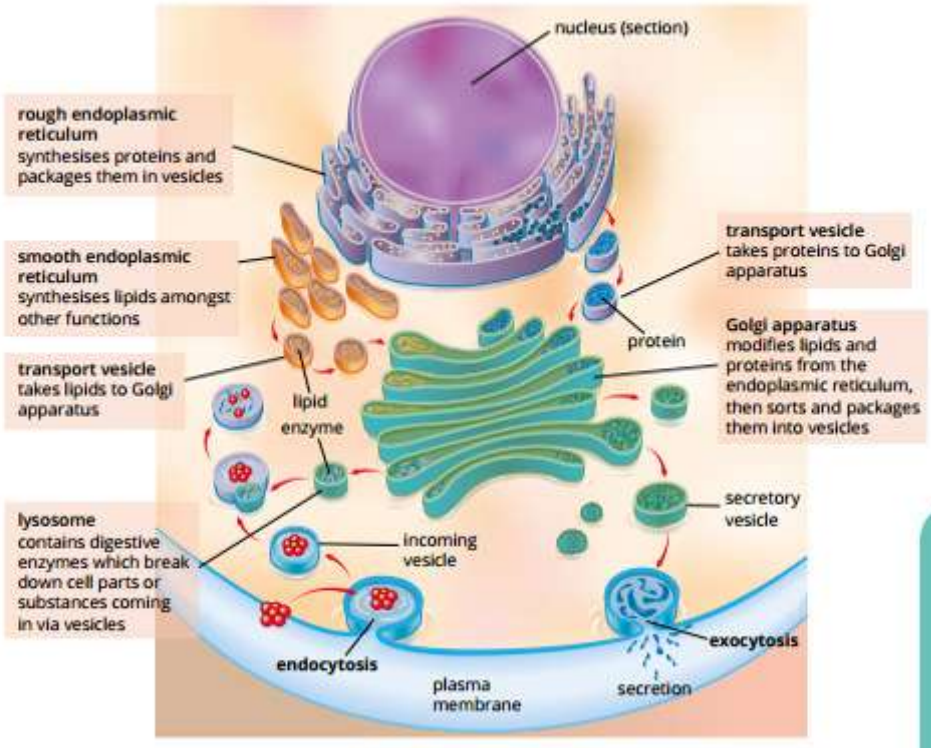


FIGURE 2.4.11 To transport large molecules that proteins/or pumps cannot transport, cells use endocytosis and exocytosis, which require vesicles and energy.

2.4 Review

SUMMARY

- Membranes are impermeable to most water-soluble molecules, ions and polar molecules. These substances can only pass through protein channels.
- Lipid-soluble substances can diffuse through the phospholipid bilayer.
- Diffusion is the passive movement of solute molecules along a concentration gradient, from a region of high solute concentration to a region of low solute concentration.
- There are two types of diffusion across plasma membranes: simple and facilitated.
- Simple diffusion involves solutes that the membrane is permeable to, including lipid-soluble substances, small molecules and water molecules. The rate of diffusion is affected by concentration, temperature and particle size.
- Facilitated diffusion is through selective channels in membranes that permit or enhance the passive movement of particular ions and molecules down their own concentration gradient. Facilitated diffusion generally occurs at a more rapid rate than simple diffusion.
- Osmosis is the net diffusion of water across a semi-permeable membrane down its own concentration gradient called the osmotic gradient (that is, from a low solute concentration to a high solute concentration).
- In active transport, energy is expended to move substances across plasma membranes through protein channels against their concentration gradient.
- Exocytosis (moving substances out of the cell) and endocytosis (moving substances into the cell) are forms of active transport involving vesicles that fuse with the plasma membrane. These forms of active transport are generally used to transport larger molecules.

KEY QUESTIONS

1 Complete the following table by stating whether the phospholipid bilayer is permeable, semi-permeable or not permeable to each substance described.

Substance	Examples	Permeability
small uncharged molecule	oxygen, carbon dioxide	
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	
small, polar molecule	water, urea	
small ion	potassium ion (K^+) sodium ion (Na^+), chloride ion (Cl^-)	
large, polar, water-soluble molecule	amino acid, glucose	

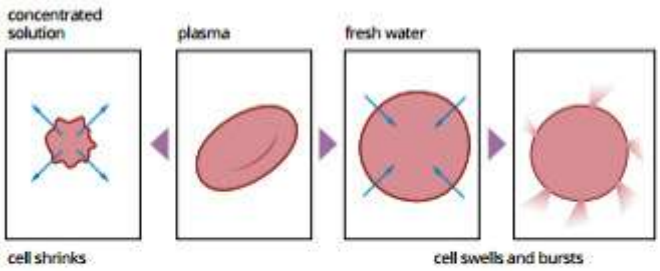
2 Describe diffusion and explain the difference between simple and facilitated diffusion. Include an example of each.

3 What are the two types of proteins used in facilitated diffusion, and how are they different?

4 What term is used for the net movement of water from a dilute to a concentrated solution down its own concentration gradient?

5 Define the term 'active transport'. Outline how this process is different from diffusion.

6 Consider the images of red blood cells in the following figure. The arrows indicate the direction of net movement of water. Using your understanding of osmosis, explain how red blood cells would (a) shrink, and (b) swell and burst.



7 For which of the following is energy required?
- **A** diffusion
- **B** facilitated diffusion
- **C** osmosis
- **D** active transport

8 **a** Use all the following terms and phrases to write a definition of diffusion:
area of low concentration, passive, area of high concentration, concentration gradient, particles, process
- **b** Explain why diffusion is called a passive process.
- **c** List the factors that affect the rate of diffusion of different types of substances across membranes.

9 Osmosis is a special kind of diffusion. Write a definition for osmosis. Use a diagram to illustrate your answer.

Chapter review

02

KEY TERMS

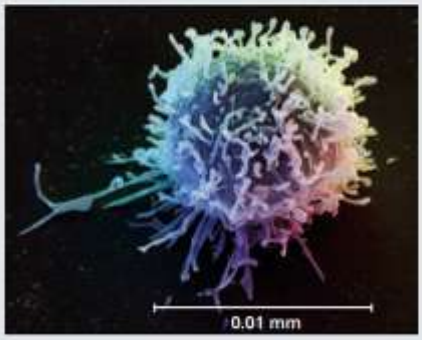
active transport
amino acid
biogenesis
carbohydrate
carrier protein
cell
cell compartmentalisation
channel protein
cholesterol
chromosome
concentration gradient
cytoplasm
cytosol
diffusion
DNA
endocytosis
enzyme
epithelium
eukaryote
exocytosis
extremophile
facilitated diffusion
genophore
glycolipid
glycoprotein
hydrophobic
inorganic compound
integral protein
internal environment
intracellular fluid
lipid
microvillus
mRNA
murein
nucleolus
organelle
organic compound
osmosis
osmotic gradient
osmotic pressure
peripheral protein
phagocytosis
phospholipid
pinocytosis
plasma membrane
plasmid
polypeptide
prokaryote
protein
recombinant DNA
ribosome
rough endoplasmic reticulum
rRNA
semi-permeable
solute
solvent
substrate
symbiosis
taxonomy
tonoplast
transmembrane protein
turgor
vesicle
villus
xylem

KEY QUESTIONS

1 Select the statement that accurately describes eukaryotic cells.
- **A** Eukaryotic cells have circular chromosomes and membrane-bound organelles, and some also have cell walls.
- **B** Eukaryotic cells have linear chromosomes but not membrane-bound organelles, and some have cell walls.
- **C** Eukaryotic cells have linear chromosomes and membrane-bound organelles, and some also have cell walls.
- **D** Eukaryotic cells have linear chromosomes and membrane-bound organelles, but not cell walls.

2 The micrometre is the unit used when stating cell sizes. There are 1000 micrometres in a millimetre. Convert 1.6 mm (millimetres) into µm (micrometres).

3 Select the answer that is closest to the diameter of the animal cell shown in the following photograph.



- **A** 10 µm
- **B** 100 µm
- **C** 1 µm
- **D** 1000 µm

4 What does cytology study?
- **A** cytosol
- **B** tonoplasts
- **C** cells
- **D** cytoplasm

5 Define cell compartmentalisation, and list three ways that it benefits a cell.

6 A cell from an organism has a distinct nucleus, green organelles, and a plasma membrane within a cell wall. In what kingdom is this organism classified?

7 State the difference between endocytosis and exocytosis. Explain what happens to substances as they are transported in each process.

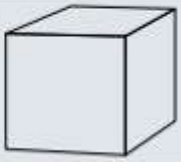
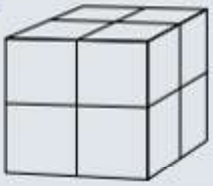
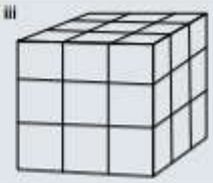
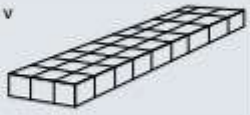
8 **a** Explain what causes blood cells to burst when a drowning person inhales fresh water.
b Explain why a plant does not burst when placed in fresh water.

9 **a** Complete the table of surface area to volume (SA : V) ratios. Show your working.

b What happens to the SA : V ratio as objects increase in size, as occurs in examples (i), (ii) and (iii) in the table?

c In the table, objects (ii) and (iv) have the same volume; so do objects (iii) and (v). How does a change in shape affect the SA : V ratio of these objects?

d Explain the significance of the SA : V ratio for organisms and/or exchange organs.

Object	Surface area	Volume	SA : V ratio
i 		1 cm × 1 cm × 1 cm = 1 cm^3	
ii 	4 cm^2 × 6 sides = 24 cm^2		
iii 			
iv 			
v 			

10 Root hair cells on the roots of plants use energy to take up some nutrients from the soil, but not others. Describe the circumstances in which energy is expended during nutrient uptake.

11 Give an example of an organism's body shape and surface area to volume ratio that is suited to:

a gaining heat from its environment

b preventing heat loss

c maximising heat loss

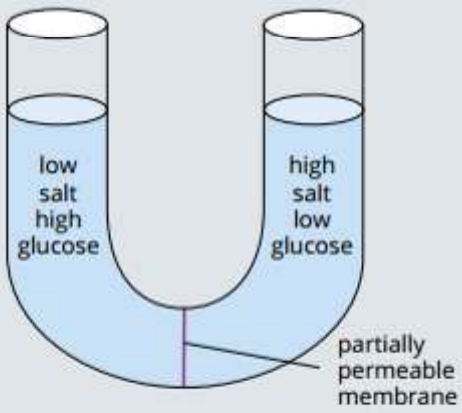
12 Two different solutions with the same volume are placed on either side of a semi-permeable membrane in a U-shaped glass tube, as shown in the following diagram. The membrane is permeable to salt but not glucose.

The tube is then left to stand for several days. Explain what you would expect to happen to:

a the salt concentration on each side of the membrane

b the glucose concentration on each side of the membrane

c the fluid levels on each side of the membrane.



CHAPTER

03 Energy transformations

By the end of this chapter you will understand the division of organisms into those that can produce their own organic materials and those that must consume the organic materials produced by others. You will also examine the way cells obtain energy from glucose to carry out cellular activities, and the way some organisms use solar energy in photosynthesis to produce organic material.

Key knowledge

- the distinction between photosynthetic autotrophs, chemosynthetic autotrophs and heterotrophs
- photosynthesis as a chemical process in which solar energy is captured and transformed to chemical energy by fixing carbon to produce a carbohydrate and releasing oxygen as a by-product
- aerobic and anaerobic cellular respiration as a chemical process that commonly uses glucose to produce energy for the cell in both autotrophs and heterotrophs.

3.1 Autotrophs and heterotrophs

FIGURE 3.1.1 Sunlight is the primary source of energy for biological systems and the organisms within them.

Although there is an enormous diversity of living organisms in the world, they have many processes and requirements in common. Whether organisms are unicellular or multicellular, and whether they live at the bottom of the ocean or in a rainforest, they all need to take in nutrients and water, exchange gases, obtain energy and remove waste products. And ultimately, most biological systems and organisms rely primarily on one source of energy for their survival: sunlight (Figure 3.1.1).

In this section you will learn how organisms are divided into groups according to how they obtain organic compounds and how they obtain energy. You will also learn that all life on Earth needs a carbon source to grow and build mass, and also an energy source.

Ecosystems are systems formed by organisms interacting with one another and their physical environment.

AUTOTROPHS AND HETEROTROPHS: PRODUCERS AND CONSUMERS

Organisms can be divided into two groups depending on the strategies they use to obtain organic compounds (see Figure 3.1.2):

- Autotrophs obtain organic compounds by converting inorganic matter. Because they produce all the organic compounds in ecosystems, they are also called producers.
- Heterotrophs obtain organic compounds from autotrophs or other heterotrophs. Because they consume organic compounds, they are also called consumers.

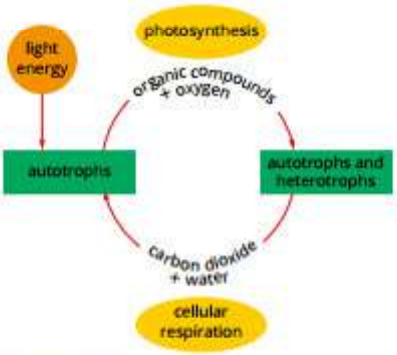


FIGURE 3.1.2 Autotrophic organisms make the organic compounds they require by combining inorganic compounds from their environment. Heterotrophic organisms obtain the organic compounds they require by eating other organisms or products of other organisms.

AUTOTROPHS

Autotrophs ('self-feeders') are able to make their own organic compounds. They use energy and inorganic molecules such as carbon dioxide and water, which come from their physical environment, to synthesise (make) organic compounds. This process is called carbon fixation because the autotroph 'fixes' the inorganic carbon into organic molecules (see Figure 3.1.3). Figure 3.1.4 shows the flow of energy from autotrophs to heterotrophs in an ecosystem.

Autotrophs can be further divided into two groups according to how they obtain the energy required for carbon fixation. These two groups are:

- photosynthetic autotrophs
- chemosynthetic autotrophs.

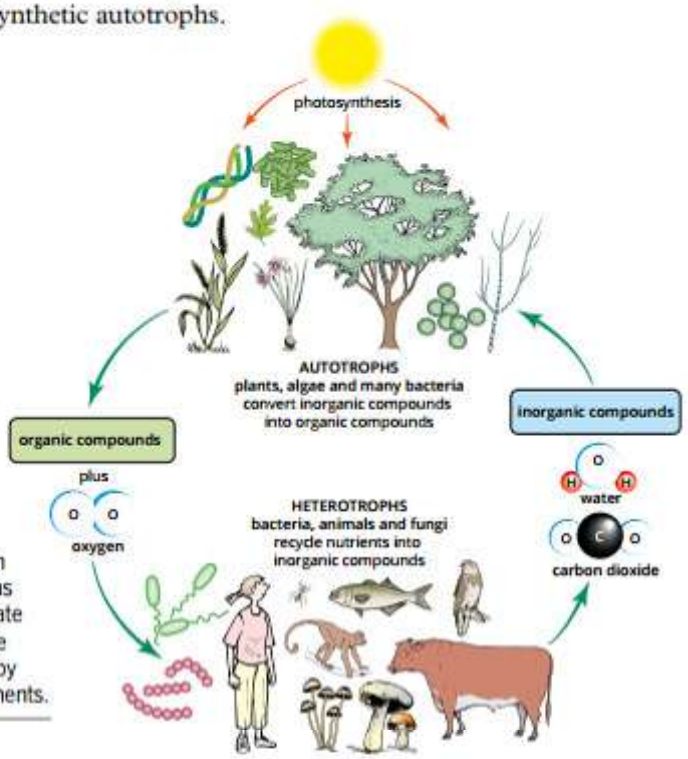


FIGURE 3.1.3 The cycling of matter through the environment, illustrating how autotrophs use energy and inorganic molecules to create organic molecules by carbon fixation. These organic molecules can then be consumed by heterotrophs to meet their energy requirements.

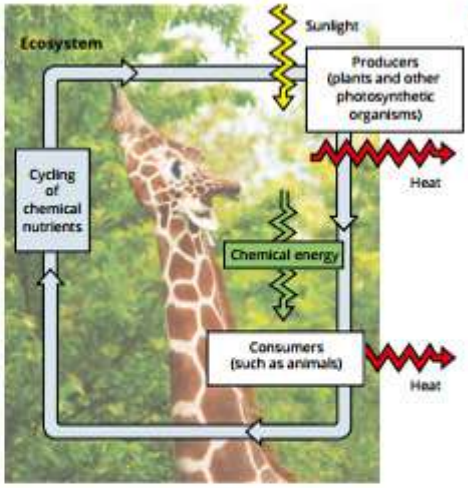


FIGURE 3.1.4 Although chemical nutrients can be recycled in an ecosystem, energy cannot be renewed. Instead, inorganic matter such as sunlight is constantly converted into organic matter by autotrophs (producers) which then feeds the heterotrophs (consumers). Without autotrophs there would be no organic chemical energy in the ecosystem.

FIGURE 3.1.5 Photoautotrophs use light energy to synthesise organic molecules from carbon dioxide and water. (a) On land, plants are the main photoautotrophs. In aquatic environments the main photoautotrophs are (b) algae such as this kelp and (c) prokaryotes called cyanobacteria.

Photosynthetic autotrophs

Photosynthetic autotrophs (photoautotrophs) are organisms that obtain the energy required for carbon fixation from light or solar energy (sunlight). They combine carbon dioxide and water using solar energy to produce organic compounds, in a process known as photosynthesis. In plants the organic compound produced by photosynthesis is glucose.

Most autotrophs are photosynthetic. The typical photosynthetic organisms you might think of are green plants, but there are also photosynthetic protists such as algae, *Euglena* and cyanobacteria (see Figure 3.1.5).

Chemosynthetic autotrophs

Chemosynthetic autotrophs obtain the energy they need for carbon fixation from inorganic chemical reactions—a process known as chemosynthesis. All known chemosynthetic organisms are prokaryotes.

Some chemosynthetic autotrophs obtain energy by the oxidation of inorganic molecules. Some of these conversions include:

- ammonium ions (NH_4^+) to nitrite ions (NO_2^-)
- nitrite ions (NO_2^-) to nitrate (NO_3^-)
- sulfide ions (S^{2-}) to sulfate ions (SO_4^{2-}).

Chemoautotrophs are able to live in the more extreme environments where these ions can be found. **Methanogens** are chemoautotrophs that live in environments where hydrogen is more readily available. They obtain energy from a carbon-fixing reaction in which carbon dioxide and hydrogen react to form a simple organic compound: methane (CH_4). Methanogens are poisoned by oxygen and live in places depleted of oxygen, such as wetlands (Figure 3.1.7) and the digestive tract of animals.

FIGURE 3.1.7 Wetlands such as these are commonly home to many chemoautotrophic methanogens.

BIOFILE

Carnivorous plants are autotrophs

Carnivorous plants such as the Venus flytrap trap and consume other organisms to obtain some nutrients, such as nitrogen, potassium and phosphorous. However, they are still considered photosynthetic autotrophs because they obtain most of their organic compounds through photosynthesis.

FIGURE 3.1.6 The Venus flytrap (*Dionaea muscipula*) is a carnivorous plant native to the United States. When hairs are triggered on the leaves, they snap shut to capture the prey.

BIOLOGY IN ACTION

Radiotrophic fungi

In 1991 scientists discovered a black mould growing on the walls inside the abandoned Chernobyl nuclear power plant in Ukraine. This was the site of the Chernobyl disaster that occurred in 1986 which is regarded as the worst nuclear power plant accident in history. The area surrounding the power plant is highly contaminated with radiation and has mostly been abandoned by humans. In the absence of people, the area has been recolonised by wildlife, and a forest has become established there (Figure 3.1.8).

FIGURE 3.1.8 The abandoned Chernobyl nuclear power plant and surrounding town are now also home to a forest.

The mould turned out to be *Cladosporium sphaerospermum*, a radiotrophic fungus. Radiotrophic fungi are autotrophs that can use radiation that is lethal to other organisms as a source of energy (Figure 3.1.9). They are usually dark in colour because they contain a dark pigment called melanin, which they can use to convert the radiation into chemical energy. This energy is then used to make organic compounds.

Researchers have found that these fungi can grow much faster when exposed to high levels of radiation. It is not yet clear whether these fungi use a process similar to photosynthesis or chemosynthesis. But because light is a kind of radiation, it seems likely that they use a process similar to photosynthesis.

Although radiotrophic fungi are common in environments where radiation levels are normal, they thrive in places where higher levels of radiation occur naturally, such as Antarctica and high-altitude regions.

FIGURE 3.1.9 High levels of radiation around the Chernobyl disaster site provide the ideal environment for *Cladosporium sphaerospermum* to flourish.

HETEROTROPHS

Heterotrophs ('other feeders') are also called consumers because they are unable to make their own food. Unlike autotrophs, heterotrophs cannot use simple inorganic substances to make organic compounds. Instead they must obtain the organic compounds they need by consuming other organisms or their products (see Figure 3.1.3, page 110).

All heterotrophs depend directly or indirectly on autotrophs for nutrients and energy. For example, a swamphen eating a soft rush stem is using an autotroph directly as a food source. That swamphen might also eat an insect that feeds on the rush, so the swamphen also depends indirectly on the plant for its food.

FIGURE 3.1.11 The purple swamphen (*Porphyrio porphyrio*) eats the seeds and soft stems of rushes, and also eats snails that feed on rushes.

BIOFILE

Euglena—autotroph and heterotroph

Some organisms are both autotrophic and heterotrophic. In sunlight ***Euglena*** protists are photoautotrophs. But when there is no sunlight they can absorb food from their environment, so they are also heterotrophic.

FIGURE 3.1.10 *Euglena* species are single-celled flagellate protists that can obtain energy from both sunlight and other organisms.

All animals and fungi are heterotrophs. Some bacteria and many protists (protozoa) are also heterotrophs. Because most heterotrophs feed on particular organisms, they can be further subdivided into groups based on their diet. One important group of heterotrophs are the parasites.

Omnivorous heterotrophs

A group of heterotrophs known as **omnivores** are organisms with a broad diet that are able to eat a mixture of both plants and animals. This distinguishes them from **carnivores**, which eat only animals, and **herbivores**, which eat only plants. Omnivores don't tend to specialise in a food source, but instead are opportunistic eaters, eating foods that are easily available to them. Humans, bears, and lizards such as the blue-tongued skink (Figure 3.1.12) are all omnivorous.

Heterotrophs obtain organic compounds by consuming other organisms.

FIGURE 3.1.12 The eastern blue-tongued skink (*Tiliqua scincoides scincoides*). This lizard is a subspecies of blue-tongued skink (*Tiliqua scincoides*) that is common throughout eastern Australia. Blue-tongued skinks are omnivorous, consuming a range of plants and animals including snails and beetles.

EXTENSION

Chemoheterotrophs and photoheterotrophs

Heterotrophs feed on organic matter, because they are unable to use inorganic sources of carbon to produce their own organic matter.

Chemoheterotrophs

Most heterotrophs are chemoheterotrophs. They obtain energy from organic compounds by cellular respiration. Animals, protists, fungi and most heterotrophic bacteria are chemoheterotrophs.

Photoheterotrophs

Photoheterotrophs use solar energy rather than organic compounds as a source of energy. Unlike photoautotrophs, photoheterotrophs cannot fix carbon from CO_2 into organic compounds such as glucose. They use organic compounds obtained from other organisms as their carbon source for growth and renewal, not as an energy source. Photoheterotrophic organisms include green non-sulfur bacteria, purple non-sulfur bacteria and heliobacteria (Figure 3.1.13).

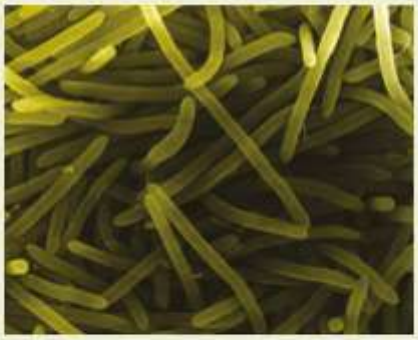


FIGURE 3.1.13 Heliobacteria are terrestrial organisms that are able to convert solar energy into chemical energy, but they still require organic sources of carbon to function.

Heterotrophs and autotrophs can be further divided according to how they acquire energy and carbon (Table 3.1.1).

Type of organism	Energy source	Carbon source
photoautotroph	solar energy (sunlight)	carbon dioxide
chemoautotroph	inorganic molecules	carbon dioxide
photoheterotroph	solar energy (sunlight)	organic matter
chemoheterotroph	organic compounds	organic matter

TABLE 3.1.1 Nutritional modes.

BIOFILE

Head lice: ectoparasitic heterotrophs

Head lice (*Pediculus humanus capitis*) are found only on human scalps. Because they live on the outside of the body, they are ectoparasites. They bite through the skin to feed on blood. Blood is a rich and concentrated source of nutrients and energy, sustaining these insects for their entire life cycle.

FIGURE 3.1.14 A head louse crawling on human hairs.

Saprotrophic heterotrophs

Another group of heterotrophs are the **saprotrophs**, which include most fungi and some bacteria. Saprotrophs eat by digesting organic material by extracellular means. This means they secrete enzymes onto dead and decaying organic material such as carcasses, leaf litter or fruit (Figure 3.1.15). Once the enzymes have broken down the large molecules, the saprophytic organisms absorb the simple organic nutrients through **endocytosis**. This process of decomposing and recycling organic matter is essential for ecosystems to function, as the process returns nutrients back into the environment to continue driving the cycle of energy.

FIGURE 3.1.15 This saprophytic mould (white 'fluff') is breaking down the strawberry to obtain nutrients.

Parasites

Parasitic heterotrophs, or parasites, derive their energy and nutrients directly from other living organisms. They feed on the cell contents, tissues or body fluids of their host. The host is usually harmed and sometimes even killed in the process. Parasites are highly diverse and can be found in all five kingdoms. Parasites that live inside the host are called endoparasites. Tapeworms and liver flukes are examples endoparasites. Parasites that live outside the host are called ectoparasites. Ticks and lice are examples of ectoparasites.

3.1 Review

SUMMARY

- Autotrophs use energy and inorganic molecules from the physical environment to produce the organic compounds they need.
- Most autotrophs, including plants and algae, are photosynthetic. That is, they use solar energy for producing energy-rich organic compounds.
- Some autotrophs, including some bacteria and archaea, are chemosynthetic, meaning they obtain energy by carrying out energy-releasing reactions between inorganic molecules.
- Heterotrophs, including animals, fungi and some bacteria and protists, obtain organic compounds by eating other organisms or their products.
- Parasitic heterotrophs obtain their energy and nutrients by feeding on the cell contents, tissues or body fluids of their hosts.

KEY QUESTIONS

1 Why are autotrophs also called producers?

2 Phytoplankton are autotrophs.
   - **a** Are they photoautotrophs or chemoautotrophs?
   - **b** How do they obtain energy?
   - **c** What kind of environment do they live in?

3 Which one of the following is an example of chemosynthesis?
   - **A** glucose production by plants
   - **B** methane production by methanogens
   - **C** carbon dioxide production by organisms
   - **D** conversion of nitrites into nitrates by prokaryotes

4 *Euglena* is both a heterotroph and an autotroph. Explain why.

5 Give an example of how heterotrophs rely both directly and indirectly on autotrophs.

6 What kind of heterotroph are humans? Explain your answer.

7 Contrast the way carnivores and saprotrophs obtain their organic compounds, giving an example of each type of organism.

3.2 Cellular respiration

Cells need energy to do work. The energy used by organisms and their cells is stored in organic compounds. In the last section you learned about the different ways that organisms acquire energy in this form. Autotrophs are able to use solar energy and inorganic molecules from the physical environment to produce organic compounds. Heterotrophs obtain organic compounds by consuming other organisms. Organic compounds are used by all organisms for growth and repair, as well as to perform everyday functions.

In this section you will study cellular respiration, the process by which chemical energy stored in organic compounds is transformed into more usable forms of chemical energy (Figures 3.2.1 and 3.2.2). You will also look at how this process varies according to the availability of free oxygen.

CELLS NEED ENERGY TO DO WORK

All living cells require energy to carry out their functions. Energy can be defined as the ability to cause change. For example, you are using energy right now to move your eyes to read these words, just as the cells inside your body are currently using energy to transport substances across their membranes. You, like all organisms, are constantly expending energy.

Energy exists in many forms. The energy in sunlight is solar energy, the heat generated by your body is thermal energy, and when you turn a page this movement involves kinetic energy. Chemical energy is the potential energy that can be released by a chemical reaction. Chemical energy is stored in the bonds or connections that join atoms together; for example, between atoms of carbon and hydrogen in organic compounds such as glucose, fats and proteins. The cells of all organisms use the energy stored in these organic compounds.

When energy is required by a cell, the bonds of organic compounds are broken and energy is released and stored in adenosine triphosphate molecules (ATP). ATP molecules store readily usable energy.

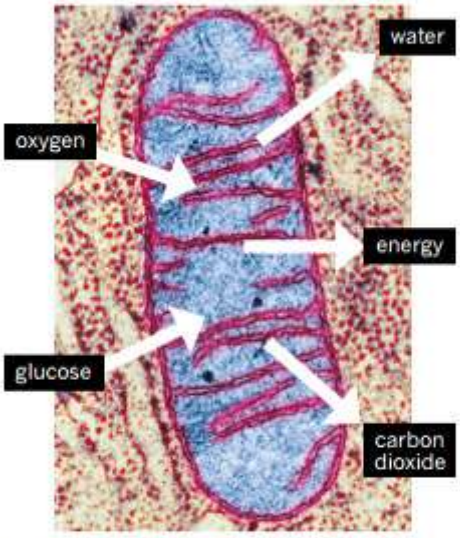


FIGURE 3.2.1 A coloured TEM of a mitochondrion, the organelle in which aerobic respiration occurs in eukaryotes. The outer membrane and the folds of the inner membrane (cristae) are coloured pink.

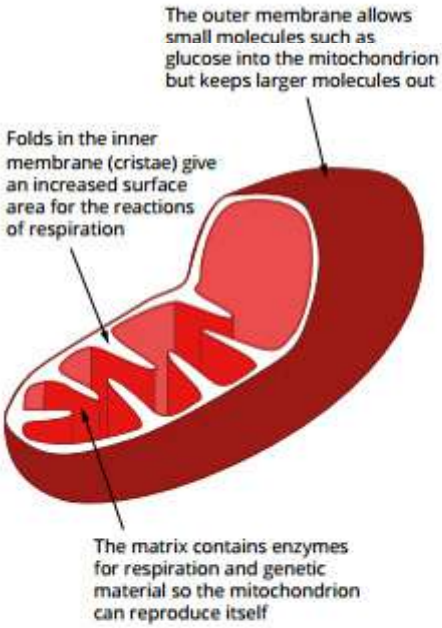


FIGURE 3.2.2 The structure of a mitochondrion is closely related to its function. The inner folds greatly increase the surface area, resulting in as much aerobic respiration as possible.

BIOFILE

Exercise and energy use

When cells convert energy from one form to another, some energy is always lost to the surroundings, usually as heat. For example, during exercise you use the chemical ATP to make your muscles contract. The more work you do, the more energy you use. When energy use increases, so does the loss of energy as heat, which warms your muscles. It is this continual generation of heat energy that allows mammals and birds to maintain a stable body temperature when their surroundings are colder.

FIGURE 3.2.3 This woman is using energy to lift the weights. Her muscle cells are using ATP to do this work, which in turn is warming her muscles because some energy is lost as heat.

ATP

ATP is the universal carrier of energy in living organisms. Molecules of ATP are the cell's store of immediately usable chemical energy that is required for cell processes.

The ATP molecule contains two high-energy bonds between the inorganic phosphate groups (Figure 3.2.4). These bonds can be easily broken to release a small 'packet' of energy. These packets of energy are used to carry out all the energy-dependent processes of cells. How many are used at once depends on how much energy is required.

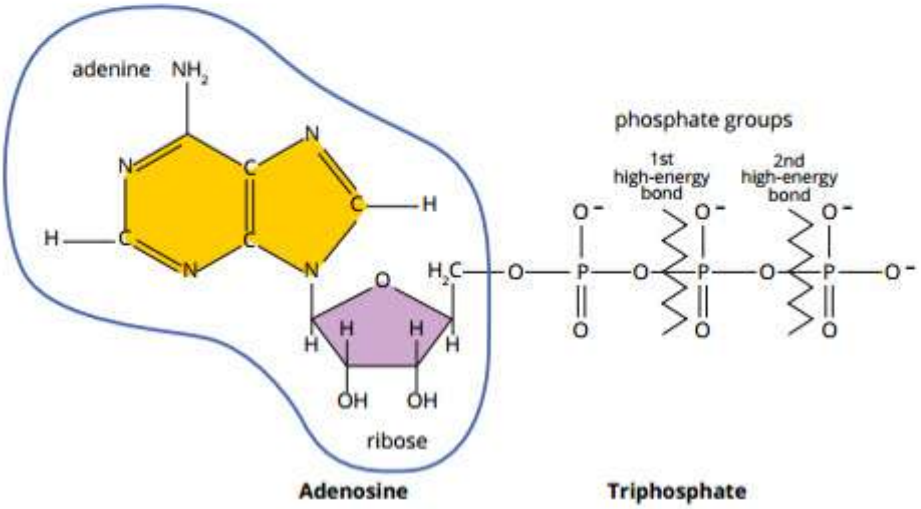


FIGURE 3.2.4 The structure of the adenosine triphosphate (ATP) molecule. It contains the sugar ribose, the nitrogenous base adenine (together creating adenosine) and a chain of three phosphate groups (triphosphate) bonded to it.

When an ATP molecule gives up its energy it splits into a molecule of ADP (adenosine diphosphate) and a molecule of phosphate. This process is reversible, because the ADP can combine with a phosphate molecule to form an ATP molecule again, using energy derived from the breakdown of glucose during cellular respiration (Figure 3.2.5). This recycling process requires much less energy than it would take to make an entirely new ATP molecule.

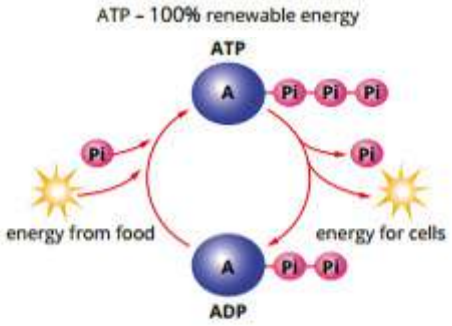


FIGURE 3.2.5 All living cells rely on one source of energy to do everything from building molecules to flexing muscles. This source of energy is adenosine triphosphate (ATP). Breaking down ATP releases energy, and cells constantly replace their ATP by adding a spare phosphate onto ADP (adenosine diphosphate). The energy for that comes from the nutrients obtained by the organism. Enzymes control the synthesis and breakdown of ATP.

BIOFILE

Other energy molecules

Glucose is the molecule most commonly used as the source of energy in cells. However, cells can also release chemical energy from other organic compounds such as fats and proteins to make ATP.

In animals, if most of the available glucose stores are gone (such as during times of food shortage), fat stores are used to provide the ATP needed for cells to continue functioning. In extreme cases, such as during long periods of starvation, even the proteins in muscles and other body tissues will be broken down to provide the energy necessary to survive. Fats provide more energy per gram (39 kJ) than carbohydrates or proteins (17 kJ).

FIGURE 3.2.6 The cells of this horse have converted stores of fat into ATP to help the horse survive.

i Although 'cellular respiration' is sometimes used to refer to both aerobic and anaerobic processes, here it refers only to the aerobic pathways of energy release that occur in mitochondria in eukaryotic cells.

CELLULAR RESPIRATION

The process by which organisms transform chemical energy from organic compounds into ATP is called cellular respiration.

Cells obtain most of their energy for making ATP by breaking apart glucose, lipids and proteins. Glucose is a sugar and is one of the energy-rich products of photosynthesis (Figure 3.2.7). The chemical energy from the glucose molecule is released in a series of steps that involve many enzymes, so that the energy is released in many small 'packets'. Each energy 'packet' can be used to produce an ATP molecule from ADP.

The breakdown of a glucose molecules results in three products:

- carbon dioxide
- water
- energy.

Of the chemical energy released in the breakdown of glucose, almost 40% is converted to energy stored in the bonds of ATP molecules during aerobic respiration. The rest is lost as heat.

The first stage of cellular respiration is glycolysis. The second stage is either aerobic respiration or anaerobic respiration (also called fermentation). The types of chemical reactions that occur in the second stage, and the amount of energy that can be harvested, depend on whether oxygen is present or not.

Cellular respiration can be divided into these two main stages:

- glycolysis
- aerobic respiration (if oxygen is present) or anaerobic respiration (if oxygen is absent). It is important to note that in a living cell if insufficient oxygen is available there will be anaerobic respiration occurring but aerobic will also be happening at the same time using all available O_2.

Glycolysis

Glycolysis is the first process that takes place in cellular respiration. It involves the splitting (lysis) of glucose into two pyruvate molecules. This occurs in the cytosol of the cell and is anaerobic; that is, it does not require oxygen. Glycolysis uses two ATP molecules in breaking down one glucose molecule, but it produces four more so there is a net production of two ATP molecules.

The process of glycolysis is common to aerobic and anaerobic respiration. The pathway followed after glycolysis depends on whether or not there is an adequate supply of molecular oxygen (see Figure 3.2.8). If there is enough oxygen, aerobic respiration takes place. If there is not enough oxygen, anaerobic respiration takes place (see Figure 3.2.9).

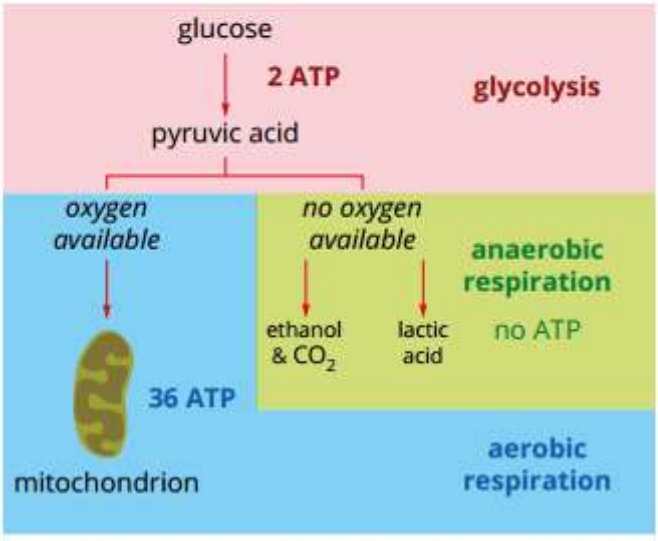


FIGURE 3.2.8 Simplified visual diagram showing the pathway of the process of cellular respiration n the presence and absence of oxygen.

The substance added to ADP to form ATP is phosphate (PO_4). This can be abbreviated to P_i which stands for inorganic phosphate.

FIGURE 3.2.7 The structure of a glucose molecule ($C_6H_{12}O_6$).

Energy is sometimes measured in calories (cal) rather than joules (J). 1 cal = 4.184 J

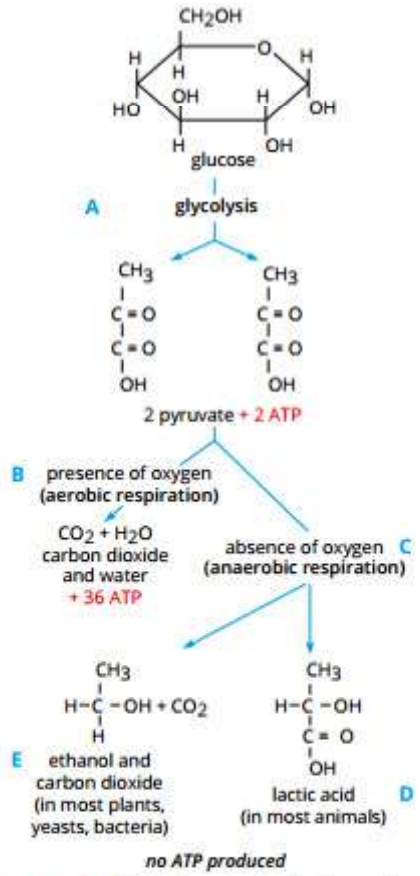


FIGURE 3.2.9 (A) During glycolysis, glucose is split into two pyruvate molecules. (B) In the presence of oxygen, aerobic respiration occurs and pyruvate is broken down into carbon dioxide and water. (C) If insufficient oxygen is present, anaerobic respiration occurs and pyruvate is converted into (D) lactic acid or (E) alcohol and carbon dioxide depending on the type of organism.

BIOFILE

Anaerobic Earth

The surface of the Earth was an anaerobic environment before photosynthesis developed. This was a world without plants, animals or insects, but many organisms still managed to survive in this environment without free oxygen. At this time glycolysis was probably the most common method of storing energy in living cells. When photosynthetic organisms evolved and multiplied, they produced so much oxygen that the Earth's atmosphere was changed. This new aerobic environment allowed the evolution of organisms that rely on oxygen to survive—including humans.

FIGURE 3.2.10 Life on Earth has changed drastically from an anaerobic environment (a) to an aerobic environment (b) which supports the variety of life we see today.

Aerobic respiration

When molecular oxygen is available, the next stage of cellular respiration after glycolysis is aerobic respiration. Aerobic respiration in cells occurs in mitochondria and uses ADP. During aerobic respiration, pyruvate molecules are broken down to produce carbon dioxide, water and ATP (Figure 3.2.11).

INPUTS **OUTPUTS**

glucose + oxygen → carbon dioxide + water + available energy

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

36–38 ADP + 36–38 P_i → 36–38 ATP

FIGURE 3.2.11 Cellular respiration with aerobic respiration involves the transformation of glucose, oxygen, ADP and phosphate into carbon dioxide, water and ATP.

BIOFILE

Transporting oxygen to the cells

Organisms that use aerobic respiration need to transport oxygen to their cells. In mammals oxygen is made available to cells via the lungs, where oxygen diffuses from the alveoli into the blood. The oxygen combines with haemoglobin to form oxyhaemoglobin, which is transported to cells by the circulatory system. Oxygen is then released from the oxyhaemoglobin and diffuses into the cells. The cells use the oxygen for aerobic respiration, which supplies them with the energy they need to function.

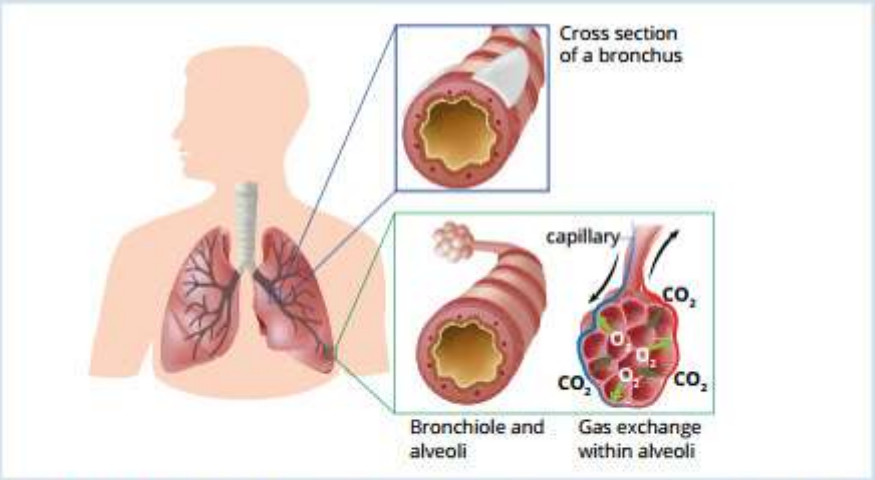


FIGURE 3.2.12 In mammals, lungs take in the oxygen needed for aerobic respiration in cells.

Mitochondria

Mitochondria are often called the power plants of cells because they produce most of the ATP used in a cell. Mitochondria are large, double-membrane organelles in which the inner membrane forms many folded layers called cristae (Figure 3.2.13). The cristae provide a large surface area on which the chemical reactions of aerobic respiration take place.

Some important points about glycolysis and aerobic respiration in mitochondria are summarised in Figure 3.2.14.

FIGURE 3.2.13 An SEM of a single mitochondrion (coloured pink) in the cytoplasm of an intestinal epithelial cell. The mitochondrion has two membranes: an outer surrounding membrane, and an inner membrane that forms folds called cristae where chemical reactions occur.

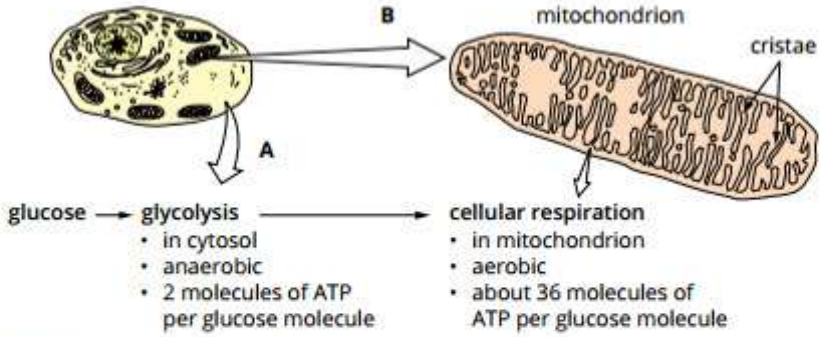


FIGURE 3.2.14 (A) Glycolysis occurs in the cytosol and produces 2 molecules of ATP per glucose molecule. (B) Aerobic respiration occurs in mitochondria and generates another 34–36 molecules of ATP.

Anaerobic respiration

If there is not enough oxygen available, aerobic respiration does not occur and the pyruvate passes into an anaerobic pathway. This anaerobic pathway is known as anaerobic respiration or fermentation. Anaerobic respiration occurs in the cytosol. During anaerobic respiration there is no further formation of ATP. The purpose of anaerobic respiration is to prevent the accumulation, or build-up, of pyruvate, which in turn allows glycolysis to continue. If the pyruvate accumulated, the process of glycolysis would be slowed and no energy would be available to the cell. Accumulation of a product can slow a chemical reaction.

In anaerobic respiration the pyruvate produced during glycolysis is converted into either lactic acid (in most animals) or carbon dioxide and alcohol (in most plants and in microorganisms such as yeasts and bacteria). These two pathways are shown in Figure 3.2.8.

Aerobic vs anaerobic respiration

Aerobic respiration and anaerobic respiration both enable organisms to maintain their energy stores, but they have different functions (Table 3.2.1). For each molecule of glucose, aerobic respiration produces almost 20 times the number of ATP molecules produced by glycolysis alone. So it is not surprising that most eukaryotic cells normally carry out aerobic respiration. Most eukaryotic cells only rely on anaerobic respiration to continue the generation of ATP by glycolysis for very short periods (seconds), or when there is not enough oxygen available for aerobic respiration.

	Aerobic respiration	Anaerobic respiration
Where it takes place	mitochondrion	cytosol
Oxygen required	yes	no
Waste products	• carbon dioxide and water	• plants, fungi, some bacteria: carbon dioxide and alcohol • animals: lactic acid
ATP produced	2 in glycolysis 34 in aerobic respiration	2 in glycolysis 0 in anaerobic respiration
Net ATP produced	36	2

TABLE 3.2.1 Comparison of aerobic and anaerobic respiration in eukaryotic cells.

BIOFILE

Sites of aerobic respiration

The number of mitochondria in a cell is related to the cell's energy requirements. Very active cells such as muscle cells may have thousands of mitochondria.

FIGURE 3.2.15 A TEM of a skeletal muscle cell. The numerous mitochondria are coloured yellow.

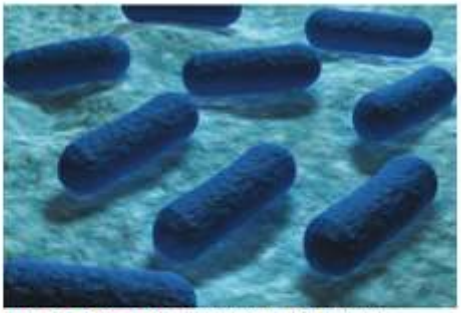


FIGURE 3.2.16 The bacterium *Escherichia coli* is a prokaryote that uses only anaerobic respiration.

CELLULAR RESPIRATION IN PROKARYOTIC CELLS

In prokaryotic cells, which lack mitochondria, cellular respiration takes place entirely in the cytosol, and the final steps are associated with the plasma membrane.

Cellular respiration in some prokaryotes does not have an aerobic pathway; this is known as true anaerobic respiration. These organisms use nitrate, sulfates, hydrogen or other substances instead of molecular oxygen. For example, the bacterium *Escherichia coli* uses nitrates or fumarates (Figure 3.2.16).

EXTENSION

Lactic acid and fatigue

During normal activities your body delivers enough oxygen to muscle cells for the aerobic breakdown of glucose to supply energy in the form of ATP. But high-intensity exercise is demanding. If your body cannot supply oxygen fast enough, your muscle switches to anaerobic respiration, so only the two ATP molecules formed in glycolysis are produced, with lactic acid as a by-product. Generally, the greater the effort, the more lactic acid is produced.

Lactic acid was identified as a possible cause of muscle fatigue 80 years ago. In a famous experiment performed in 1929, a frog's leg was stimulated electrically and the power of its contractions were measured. More lactic acid built up with each twitch. As the acid increased, the leg twitch became less powerful. As a result it was assumed that the build-up of lactic acid was the cause of muscle fatigue.

But the work of scientists at La Trobe University in 2004 disproved this hypothesis. Professors Graham Lamb and George Stephenson isolated single muscle fibres from rat muscle—a single cell half the thickness of a human hair—and then peeled off the surface membrane to give access to the intracellular environment. These 'skinned' fibres respond normally to electrical stimulation when bathed in a solution mimicking the normal intracellular environment (Figure 3.2.17).

If the lactic acid hypothesis was correct, the fibre should have quickly tired when lactic acid was added to the solution. But it did not. In fact, when the fibre did eventually tire, adding lactic acid caused it to regain strength because the intracellular acidity prevented the electrical signals within the fibre (action potentials), from fading out. So rather than causing muscle fatigue, lactic acid seems to help prevent it.

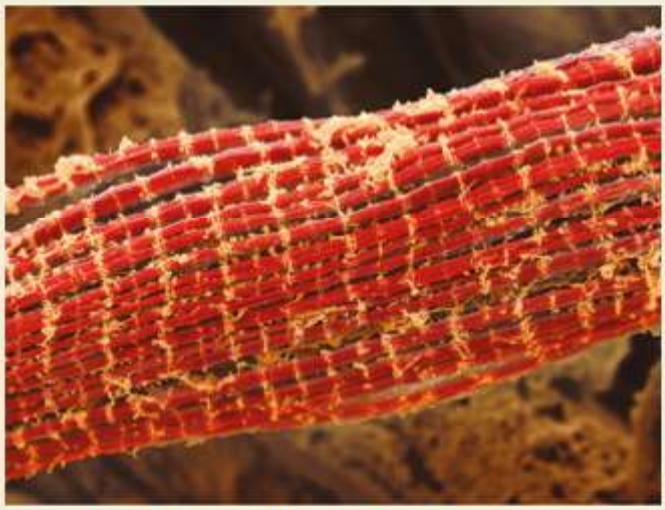


FIGURE 3.2.17 A coloured SEM of a skeletal muscle fibre, which consists of a bundle of smaller fibres called myofibrils that can contract.

Instead, the main causes of muscle fatigue are the near-exhaustion of ATP and related changes, such as an increase in inorganic phosphate. The muscle fibres sense when the ATP drops to a critically low level, and reduce their energy expenditure in response; that is, they fatigue, thus preventing the last of the ATP from being used up.

3.2 Review

SUMMARY

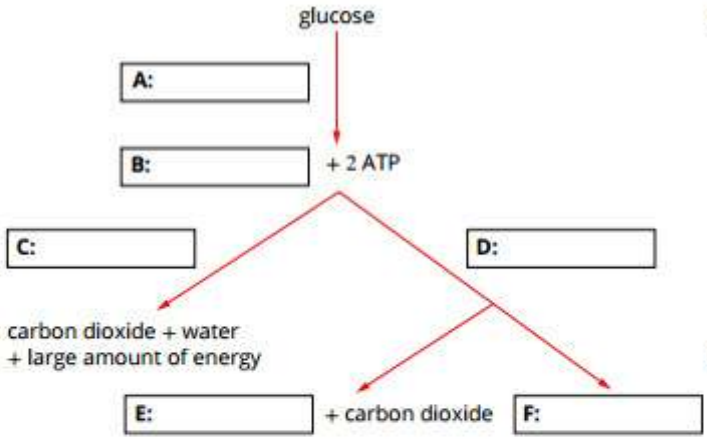
- Cells use chemical energy in the form of ATP to carry out cell functions.
- When cells convert energy from one form into another, some is lost to the surroundings, usually in the form of heat energy.
- Cells produce ATP by the process of cellular respiration.
- Cellular respiration takes place in two stages. The first stage is glycolysis, and the second stage is either aerobic respiration (if oxygen is available) or anaerobic respiration (if oxygen is not available).
- Glycolysis takes place in the cytosol and generates two ATP molecules and two molecules of pyruvate per molecule of glucose. It does not require oxygen.
- In aerobic respiration, pyruvate produced in the cytosol by glycolysis passes into a mitochondrion, where it is broken down to carbon dioxide and water along a complex aerobic pathway. For every two molecules of pyruvate, a further 34 molecules of ATP are generated.
- In anaerobic respiration, pyruvate is converted in the cytosol to lactic acid (in most animals) or alcohol and carbon dioxide (in plants, bacteria and yeasts), and no more ATP is produced.

KEY QUESTIONS

1 What is chemical energy?

2 In what form is energy available to use in cells?

3 The figure below is a summary of the major processes that occur during cellular respiration. Provide the most appropriate labels for A, B, C, D, E and F.



4 Define glycolysis and state where it occurs in a eukaryotic cell.

5 What is the difference between aerobic and anaerobic respiration?

6 What is the major benefit to cells in using aerobic respiration rather than anaerobic respiration?

7 Which one of the following describes anaerobic respiration?

A the conversion of pyruvate into ethanol and carbon dioxide in the absence of oxygen

B the conversion of pyruvate into lactic acid in the presence of oxygen

C the production of ethanol and carbon dioxide in the presence of oxygen

D the reaction of yeast and oxygen resulting in lactic acid in the absence of oxygen

8 Some bacteria respire aerobically. Compare the cellular location of bacterial aerobic respiration to that in eukaryotic cells.

3.3 Photosynthesis

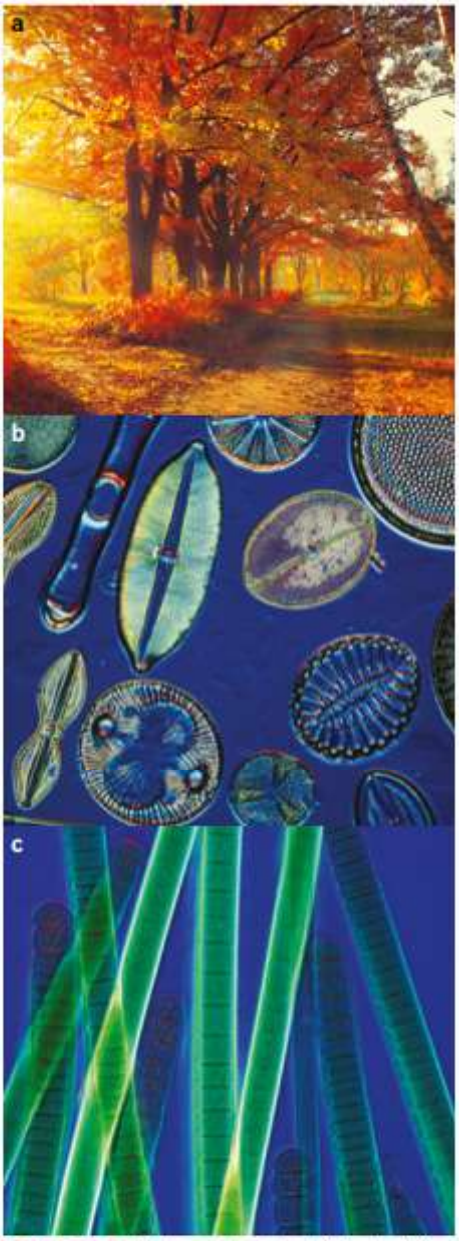


FIGURE 3.3.2 Photosynthesis in (a) plants, (b) algae and (c) cyanobacteria provide the matter and energy for most life on Earth.

Energy cannot be created or destroyed, but it can be changed from one form into another. To carry out their activities, cells must first obtain energy in a form they can change into chemical energy stored in the bonds of ATP. You have learnt how this is done using glucose. All living things depend on organic compounds such as glucose for cellular function (Figure 3.3.1). Animals obtain their glucose by eating other organisms and breaking down the organic molecules. Plants make their own glucose from raw materials.

Plants produce glucose by photosynthesis. Photosynthesis is the process in which plants and other photoautotrophic organisms obtain energy from sunlight to make their own organic compounds (Figure 3.3.2). This section will focus on photosynthesis in plants.

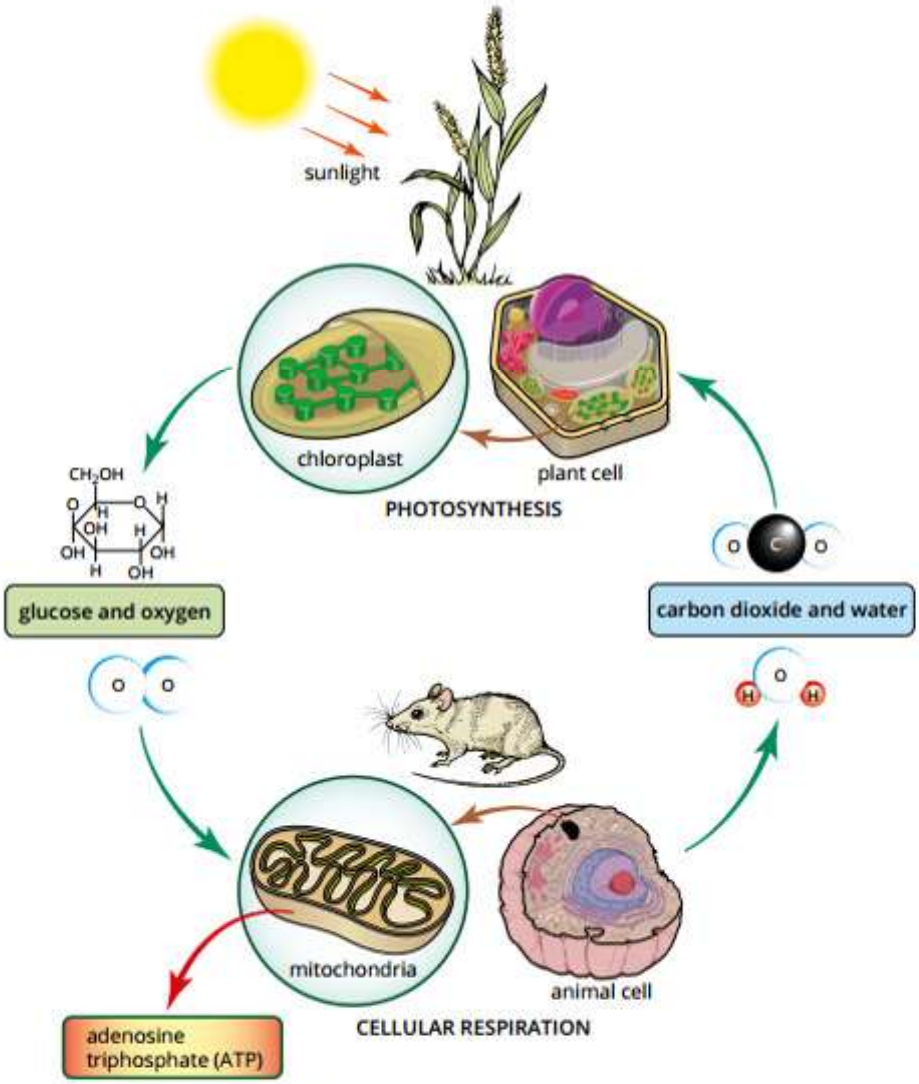


FIGURE 3.3.1 The cycle of how plants obtain their energy using photosynthesis and animals obtain their energy via cellular respiration.

PHOTOSYNTHESIS

Simple experiments show that when plants have light, water and carbon dioxide they make glucose in their green parts, such as leaves. They trap the energy of sunlight and convert it into chemical energy, which they store in the bonds of glucose molecules. This enzyme-controlled process is photosynthesis (photo meaning 'light', synthesis meaning 'putting together'). All photosynthetic organisms, from single-celled algae to the largest trees, produce glucose in the same way (Figure 3.3.3).

> **i** Photosynthesis is sometimes called 'carbon fixation' because carbon atoms from the air are incorporated ('fixed') into organic molecules.

Chloroplasts

Chloroplasts occur in mesophyll cells, which make up the central part of leaves in vascular plants (Figure 3.3.4). In non-vascular plants such as mosses, chloroplasts occur throughout the leaves and often in other plant parts such as stems.

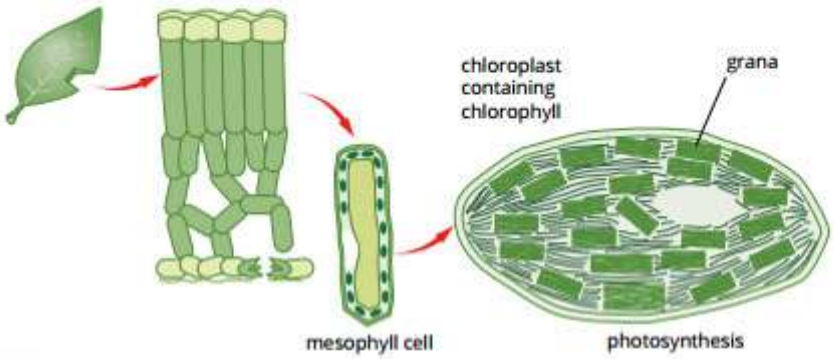


FIGURE 3.3.4 The location of chloroplasts in mesophyll cells of a leaf in a vascular plant.

FIGURE 3.3.3 Leaves, and some stems, are green because the mesophyll cells contain many chloroplasts, the organelles in which photosynthesis takes place. Fruits (such as these blueberries) and seeds contain no chlorophyll and do not take part in photosynthesis.

The leaves and sometimes stems of plants are green because they contain large amounts of the green pigment chlorophyll. In plants and algae, chlorophyll is contained in large double-membrane organelles called chloroplasts (Figure 3.3.5). Each chloroplast contains stacks of flattened membranes called grana (singular granum).

Photosynthesis takes place in these chloroplasts. The grana contain the chlorophyll pigments where light reactions occur during photosynthesis.

Chloroplasts in plants are generally shaped like a biconvex lens about 5–8 micrometres in diameter. The outer membrane is highly permeable but the inner membrane is impermeable and surrounds the area filled with a liquid called stroma. Stroma contains a number of enzymes, spherical DNA and ribosomes. The grana consist of stacks of small disc-shaped structures called thylakoids where chlorophyll is made (Figure 3.3.6).

FIGURE 3.3.5 A TEM of two chloroplasts in a cell in the leaf of a pea, *Pisum sativum*. The chloroplasts are seen here in side view, and the grana are coloured yellow for clarity.

Stages of photosynthesis

Photosynthesis is a complex process in which solar energy is converted into chemical energy stored in the form of glucose, which can be used by all organisms. Photosynthesis occurs in two stages: the light-dependent reactions and the light-independent reactions.

Stage 1: Light-dependent reactions

In the light-dependent reactions, chlorophyll captures solar energy and uses it to produce ATP. During this process, photolysis occurs where water is split into hydrogen ions and oxygen gas. The light-dependent reactions occur on the thylakoid membranes of the chloroplast, where chlorophyll molecules are located.

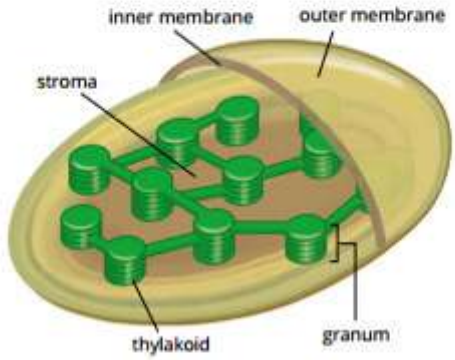


FIG 3.3.6 Three-dimensional model of the structure of a chloroplast.

The light-dependent reactions split water in the presence of solar energy (light) and chlorophyll, into hydrogen ions and molecular oxygen, and also produce ATP.

$$\text{water} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{hydrogen ions} + \text{oxygen} + \text{ATP}$$

Stage 2: Light-independent reactions

The light-independent reactions (also called dark reactions) produce glucose, water and ADP. They are called 'light-independent' because they do not require solar energy. ATP made during the light-dependent stage provides the energy for this reaction. This energy is needed to combine carbon dioxide with hydrogen ions (also from the light-dependent stage) to form glucose, an energy-rich molecule, and water. The light-independent reactions take place in the stroma of the chloroplast.

The light-independent (or dark) reactions use the products of the light-dependent reactions to produce glucose, water and ADP.

$$\text{hydrogen ions} + \text{ATP} + \text{carbon dioxide} \rightarrow \text{glucose} + \text{water} + \text{ADP}$$

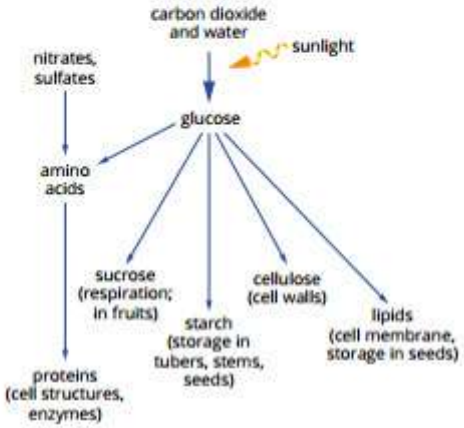


FIGURE 3.3.7 Plants can make all the organic compounds they need from the glucose they produce through photosynthesis.

The reactions that occur in photosynthesis can be summarised as follows:

Word equation: water + carbon dioxide → glucose + oxygen

Chemical equation: $6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$

Photosynthesis is critically important for life on Earth because the production of plant matter is essential in providing energy and biomass in terrestrial ecosystems. Plants can produce all the organic compounds they need from the glucose they produce through photosynthesis, as long as they have the necessary minerals (Figure 3.3.7).

Biomass is the total amount of plant and animal tissues in a defined area.

BIOLOGY IN ACTION

Bionic leaf and bacteria make liquid fuel

Scientists from Harvard University have created a system that uses bacteria and solar energy to manufacture a liquid fuel from water and carbon dioxide. The researchers set out to develop a renewable energy production system that would mimic the process of photosynthesis but also be more efficient. They achieved this by creating a structure known as the Bionic Leaf and pairing it with bacteria that use hydrogen and carbon dioxide as their energy sources.

The Bionic Leaf uses electricity generated by a solar panel to split water into its component elements (hydrogen and oxygen), just as photosynthesis does. The electrodes of the Bionic Leaf are submerged in a vial containing water and the soil bacterium *Ralstonia eutropha* (Figure 3.3.10). The water-splitting reaction occurs when an electric voltage from the solar panels is applied to the electrodes of the artificial leaf. The bacteria feed on the hydrogen generated from the reaction, along with carbon dioxide bubbles that are added to the system. The bacteria use this food source and produce isopropanol as a byproduct.

CONTROLLING THE RATE OF PHOTOSYNTHESIS

Three main factors control the rate of photosynthesis:

- light intensity
- carbon dioxide concentration
- temperature.

The availability or concentrations of these factors may limit the rate of the reactions. For each factor there is an optimum amount at which photosynthetic reactions proceed at the fastest rate. Below the optimum level, reactions are slower. At levels above the optimum, reactions do not proceed any faster, and sometimes occur more slowly.

The factor that is present in the smallest amount is the limiting factor. Therefore, only one factor will be limiting at a particular time. For example, if a plant is in the process of photosynthesis and there is a large amount of carbon dioxide available but not enough light, then light is a limiting factor. And if there is enough light and not enough carbon dioxide, then the concentration of carbon dioxide is the limiting factor (Figure 3.3.8).

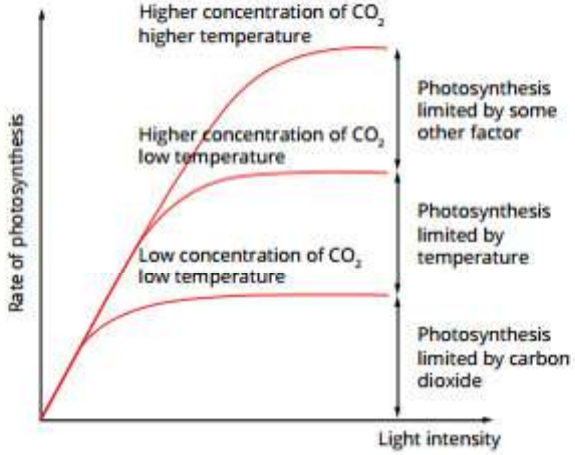


FIGURE 3.3.8 Light intensity, temperature and carbon dioxide are limiting factors for photosynthesis. Other factors might also be limiting in some circumstances.

BIOFILE

Plant poisons

Poisons are used in agriculture because weeds and other pests reduce crop yields. Many lethal poisons are effective because they interfere with the energy transformations of organisms. Some interfere with photosynthesis and are therefore selective for plants. For example, herbicides such as amitrole and glyphosate inhibit the production of chlorophyll, and paraquat and diquat block the light-dependent reactions in the first part of photosynthesis.

FIGURE 3.3.9 Grasses sprayed with glyphosate die within two weeks as a result of the inhibition of chlorophyll synthesis.

This system can now convert water and carbon dioxide to fuel at an efficiency of 3.2%, which is triple the efficiency of photosynthesis. This efficiency is thanks to the solar panels, which have a greater capacity to harvest sunlight than most plants do.

The researchers' findings were published in 2015 and have great potential for use in many powerful applications. Efficient renewable energy production and storage is one of the important areas where this technology could be applied. Genetic engineering of bacteria also creates many possibilities for the synthesis and metabolism of a wide variety of chemicals. This might create countless applications for the technology in both the production of compounds and the removal of chemical pollutants from the environment.

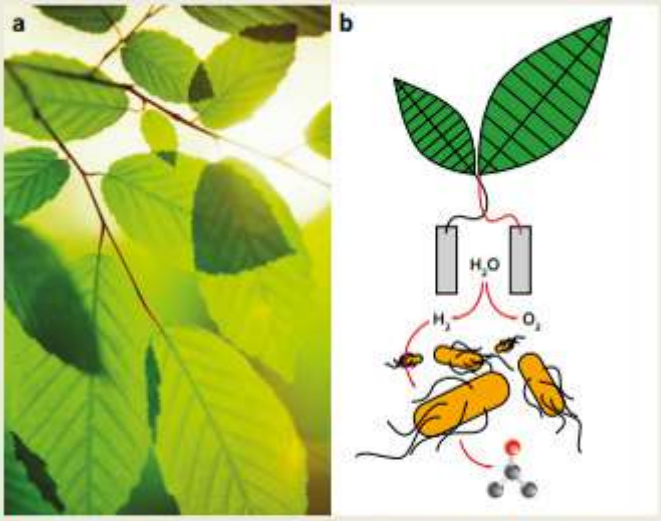


FIGURE 3.3.10 The Bionic Leaf system mimics the natural process of photosynthesis. Using electricity harnessed from sunlight, the Bionic Leaf splits water into hydrogen and oxygen, providing a food source for bacteria that produce the alcohol isopropanol, which can be used as a fuel.

BIOFILE

Photosynthesis in non-green plants, protists and cyanobacteria

All plants (as well as many protists and cyanobacteria) contain chlorophyll, but not all are green. Some plants have yellow, red or purple leaves, and protists and cyanobacteria can be red, blue or other colours. These organisms contain chlorophyll but also other pigments, including phycobiliproteins and carotenoids that mask the green chlorophyll. Phycobiliproteins and carotenoids assist in photosynthesis by absorbing different wavelengths of light. Phycobiliproteins are especially useful in deep water, where only green wavelengths can penetrate. Pigments other than chlorophyll also protect plants from over-exposure to sunlight and attract pollinators.

FIGURE 3.3.11 The purple oxalis (*Oxalis triangularis*) has purple leaves, but these still contain chloroplasts and chlorophyll and carry out photosynthesis.

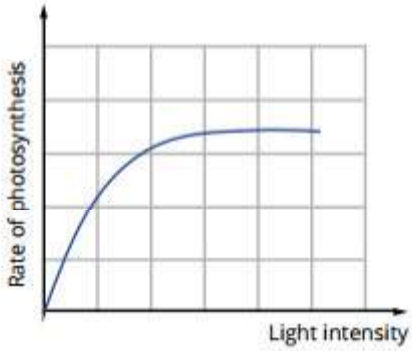


FIGURE 3.3.12 The effect of light intensity on the rate of photosynthesis.

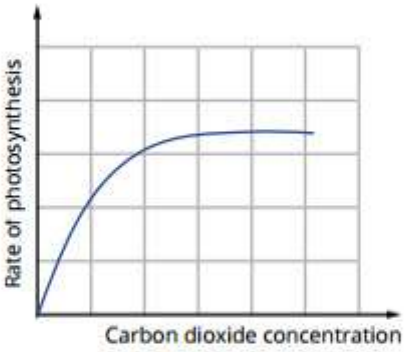


FIGURE 3.3.13 The effect of carbon dioxide levels on the rate of photosynthesis.

Light intensity

Light intensity can affect the rate of photosynthesis. When the light intensity is low, the light-dependent reactions (the production of ATP and the splitting of water molecules) cannot occur. So at night, light intensity is the limiting factor because photosynthesis cannot occur. As the light intensity increases from this point, the rate of photosynthesis will increase. However, at a certain light intensity the rate of photosynthesis will not be affected by further increases in light intensity. This effect can be seen in Figure 3.3.12.

Carbon dioxide levels

Carbon dioxide availability affects the rate of photosynthesis because photosynthesis uses the carbon dioxide to make glucose. When there is no carbon dioxide available, photosynthesis cannot occur, so carbon dioxide is a limiting factor. As carbon dioxide becomes available, photosynthesis begins. As with light, the rate of photosynthesis will increase as carbon dioxide levels increase until the carbon dioxide levels reach a certain point (Figure 3.3.13).

Temperature

Temperature also affects the rate of photosynthesis. All light-dependent and light-independent reactions are catalysed by enzymes. Enzyme activity increases as temperature increases, but they become denatured above optimum temperatures. For this reason the rate of photosynthesis will approximately double for every increase in temperature until the optimum temperature is reached. However, above the optimum temperature, the rate of photosynthesis will decline steeply (as the enzymes become denatured and the chemical processes involved in the light-independent reactions cannot be catalysed) (see Figure 3.3.14). Different plants are evolved to different environments, hence there is no fixed optimum temperature for plants. A cactus will have a higher optimum temperature compared to an aquatic plant that is found in a cool environment.

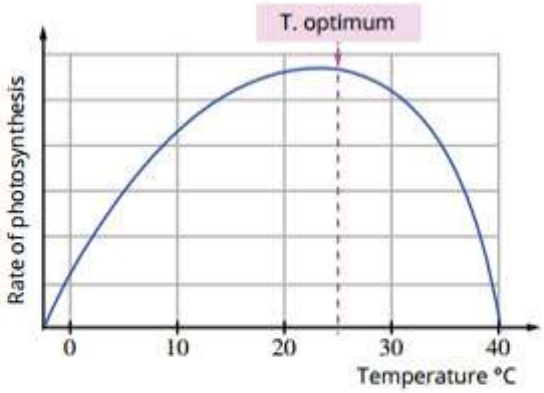


FIGURE 3.3.14 The effect of temperature on the rate of photosynthesis.

BALANCING PHOTOSYNTHESIS AND CELLULAR RESPIRATION

In Section 3.2 you learnt that cells release chemical energy by breaking apart glucose molecules. This process is called cellular respiration. As well as producing energy, in the form of ATP, cellular respiration produces carbon dioxide and water.

Cellular respiration occurs continuously, whereas photosynthesis occurs only during daylight. So plants and algae are producing carbon dioxide and using oxygen continuously through cellular respiration, but during the day this is masked because photosynthesis is also occurring, using carbon dioxide and producing oxygen.

The light compensation point is the level of light at which the rates of photosynthesis and cellular respiration of a photosynthetic organism are equal and there is no net exchange of oxygen, as shown in Figure 3.3.15. At this point the amount of oxygen used in cellular respiration and the amount produced by photosynthesis are equal.

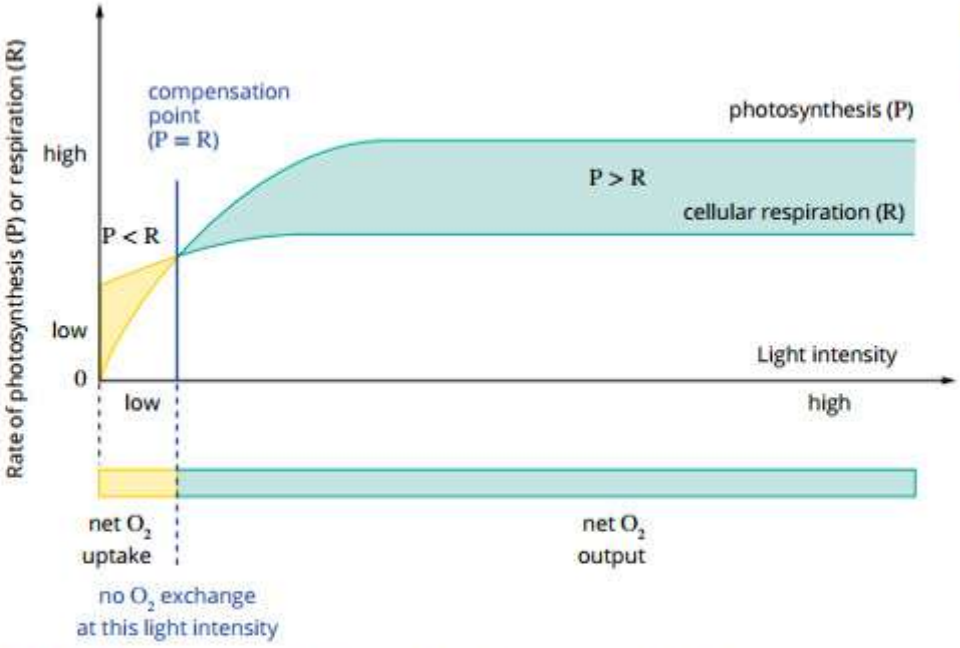


FIGURE 3.3.15 At low levels of light intensity the rate of cellular respiration is greater than the rate of photosynthesis, so there is a net uptake of oxygen by plants. At high light levels the rate of photosynthesis is greater than the rate of cellular respiration, so there is a net output of oxygen by plants. The compensation point is the level of light at which the rates of respiration and photosynthesis are equal and therefore there is no net exchange of oxygen.

BIOFILE

Plants in shade

Some plants are better adapted to live in shade because they have low respiration rates. They have fewer cells per leaf and lower concentrations of proteins compared to species that grow in sunnier places. In terms of energy requirements, they can be thought of as very cheap to run. Shade-tolerant plants also absorb light very effectively. Some plants that grow in dark environments have a lens-like arrangement in the upper epidermal cells that focuses light onto their photosynthetic cells below.

FIGURE 3.3.16 Most ferns, such as this maidenhair fern (*Adiantum pedatum*), are adapted to thrive in shady environments.

3.3 Review

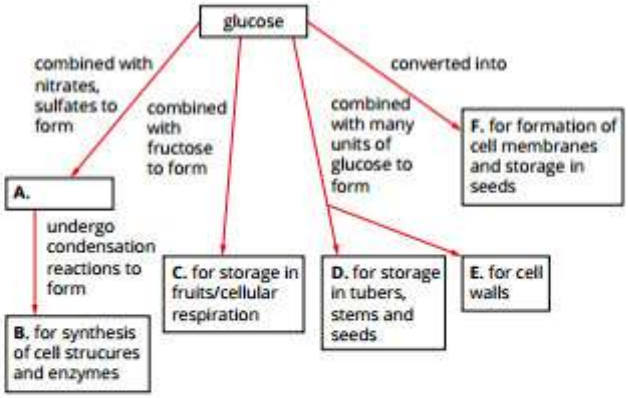
SUMMARY

- Plants produce their own organic compounds from inorganic molecules.
- During photosynthesis, plants trap solar energy, and then use this energy to split water molecules. Carbon dioxide is then combined with hydrogen to produce glucose. Oxygen is released to the environment as a waste product.
- Through photosynthesis, solar energy is transformed to chemical energy, which is stored in the bonds of glucose molecules.
- Photosynthesis occurs in organelles called chloroplasts that contain chlorophyll.
- Light intensity, carbon dioxide availability and temperature may limit the rate of photosynthesis.
- The reactions that occur during photosynthesis can be summarised by an overall equation:
  word equation:
  water + carbon dioxide → glucose + oxygen
  chemical equation:
  $6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$
- Photosynthesis generally occurs only during daylight, but cellular respiration occurs continuously.
- The light compensation point is the level of light at which the rates of photosynthesis and cellular respiration of a photosynthetic organism are equal. At this point the amount of oxygen produced and the amount used is equal, so there is no net exchange of oxygen.

KEY QUESTIONS

1 What molecule is broken down using solar energy during photosynthesis?

2 The figure below is a summary of the major processes that occur during photosynthesis. State the correct term for each of letters A, B, C, D, E and F.



3 State whether each of the following statements is true or false.

a Chlorophyll is a pigment that causes green colouring of leaves.

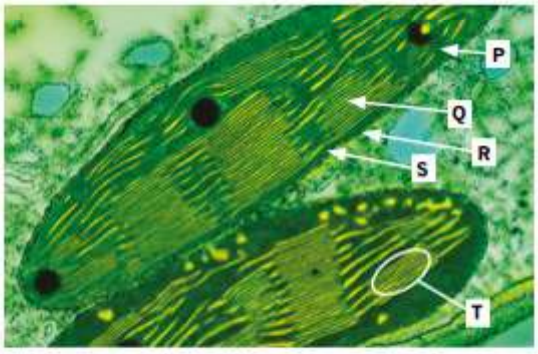
b Chloroplasts are pigments that absorb light.

c Chlorophyll is located in the thylakoid membranes.

d Chlorophyll absorbs light energy, which is then transformed into chemical energy.

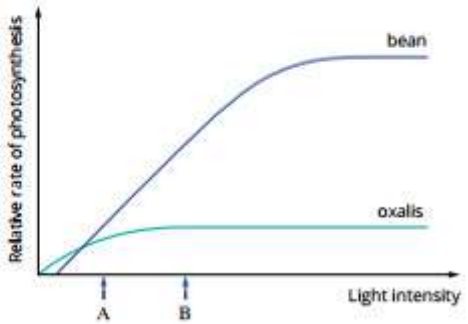
4 How many glucose molecules would be produced if 24 carbon dioxide and 24 water molecules were used in photosynthesis?

5 The figure below shows a transmission electron micrograph of a chloroplast. Identify structures P, Q, R, S and T.



6 The following graph shows the rate of photosynthesis in a bean plant, adapted to high light intensity, and an oxalis plant, adapted to low light intensity.

a What is the limiting factor at point A for each plant?



b What is the limiting factor at point B for each plant?

7 What is the light compensation point, and what happens at this point?

Chapter review

03

KEY TERMS

ADP
aerobic
anaerobic
ATP
autotroph
biomass
carbon fixation
carnivore
cellular respiration
chemical energy
chemoheterotroph
chemosynthesis
chlorophyll
chloroplast
ecosystem
endocytosis
fermentation
glycolysis
granum (plural grana)
herbivore
heterotroph
light compensation point
methanogen
mitochondrion
omnivore
parasite
photoheterotroph
photosynthesis
saprotroph
thylakoid

KEY QUESTIONS

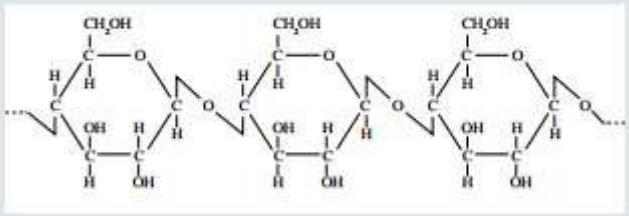
1 Distinguish between autotrophs and heterotrophs.

2 Contrast photosynthetic autotrophs with chemosynthetic autotrophs.

3 Chemoautotrophs acquire energy from inorganic chemical reactions.
- **a** Name one chemical conversion used by a chemoautotroph.
- **b** Name one chemoautotroph and the organic compound it produces.

4 List the five types of heterotrophs, and then spend 30 seconds writing down as many examples as you can think of for each type.

5 Cellulose is a complex carbohydrate that is made up of many individual units of glucose. The molecule shown below, composed of carbon, hydrogen and oxygen, was found in the gut of an animal.



- **a** Describe how an autotroph would have obtained this molecule.
- **b** Which one of the following animals would not have this molecule in its gut?
  - **A** human
  - **B** cow
  - **C** lion
  - **D** pig

6 Briefly describe what happens to pyruvate in the two processes that can occur after glycolysis when:
- **a** oxygen is present
- **b** oxygen is absent.

7 What is the approximate efficiency of anaerobic respiration compared to aerobic respiration in the release of energy from one glucose molecule?

8 The following expressions can be used to write a word equation for photosynthesis and cellular respiration.
- P carbon dioxide and water
- Q carbon dioxide, water and energy
- R solar energy and chlorophyll
- S glucose and oxygen

Complete the word equation for photosynthesis and cellular aerobic respiration using the statements provided.

Word equation for photosynthesis:

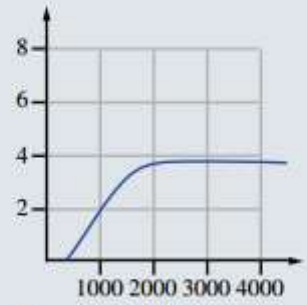
Word equation for cellular respiration:

9 Explain why photosynthesis is not the opposite of aerobic respiration.

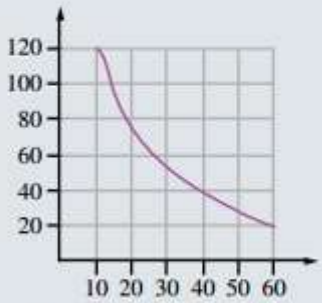
10 There are two stages in photosynthesis. Outline what occurs in each stage.

11 Pyridazinone herbicides are used in agriculture to reduce the number of pest plant species. Pyridazinone herbicides inhibit enzymes found in the light-dependent stage of photosynthesis. Explain how pyridazinone herbicides might act on a pest plant.

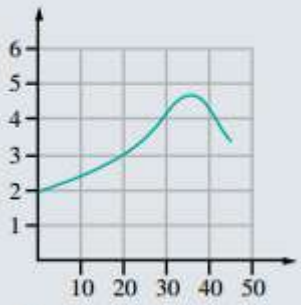
12 The following graphs represent the changes in rate of photosynthesis when temperature, light intensity or distance from light source are increased. Label each graph with its correct factor.



A

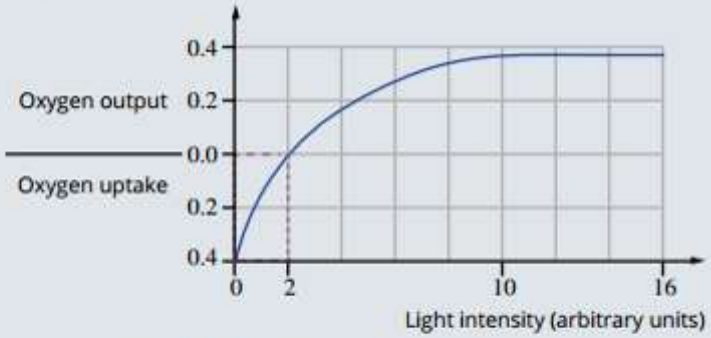


B



C

13 The following graph shows the relationship between net oxygen uptake or output and light intensity for a green plant.



Explain what is happening when the light intensity is:

a 2 units

b 16 units.

14 Draw up tables comparing:

a photosynthetic autotrophs, chemosynthetic autotrophs and heterotrophs

b photosynthesis and cellular respiration.

CHAPTER

04 Functioning systems

In this chapter you will learn about how the cells of multicellular organisms are organised to fulfil the needs of each cell and enable the whole organism to survive, grow, reproduce and take full advantage of multicellularity.

As multicellular organisms increase in complexity, their cells achieve higher levels of organisation. The levels of organisation in multicellular organisms are: specialised cells, tissues, organs and systems. You will look at each of these levels of organisation and the specialised structures and functions that have evolved to meet the needs of complex organisms. Although there are many advantages to multicellularity, there are also many challenges. You will explore some of these challenges and the functional adaptations that complex multicellular organisms have developed to overcome them.

The most complex plants, vascular plants, are land plants with specialised conducting tissue. The cells in these plants are organised into tissues, organs and systems. In this chapter you will examine the cellular organisation of vascular plants and how this organisation achieves the intake, movement and loss of water from the plant.

Cellular organisation in more complex multicellular organisms will also be explored. You will select and examine the structure and function of one mammalian system: circulatory, respiratory, digestive or excretory. You will also learn about the interconnections between the systems, how integral these connections are to the healthy functioning of the organism and the biological consequences of cellular, tissue, organ and system malfunctions for the organism.

Key knowledge

- a study of one selected vascular plant with reference to how its cells are specialised and organised (cells into tissues, tissues into organs and organs into systems) for the intake, movement and loss of water from the plant (*also covers the organisation of organs into systems in vascular plants.*)
- a study of one selected mammalian system (circulatory, digestive, excretory or respiratory) with reference to how cells in the system are specialised and organised (cells into tissues, tissues into organs and organs into systems), how a specific malfunction can lead to biological consequences and how the system is interconnected to other systems for the survival of the organism.

4.1 Multicellularity and cell specialisation

FIGURE 4.1.1 The simplest form of organisation in organisms is a single cell. *Euglena* is a eukaryotic protist that carries out all the functions and activities necessary for life in one cell.

Cells carry out all the functions necessary to sustain life, including obtaining nutrients and water, exchanging gases, sourcing energy, removing waste products and reproducing.

In unicellular (single-celled) organisms, such as the prokaryote *Escherichia coli* and the eukaryote *Euglena* (Figure 4.1.1), a single cell must carry out these functions. But in multicellular organisms these functions are shared between different types of specialised cells.

A multicellular organism is like a community of cells that work cooperatively for the survival and reproduction of the organism. All multicellular organisms consist of eukaryotic cells. There is an enormous diversity, from simple mosses, sponges and corals (Figure 4.1.2) to complex flowering plants, birds and mammals.

Prokaryotes are not multicellular organisms. However, some bacteria such as cyanobacteria grow in chains of cells, and others form aggregates or colonies of cells that behave in a coordinated fashion, such as species that form biofilms.

FIGURE 4.1.2 Corals look like single multicellular organisms, but they are actually groups of multicellular organisms (known as polyps) living in colonies.

Unicellular	Multicellular
Single cell	Many cells
Prokaryotes	Eukaryotes
One cell carries out all the functions to sustain life	Cells are specialised to perform specific functions required by the organism
Functions are carried out by different organelles within the cell	Functions are carried out at cellular, tissue, organ and organ system levels
Microscopic size – surface area to volume ratio limits size	Macroscopic size – increasing the number of cells allows increased body size
Short lifespan due to energetically expensive workload	Long lifespan as work is efficiently divided between specialised cells
Mostly asexual, clonal reproduction	Mostly sexual reproduction
Whole organism is involved in reproduction	Only cells specialised for reproduction will reproduce (gametes)

TABLE 4.1.1 Features of multicellular and unicellular organisms.

In this section you will explore the origin of multicellularity, the role of cell specialisation in multicellular organisms, and the advantages of being multicellular.

MULTICELLULARITY

For an organism to be considered truly multicellular:

- its cells (except the reproductive cells) must have the same DNA
- its cells must be connected and must communicate and cooperate to function as a single organism
- it must have different cells that are specialised and responsible for specific functions (one of which must be reproduction)
- its cells must be dependent on each other for survival.

The features of unicellular and multicellular organisms are listed in Table 4.1.1.

EXTENSION

Evolution of multicellular organisms

Multicellularity is thought to have evolved a number of times. However, the exact mechanism of its **evolution** is not fully understood, and it is possible that a different mechanism was involved each time. Scientists have proposed three possible mechanisms for the development of multicellularity:

- the symbiotic theory
- the syncytial theory
- the colonial theory.

The symbiotic theory

The symbiotic theory suggests that multicellular organisms developed when different species of unicellular organisms began to cooperate. Because this benefited each organism (Figure 4.1.3), over time the cells from the different species became dependent on each other for survival and began to specialise and carry out different functions. Eventually the DNA of the different species combined and a new multicellular organism evolved.

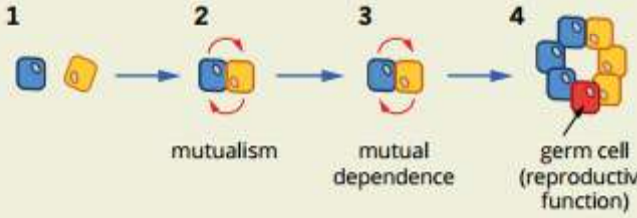


FIGURE 4.1.3 The symbiotic theory of the evolution of multicellular organisms proposes that two independent unicellular organisms (1) began to cooperate, gaining mutual benefit from their relationship (2). Eventually these two independent cells became dependent on one other for survival (3) and their cells became adapted to carry out different functions (4).

This type of mutually beneficial relationship, known as **symbiosis**, is common among living things (see Section 7.1).

A major problem with this theory is that it does not explain how the DNA of the two species would have initially combined.

The syncytial theory

The syncytial theory, also called the cellularisation theory, suggests that a single cell with multiple nuclei evolved internal membranes that partitioned each of the nuclei. The partitions then began to specialise and eventually became separate cells, forming a multicellular organism (Figure 4.1.4).

Evidence that supports this theory includes the large number of organisms such as ciliates and slime moulds that have multiple nuclei. Ciliates are protists characterised by the presence of cilia. Ciliates have two nuclei: a smaller one for reproduction and a larger one for general cell functioning. Some slime moulds (which are also protists) spend part of their life cycle as a plasmodium, which means their cells are a multinucleate mass of cytoplasm (Figure 4.1.5).

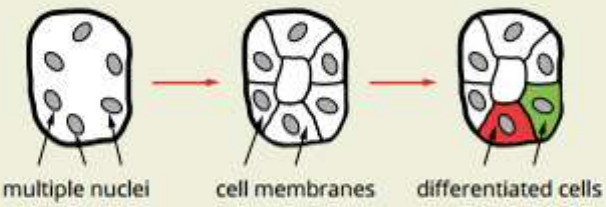


FIGURE 4.1.4 The syncytial theory proposes that multicellular organisms developed from a single-celled organism with multiple nuclei that formed internal membranes and began to specialise.

FIGURE 4.1.5 The plasmodial stage of a slime mould. In this stage of the life cycle the cells are a multinucleate mass of cytoplasm.

Two arguments against this theory are that the multiple nuclei tend to have different roles, and that they are present in only one stage in the organism's life cycle.

The colonial theory

The colonial theory suggests that when a single cell divided the new cells did not separate fully. This partial cell division continued, and the cells formed a **colony** and began to specialise and carry out different functions (see Figure 4.1.6). Eventually some formed reproductive cells and the new multicellular organism was then capable of replicating itself.

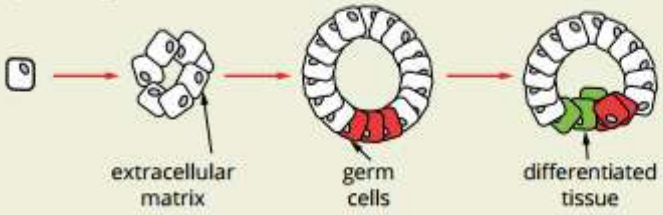


FIGURE 4.1.6 The colonial theory proposes that, during cell division, cells do not divide properly and eventually form a colony of specialised cells.

continued overleaf

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At present the colonial theory appears to be the most likely mechanism for the evolution of multicellular cells. Unlike the symbiotic theory, it explains why the DNA of cells in modern organisms is the same. Also, the formation of colonial organisms has been observed on many occasions.

An example is the unicellular amoeba *Dictyostelium*. When food is scarce the individual cells group together and move in search of food. The colony moves in a coordinated fashion, and individual cells begin to develop some specialisations.

Another example of a colonial organism is *Volvox*. A typical *Volvox* colony consists of hundreds to thousands of cells. Each cell has two flagella and an eyespot. The colony, which is shaped like a hollow ball (Figure 4.1.7), swims in a coordinated way toward light. The cells at the front of the colony have more developed eyespots, while the cells at the rear of the colony have more developed flagella. New *Volvox* colonies grow inside the sphere, and the parent *Volvox* colony turns itself inside out to release them. *Volvox* is more complex than some other colonial organisms, but it is not truly multicellular like metazoa, plants and animals. The term pluricellular is often used to distinguish this type of colonial organism from true multicellular organisms.

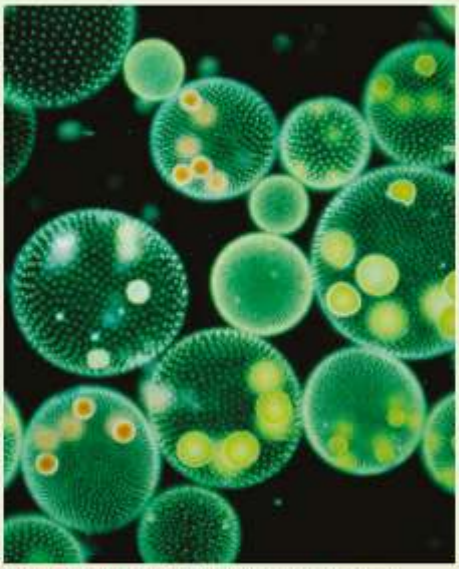


FIGURE 4.1.7 A light micrograph image of *Volvox* colonies.

BIOFILE

The earliest multicellular animals

The earliest known multicellular animals are the Ediacaran animals. They are named after the Ediacara Hills in the Flinders Ranges of South Australia where their fossils were first discovered. Ediacarans evolved more than 600 million years ago. Some resemble modern sea jellies or segmented worms. Others are unlike any other known organisms.

FIGURE 4.1.8 A representation of Ediacaran animals, the earliest known multicellular animals.

CELL SPECIALISATION

All multicellular organisms begin life as a single cell that resulted from the fusion of two highly specialised cells called gametes. These gametes are called the egg (or ovum) and sperm. Gametes are unique in being able to fuse together to form a single cell, called a zygote. This one cell contains all the genetic information required to develop into a fully functional multicellular organism. The zygote develops by cell division into an embryo (Figure 4.1.9). It is through cell replication (see Chapter 8) and cell differentiation that one single cell can become the trillions of highly specialised cells that make up an organism.

FIGURE 4.1.9 A zygote undergoing the first mitotic divisions leading to the development of a multicellular embryo.

Cell differentiation

Cell differentiation is the process by which unspecialised cells, called stem cells, become specialised cells. It takes place in all multicellular organisms. Stem cells are present in the embryo and some adult tissues of animals, and in meristem tissue in plants. Stem cells retain the ability to divide while specialised cells usually can no longer divide.

The process of cell differentiation begins shortly after fertilisation. Five days after fertilisation the human zygote becomes a blastula (called a blastocyst in mammals). This is the early stage of embryonic development, when cell differentiation begins. Embryonic stem cells originate in the blastula and make up the primary germ layers (the ectoderm, mesoderm and endoderm) that differentiate to form specialised cells, tissues and organs in animals (see Figure 4.1.10).

i Unlike most animal cells, many cells in a plant's meristem tissue are able to continue differentiating and specialising throughout their entire life.

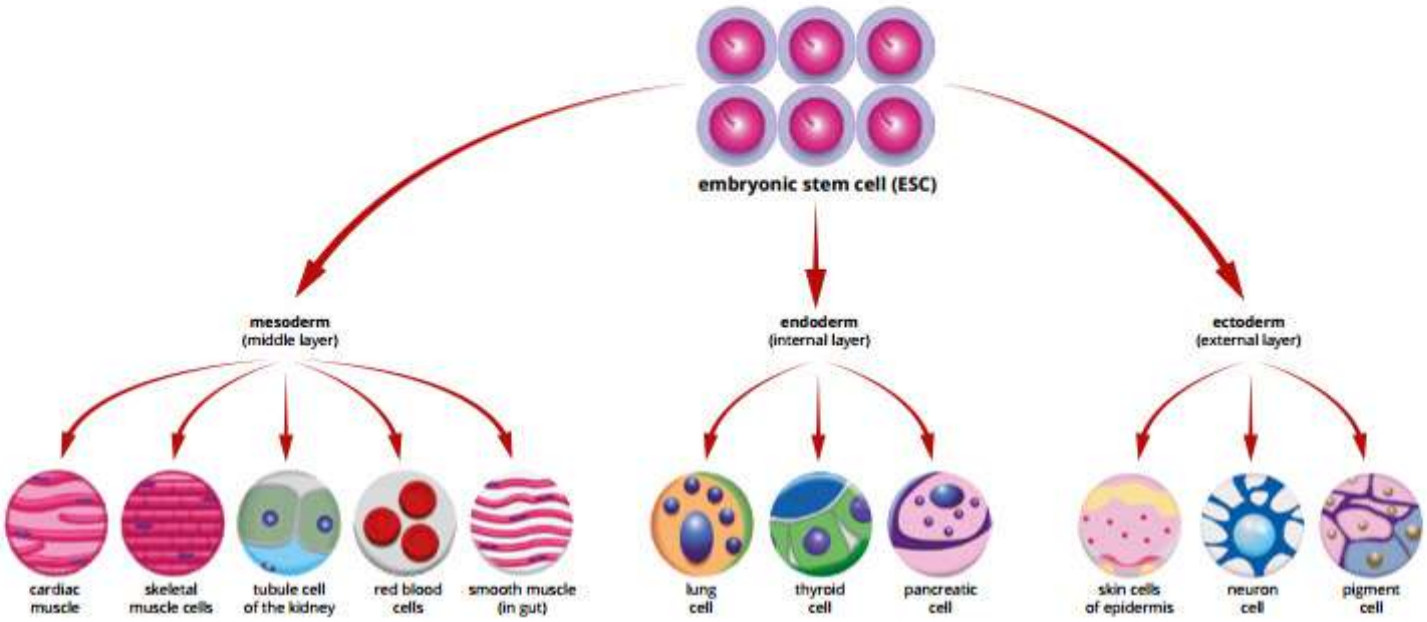


FIGURE 4.1.10 Embryonic stem cells produce every cell type required by the organism. In most multicellular organisms, stem cells make up three primary germ layers during embryonic development: the ectoderm, mesoderm and endoderm. The germ layers differentiate to form specialised cells, tissue and organs.

In plants, cell differentiation and cell specialisation derives from cells in the meristem tissue. The meristematic cells are unspecialised embryonic cells at the tips of shoots and roots (Figure 4.1.11). Organs such as leaves and flowers develop from cells in the shoot apical meristem, while root growth comes from the cells of the root apical meristem.

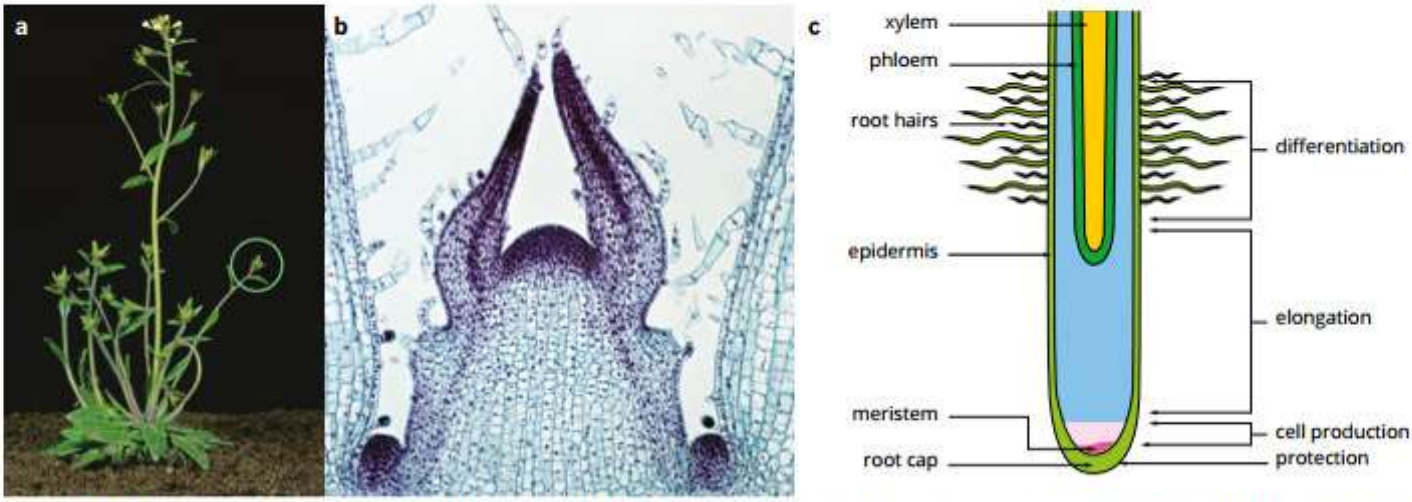


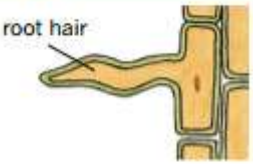
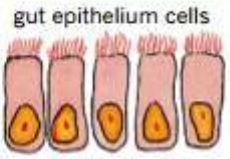
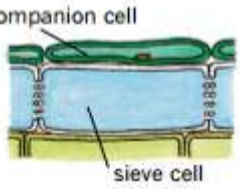
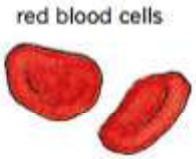
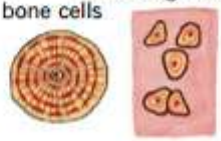
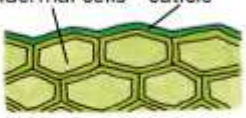
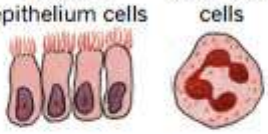
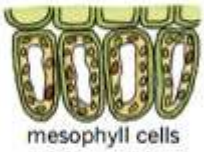
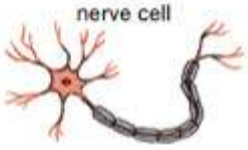
FIGURE 4.1.11 Plant cell production, growth and differentiation derives from unspecialised embryonic cells in the meristem. These cells are in the tips of shoots and roots in plants. (a) A thale cress (*Arabidopsis thaliana*) plant with the growing shoot tip highlighted. (b) Magnified image of stem cells in the shoot apical meristem. (c) The structures and regions of cell differentiation in the root meristem.

Gene expression

All the genes required to produce every type of cell needed by an organism are present after fertilisation. Gene expression is the process in which the information stored in genes is used to build the different structures in a cell. Gene expression determines how a cell will differentiate and function. In specialised cells only some genes are active or expressed. For example, in developing red blood cells, the genes for haemoglobin are expressed, while in gland cells the genes that code for different hormones, such as insulin, are expressed.

The internal and external structure of a cell is the basis for the functions it performs. Examples of the structures and functions of specialised cells in plants and animals are shown in Table 4.1.2. Cells specialisation is an advantage because cells are more efficient when they have only one function rather than many. This makes multicellular organisms much more energy efficient than unicellular organisms.

TABLE 4.1.2 The structure and function of some specialised cells in plants and animals.

Cell function	Cell specialisation	
	Plant cells	Animal cells
Exchange		
Transport		
Strength/support		
Protection/defence		
Photosynthesis		
Movement		
Communication		

A nerve cell is specialised to carry signals rapidly over long distances. It could not do this if it also had to break down food to obtain nutrients or protect against disease. A red blood cell, which is essentially a bag of haemoglobin that carries oxygen around the body, cannot also protect the organism from an invading bacterium, which is the role of white blood cells. In plants, different cells are specialised for photosynthesis, exchange of substances (with other cells or the environment) and fluid transport.

An example of animal cell specialisation: your skin

The human body consists of about 210 different types of cells. Each of these cell types differentiates from unspecialised stem cells during embryonic development.

One of the highly specialised organs of the human body is the skin, which consists of highly specialised cells. The outer layer of skin (the epidermis) alone consists of four different cell types (Figure 4.1.12), and these interact with many others. Nerve cells, red and white blood cells, muscle cells and gland cells all contribute to the correct functioning of the skin cells in their role of protection, thermoregulation and sensation.

The structures of the specialised skin cells can give you clues about their function. The keratin-producing keratinocytes are the most common type of skin cell, making up around 90 to 95% of the epidermis. The flat, scale-like structure of keratinocytes (also called squamous cells) helps them in their role of maintaining the structural integrity of the skin and tight junctions between them create an effective barrier. Keratinocytes also interact with nerve cells, antigen-processing Langerhans cells, sensory-processing Merkel cells and melanin-producing melanocytes.

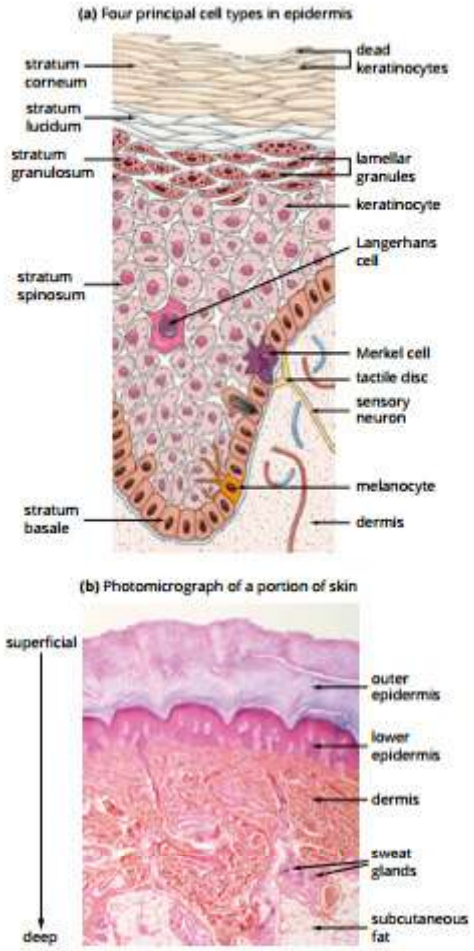


FIGURE 4.1.12 Overview of the different cell types that play a role in the functioning of the highly specialised epidermis, or upper layer, of human skin.

BIOLOGY IN ACTION

Malfunctions in specialised cells: sickle cell disease

Sickle cell disease is an inherited disorder that causes a chemical change in haemoglobin in red blood cells. This chemical change makes haemoglobin molecules form long, rigid strands that make the red blood cells sickle-shaped (Figure 4.1.13) and inflexible, blocking small blood vessels. Because of the change to the cell structure, sickle cells cannot transport oxygen effectively. Normal red blood cells have a lifespan of about 120 days, but sickle cells often die within 20 days. Sickle-cell disease can result in anaemia, pain, fatigue and joint swelling, and can be fatal if left untreated.

FIGURE 4.1.13 Two sickle cells are visible with normal, biconcave-shaped red blood cells in this coloured scanning electron micrograph.

ADVANTAGES AND DISADVANTAGES OF MULTICELLULARITY

Almost all the life forms you can see around you are multicellular, eukaryotic organisms. The microscopic prokaryotes that surround you are invisible to the naked eye, yet they are incredibly abundant, diverse, survive in a remarkable range of environments and have been around for billions of years. Despite the success of prokaryotes, multicellular organisms continue to evolve and thrive, suggesting that being multicellular with specialised cells must have its advantages. Table 4.1.3 lists some advantages and also some disadvantages of multicellularity and cell specialisation.

The advantages of multicellularity probably outweigh the disadvantages. It is not surprising then that evolution by natural selection has favoured complex multicellular organisms that are organised into tissues, organs and organ systems.

Advantages	Disadvantages
1 Multicellularity is energy-efficient because specialised cells do not waste energy trying to complete all the functions necessary for life.	**1** More cells means more energy is required for survival.
2 Multicellular organisms have longer lifespans than unicellular organisms because they are more energetically efficient.	**2** The cells cannot function independently; they are dependent on the whole organism for survival.
3 Sexual reproduction and genetic recombination promotes increasing complexity and specialisation over generations, compared to asexual, clonal reproduction in unicellular organisms.	**3** More energy is required for reproduction; most animals need to find a mate to reproduce, and most plants need another plant in order to reproduce.
4 Multicellular organisms are less vulnerable to short-term changes in their environment. There are more systems to cope with change, and cell death does not necessarily affect the survival of the organism.	**4** Populations of multicellular organisms take much longer to evolve and adapt to long-term changes in their environment because they have much longer generation times than unicellular organisms.
5 Multicellular organisms can grow significantly larger than unicellular organisms. Unicellular organisms must be small to obtain nutrients and remove waste efficiently by diffusion.	
6 Increased size and specialisation of limbs means multicellular organisms are more mobile and therefore more efficient at locating resources and avoiding predators and other negative stimuli.	
7 Multicellular organisms can perform more functions than unicellular organisms.	

TABLE 4.1.3 Advantages and disadvantages of multicellularity and cell specialisation.

BIOFILE

How many cells do you have?

A team of European scientists recently calculated that the human body is made up of about 37 000 billion cells. Most of these are red blood cells (26 000 billion), but you also have about 1.8 billion bone cells, 3 billion pancreas cells, 6 billion heart cells, 10 billion kidney cells, 15 billion muscle cells, 17 billion brain cells, 50 billion fat cells, 360 billion liver cells and 3100 billion nerve cells.

But the most common cells in your body are not part of you. In your digestive tract alone there are about 100 trillion bacteria and other unicellular microorganisms; that's almost three times the number of cells that make up your body!

FIGURE 4.1.14 The digestive tract where there are about 100 trillion bacteria and other unicellular microorganisms.

4.1 Review

SUMMARY

- For an organism to be considered truly multicellular:
  - its non-reproductive cells must have identical DNA
  - its cells must be connected and must communicate and cooperate to function as a single organism
  - it must have different cells that are specialised to carry out specific functions, one of which must be reproduction
  - its cells must be dependent on each other for survival.
- Multicellularity is thought to have evolved a number of times. The colonial theory is the most likely explanation for the evolution of multicellular organisms.
- Cell replication and differentiation enable a single cell to produce the trillions of highly specialised cells that make up an organism.
- Specialised cell function results from expression of particular sets of genes.
- The internal and external structures of a specialised cell are related to the function it performs.
- Despite the success of prokaryotes, multicellular organisms continue to evolve and thrive, suggesting that being multicellular with specialised cells must have its advantages.
- Advantages of multicellularity:
  - Increased size and mobility helps organisms find ideal conditions and avoid predators and negative stimuli.
  - Organisms are less vulnerable to short-term environmental changes.
  - Cell specialisation results in energy efficiency.
  - Organisms can perform more complex functions.
  - Longer lifespans.
  - Increased complexity over generations through sexual reproduction and genetic recombination.
- Disadvantages of multicellularity:
  - More energy is required for survival and reproduction.
  - Cells cannot function independently.
  - It takes longer for populations to evolve and adapt.

KEY QUESTIONS

1 What are the four characteristics that an organism must have to be considered truly multicellular?

The tawny frogmouth (*Podargus strigoides*) and the narrow-leaved black peppermint (*Eucalyptus nicholii*) it is sitting in, are clearly multicellular organisms.

2 List five differences between unicellular and multicellular organisms.

3 What is cell differentiation and why is it important for multicellularity?

4 Explain how cell differentiation differs in animal cells and plant cells.

5 What is it that determines how a cell will differentiate and what functions it will perform?

4.2 Levels of organisation in multicellular organisms

FIGURE 4.2.1 A complex multicellular organism such as a lion is more than just a mass of specialised cells. The cells are organised so that they can work together.

A multicellular organism can consist of many trillions of cells. In a mammal, such as a lion or human, these cells consist of hundreds of different types of specialised cells (see Figure 4.2.1). Examples of these include muscle cells, red blood cells, bone cells and nerve cells. Each of these cell types has a specific function that contributes to the survival and reproduction of the whole organism.

While multicellularity has many advantages, it also has a number of challenges. An individual muscle cell is capable of shortening, yet on its own could not possibly bring about movement in a large organism. The same muscle cell will require nutrients and oxygen and produce waste. To ensure the cells can carry out their functions correctly and maintain healthy systems, the organism must expend energy finding the resources to fuel all of its cells.

In this section you will look more closely at multicellular organisms and how they are organised to overcome these challenges and take full advantage of multicellularity.

LEVELS OF CELLULAR ORGANISATION

A cell must be able to obtain nutrients and remove waste, and physical conditions such as temperature, solute concentration and pH must remain within the tolerable limits of the cell. If any of these conditions are not met in a multicellular organism, the cell could die.

One advantage of being a large multicellular organism is that most body cells are isolated from the external environment by a protective outer layer called the epidermis. This outer layer provides a buffer against changes in the external environment, allowing conditions on the inside of the organism to be maintained at suitable levels for the efficient functioning of cells.

However, the isolation of the internal environment from the external environment means that most cells do not have direct access to their essential requirements such as oxygen. It also means that wastes expelled from the cells need to be removed from the internal environment so that they do not accumulate there. As an organism increases in size and complexity, greater cooperation and coordination is required between its cells—the cells must be organised. In fact, the term organism is derived from the French word *organisme*, which means 'organise'.

Multicellular organisms, depending on their complexity, can be organised into the following levels to provide the needs of the entire organism:

- specialised cells
- tissues
- organs
- systems.

Specialised cells

Specialised cells are cells that have a specific function. All cells are adapted to perform particular jobs in a multicellular organism and have unique structural adaptations that enable them to carry out these functions. These specialised cells are the building blocks of complex tissues and organs in multicellular organisms. Examples of specialised cells in plants are root hairs, palisade cells and guard cells. In animals they include myocytes (muscle cells), erythrocytes (red blood cells), epithelial cells and neurons.

Tissues

Specialised cells are organised into tissues. Tissues are groups of similar cells working together to carry out a particular function in a multicellular organism. For some organisms, this level of organisation is sufficient to meet all its needs.

But as organisms become more complex, tissues alone may not be enough to carry out all the tasks required, and so tissues have evolved to group together in distinct structures called organs.

Organs

An organ consists of two or more tissues that work together to perform one or more specialised tasks. An organ is commonly recognisable as a distinct structure. Examples of organs are flowers, leaves and roots in vascular plants, and the heart, liver and brain in mammals.

Systems

In multicellular organisms, an organ rarely functions independently of other organs. Instead, organs form an organ system, commonly referred to simply as a system. A system is a group of organs that work together to perform a vital task, such as the circulatory and respiratory systems in humans.

Organisms

The final level of organisation is the organism itself. In a complex animal, systems work together and contribute to the successful functioning and reproduction of the whole organism (Figures 4.2.2 and 4.2.3).

As biological structures and functions become more complex, cells become more and more specialised.

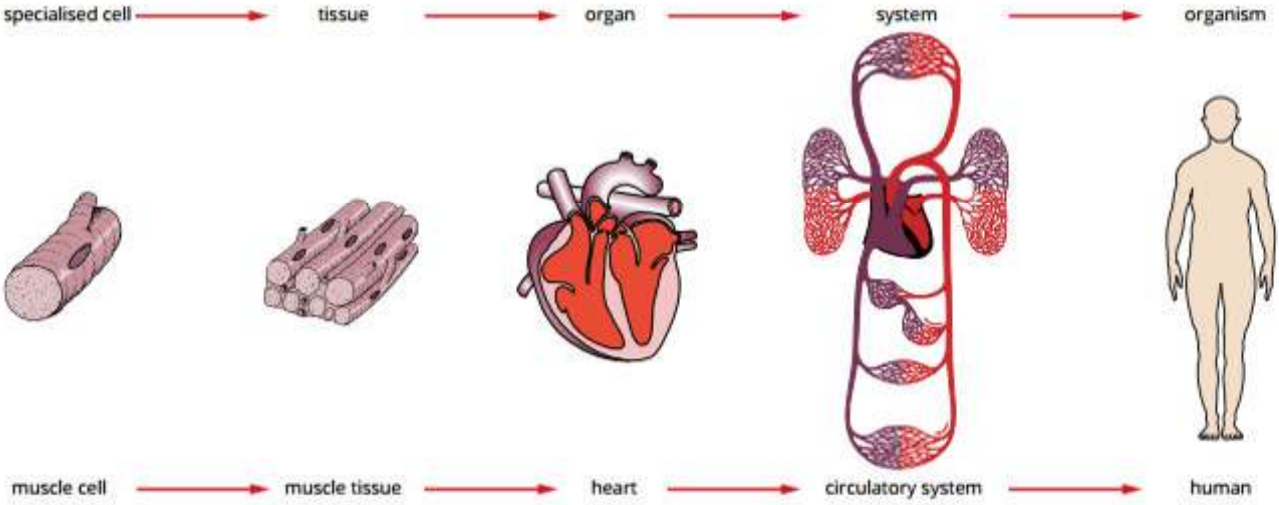


FIGURE 4.2.2 The levels of organisation in a complex multicellular animal: cell, tissue, organ, system and organism.

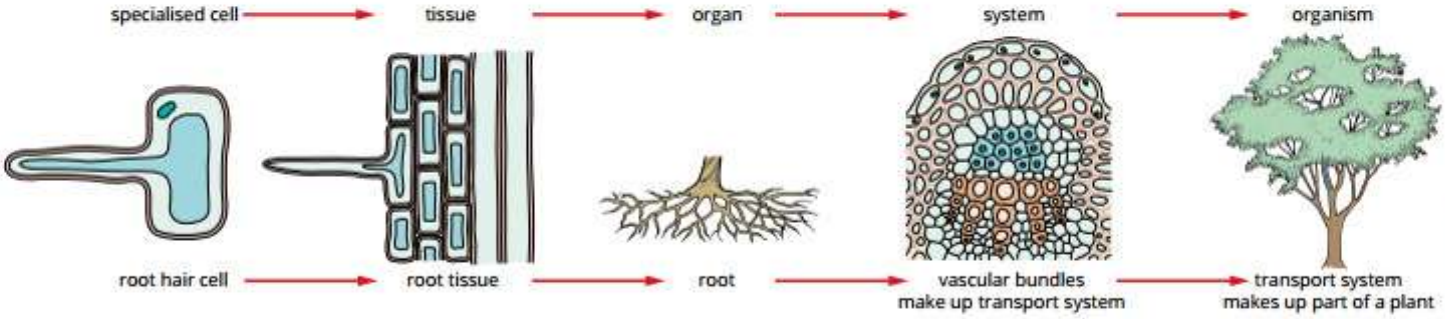


FIGURE 4.2.3 The levels of organisation in a complex multicellular plant: cell, tissue, organ, organ system and organism.

ORGANISATION IN SIMPLE MULTICELLULAR ORGANISMS

Some multicellular organisms are organised only at the cellular level. This includes simple multicellular organisms such as sponges and sea jellies. These animals are considered to be tissue-less multicellular organisms, as their cells are not organised into discrete, functioning systems within the organism.

Although simple multicellular organisms are more complex than unicellular organisms like *Euglena*, they can survive without organising their cells into true tissues and organs because they are often only a few cells thick (Figure 4.2.4). This means that materials can diffuse easily into and between cells. This lack of organisational complexity also means that many simple multicellular organisms, such as sponges and sea stars, can regenerate, building new limbs or even an entirely new organism from just a tiny piece of their body or a single cell.

In sponges, the body is hollow and consists of two layers of eukaryotic cells separated by a jelly-like substance. The outer layer protects the sponge and also contains tiny pores through which water and their food can enter. Sponges are filter feeders, filtering plankton, bacteria, dinoflagellates and many other microscopic organisms from the water around them. Digestion is carried out within food vacuoles inside the cells of the sponge. The inner layer consists of a number of cell types, including collar cells and amoebocytes (see Figure 4.2.4).

BIOFILE

Sponge defences: complex specialisations in simple organisms

Sponges are simple multicellular animals found in marine environments, often fixed to rocks and reefs. They have some interesting defences that protect them against predators and disease-causing organisms. Sponges produce toxins that prevent predators from eating them, and powerful antibiotics that fight infection from bacteria. Scientists are studying these chemicals as possible new drugs for human use.

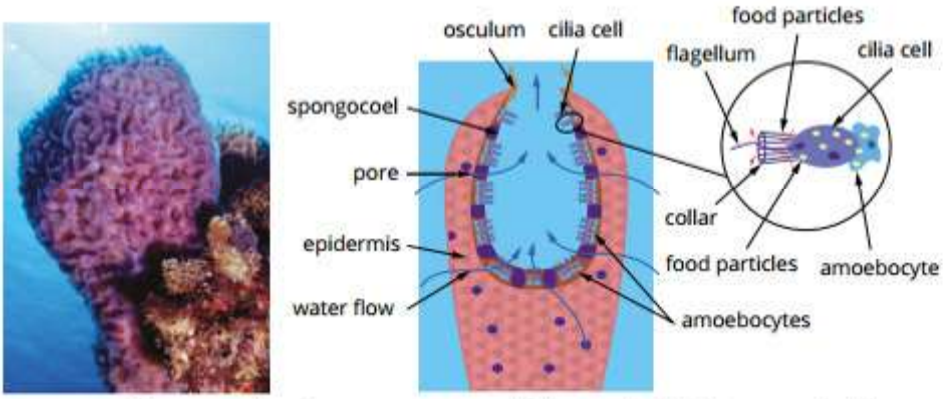


FIGURE 4.2.4 Sponges such as the azure vase sponge (*Callyspongia plicifera*) are organised at the cellular level, with different types of cells performing different functions. Although the cells work together, they do not form true tissues or organs. Sponges are often referred to as tissueless multicellular organisms.

Despite the simple organisation of these organisms, each of the different cell types found within them has a specialised function that contributes to their survival and reproduction (Table 4.2.1). An example of a highly specialised cell in a simple multicellular organism can be seen in Figure 4.2.5.

Cell type	Function	Structure
epidermal cells	• protect the inner layer of cells	• thin, leathery • closely packed together
collar cells	• move water through the sponge's pores and into the central cavity (spongocoel) using the motion of their flagella • absorb nutrients	• flagella • hollow 'collar'
amoebocytes	• ingest and digest food caught by the collar cells • transport nutrients to the other cells of the sponge	• mobile and flexible

TABLE 4.2.1 Structure and function of specialised cell types in sponges.

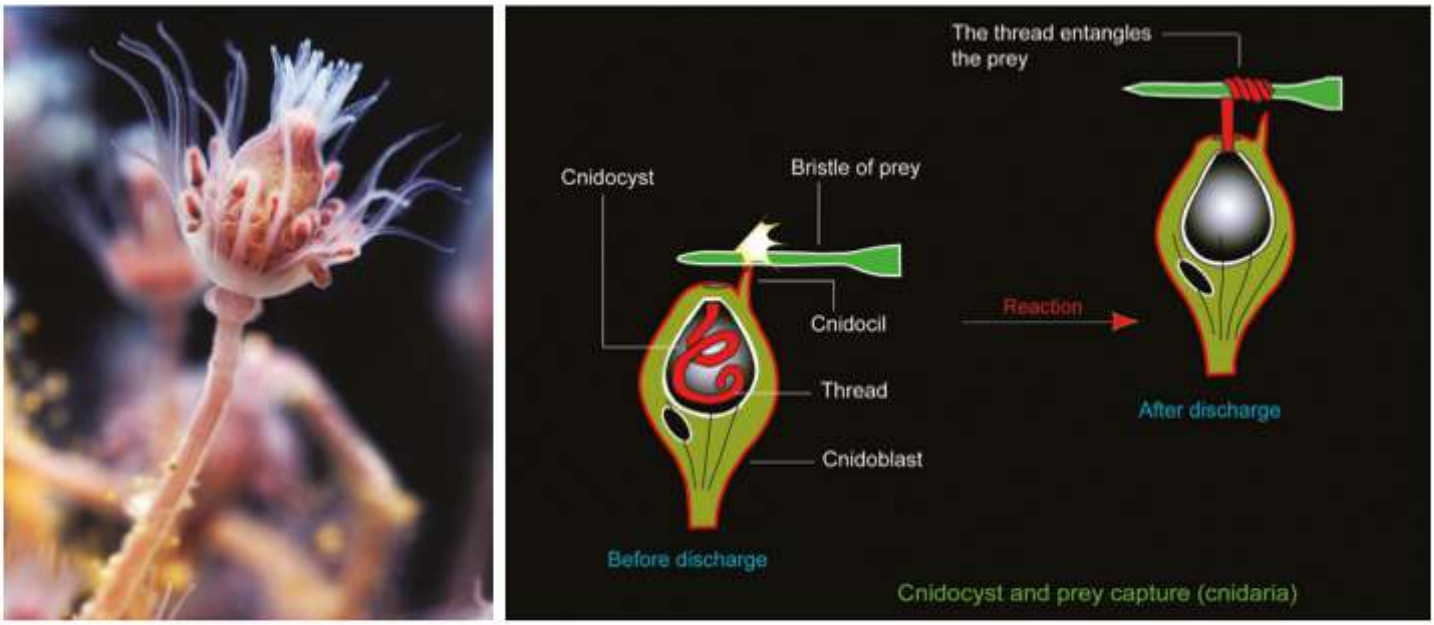


FIGURE 4.2.5 Simple multicellular organisms often have complex, specialised cells. This cnidarian (*Ectopleura larynx*) is a marine animal with cells along its tentacles called cnidocytes or nematocytes. These cells are specialised to capture prey. A thread is fired from the cnidocyst, a capsule within the cnidocyte, wrapping around and trapping prey. Other cnidarians, such as sea jellies or anemones, have cnidocysts that contain toxins that sting and paralyse prey.

ORGANISATION IN COMPLEX VASCULAR PLANTS

A cellular level of organisation cannot meet the needs of larger and more complex organisms such as vascular plants. Consequently, cells in complex plants such as angiosperms (flowering plants) and conifers are organised into higher levels of organisation: tissues, organs and organ systems.

In comparison, non-vascular plants, such as algae and mosses, do not have vascular tissue or true organs. Instead they have simplified tissues and absorb water directly through their cell walls, transporting it between cells via osmosis. The absence of vascular tissue in non-vascular plants also limits their size due to the lack of structural support and limited area over which they can transport water and nutrients.

Specialised cells in vascular plants

Specialised cells are cells that are adapted to carry out a specific function. Some of the most important functions in vascular plants are involved in the transport of nutrients and water and acquiring energy via photosynthesis. There are many specialised cells within the vascular tissue of plants for these functions. You will learn more about these specialised cells in Section 4.3.

Tissues in complex plants

The characteristic tissues in vascular plants (and the basis of this type of plant's name) are the vascular tissues, which are involved in the transport of water and nutrients throughout the plant. There are two types of vascular tissue: xylem and phloem.

Organs in complex plants

The major organs of vascular plants are as follows:

- Roots—responsible for absorbing and storing water and nutrients (mineral ions) required by the plant from the soil. Roots also function to support and anchor the plant to the ground. Root systems are often extremely complex and can be much larger than the above ground structures of the plant. The large root systems of many trees in nutrient-poor rainforest soils do not penetrate deep into the soil layers and instead grow above ground (Figure 4.2.6).

FIGURE 4.2.6 Two major organs of vascular plants are the leaves and roots, both of which are visible in this Amazonian tree with exposed buttress roots.

FIGURE 4.2.7 Several of the major organs of vascular plants can be seen on this orange tree, including leaves, flowers, fruits and stems.

- Leaves—the primary organ of photosynthesis. Photosynthesis is carried out to convert light energy into the chemical energy that fuels the organism's cells. The overall shape and organisation of leaves makes them well suited for their purpose. The major tissues making up a leaf are the epidermis, photosynthetic tissue and vascular tissue. The vascular tissue (xylem and phloem) is visible as veins in the leaf structure (Figure 4.2.7).
- Stems—primary functions of the stems are to support the plants leaves, flowers and fruit; to store nutrients; to transport water and nutrients between the roots and the shoots; and to grow new plant tissue. The stem is made up of three tissue types: dermal tissue, ground tissue and vascular tissue. The structure of stems varies widely between different species. The stems of strawberry runners are flexible and fleshy, while the stem or trunk of an oak tree is thick and woody. Some stems are even edible, such as asparagus and celery stalks.
- Flowers—the reproductive structures found in angiosperms. The function of a flower is to facilitate the fertilisation of the ovules (contained within the ovary) by the sperm (contained within pollen). The structures of many flowers are highly specialised to attract pollinators, such as bees, moths and fruit bats, to disperse the pollen from one flower to another. Other flowers produce pollen that is specialised for wind dispersal. Following fertilisation, the seeds develop and the surrounding ovary grows into a fruit.
- Fruits—protect the developing seeds of the plant and help seeds to disperse from the parent plant. Fruits develop from the mature ovaries of flowers and often have a fleshy outer layer that surrounds the seeds. The outer structure of the fruit is often specialised to attract animals that aid in the dispersal of the seeds. Some animals, such as birds, eat the fruit and later excrete the seeds, while other animals disperse seeds that have attached to their fur. Examples of fruits are berries, peaches, tomatoes, nuts and legumes.

Systems in complex plants

Vascular plants have two organ systems: the root system and the shoot system (Figure 4.2.6). The root system is usually underground and functions to support the structure of the plant and absorb water and nutrients from the soil. The shoot system is made up of two parts: the non-reproductive (vegetative) parts of the plant, such as leaves and stems, and the reproductive parts, such as flowers and fruits. You will learn more about vascular plants in Section 4.3.

ORGANISATION IN COMPLEX ANIMALS

The animal kingdom includes the most complex types of multicellular organisms. An organ level of organisation is not enough to meet the needs of the most complex animals. For this reason, specialised cells of complex animals are organised into tissues, organs and systems.

Specialised cells in complex animals

Most complex animals are made up of hundreds of different cell types that are specialised to perform different functions. The roles of these cells are critical to the healthy functioning of the tissue, organ and organ systems of animals.

Tissues in complex animals

Specialised cells working together to complete a specific function are called a tissue. For example, a human red blood cell is perfectly adapted to absorbing and releasing oxygen as it travels around the body. However, one red blood cell cannot possibly carry all the oxygen that a human body needs. Billions of red blood cells need to work together to meet the needs of a human.

Cells do not need to be identical to be considered a tissue; they just need to be working together to carry out a particular function. Blood, for example, is a tissue that consists of red blood cells, white blood cells and platelets all working together.

Tissues in vertebrates are grouped into four basic types (Figure 4.2.8):

- muscle tissue, formed by cells that can contract (for example, skeletal and cardiac tissue)
- nerve tissue, consisting of highly specialised cells called neurons that sense stimuli and transmit signals (Figure 4.2.9). This is essential for communication and coordination in complex multicellular animals.
- connective tissue, forming the supporting and connecting structures of the body (for example, bone and blood)
- epithelial tissue, one or more layers of cells that cover most internal and external surfaces of the organism (for example, skin and intestinal lining).

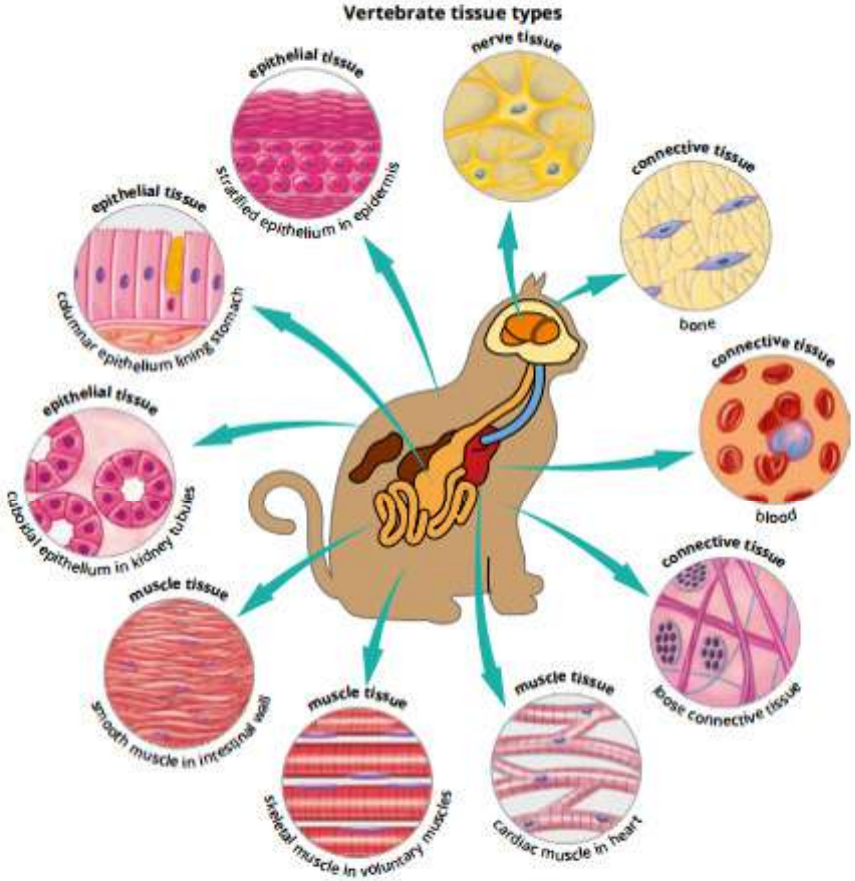


FIGURE 4.2.8 Complex multicellular organisms are made up of a diverse array of tissue types, specialised for many different functions.

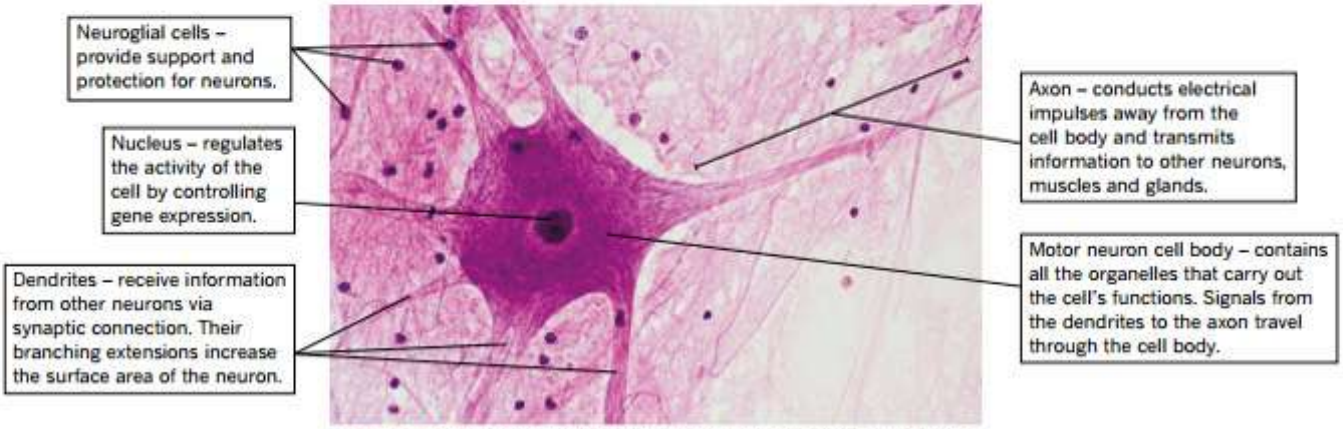


FIGURE 4.2.9 Motor neuron cell and surrounding neuroglial cells from the spinal cord. These specialised structures are part of the tissue of the nervous system that is responsible for communicating signals that regulate and control bodily functions and activity in animals.

Organs in complex animals

FIGURE 4.2.10 The head of a median wasp (*Dolichovespula media*), showing the external structure of the compound eyes.

An organ is a structure made up of two or more tissues that perform a specific function. Some of the many organs in complex animals include the eye, skin and heart.

The eye

The function of the eye organ is vision. Insects have compound eyes that consist of thousands of individual units called ommatidia (Figures 4.2.10 and 4.2.11). Each ommatidium is like a single eye and collectively they are oriented to receive light from different directions, giving an insect a very wide angle of view. Each ommatidium consists of a lens, crystalline cone, light sensitive visual cells and pigment cells (Figure 4.2.11). The pigment cells ensure that light hits the visual cells at the correct angle. The visual cells transfer a message to the optic nerve, which transmits information to the brain.

Insect vision is quite different to that of humans. The image generated is more like a light and dark mosaic, rather than a sharp image. Insect eyes are also capable of detecting very fast movement from a wide range of directions. This is why insects always seem to react very quickly to danger, such as a human hand.

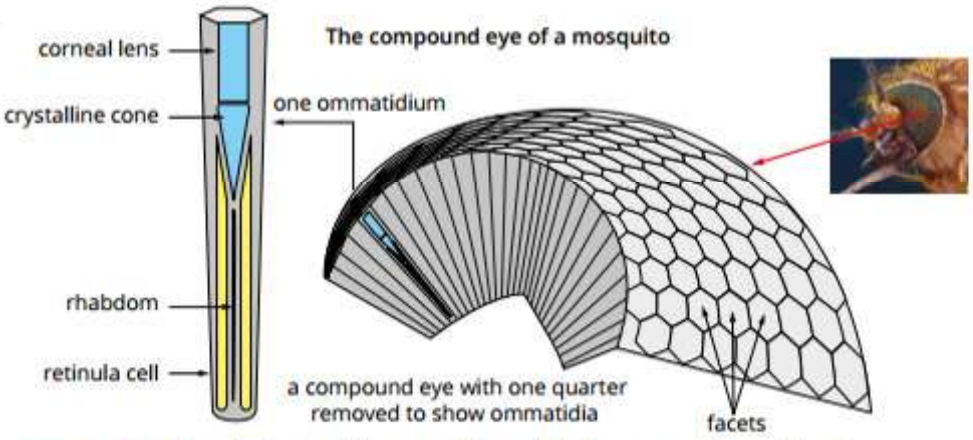


FIGURE 4.2.11 Internal structure of the ommatidium within the compound eyes of insects.

Skin

The largest organ of the human body is the skin. In an average adult, the skin is over 1.8 square metres and makes up 6–10% of the body's total weight. It is considered to be an organ as it carries out a number of specific functions, including regulating temperature, preventing water loss and sensing the environment. Skin also provides a protective barrier and contributes to a stable internal environment for the other cells, tissues, organs and systems that make up a human.

Skin in humans is divided into three layers: epidermis, dermis and subcutis (the subcutaneous fatty layer) (Figure 4.2.12).

The epidermis is the outermost layer and consists mostly of keratinocytes. Keratinocytes are cells that contain keratin and create a tough, waterproof layer for the body. The outer layer of the epidermis consists of dead cells, which are continually replaced by dividing cells below. This layer of dead cells varies enormously over the body and is ten times thicker on the soles of the feet than on the face.

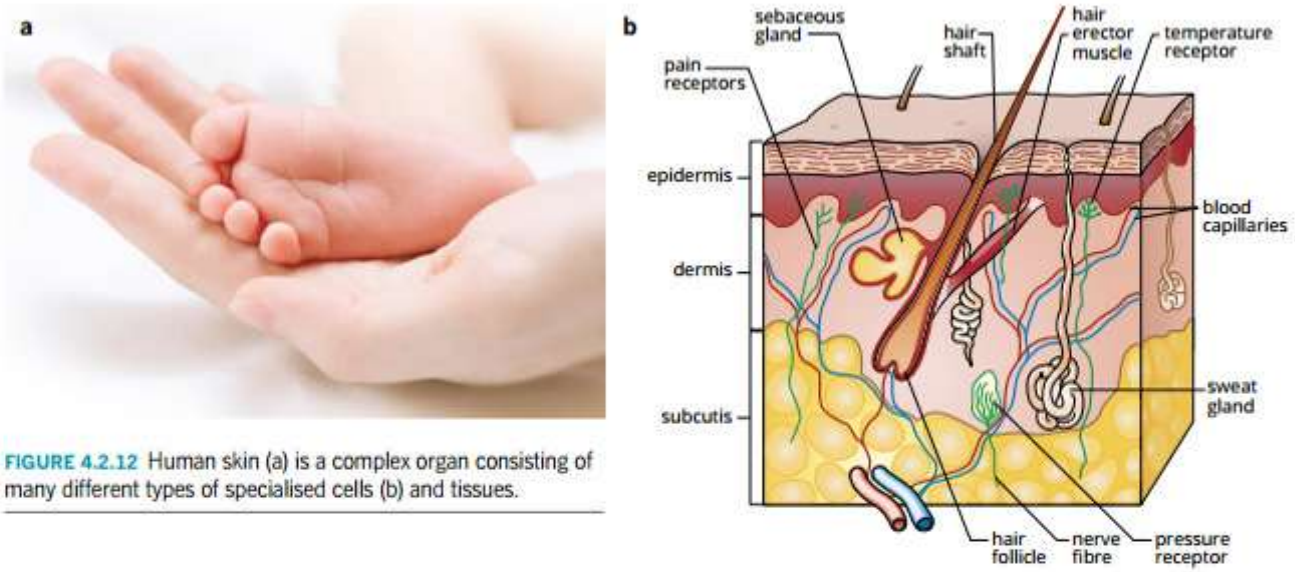


FIGURE 4.2.12 Human skin (a) is a complex organ consisting of many different types of specialised cells (b) and tissues.

The dermis includes a range of nerves and receptors to sense external stimuli such as temperature, pressure and touch. Some touch receptors are attached to hair cells, while pain receptors are close to the surface of the skin in the dermis or epidermis. Sweat glands aid in cooling by releasing a watery substance onto the epidermis via pores. Sebum is released by the sebaceous glands to help keep the skin and hair cells pliable. Sebum is also thought to have a mildly antiseptic effect on bacteria because of some of the fatty acid molecules present. The dermis has a rich supply of blood vessels that control blood flow through the skin, regulating the body temperature of the whole organism. The dermis also contains fibres of collagen and elastin, which give the skin strength and elasticity.

The final layer of human skin, the subcutis, consists mainly of fat cells. These act as a food reserve for the body and also provide insulation and cushion physical impact.

The heart

The heart beats continuously throughout the life of the organism, transporting nutrients and oxygen to cells and assisting in the removal of carbon dioxide and other waste products of cells. In a single year, the human heart beats over 30 million times!

The heart is actually two separate pumps. The right-hand pump receives blood from the body and pumps it to the lungs. The left-hand pump receives blood from the lungs and pumps it to the body.

Blood moves from the right ventricle to the lungs, where oxygen binds to the haemoglobin in the red blood cells and carbon dioxides diffuses into the lungs and is exhaled. Oxygen-rich blood then returns to the heart via the left atrium and moves to the left ventricle, which pumps the blood under high pressure to the body via the aorta. Blood eventually returns to the heart via the right atrium, completing the circuit (see Figure 4.2.13).

The heart consists of a number of tissues. Most of the heart is composed of cardiac muscle tissue, which contracts to force blood through the heart and out to the body. Connective tissue makes up valves, which ensure blood moves through the heart in the right direction.

Nerve tissue controls the heart rate. The most important nerve tissue is the sinoatrial node located in the right atrium. This node generates the electrical impulses that sweep across the heart causing it to contract and pump blood. It is often referred to as the natural pacemaker.

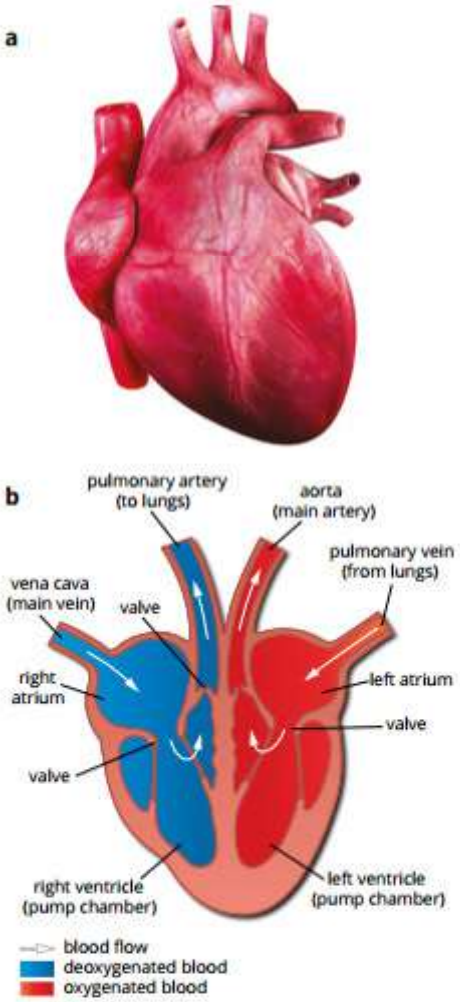


FIGURE 4.2.13 The human heart, from (a) anatomical and (b) diagrammatic perspectives. The diagram shows the direction of blood flow into the heart through the veins, to the atria and ventricles. Blood then flows out of the heart, either to the lungs via the pulmonary artery or to the rest of the body via the aorta.

BIOLOGY IN ACTION

Organs on chips could end animal testing

The development of micro-devices that simulate organ-level functions could revolutionise the research and development of drugs and potentially end the need for animal testing. The organs-on-chips are being developed by researchers at Harvard University to mimic the mechanical and chemical functions of organs on a micro-scale. The technology will enable much faster, cheaper and accurate research and testing of the safety and effectiveness of drugs, cosmetics, cleaning products and environmental pollutants, while reducing the need for the ethically unsound use of animals in the laboratory.

The memory stick-sized chips are made from a clear, flexible polymer membrane that is lined with living human cells. The membrane sits at the centre of the chip, surrounded by fluid and air conducting micro-channels. Because the chips are transparent, scientists are able to observe the internal physiological processes of the organs in real time (Figure 4.2.14). The organs-on-chips give scientists insight into the functioning of cells, tissues and organs in a way that has never before been possible.

Lung, kidney, liver, bone marrow and peristaltic gut-on-a-chip have already been completed, and skin-on-a-chip is currently under development. The lung-on-a-chip consists of a porous membrane coated with human capillary cells on one side and human lung cells on the other side. Air flows through a channel on the lung cell side, while blood-like fluid containing red and white blood cells flows on the capillary side. A vacuum simulates the motion of breathing, stretching and relaxing the cells on the chip as if they were in a lung in a living organism (Figure 4.2.15). Using the lung-on-a-chip, researchers have mimicked the effects of a lung infection. After introducing bacteria to the air channel, scientists observed white blood cells crossing the membrane to engulf bacteria that were attaching to the lung cells.

By 2017, the researchers hope to have ten organs-on-chips ready for testing. Once enough micro-organs have been developed, scientists can connect them to simulate a whole human system. This research paves the way for truly personalised medicine—your cells can be used to test drug compatibility and effectiveness.

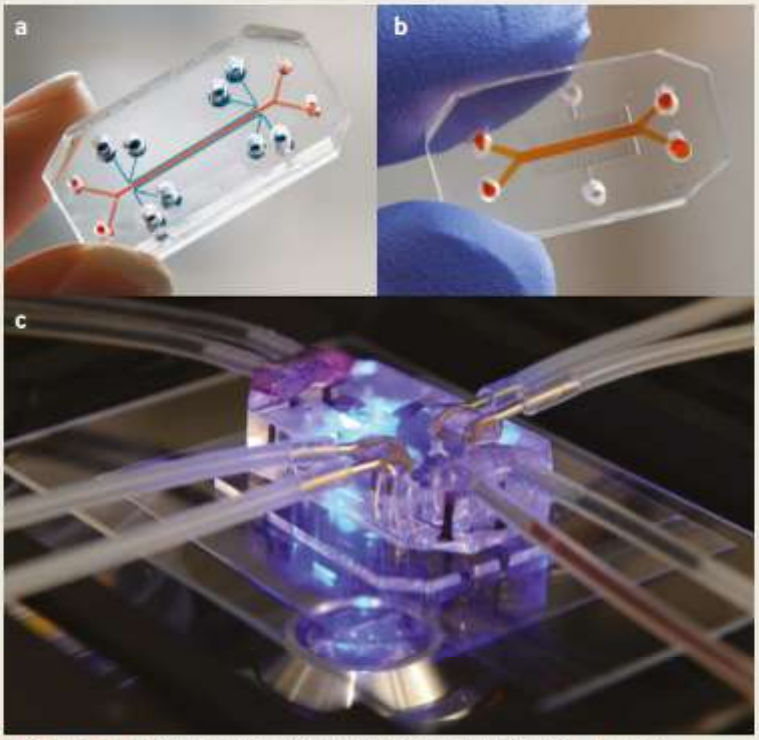


FIGURE 4.2.14 The lung-on-a-chip (a) and gut-on-a-chip (b) simulate the functions of living human organs. A series of micro-channels through the chip deliver vital fluids and gases to living cells (c). Organs-on-chips have enormous potential for the research and testing of drugs and chemicals, potentially ending the need for animal testing.

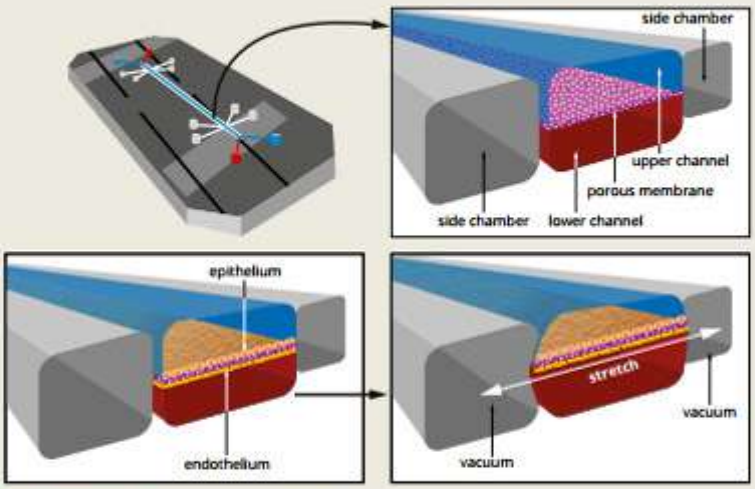


FIGURE 4.2.15 Internal view of a lung-on-a-chip lined with living human lung cells (epithelium) and capillary cells (endothelium). Air flows through the upper channel across the lung cells, while the lower chamber conducts blood-like fluid. The side chambers function as vacuums to mimic the stretching and relaxing motion of breathing lungs.

Systems in complex animals

The organisation of cells into tissues may be enough to fulfil the biological requirements of simple animals, but more complex animals require further organisation of their organs. Systems are groups of functionally similar organs working together as a unit.

The major systems in complex animals are as follows:

- respiratory system
- circulatory system
- digestive system
- excretory system
- immune system
- nervous system
- endocrine system (glands and hormone secretion)
- reproductive system
- muscular system
- skeletal system
- integumentary system (skin, hair, nails and sweat glands).

Many animals have systems that perform similar functions, but the structure can vary greatly between organisms (Figure 4.2.16). The circulatory system is an example of how systems can be structured differently but still carry out the same functions. In humans and all other vertebrates the circulatory system is a closed system. In a closed circulatory system the blood is enclosed within a system of blood vessels and the heart. Some invertebrates, such as earthworms, also have a closed system (Figure 4.2.16).

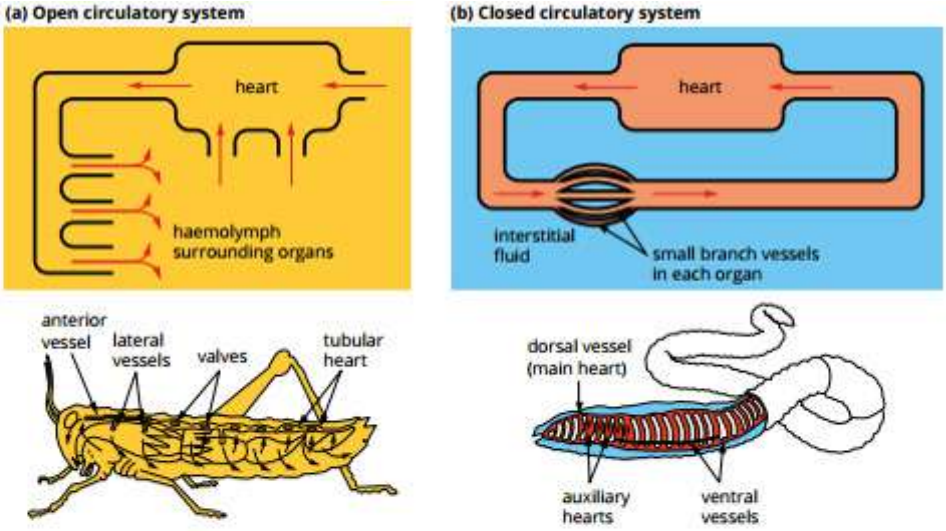


FIGURE 4.2.16 The open circulatory system of a grasshopper (a) and the closed circulatory system of an earthworm (b) have a number of significant differences, but both systems have the same function. Both systems supply the cells of the body with nutrients and oxygen and transport wastes away from the cells to the organs that excrete them.

Arthropods, including insects, have an open circulatory system. An open circulatory system has a heart or heart-like structure but no blood vessels (see Figure 4.2.16). There is also no distinction between blood and extracellular fluid. This single fluid in open circulatory systems is called haemolymph. The haemolymph is in direct contact with all cells and is kept moving by the beating of the heart and sometimes the movement of the organism itself.

Organ systems in complex animals are examined in more detail in Section 4.4.

EXTENSION

Respiratory systems

All animals need oxygen and produce carbon dioxide, which must be transported out of the organism. The respiratory system is responsible for these functions in complex animals. It is important to distinguish the organ system of respiration from cellular respiration. Cellular respiration functions to convert nutrients to energy within a cell, while the organ respiratory system in complex animals transports carbon dioxide and oxygen between cells and the external environment. The following looks at three different respiratory systems that accomplish this task.

Insect respiratory system

Insects exchange oxygen and carbon dioxide between the atmosphere and their cells directly. There is no circulatory system involved. Gas exchange takes place across a network of fine internal air-filled tubes—the tracheae and the finer tracheoles—that open to the atmosphere through spiracles that can open and close (see Figure 4.2.17). The tracheoles branch into smaller and smaller tubes, reaching all tissue. Oxygen moves into the tissues and carbon dioxide enters the tracheae to be expelled from the body.

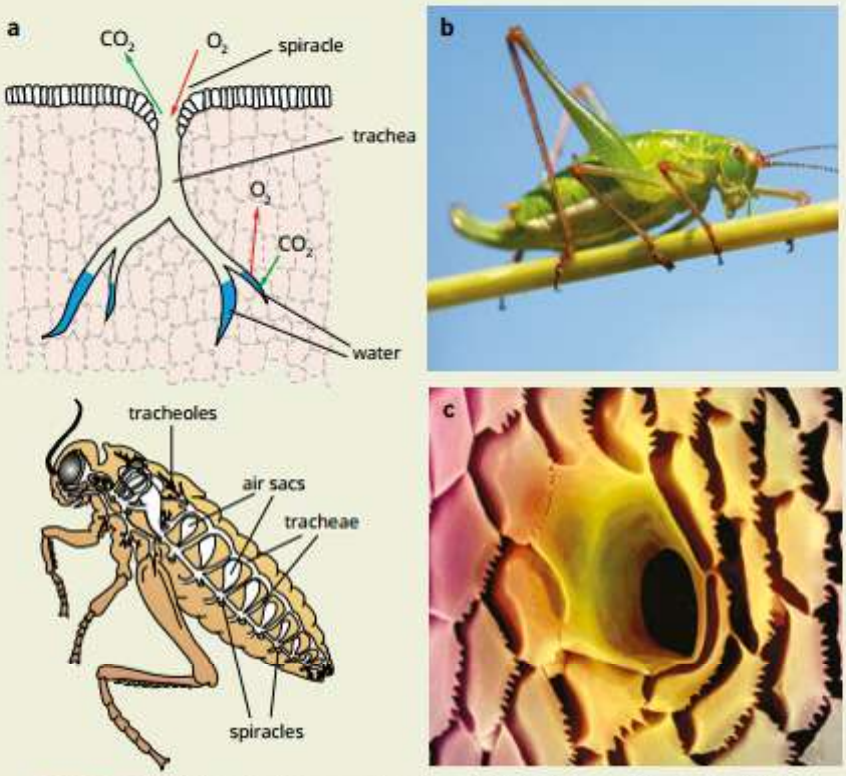


FIGURE 4.2.17 (a) Insects have a system of air-filled tracheae and tracheoles that penetrate every tissue, bringing air into close contact with their cells. (b) Some insects, like this grasshopper, also have air sacs that can be pumped like bellows to move air through the system. (c) Coloured SEM of an ant spiracle.

This process of gas exchange is quite slow, so some larger insects pump their abdomens to help speed up the movement of these gases. Some insects, such as grasshoppers, also have air sacs that can be pumped like bellows to move air through the system.

The structure of this type of respiratory system is one of the factors that limits the size of insects.

Fish respiratory system

Gills are the principal organs of the respiratory system in fish. Oxygen is not very soluble in water, so the respiratory system needs to be very efficient. Fish gills are composed of several gill arches on either side of the pharynx (throat) (see Figures 4.2.18 and 4.2.19). Each gill arch is composed of rows of filaments, which in turn are composed of lamellae. The lamellae are closely packed rows of leaf-like structures where oxygen diffuses into the blood and carbon dioxide diffuses from the blood into the surrounding water. Water is drawn into the pharynx through the mouth and then pushed between the gill arches by compressing the pharynx with the mouth closed. This forces water between individual gill lamellae. The lamellae provide a large surface area for gas exchange and are visibly red because they contain many blood vessels. Water then passes out under the operculum, which covers and protects the fragile gills.

FIGURE 4.2.18 The gill arches of this juvenile Mediterranean dusky grouper (*Epinephelus marginatus*) can be seen along the side of its pharynx.

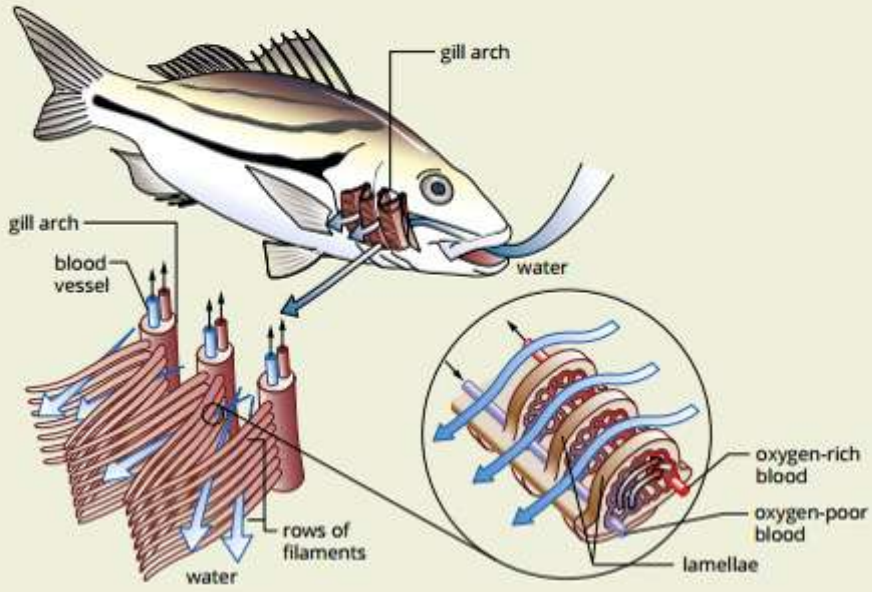


FIGURE 4.2.19 Water flows in one direction across fish gills: through the mouth and pharynx, past the gills and out under the operculum.

BIOFILE

Ram ventilation

To increase water flow across the gills and improve the efficiency of gas exchange, some very active fish such as tuna use a technique called ram ventilation. In this process the fish swims in a straight line with its mouth open, thus increasing water flow across the gills.

FIGURE 4.2.21 Fish such as this Atlantic bluefin tuna (*Thunnus thynnus*) often swim with their mouths open to create a fast, continuous flow of water across their gills.

Bird respiratory system

Birds have the most efficient respiratory system of all animals. Most birds can fly and are usually very active. This means a bird has a high demand for oxygen and needs to be light.

As with mammals, gas exchange for birds takes place in the lungs. Bird lungs are similar to those of mammals, but instead of alveoli they have a system of microscopic tubules called air capillaries. In the air capillaries, oxygen moves into the blood and carbon dioxide moves from the blood into the lungs to be exhaled.

Birds have relatively small lungs that do not expand and contract like those of a mammal. Unlike mammals, birds do not have a diaphragm, but instead rely on pressure changes in air sacs to move air in and out of their respiratory system (Figure 4.2.20). The respiratory system of a bird has seven, eight or nine air sacs, depending on the species. During inhalation, air is drawn into the posterior air sacs and air from the lungs moves into the anterior air sacs. During exhalation the air sacs collapse, which pushes air from the posterior air sacs into the lungs. At the same time the air in the anterior air sacs is expelled via the trachea. This process of exhalation creates a one-way flow of fresh air through the bird's lungs, which is extremely efficient. The large number of air sacs also makes the bird very lightweight.

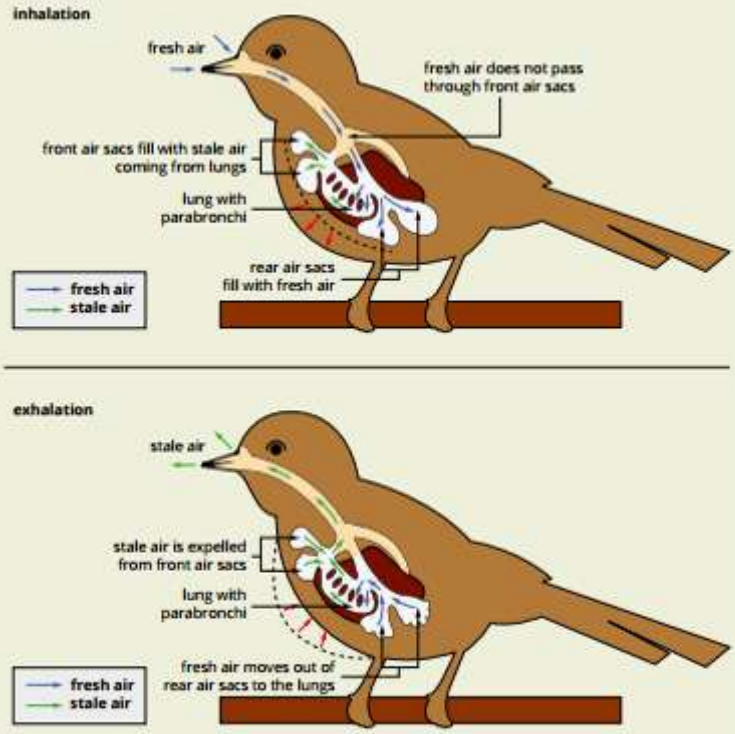


FIGURE 4.2.20 The respiratory system of birds consists of small lungs and several air sacs. This system is extremely efficient and light to meet the demands of flight.

4.2 Review

SUMMARY

- In multicellular organisms, greater cooperation and coordination is required between cells because:
  - not all cells have direct access to the external environment, so they need some means of receiving nutrients and removing their accumulated wastes
  - specialised cells fulfil their own needs, but alone they cannot maintain a whole multicellular organism.
- Specialised cells perform a specific function, and this is reflected in their structure.
- Tissues are groups of specialised cells working together to carry out a particular function.
- An organ consists of two or more tissues that work together to perform a specialised task. It is often recognisable as a distinct structure.
- A system is a group of organs that work together to perform a vital task.
- The highest level of organisation is the organism itself.

KEY QUESTIONS

1 Put the following levels of organisation in the correct order, from simplest to most complex.
organ, specialised cells, system, tissue

2 Why is it important for multicellular organisms to be organised into cell groups, tissues, organs and systems?

3 Define tissue (as used in biology), and give an example of a tissue in vascular plants and animals.

4 Why are animals such as sponges and sea jellies considered to be tissueless multicellular organisms?

5 Give four examples of organs in vascular plants and describe their functions.

6 Describe an organ system in vertebrates and how it supports the survival of the organism.

7 Match each specialised cell with its function.

red blood cell	transports water
white blood cell	gives rise to specialised cells
nerve cell	increased surface area for uptake of water
guard cell	protects against pathogens
muscle cell	carries oxygen around the body
epidermal cell	barrier against environmental stressors
meristem cell	carries signals around the body
xylem cell	allows movement of body parts
root hair cell	prevents water loss and regulates gas exchange

4.3 Transportation in vascular plants

In single-celled and simple multicellular organisms, such as algae and sponges, all cells exchange substances directly with the environment to obtain required substances and remove wastes. This direct exchange is sufficient to meet their needs.

Direct exchange of substances in single-celled and simple multicellular organisms is possible because they have a relatively large surface area to volume ratio. This means that the distance substances need to travel within the organism to get to the surface area for exchange is quite short.

In more complex multicellular organisms such as mammals and vascular plants, specialised units of organisation have evolved to move substances, such as nutrients and wastes, around the organism. For example, most terrestrial plants have specialised tissues for fluid transport. In vascular plants transport occurs inside closed vessels organised into vascular bundles that move water, mineral ions and sugars around the plant (Figure 4.3.1). They consist of:

- xylem vessels that transport water and nutrients to the leaf from the roots
- phloem vessels that transport sugars produced during photosynthesis from the leaves to the roots
- a sheath of lignin that strengthens and supports the tissue.

In this section you will learn about the tissues and organs that transport water and mineral ions in vascular plants.

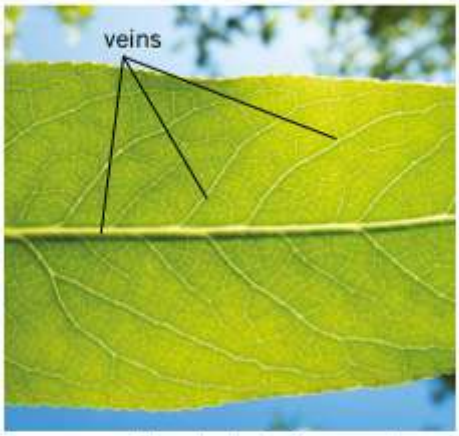


FIGURE 4.3.1 The veins in a leaf are vascular tissue that is specialised for transporting water and organic solutes throughout the plant. Each vein is made up of a vascular bundle of xylem, phloem and a lignin sheath.

VASCULAR PLANTS

Vascular plants include ferns, cycads, conifers and flowering plants and usually grow in terrestrial environments. They are characterised by the presence of vascular tissue, which is tissue that is specialised for transporting fluids.

Plant tissue is also organised into organs. Two of the major organs in plants are leaves and roots (Figure 4.3.2). In vascular plants, vascular tissue is found within both of these organs.

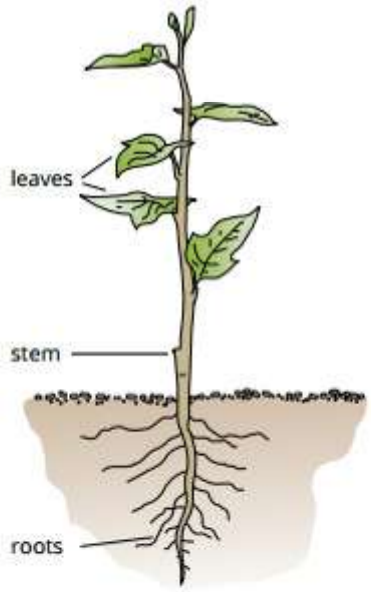


FIGURE 4.3.2 The basic structure of a vascular plant comprises leaves (for photosynthesis), stem (for support) and roots (water absorption and to anchor into soil).

Transportation in vascular plants

Like all plants, vascular plants are autotrophs or producers, manufacturing their food from light energy by photosynthesis.

For photosynthesis, plants need water, carbon dioxide and sunlight for energy. Water is absorbed through the roots, and carbon dioxide is absorbed via the leaves. Photosynthesis occurs in the leaves and produces the sugars that are needed by all active cells of the plant.

In large vascular plants, the leaves can be a long way from where water is absorbed via the roots, and the active cells in the roots requiring sugars for the energy requirements of nutrient uptake can be a long way from where photosynthesis occurs in the leaves. In tall trees like the Californian redwoods pictured in Figure 4.3.3, water and nutrients need to be transported over 100 metres from the roots to the upper branches!

FIGURE 4.3.3 The tallest trees in the world are giant sequoias (*Sequoiadendron giganteum*) of California. These trees can reach a height of more than 115 m above the ground. Their root system is relatively shallow but water still needs to travel a great distance from where it is absorbed via the roots and root hairs to the leaves, where it is used during photosynthesis.

Transport of these substances to the locations where they are needed is made possible by the presence of vascular tissue.

Vascular tissue transports:

- water and mineral ions obtained from the soil by the roots throughout the plant
- sugars made in the leaves to other parts of the plant.

Vascular tissue is easily visible in leaves as parallel veins in grasses, branching veins in many other leaves and the stringy parts of celery.

STRUCTURE AND FUNCTION OF VASCULAR TISSUE

In vascular plants, there are two types of vascular tissue:

- Xylem transports water and inorganic nutrients (mineral ions) absorbed from the soil up the plant.
- Phloem transports dissolved sugars, which are produced in the leaves by photosynthesis, throughout the plant. Other organic substances, such as amino acids are also transported in the phloem.

Xylem and phloem contain continuous, closed tubular pathways through roots, stems and leaves (Figure 4.3.4). Fluids flow through these tubules to all parts of the plant. All cells are close to vascular tissue.

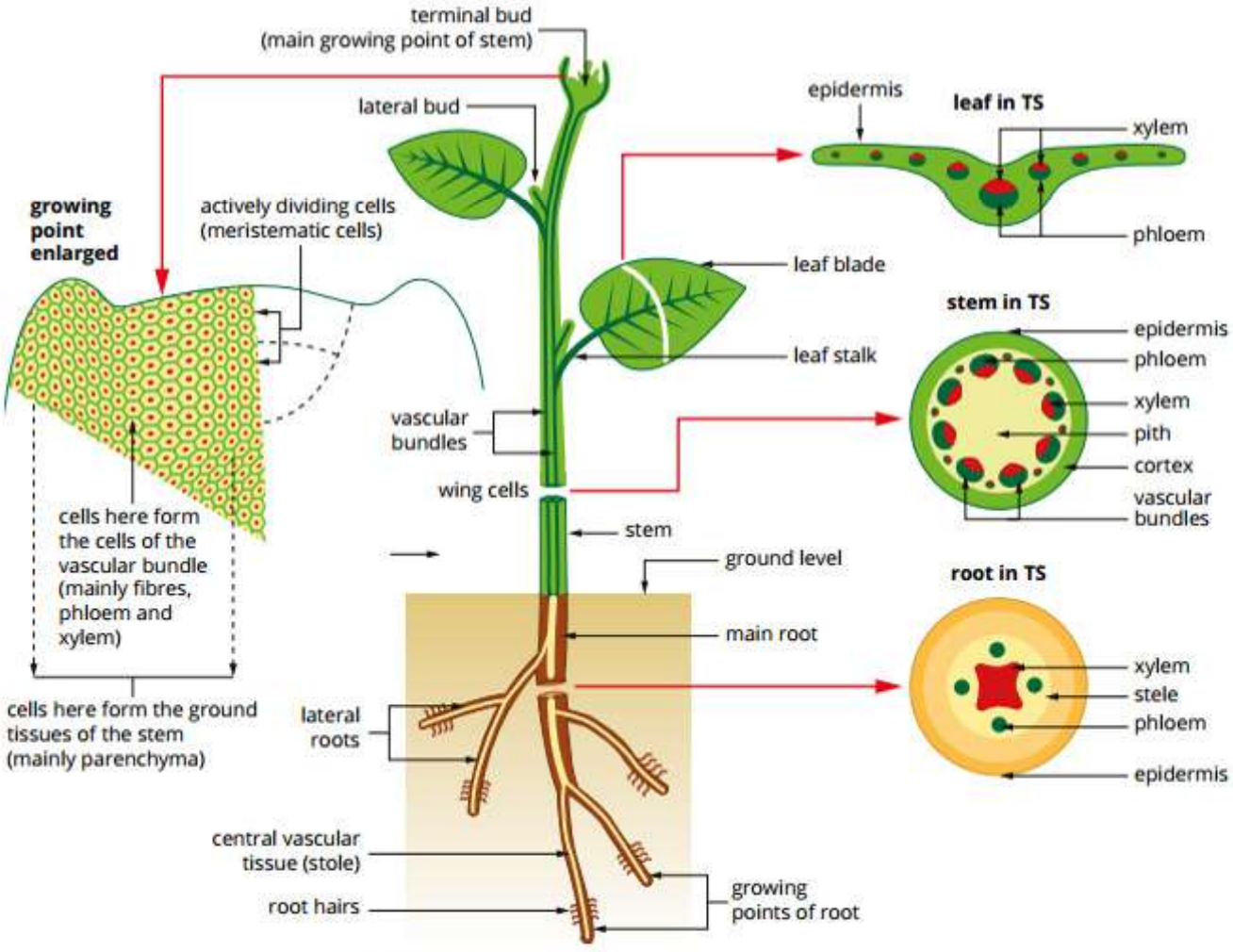


FIGURE 4.3.4 The main function of the transport system in plants is to transport water and organic solutes from the roots to the leaves and to transport food manufactured in the leaves (sucrose and amino acids) to the other plant tissues. The transport system tissues, the xylem and phloem, are continuous, tubular pathways through the roots, stems and leaves. (TS means transverse section.)

The arrangement of xylem and phloem tissues in roots, stems and leaves is distinctive. Roots have a central core of xylem in a star or cross shape, with phloem between the arms of the xylem. In stems and leaves the xylem and phloem are grouped into vascular bundles, as shown in Figure 4.3.5. These vascular bundles extend into the leaves.

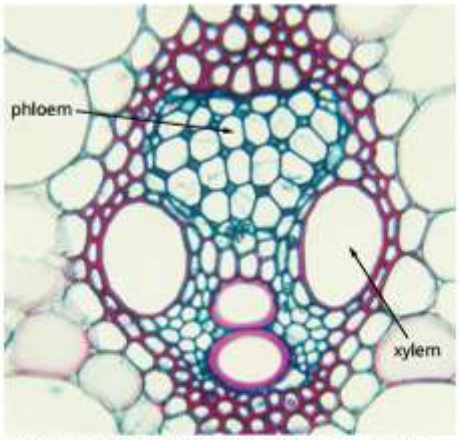


FIGURE 4.3.5 A cross-section through a stem, showing a vascular bundle containing xylem and phloem.

Xylem

Xylem is the vascular tissue that transports water and mineral ions obtained from the soil throughout the plant. It is composed of mainly of xylem vessels and tracheids.

Xylem vessels

A **mature xylem** vessel is a long, water-filled tube consisting of elongated cells joined end to end (Figure 4.3.6). As these cells mature, the cell wall is strengthened with lignin, becoming stronger and more rigid, and the cytoplasm and nucleus disintegrate. Mature xylem vessels have:

- cylindrical skeletons of dead cells joined end to end to form continuous tubes
- perforated or complete openings at each end, like a straw, so that fluid can flow directly through them
- pits (un-thickened areas) and perforations in the sidewalls that allow sideways movement of substances between neighbouring vessels in the vascular bundle
- no nucleus or cytoplasm.

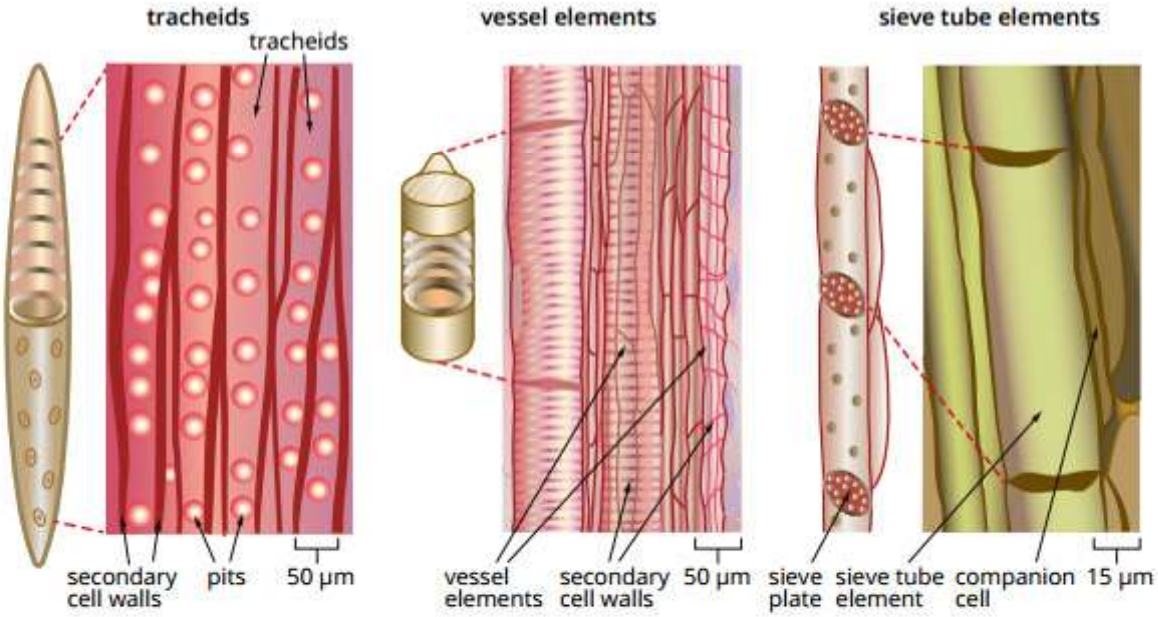


FIGURE 4.3.6 Water and mineral ions travel through tracheids and vessels in the xylem tissue. This figure shows the different forms of individual xylem elements. Tracheids exist singly and are connected through pits along their cell walls, while xylem vessels are joined end to end to form a long tube.

Tracheids

Tracheids are single large, tapering water-filled cells that form part of the xylem tissue in all vascular plants (Figure 4.3.6). When mature, tracheids lose their nucleus and cytoplasm. This leads to cell death but creates an open structure for water to flow through. Mature tracheids have:

- cylindrical skeletons of dead cells joined to form continuous tubes, like xylem vessels
- pits and perforations in their lignified cell walls
- no nucleus or cytoplasm.

Unlike xylem vessels, tracheids are not connected end to end. Instead their ends overlap and water is transferred horizontally through the adjoining pits.

BIOFILE

Transport in 'non-vascular' plants

Bryophytes (mosses, liverworts and hornworts) are often called non-vascular plants because they do not have a system like that in vascular plants for transporting fluids. Most species can take in nutrients and water directly into their cells by diffusion.

However, a large number of bryophyte species have an internal transport system for conducting fluids, so 'non-vascular' is not really correct. One major difference between bryophytes and vascular plants is that the cell walls of bryophytes do not contain lignin, which gives extra strength to the wall and enables plants to grow much taller. Non-vascular plants should really be called non-lignified plants.

The transport system in bryophytes consists of long cells called hydroids that are bundled together to form a tissue called the hydrome. Some species also have cells in the hydrome that have a lignin-like substance in the cell walls, giving them more rigidity. One of these is the largest non-vascular plant in the world, the giant dawsonia (*Dawsonia superba*) (Figure 4.3.7). It is a moss that grows in wet forests and rainforests in Australia and New Zealand, and reaches 65 cm in height—taller than many vascular plants.

FIGURE 4.3.7 The giant dawsonia (*Dawsonia superba*) has an internal transport system and is taller than many vascular plants.

Phloem

Phloem transports organic solutes, especially sugars such as sucrose, from the site of synthesis (leaves) to the site of use or storage (stems and roots). It is composed of sieve tubes, companion cells, parenchyma cells and sclerenchyma cells (Figure 4.3.8).

Unlike xylem vessels, mature phloem sieve tubes are living cells with no nucleus and no lignin in the cell walls. Sieve tubes form linear rows of elongated cells. Their cell walls are perforated at each end by a number of holes or pores, forming sieve plates. Strands of cytoplasm (plasmodesmata) pass through these perforations, connecting one cell with the next.

Sieve tube cells are usually closely associated with one or more companion cells, connected by plasmodesmata. Both sieve tube cells and companion cells have thin cell walls. But unlike sieve tube cells the companion cells retain their nucleus, which probably enables the sieve tube cells to continue functioning.

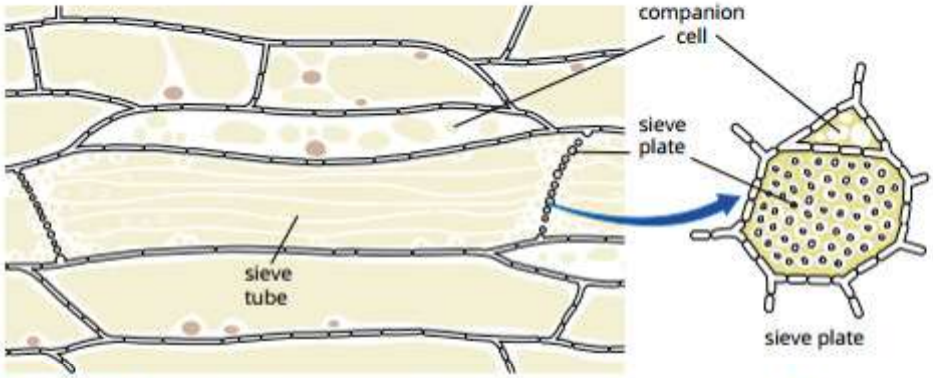


FIGURE 4.3.8 The cytoplasm of sieve tubes in phloem is continuous from cell to cell through the sieve plates. Adjacent companion cells probably enable sieve tube cells to continue functioning, since sieve tube cells do not have a nucleus.

BIOLOGY IN ACTION

The Separation Tree

On 15 November 1850, citizens gathered under the canopy of a majestic river red gum (*Eucalyptus camaldulensis*) in the newly established Royal Botanic Gardens in Melbourne. Superintendent Charles La Trobe announced that Victoria would separate from New South Wales and become a new colony of the United Kingdom. The tree was commemorated with a plaque and named the Separation Tree. The tree is now heritage-listed and is believed to be over 400 years old.

Sadly, the Separation Tree was attacked in 2010 and 2013 by vandals, who removed deep strips of bark from the trunk (Figure 4.3.9). This is known as ring-barking or girdling, and involves removing a strip of bark from the whole circumference of the trunk. The bark that is removed contains the cork cambium, phloem tissue, vascular cambium and sometimes the xylem tissue (Figure 4.3.10).

FIGURE 4.3.9 The Separation Tree following the first vandalism attack in 2010.

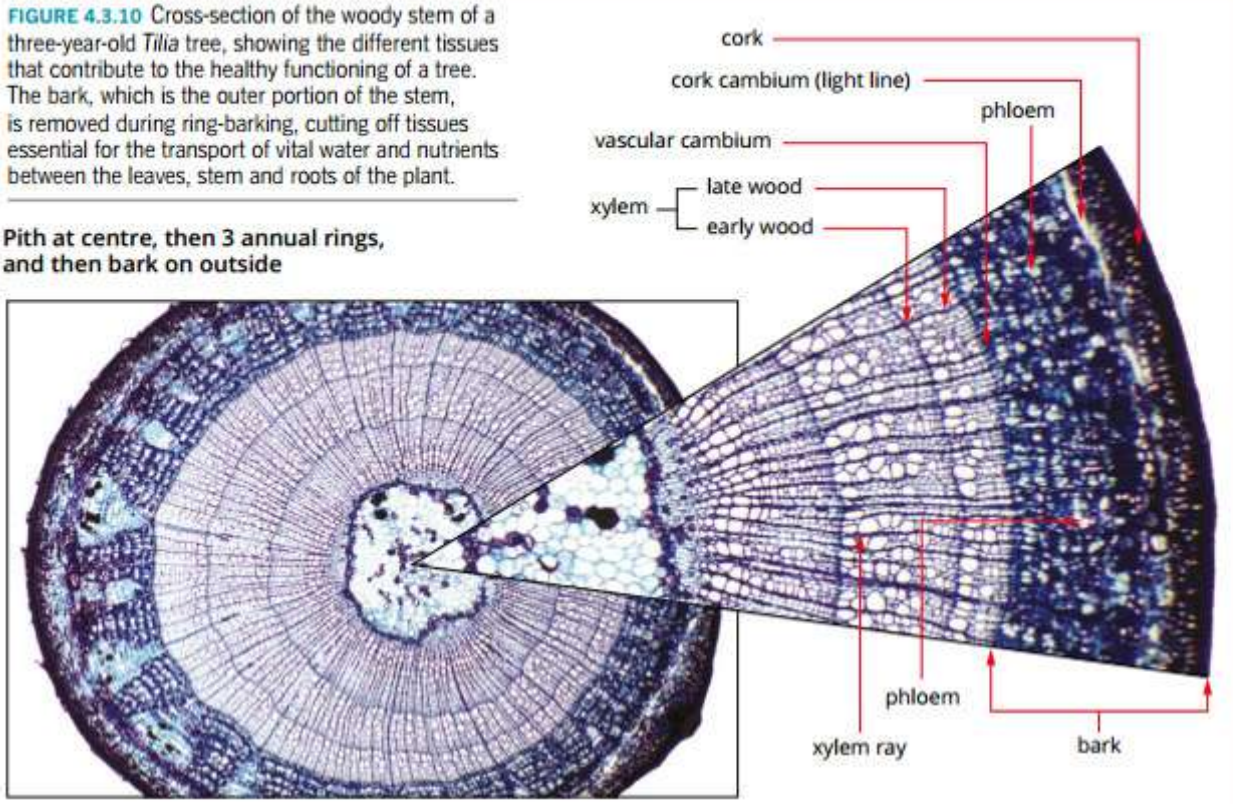


FIGURE 4.3.10 Cross-section of the woody stem of a three-year-old *Tilia* tree, showing the different tissues that contribute to the healthy functioning of a tree. The bark, which is the outer portion of the stem, is removed during ring-barking, cutting off tissues essential for the transport of vital water and nutrients between the leaves, stem and roots of the plant.

Although the leaves of the Separation Tree were still able to photosynthesise and produce sugars, these sugars could no longer be transported to the roots, and the roots starved. Despite efforts to save the tree, it was confirmed in February 2015 that it was dying. For safety reasons, the branches and upper trunk of the Separation Tree have now been removed.

You can see just how many significant events the Separation Tree witnessed in its lifetime in Figure 4.3.11. The tree will continue to live on in many ways. The base of the trunk remains in the Royal Botanic Gardens, along with the commemorative plaque, and there are also plans to honour the Separation Tree by using the wood from its branches to make special souvenirs. Some seeds from the Separation Tree have been sent to schools to grow new trees, and others are stored in the Royal Botanic Gardens nursery. The Separation Tree also has three living offspring that were planted 5, 10 and 64 years ago in the Royal Botanic Gardens.

FIGURE 4.3.11 The Separation Tree lived during many significant events in its 400-year lifetime. The heritage-listed tree died after vandals ring-barked it. Its trunk remains with a commemorative plaque in the Royal Botanic Gardens, Melbourne.

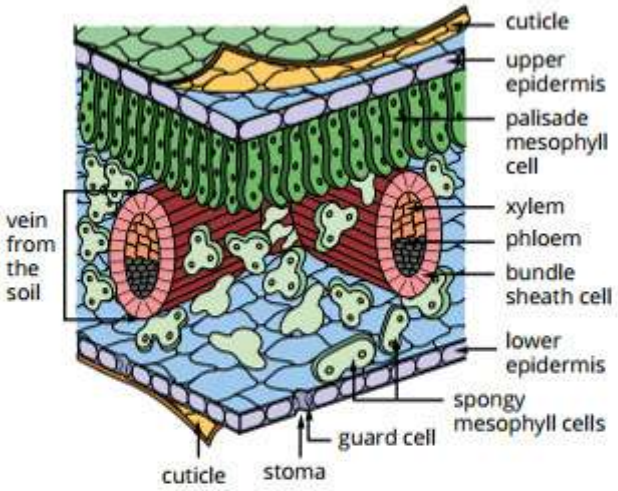


FIGURE 4.3.12 The three distinct layers of cells in leaves are the upper epidermis, the mesophyll and the lower epidermis.

Leaves

In vascular plants a leaf is an organ composed of three distinct layers of specialised cells, or tissues (see Figure 4.3.12):

- upper epidermis
- mesophyll
- lower epidermis.

The epidermis is a layer of cells covering the entire leaf. It secretes a waterproof waxy layer called the cuticle. Together the epidermis and cuticle provide a barrier that protects the cells and tissues inside the leaf and prevents excessive water loss. The epidermal cells lack chloroplasts but are transparent, allowing sunlight to reach the photosynthetic cells below.

Within the lower epidermis are stomata (singular stoma). Each stoma consists of two highly specialised epidermal cells called guard cells. The guard cells surround a pore, creating an opening through the epidermis and cuticle. They regulate gas exchange and water loss by changing shape, which causes the pore to open or close.

Between the epidermal layers are the mesophyll cells where photosynthesis takes place. The cells closest to the upper epidermis are the palisade mesophyll cells. These cells contain many chloroplasts and are tightly packed together. The spongy mesophyll cells below the palisade mesophyll cells are loosely packed together, with air spaces between them to allow gas exchange. These cells contain fewer chloroplasts.

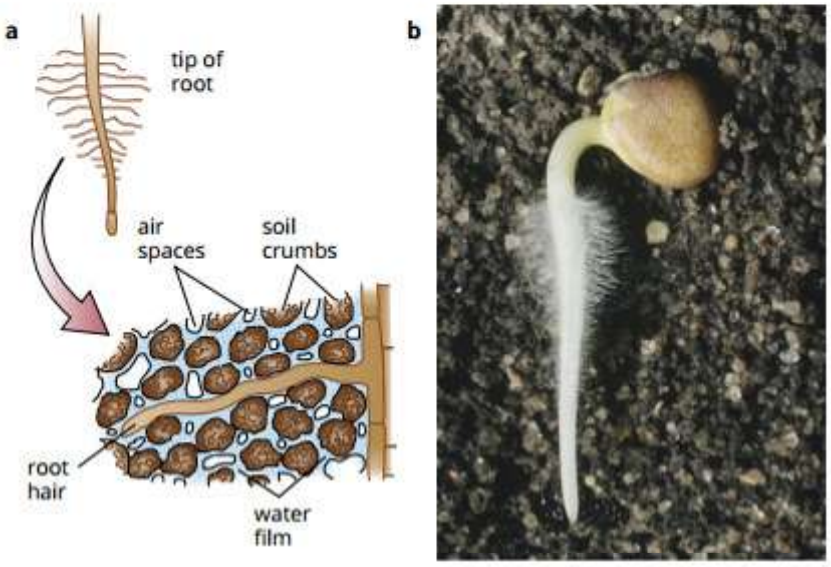


FIGURE 4.3.13 (a) Water and inorganic nutrients are absorbed by roots from soil water through many fine root hairs. (b) Root hairs on a radish seedling. The branched structure of the fine root hairs provides a greater surface area for the radish seedling to absorb water.

The vascular tissue (xylem and phloem) is also located between the two layers of epidermal cells. Vascular tissue is often visible in leaves as veins.

Table 4.3.1 summarises the structure and function of the parts of leaves.

Leaf tissue	Structure	Function
cuticle	thin, waxy waterproof layer	protects the inner cells, prevents water loss and allows sunlight to penetrate
epidermis (upper and lower)	transparent and usually thin	protects the inner cells, prevents water loss and allow sunlight to penetrate for photosynthesis
epidermis and cuticle	contains guard cells surrounding stomata	regulate gas exchange and water loss by opening and closing
mesophyll	palisade mesophyll; tightly packed column-shaped cells with many chloroplasts, close to upper epidermis	photosynthesis
	spongy mesophyll; loosely packed, with air spaces around the cels	allows gas exchange, including the diffusion of carbon dioxide throughout the leaf
xylem and phloem	tubular vessels	transport fluids

TABLE 4.3.1 The structure and function of the specialised cells and tissues of leaves.

MOVEMENT OF WATER AND SOLUTES

Root absorption

The major function of roots is to take in water (which is essential for photosynthesis, nutrient transfer and transpiration) and mineral ions such as nitrogen, phosphorus and potassium (which are needed to manufacture a range of organic compounds, including amino acids, proteins and lipids) from the soil.

Roots have a branched structure that increases the surface area of the roots and their capacity to absorb water and mineral ions (Figure 4.3.13).

Water pathways

There are two possible pathways for movement of water and mineral ions absorbed from the soil via the roots: the extracellular pathway and the cytoplasmic pathway.

In the extracellular pathway, most water and some mineral ions pass in or between cell walls (Figure 4.3.14).

In the cytoplasmic pathway, most mineral ions and some water pass through the cytoplasm of living root cells (Figure 4.3.14).

The cytoplasmic pathway involves substances entering a root hair cell by crossing the cell's plasma membrane, and then passing from cell to cell through plasmodesmata. The three types of transport that move substances across plasma membranes along the cytoplasmic pathway are as follows:

- Active transport. Most dissolved mineral ions are selectively taken into roots by active transport. Proteins in the plasma membrane of root cells, specific for each ion, are used for this purpose. As a result, the concentration of ions in the vascular tissue of roots can be more than 100 times their concentration in the water of the surrounding soil.
- Osmosis. The high concentration of ions in the vascular tissues of terrestrial plants creates a very large osmotic concentration gradient. Large amounts of water move into root cells along this concentration gradient.
- Diffusion. Some mineral ions such as potassium and phosphate enter the roots by diffusion. The uptake of these nutrients therefore depends on the rate of water uptake.

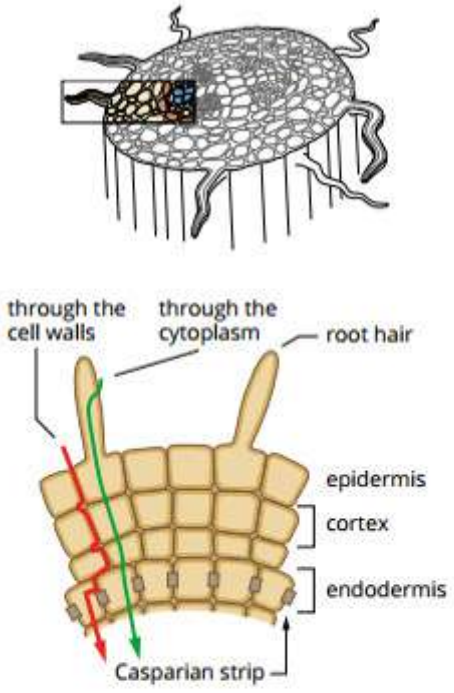


FIGURE 4.3.14 Water and mineral ions move through the roots via the extracellular pathway (red arrow) and the cytoplasmic pathway (green arrow). From the Casparian strip, water can no longer travel along the extracellular pathway and is forced into the cytoplasm before moving into the xylem.

BIOFILE

Root pressure

In some plants the osmotic gradient draws in so much water from the roots that it can travel up to 10 metres up the stem. This is known as **root pressure** (Figure 4.3.15). Root pressure causes the rising of sap (water and mineral ions) in spring in deciduous plants such as birch trees, but does not occur in all plants.

Root pressure also results in a process called **guttation** in some small plants. This is the loss of liquid water and sometimes other substances from leaves (unlike transpiration, which is the loss of pure water in the form of water vapour). Water is lost through special pores at the ends of leaf veins (Figure 4.3.16). Guttation usually occurs at night when the air is moist. In tropical conditions, where humidity in the surrounding air is so high that little transpiration occurs, guttation assists the survival of plants by ensuring the continual upward movement of sap, which transports essential mineral ions from the soil to the leaves.

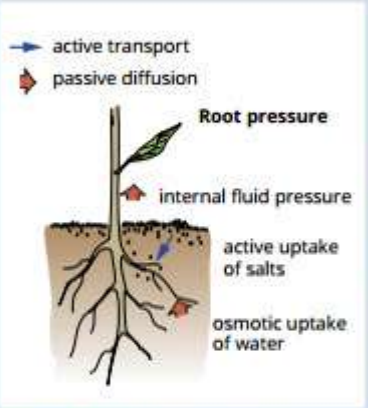


FIGURE 4.3.15 Internal fluid pressure (root pressure) in the roots of some plants causes fluid to rise through the xylem vessels.

FIGURE 4.3.16 Root pressure in small plants can force droplets of water from specialised pores at the tips of leaf veins, a process called guttation.

Entering the xylem

From either of the two pathways through the roots, water and mineral ions must then reach the xylem tissue. Between the roots and the xylem is a waterproof layer of cells that form a barrier known as the Casparian strip (Figure 4.3.14). At this barrier, water travelling through the extracellular pathway is forced into the cytoplasm. In this way the Casparian strip ensures the regulation of the substances entering the xylem.

Transpiration

Transpiration is the passive movement of water through a plant from the roots, including its evaporation through the stomatal pores in leaves (Figure 4.3.17). The plant uses a small amount of water for metabolic processes, but 99% of the water absorbed by the roots is lost via transpiration.

Transpiration is a passive process: it does not require energy expenditure by the plant. It is driven by the heat energy in sunlight, which breaks the **cohesive bonds** between water molecules, allowing evaporation through the stomata.

Water molecules are very cohesive; that is, they have a strong tendency to stick together. When water evaporates from the cell walls of the leaf, cohesion between the water molecules remaining in the leaf draws water from nearby xylem vessels to replace the lost water.

In this way thousands of leaf cells, each drawing water from xylem, create a differential pressure that pulls water up xylem vessels from the roots. This continuous one-way flow of water from roots to leaves is called the transpiration stream. The pull of transpiration can be strong enough to draw water to the top of the tallest tree, over 100 metres high.

Although transpiration is the cause of 99% of a plant's water loss, it is vital because it enables plants to:

- absorb the water necessary for the process of photosynthesis
- transport mineral salts to leaf cells and fruits
- cool down and not become overheated.

The flow of the transpiration stream does not require an intact root system. It continues when cut flowers and leafy shoots are placed in a vase of water. It also continues in the roots after the stem dies.

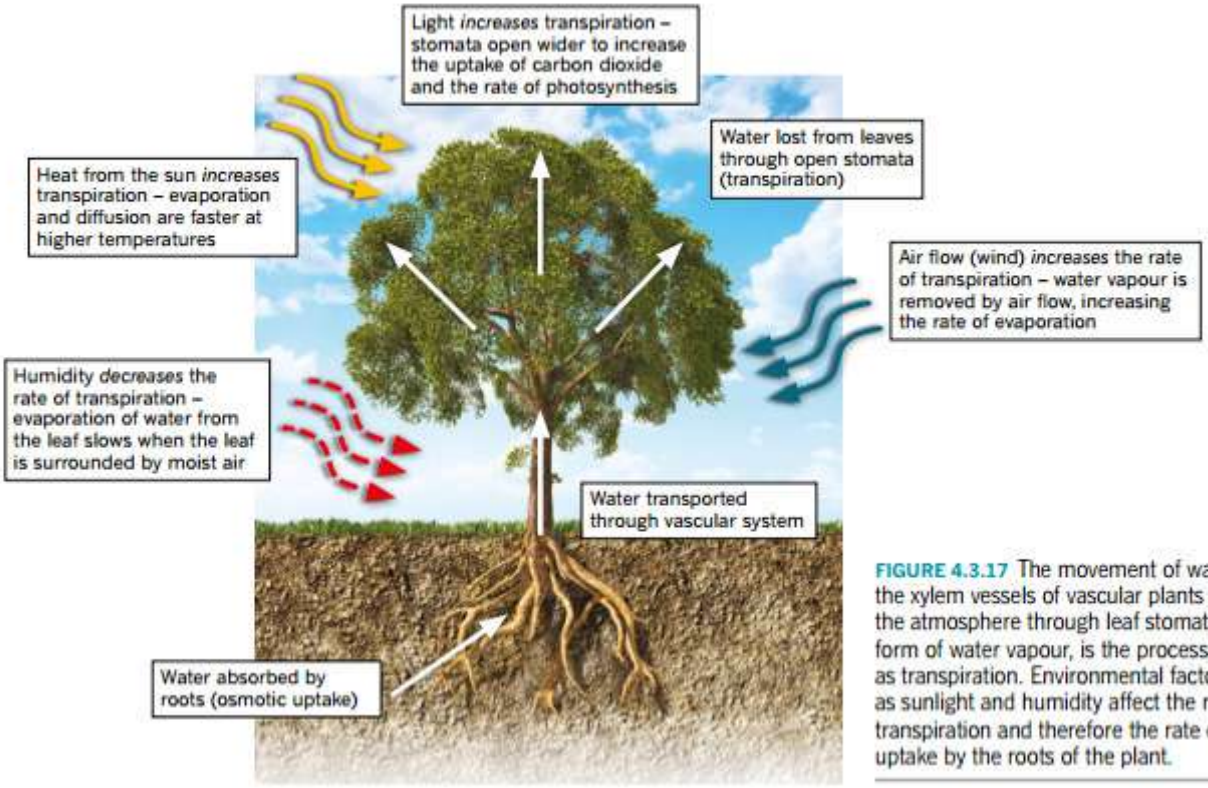


FIGURE 4.3.17 The movement of water through the xylem vessels of vascular plants and into the atmosphere through leaf stomata, in the form of water vapour, is the process known as transpiration. Environmental factors such as sunlight and humidity affect the rate of transpiration and therefore the rate of water uptake by the roots of the plant.

Factors that affect transpiration rates

Water vapour is lost from leaves mainly by transpiration through open stomata. The total surface area across which transpiration takes place is related to the degree of opening of all stomata. This is by far the most important factor affecting the rate of transpiration. The greater the number of stomata and more open they are, the more surface area there is from which water can be lost (Figure 4.3.18).

Other factors that affect the rate of transpiration (Figure 4.3.17) include:

- humidity—Transpiration rates decrease when there is a lot of water vapour in the air (that is, a high level of humidity), because this reduces the water concentration gradient between leaf spaces and air, so fewer water molecules evaporate into the air.
- temperature—Transpiration rates increase as temperature increases because heat energy increases the rate of evaporation of water.
- wind—Air currents increase the rate of transpiration by moving water vapour away from the leaf and therefore increasing the rate of evaporation of water.

The rate of transpiration is low at night because it is cooler and more humid, and because stomata are usually closed.

The leaves of some plants that live in exposed conditions have developed structural features that reduce the rate of transpiration. For example, some plants have hairs on the leaf surface, which create a layer of relatively undisturbed, humid air.

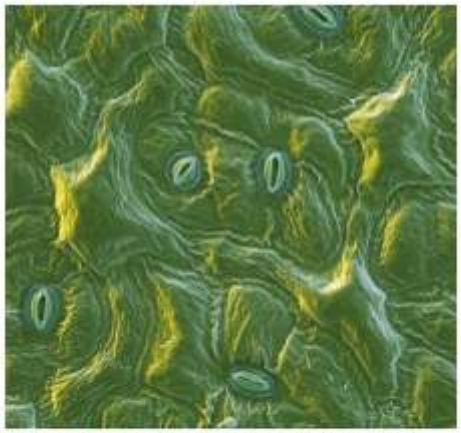


FIGURE 4.3.18 Stomata on the surface of a cabbage leaf, viewed at high magnification. Stomata regulate the exchange of gas and water between the plant and the atmosphere. The opening and closing of the stomata is controlled by two guard cells on either side of the pore. Stomata open during the day to exchange gases during photosynthesis and close at night to minimise water loss.

Translocation: sources and sinks

The transport of organic solutes from the leaves to other tissues in the plant is known as translocation. Leaves produce carbohydrates in the form of sugars during photosynthesis. The non-photosynthetic tissues of the plant also need these carbohydrates and other organic compounds, such as amino acids, hormones and proteins, so these nutrients are transported from the sources (the leaves) to the sinks (regions where the nutrients are needed, such as roots, stems, flowers and fruits).

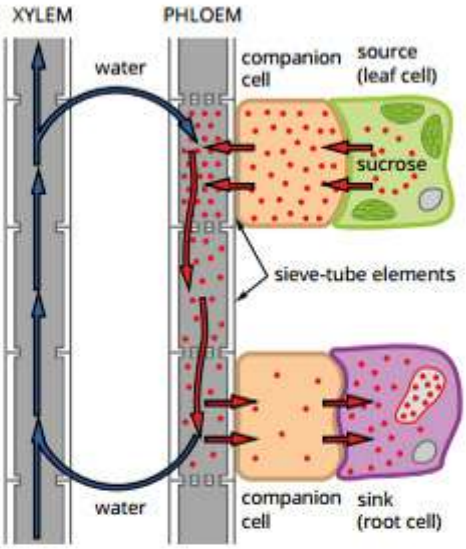


FIGURE 4.3.19 The movement of fluid through the phloem is the result of active pumping of sugars, with water flowing along an osmotic gradient. Sugars and water enter the phloem sieve tubes in leaves in this way and are translocated throughout the plant. Sugars are actively unloaded from sieve tubes where they are required.

The tissue through which these organic solutes move is the phloem, and the material that flows through it is known as phloem sap. This sap is composed of around 90% sucrose. Sucrose is a disaccharide that dissolves easily in water, making it a good transport material. It is produced in the chloroplasts of the chlorenchyma (parenchyma cells with chloroplasts) and pumped into the companion cells. From the companion cells the sucrose flows into the sieve tube cells (Figure 4.3.19). Transport in individual sieve tube cells is in one direction only, but bundles of sieve tube cells are able to transport sap in both directions: upwards to leaves and fruit, or downwards to the roots.

Translocation is an active process. It involves the flow of cytoplasm in sieve tubes driven by a pressure gradient, and requires the expenditure of energy by the plant. This pressure gradient begins in the leaves, where sucrose is actively pumped into phloem sieve tube cells. This creates an osmotic gradient that draws water passively into the sieve cells. As water enters, it increases the fluid pressure (turgor) in sieve cells, which pushes fluid from these cells into adjacent sieve cells.

While this is happening in the leaves, sucrose is being actively removed from sieve cells in roots, growing shoots and developing fruit. This causes an osmotic gradient that draws water out of sieve cells and lowers their turgor pressure.

Fluid pressure is therefore high in sieve tube cells in leaves and low in sieve tube cells in roots and growing shoots. A bulk flow of the contents of sieve tubes occurs along this fluid pressure gradient, from sources to sinks. Translocation stops if the cells in the stem die.

BIOFILE

Water transport adaptations in desert plants

Plants that live in deserts need specialised strategies to survive the hot, dry conditions. In an environment where water is scarce, plants have developed special structures that enable extremely efficient uptake and storage of this precious resource.

Cactus plants are specialised to hold large volumes of water in their fleshy leaves, stems and roots. When water does come along, they need to be able to absorb as much as possible, as fast as possible. Their roots are shallow and cover a large area, enabling them to harvest as much water from the soil as possible.

Once cacti have water, they need to hold on to it. Most cacti are spiny, bitter tasting or toxic, which deters thirsty animals. A thick, waxy cuticle also protects the leaves from damage and reduces water evaporation. While most plants open their stomata during the day, in a hot, dry environment this would lead to massive water loss through transpiration. To overcome this problem, cacti open their stomata at night and use crassulacean acid metabolism (CAM) photosynthesis (see Section 3.3). At night when stomata are open, carbon dioxide is taken in and converted to malic acid, which is stored in the vacuoles of mesophyll cells. In daylight, when the stomata stay closed to reduce water loss, the stored malic acid is broken down, releasing carbon dioxide which diffuses into chloroplasts for conversion into glucose and carbohydrates, completing the photosynthetic process. CAM photosynthesis is excellent for conserving water, but the rate of photosynthesis is slow. This is why many cacti grow very slowly.

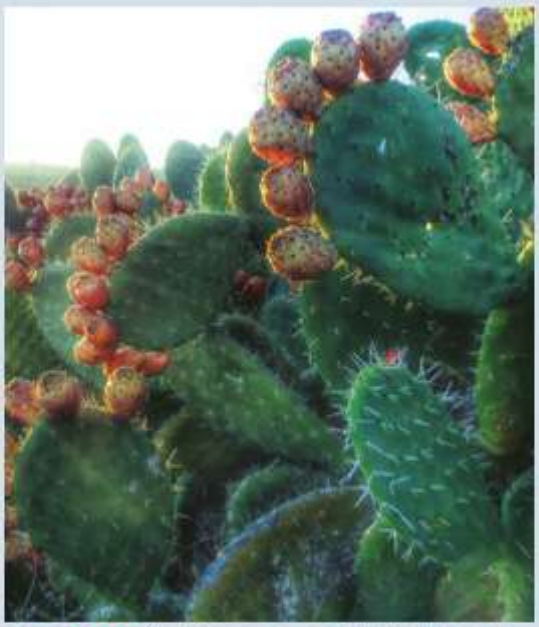


FIGURE 4.3.20 Cacti have many special adaptations to overcome the problem of water uptake and storage in harsh, dry environments.

4.3 Review

SUMMARY

- Most terrestrial plants, including ferns, conifers and flowering plants, have vascular tissues (xylem and phloem) that are specialised for transporting fluid.
- The vascular tissues are:
  - xylem, which carries water and mineral ions from roots to leaves
  - phloem, which carries sugars and other organic molecules from leaves to roots.
- Xylem vessels:
  - are the skeletons of dead elongated cells
  - have perforations at each end
  - are joined end to end to form continuous tubes and allow the flow of fluid
  - have pits (thinner areas) in the side walls that enable the movement of substances into and out of the adjacent companion cells.
- Xylem tracheids:
  - like xylem vessels are dead and have pits in their lignified cell walls and have no nucleus or cytoplasm
  - unlike xylem vessels, are not connected end to end; their ends overlap and water is transferred horizontally through the adjoining pits.
- Water and inorganic nutrients (mineral ions) are absorbed by the root hairs from the soil by one of two pathways:
  - extracellular pathway
  - cytoplasmic pathway.
- Water and mineral ions are transported through xylem vessels as sap. This transportation occurs in one direction only: from roots to leaves.
- Transpiration is the evaporation of water from stomata in leaves. It is a passive process (driven by energy from the sun) that also draws water up from the roots, through the xylem, following what is known as the transpiration stream.
- The rate of transpiration is affected by:
  - the number of stomata and their degree of opening
  - temperature
  - humidity
  - wind.
- Translocation is the transport of organic materials from the leaves to the roots, stem, flowers and fruits of the plant, through the sieve tube cells and companion cells of the phloem tissue.
- Translocation is an active process and requires an expenditure of energy by the plant.
- Translocation is driven by a pressure gradient that begins in leaves (sources), where sucrose is actively pumped into phloem sieve cells while being actively removed from sieve cells in roots, growing shoots and developing fruit (sinks).

KEY QUESTIONS

1 What are the two types of vascular tissue in plants and their functions?

2 Why is there a limit to the size non-vascular plants can grow?

3 How does ring-barking affect translocation? What impact does this have on the health of a tree?

4 What are the two possible pathways for the movement of water and mineral ions, absorbed from the soil, through the roots?

5 How is it possible for the tallest trees to transport water from their roots to their uppermost branches, sometimes over 100 metres high?

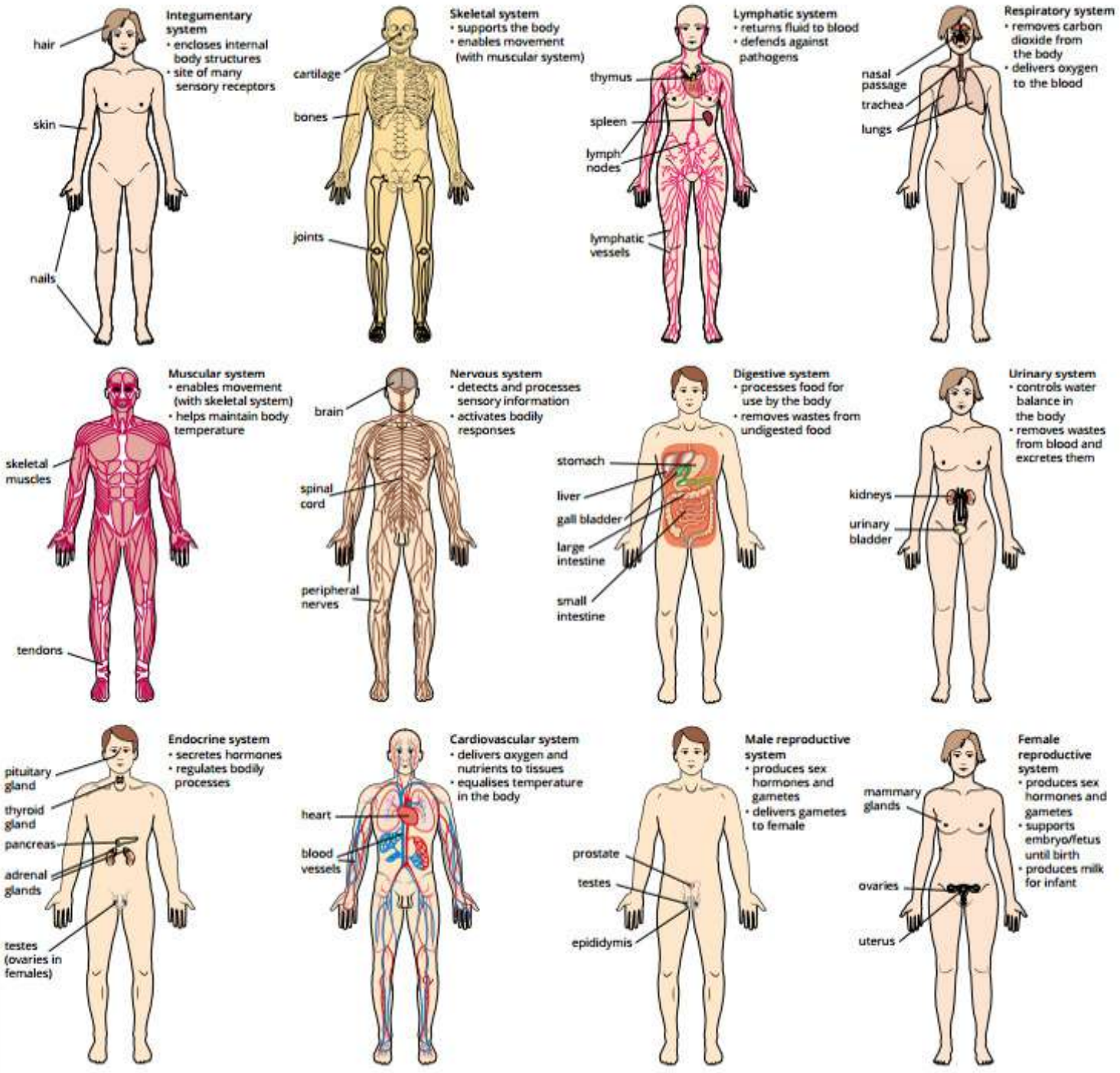
6 Why is transpiration vital to plants?

7 State whether each of the following environmental factors increases or decreases transpiration rates in plants.
   a high temperature
   b high humidity
   c darkness
   d strong wind

4.4 Mammalian systems

Mammals, including humans, are composed of billions or even trillions of specialised cells organised into tissues, organs and systems. There are many advantages to this level of complexity but, as with vascular plants, there are also challenges. For example, specialised cells cannot survive independently and must rely on other cells and the survival of the organism as a whole.

FIGURE 4.4.1 Systems of the human body.



The grouping of organs into systems is the highest level of biological complexity. There are eleven organ systems in mammals, each with specialised roles that are essential for the correct functioning of the organism (Figure 4.4.1). These systems do not work in isolation; they have vital connections to one another, and many of their functions overlap. Each of the systems ultimately functions to maintain homeostasis and ensure the survival and reproduction of the organism.

This section examines each of the mammalian systems, how these systems interconnect, and the consequences for the organism when a system malfunctions.

DISTRIBUTING MATERIALS: MAMMALIAN TRANSPORT SYSTEMS

The structure and function of transport systems are similar in all mammals. Mammals have two transport systems: the blood circulatory system and the lymphatic system. The blood circulatory system:

- is a closed circulatory system
- uses blood as the circulatory fluid
- provides the majority of transport needs in mammals.

The lymphatic system:

- is an open circulatory system
- circulates colourless **lymph** fluid
- plays vital roles in maintaining osmotic and fluid balance in tissues and supporting immune defences.

THE CIRCULATORY SYSTEM

In simple multicellular organisms, nutrients are transported by diffusion between cells (see page 174). Diffusion only works over short distances from cell to cell. In large, complex animals, diffusion is not sufficient to deliver essential nutrients to all of the organism's cells. It is for this reason that specialised circulatory systems, with networks of pipes and chambers, have evolved to transport vital nutrients to all cells in complex multicellular organisms.

The mammalian circulatory system (Figure 4.4.2) is a closed system that transports substances throughout the body. The vital metabolic products of the body are transported via the blood. The blood and the circulatory tissues and organs ensure that all cells have a ready supply of nutrients and oxygen and a means to transport away metabolic wastes. In mammals, the highly branched network of the circulatory system means that no cell is more than 1 mm from a capillary. This ensures there is efficient nourishment and waste removal for all cells in the body.

Circulation pathways

Blood circulates around the body via two sequential pathways (Figure 4.4.3):

- Pulmonary circulation transports blood to and from the lungs. Deoxygenated blood is pumped from the heart to the lungs, where it is oxygenated before returning to the heart.
- Systemic circulation transports blood to and from the rest of the body. This system is larger than the pulmonary circulatory system because the heart must pump blood to all the organs in the body. Oxygenated blood is pumped from the heart to the organs, where it gives up its oxygen to the cells, before returning to the heart.

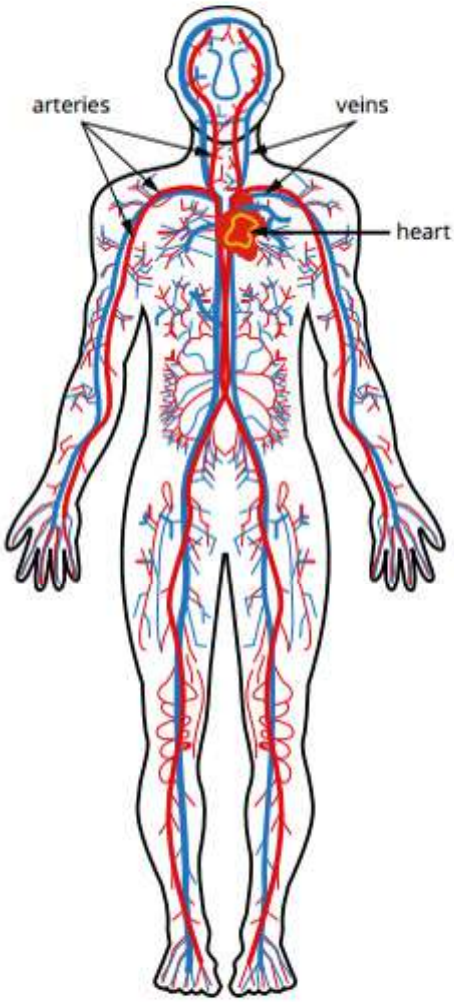


FIGURE 4.4.2 The circulatory system is the main transport system in mammals. It is composed of the heart, blood and blood vessels and is responsible for transporting dissolved gases, nutrients and waste products.

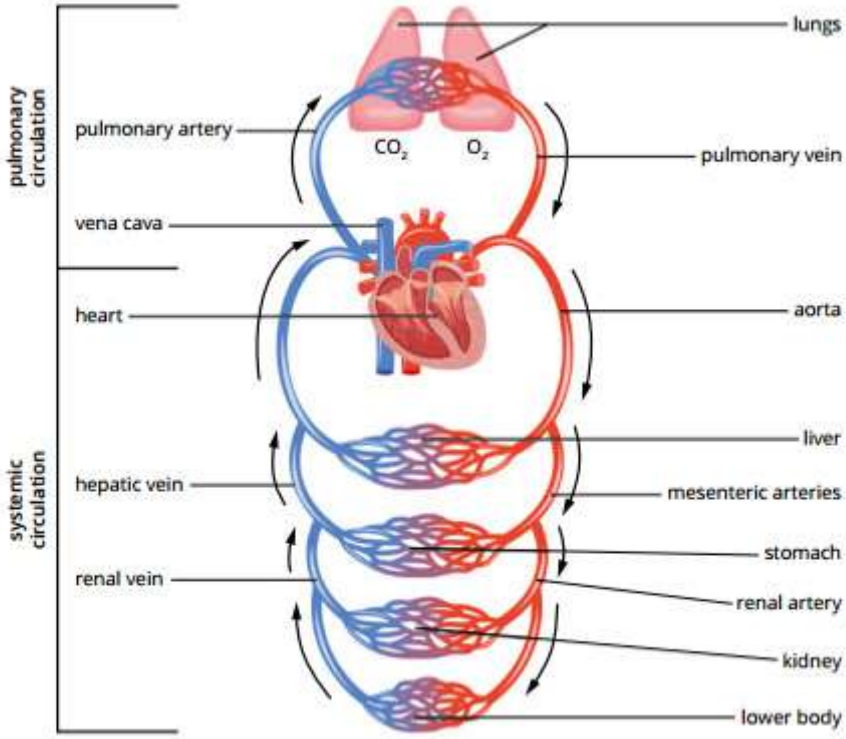


FIGURE 4.4.3 Pulmonary circulation transports blood to and from the lungs. Systemic circulation transports blood to and from all the systems in the mammalian body.

Components of the circulatory system

The key components of the circulatory system are:

- the heart, which in humans is a four-chambered muscular pump with two pumping chambers (ventricles) and two receiving chambers (atria). It is responsible for moving blood throughout the circulatory system. The right side of the heart pumps deoxygenated blood, while the left side pumps oxygenated blood.
- veins and arteries, a network of muscular vessels carrying blood to and from the heart, divided into:
  - pulmonary vessels, which carry blood to and from the lungs
  - systemic vessels, which carry blood to and from all other parts of the body
  - capillaries, which are numerous very fine vessels with thin walls that provide a large surface area across which exchange of substances occurs and which connect the arteries and the veins
- blood, which is the circulating fluid and is highly specialised for transport and immune defence.

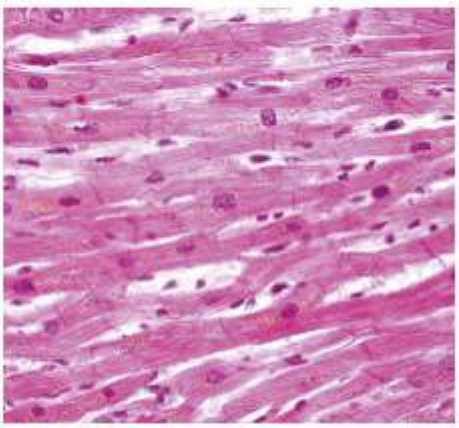


FIGURE 4.4.4 Cardiac muscle tissue is made of highly specialised muscle cells that are found only in the heart. The dark bodies are nuclei.

The heart

The mammalian heart is in the centre of the chest, between the lungs, surrounded by the protective rib cage. It consists of a number of tissues including cardiac muscle (Figure 4.4.4), connective tissue and nerve tissue. Connective tissue makes up the valves and nerve tissue controls the heart rate.

The mammalian heart has four chambers (Figure 4.4.5). The upper receiving chambers, which have thinner walls, are the atria. Each atrium opens into one of the lower, thicker-walled chambers, called ventricles. Blood moves through the heart in one direction because of the presence of four one-way valves: one between each atria and the ventricle below, and one between each ventricle and its outgoing artery.

Both sides of the heart function in a coordinated way: first both atria contract, then both ventricles contract.

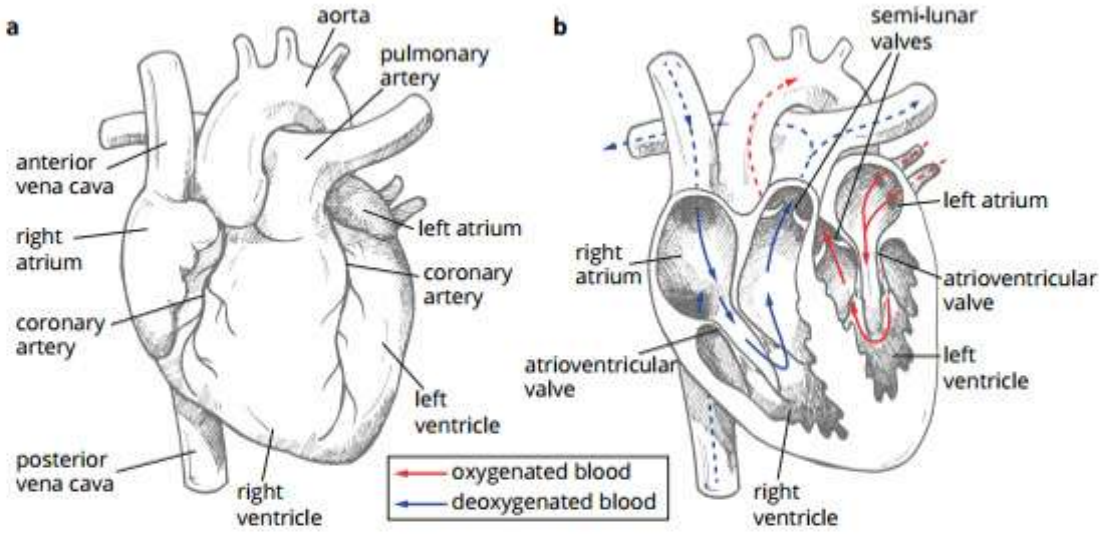


FIGURE 4.4.5 The human heart. (a) View of the ventral surface of the heart. (b) Ventral surface opened to show the major vessels, valves and the greater thickness of the left ventricle.

Deoxygenated blood (blood with a low oxygen concentration), returns from the body through the venae cavae (singular, vena cava), flowing into the right atrium and through a valve into the right ventricle as both chambers relax between contractions. The atrium contracts first, further filling the right ventricle. As the ventricle contracts, the rising ventricular pressure closes the atrioventricular valve (between atrium and ventricle) and opens the semilunar valve (between the ventricles and the opening of the pulmonary artery), causing blood to be ejected into the pulmonary artery towards the lungs.

In the lungs, blood loses carbon dioxide and gains oxygen by diffusion as blood flows through the narrow capillaries around the alveoli. Oxygenated blood (blood with a high oxygen concentration) returns from the lungs to the left atrium through the pulmonary veins and is then pumped by the left ventricle to the rest of the body via the aorta.

During a complete circuit around the body, blood passes through each side of the heart. In humans, one complete circuit takes about 45 seconds.

Table 4.4.1 summarises the functions of the main parts of the human heart.

Structure	Type	Function
right atrium	chamber (upper)	receives deoxygenated blood returned from the body
right ventricle	chamber (lower)	receives deoxygenated blood from the right atrium and pumps it to the lungs
left atrium	chamber (upper)	receives oxygenated blood from the lungs
left ventricle	chamber (lower)	receives oxygenated blood from the left atrium and pumps it to the rest of the body
venae cavae	vessels (veins)	deoxygenated blood returns from the body to the right atrium
pulmonary artery	vessel (artery)	deoxygenated blood is pumped by the right ventricle and flows to the lungs
pulmonary veins	vessels (veins)	oxygenated blood returns from the lungs to the left atrium
aorta	vessel (artery)	oxygenated blood is pumped from the left ventricle and flows to the rest of the body

TABLE 4.4.1 The main components of the human heart and their functions.

BIOFILE

Oxygen to the brain

In humans it would take over a year for oxygen to diffuse from the lungs to the brain, but the brain cannot function if it is deprived of oxygen for more than about 6 minutes. The circulatory system delivers oxygen from the lungs to the brain in less than 4 seconds—the time it takes for the heart to beat four or five times.

BIOFILE

Still-beating hearts

A mammalian heart can keep beating even if it is separated from the body because it has its own electrical impulses. This property can be used in a type of heart transplant called a 'living organ transplant' where a still-beating heart is transplanted into a patient.

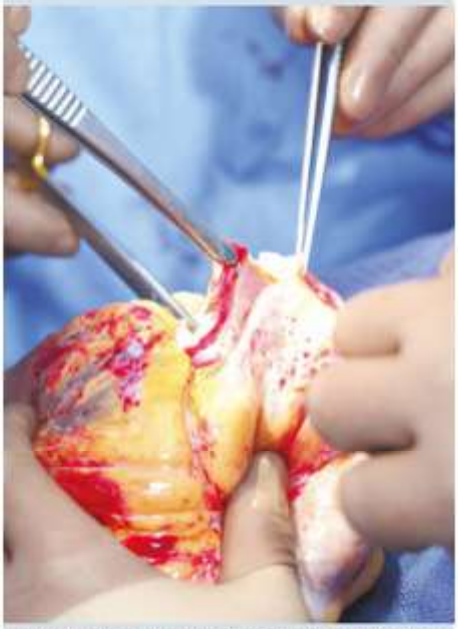


FIGURE 4.4.6 A human heart being prepared for transplant.

The heart is an active organ

The heart is a continuously active muscular organ, so it has a high requirement for nutrients and oxygen. The cells of the heart have their own rich blood supply via the coronary circulation.

The coronary circulation consists of vessels that spread across the surface of the heart and penetrate into the heart tissue. They include:

- arteries
- arterioles
- capillaries
- venules
- veins.

Arteries, veins and capillaries

Blood vessels (Figure 4.4.7) are named according to their structure and position in the circulatory system:

- arteries transport blood away from the heart
- veins transport blood towards the heart
- capillaries are the narrow exchange vessels between arteries and veins.

Arteries and veins are composed of the same layers of tissue, but arteries have more muscular walls, and veins are more easily stretched. Capillaries have very thin walls consisting of only a single layer of flattened epithelial cells.

The structure, function and other features of the blood vessels in the circulatory system are summarised in Table 4.4.2.

	Arteries	Veins	Capillaries
Structure	• consist of an epithelial layer of cells, an elastic layer, muscle wall and connective tissue • same structure as veins but thicker muscular walls	• consist of an epithelial layer of cells, an elastic layer, muscle wall and connective tissue • same structure as arteries but thinner muscle walls	• consist of a single layer of flattened epithelial cells • very thin walls
Function	• transport blood away from the heart	• transport blood towards the heart	• connect arteries to veins • deliver nutrients and other substances to extracellular fluids, and receive wastes
Other features	• higher blood pressure than veins	• contain many one-way valves • lower blood pressure than arteries	• very numerous • form a network within tissues to be near most cells

TABLE 4.4.2 Structure and function of the blood vessels in the circulatory system.

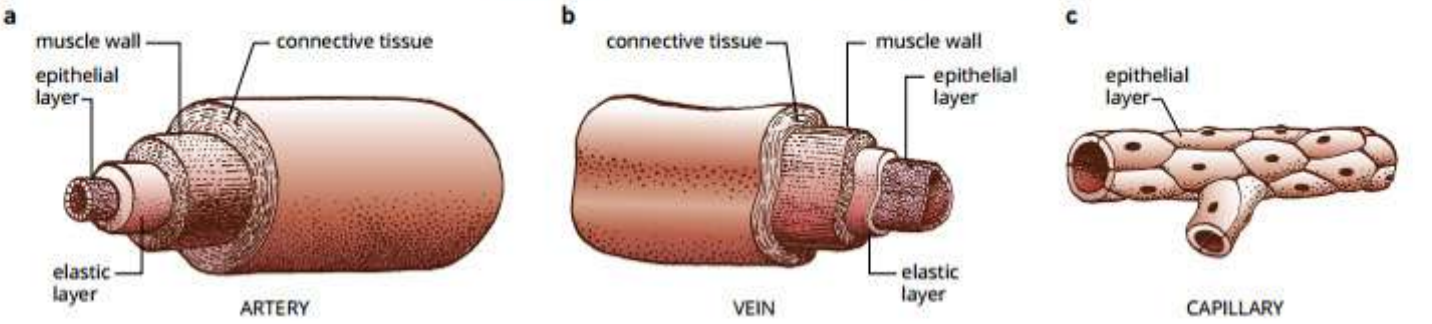


FIGURE 4.4.7 Wall structures of (a) an artery, (b) a vein and (c) a capillary.

Capillaries

Capillaries are the smallest of the blood vessels; their internal diameter is so small that blood cells have to travel through them in a single file (Figure 4.4.8). The capillaries connect arteries to veins, deliver oxygen, nutrients and other substances to extracellular fluids via diffusion, and receive carbon dioxide and other wastes. Capillary walls are extremely thin (just one epithelial cell thick) and porous, which allows substances to pass in and out of the circulatory system. Because of their important role in the transport of oxygen and nutrients to tissues, capillaries are most abundant in metabolically active tissues and organs, such as muscle tissue.

Capillaries are distributed throughout the body as an enormous branched network, providing a vast surface area for the exchange of materials between the blood and extracellular fluid. The interwoven network of blood vessels is known as a capillary bed. To ensure that materials are transported rapidly and efficiently, most cells are no more than 1 mm away from the nearest capillary.

Exchange between blood plasma and extracellular fluid occurs by diffusion and filtration across capillary walls. Ions and small molecules such as glucose and amino acids diffuse through the capillary wall, along concentration gradients. Filtration occurs because of two opposite forces: hydrostatic pressure (or blood pressure) and osmotic pressure (Figure 4.4.9). The pressure from these two forces pushes fluid into and out of the capillaries. Hydrostatic pressure is a result of blood pushing outwards on the capillary walls. Osmotic pressure results from the differing solute concentrations between the blood and the extracellular fluid.

Because blood is hypertonic (more concentrated) than the extracellular fluid, water tries to move through the capillary walls into the blood, putting an inward pressure on the capillaries. The pressure varies along the length of a capillary, but overall the hydrostatic pressure is greater than the osmotic pressure, so more fluid filters out of the capillary than filters in (see Figure 4.4.9). This pressure results in a small amount of protein leakage through the capillary wall cells. When blood pressure increases, this leakage is higher and can result in fluid loss to tissues, causing swelling. Reabsorption allows around 85% of the fluid to return to the capillaries, while the remaining 15% enters the lymphatic system.

In some tissues, such as the gut and liver, the capillaries are more permeable and allow large molecules to cross. This helps the absorption of digested foods from the gut and enables the liver to take in materials to be broken down. In contrast, capillary permeability in the brain is very low, and access of substances to brain tissue is tightly controlled. Nerve tissue is very sensitive to its environment, so it is important that the composition of the extracellular fluid surrounding the brain and spinal cord is carefully regulated.

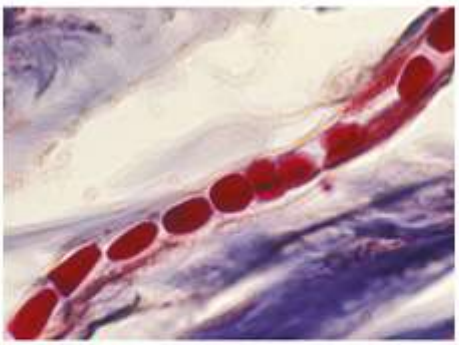


FIGURE 4.4.8 Red blood cells flowing in single file through a capillary.

BIOFILE

Length and surface area of capillaries

The total length of blood vessels in an average human body is nearly 100 000 kilometres. Most of this length is capillaries, which provide a total surface area of over 1000 square metres for the exchange of nutrients, oxygen, carbon dioxide and wastes between blood and extracellular fluid.

A capillary has a diameter of 5–10 µm, so red blood cells (about 7–10 µm in diameter) pass very close to the capillary walls. When the wall of a red blood cell presses against a capillary wall, there is an exchange of oxygen and carbon dioxide. The flattened shape and lack of a nucleus in red blood cells are believed to enhance their transport capability by increasing the surface area available for exchange. Their membrane structure makes them very flexible, allowing them to fold and squeeze through the narrow capillaries.

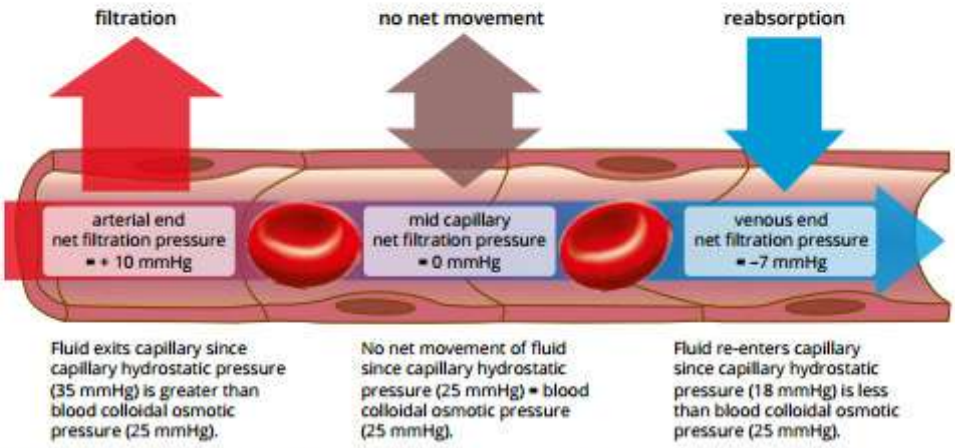


FIGURE 4.4.9 Filtration of fluid across capillary walls is a result of hydrostatic pressure (blood pressure) pushing outwards and osmotic pressure pushing inwards. Overall hydrostatic pressure is greater and so fluid leaks into the extracellular environment.

Blood

Mammalian blood is a fluid containing cells and cellular fragments. The fluid portion of blood is plasma, which is a pale yellow liquid containing ions, dissolved gases, proteins, hormones, nutrients and wastes. The cellular elements of blood include red blood cells (erythrocytes), white blood cells (leukocytes) and platelets (Figure 4.4.10). They are produced by cells located in the red bone marrow, found in the upper ends of long bones and in flat bones like the skull, ribs and pelvis. Blood is a tissue because it is made up of many similar cells working together (see Figure 4.4.11).

FIGURE 4.4.10 Centrifuged blood separates into plasma (clear yellow fluid) and the cellular elements (dark red solids).

Red blood cells

Red blood cells make up around 40% of the blood in humans, and a single drop of blood contains about 5 million red blood cells. Mature red blood cells are concave on each side and highly flexible. They lack a nucleus and are full of the red pigment haemoglobin. Unlike carbon dioxide, oxygen is relatively insoluble. The function of haemoglobin is to bind the oxygen and transport it to the cells.

White blood cells

White blood cells are slightly larger than red blood cells, but there are far fewer of them (Figure 4.4.11). A drop of blood contains between 5000 and 10 000 white blood cells, but more are held in reserve in organs such as the spleen, kidney, thymus and thyroid gland.

There are several different types of white blood cells. The two most numerous types are phagocytes (neutrophils) and lymphocytes, both of which are involved in defence against microorganisms.

- Phagocytes remove debris and fight infections. They are attracted to a site of infection, squeeze through tiny gaps in capillary walls and engulf harmful bacteria and damaged cells.
- Lymphocytes are responsible for the production of antibodies and the development of immune responses.

Platelets

Platelets are fragments of cells. They are much smaller than red and white blood cells and contain substances that are important in preventing blood loss and promoting blood clotting (see Figure 4.4.11).

BIOFILE

Red blood cell cycle

Red blood cells live for about 120 days. Old or damaged cells are removed and broken down by the liver or spleen, and important substances such as iron are retained and re-used by the body. Every second, 2.5 million new red blood cells are released into your bloodstream, and another 2.5 million old ones are removed and destroyed.

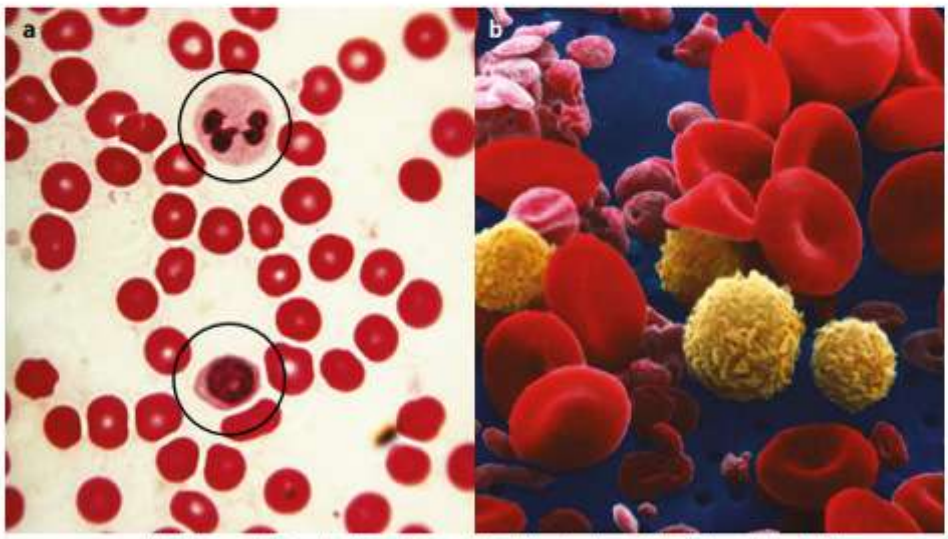


FIGURE 4.4.11 (a) Many red blood cells and two white blood cells (circled) viewed by light microscopy. (b) A coloured SEM showing human blood tissue. The red concave discs are red blood cells, the yellow spheres are white blood cells and the smaller pink cells are platelets.

BIOLOGY IN ACTION

Blood pressure

Blood pressure is caused by the contraction of the ventricles. The muscular wall of the left ventricle is almost twice as thick as that of the right ventricle. This is because the left ventricle has to pump blood to all the organs, while the right ventricle pumps blood only to the lungs. The right ventricle therefore contracts with less force, resulting in lower blood pressure in the right ventricle and pulmonary arteries, compared with the pressure produced by the more muscular left side of the heart.

In arteries, blood pressure fluctuates with each heartbeat, producing a pressure wave that can be felt as a pulse where arteries pass close to the surface of the skin, such as at the wrist. The higher systolic pressure occurs when the ventricle contracts, and the lower diastolic pressure occurs when it relaxes.

Measuring blood pressure

Normal blood pressure in human adults, which is measured in the large artery of the arm, is about 120/80 mmHg (millimetres of mercury as measured with an instrument called a sphygmomanometer containing a column of mercury; modern blood pressure meters do not contain mercury). Your doctor might call this '120 over 80'. That is, the systolic pressure in the artery of the upper arm is 120 mmHg and the diastolic pressure is 80 mmHg.

Arteries branch to form smaller arteries, called arterioles, which eventually flow into capillaries. As blood flows along the arterioles towards capillaries, blood pressure decreases dramatically. The variation between systolic and diastolic pressure also lessens as blood flows into the smaller arteries, and the difference disappears completely in the capillaries and veins (Figure 4.4.12).

In veins, blood pressure continues to decrease as the blood nears the heart. Blood moves along veins towards the heart with the assistance of the compression of veins by muscles during body movements. Veins have many one-way valves, so when they are compressed any blood contained in that region will be pushed out in one direction only, towards the heart. This mechanism for returning blood to the heart is particularly important in legs, where blood has to be returned against gravity.

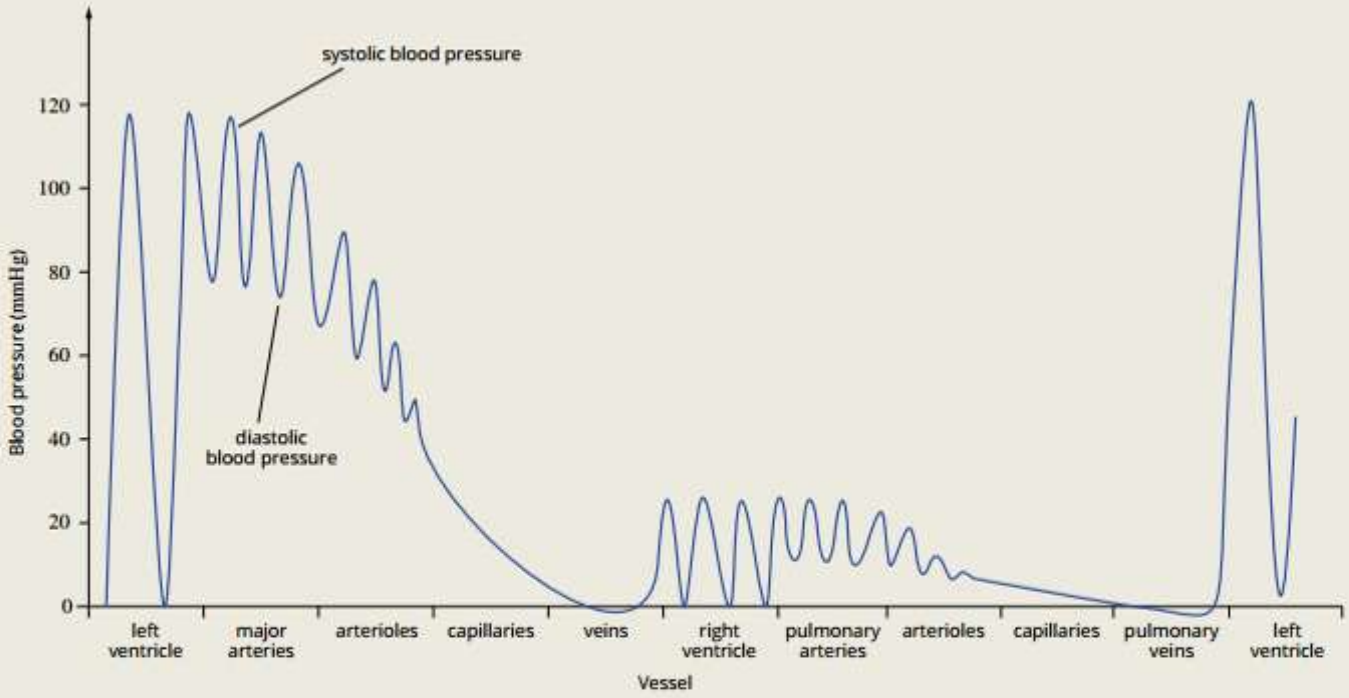


FIGURE 4.4.12 Blood pressure in vessels throughout the human circulatory system. Systolic and diastolic pressures fluctuate in arteries and arterioles, and are reduced to almost zero as blood flows through the capillaries. Blood pressure is lower in pulmonary arteries than in systemic arteries. The right ventricle, which pumps blood to the lungs, has a thinner muscle wall and therefore generates a lower pumping pressure than the left ventricle.

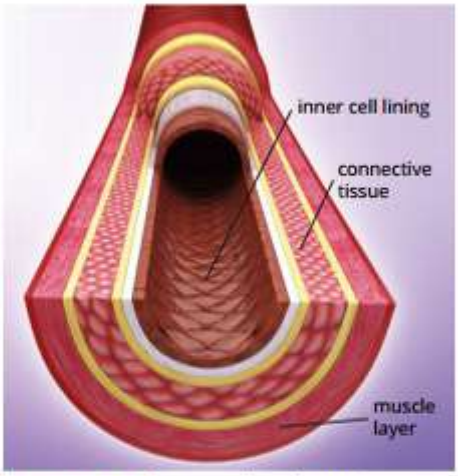


FIGURE 4.4.13 Cross-section of an artery, showing the different layers of muscle and connective tissue that support the inner cell lining.

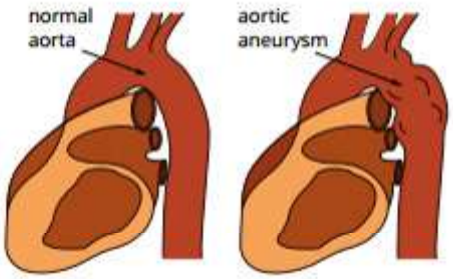


FIGURE 4.4.14 Structure of a healthy aorta compared to an aorta with an aneurysm.

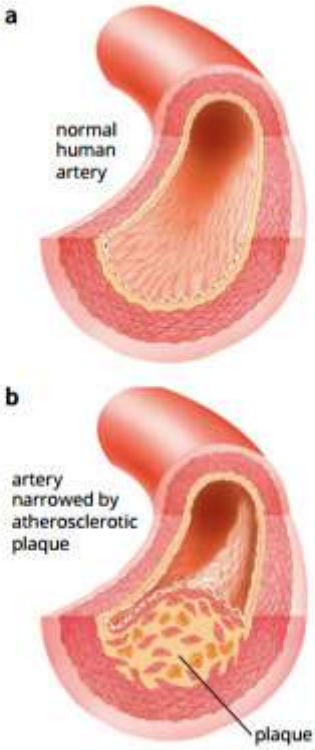


FIGURE 4.4.15 Cross-sections of (a) a normal artery and (b) an artery with atherosclerosis, showing the thickening of the arterial wall caused by a build-up of plaque.

Malfunctions of the circulatory system

Marfan syndrome

Marfan syndrome is an inherited disorder that affects connective tissue. Connective tissue occurs throughout the body and has the principal function of holding together and supporting other tissue (Figure 4.4.13). The cells of connective tissue are held in an extracellular matrix. The extracellular matrix varies in different connective tissues, from hard and tough (such as in bone) to jelly-like (such as in fatty tissue).

Marfan syndrome is caused by a defective glycoprotein (fibrillin-1) that, when functioning correctly, forms elastic fibres in connective tissue and assists in intercellular communication. When this glycoprotein is defective the connective tissue tends to be weakened, affecting its function and causing a range of malfunctions in tissues and organs throughout the body.

Weakened connective tissue has the most serious consequences in the heart, lungs, joints, eyes, spinal cord, skeleton and in particular the major blood vessels, such as the aorta. The aorta is the largest blood vessel in the body. Blood is pumped from the heart through the aorta to the body under considerable pressure. Weakened connective tissue in the aorta can lead to two major problems:

- The aorta may stretch and bulge under pressure (Figure 4.4.14). This is referred to as an aneurysm. Aneurysms can cause pain, and blood flow may be slowed through the bulge. Slowed blood flow can lead to blood clots, which can break off, travel to the brain and cause a stroke, or to the lungs and cause a pulmonary embolism. It can also result in death if the aneurysm ruptures.
- The aorta may begin to tear, so that blood leaks between the layers of the aorta. This can cause pain, lack of blood flow to the tissues and, if left untreated, death.

Both of these conditions are treatable via surgery if diagnosed early.

Arteriosclerosis and atherosclerosis

With age, the arteries lose collagen and elastin filaments and gradually become less elastic and harden. This hardening of the arteries is referred to as arteriosclerosis. Arteriosclerosis puts stress on the heart because it has to pump harder to push the blood through the inflexible arteries.

Over time, fatty substances, cholesterol and calcium can build up inside these hardened arteries, causing them to narrow (Figure 4.4.15). This specific type of arteriosclerosis is called atherosclerosis.

Both arteriosclerosis and atherosclerosis can affect arteries and arterioles in all parts of the body and restrict the flow of blood to tissues and organs. If atherosclerosis has developed, plaque can break away or blood clots can form around the plaque. Both these situations can cause a stroke or heart attack.

Atherosclerosis can affect the coronary blood vessels that supply blood to the heart muscle. A build-up of plaque restricts the supply of nutrients and oxygen to the heart tissue. If the coronary vessels become too narrow or completely blocked, a heart attack can result, possibly leading to the death of heart tissue.

Everyone will eventually develop some degree of arteriosclerosis, but what causes it to develop more rapidly in some individuals and progress to the more life threatening atherosclerosis is not fully understood. What is known is that high blood pressure, along with high levels of cholesterol and triglycerides in the blood, increase the chance of developing atherosclerosis, so smoking, poor diet, lack of exercise and obesity are risk factors.

THE LYMPHATIC SYSTEM

The lymphatic system is the second transport system in mammals. The lymphatic system:

- is an open system
- consists of lymph vessels, lymph nodes and organs such as the thymus and spleen
- transports a colourless liquid called lymph
- transports lymph in one direction, from the tissues to the heart.

The lymphatic system has several roles. One of its main roles is to return extracellular fluid containing proteins that have leaked out of the capillaries back into the circulatory system. Without the constant removal of leaked proteins from the extracellular fluid by the lymph capillaries, fluid would accumulate in the tissues. Once inside the lymphatic system, this fluid is called lymph.

The structure of the lymphatic system is similar to the venous part of the circulatory system (Figure 4.4.16). Fine lymphatic capillaries join to form increasingly larger vessels that eventually empty into the large veins near the heart. The structures of lymph capillaries and vessels are similar to the capillaries and veins of the blood vascular system.

Some of the larger lymph vessels can contract, but most lymph flow results from the external compression of lymph vessels by muscular activity, such as during movement and breathing. When vessels are compressed, the lymph fluid is forced in one direction because of numerous one-way valves, like those in veins, located along the vessels. When a person is inactive (such as standing still or sitting) for a long time, the fluid drainage from tissues decreases and causes swelling. This is especially so in the legs, because fluid drainage must work against gravity.

The lymphatic system also plays a vital role in the immune system. Invading pathogens are transported in the lymph to the lymph nodes (Figure 4.4.16), where bacteria, viruses and cancer cells are trapped and destroyed by phagocytes and lymphocytes. This is why your lymph nodes swell up when you have an infection.

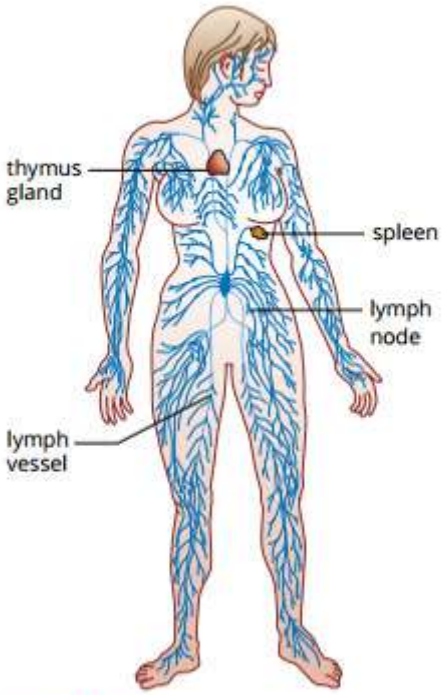


FIGURE 4.4.16 The distribution of lymph vessels throughout the body. The blood circulatory system loses around 3 litres of fluid into the extracellular fluid every 24 hours. The lymphatic system collects and returns this fluid to the circulatory system.

Malfunctions of the lymphatic system

Deep vein thrombosis

People who sit for long periods of time, such as passengers on a long flight, are encouraged to stretch and exercise regularly to assist the movement of lymph and venous blood back to the heart. Failure to do this can result in swelling in the feet, ankles and legs because fluid accumulates in these areas. This can lead to a condition called deep vein thrombosis (DVT), a blood clot that forms in the veins of the leg. DVT can result in pulmonary embolism, a blockage of the main artery of the lungs, if the clot breaks away and is carried by the bloodstream to a lung and lodges there (Figure 4.4.17). A pulmonary embolism can cause difficulty in breathing, chest pain, heart palpitations and, if the clot completely blocks an artery, death. Regular exercise, a healthy diet and not smoking all reduce the risk of DVT.

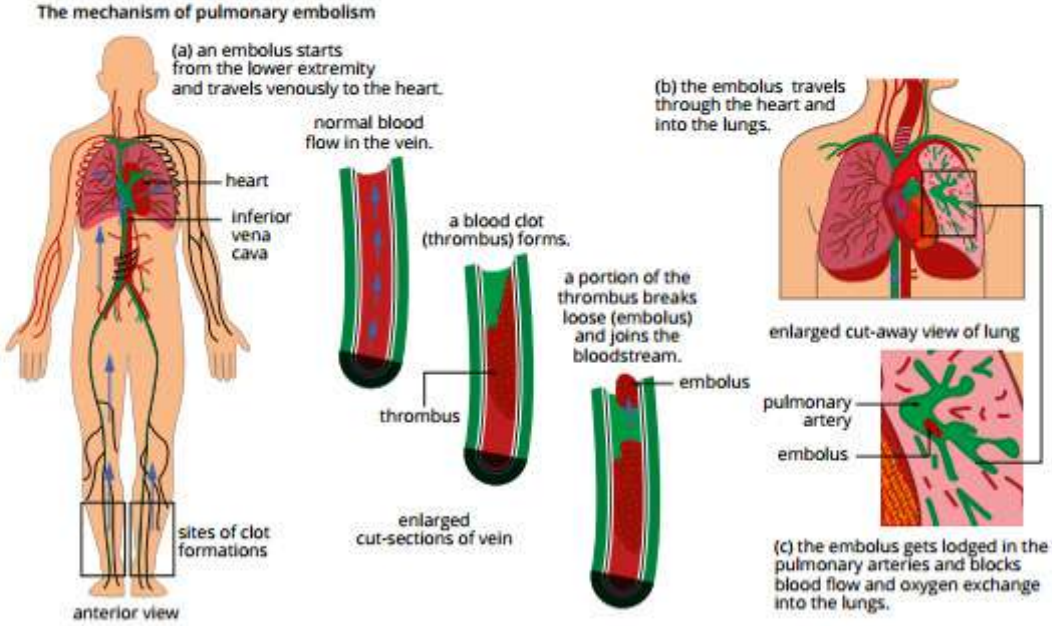


FIGURE 4.4.17 The mechanism of pulmonary embolism resulting from deep vein thrombosis (DVT). A pulmonary embolism can occur when a blood clot (embolus) breaks off and lodges in a lung, blocking oxygen exchange.

GAS EXCHANGE: THE RESPIRATORY SYSTEM

Organisms must exchange oxygen and carbon dioxide with their environments to maintain the important energy-transforming process: cellular respiration. Disruption of this exchange—for example, by respiratory illness in humans—can have serious consequences.

In aerobic (oxygen-dependent) organisms, the rate at which oxygen is supplied to cells limits the amount of energy that can be released from glucose for cellular activities. Carbon dioxide, which is produced as a waste product during cellular respiration, forms a weak acid in solution with water. If carbon dioxide is allowed to accumulate in the body fluids, the pH will decrease (that is, acidity will increase), with damaging effects on the structure and function of many important molecules. So it is important that carbon dioxide is removed efficiently.

In single-celled and very small organisms with high surface area to volume ratios, adequate levels of gas exchange occur directly with the environment. In larger animals that have a high metabolic rate and a need for highly efficient gas exchange, well-developed mechanisms to ventilate their gas exchange surfaces are required. This surface is linked closely to blood transport systems so that gases move efficiently between cells and the environment.

A system is a group of organs working together to perform one or more functions that contribute to the survival, growth and reproduction of the organism. Like specialised cells, tissues and organs, systems must work together. For example, the circulatory system interconnects with all of the other systems of the human body. Three of these are the digestive system (nutrient absorption), respiratory system (gas exchange) and excretory system (waste removal).

Diffusion

Gas exchange always takes place by **diffusion** across a moist plasma membrane. Diffusion is the passive movement of a substance along its concentration gradient from a region of high concentration to a region of low concentration. The immediate environment of cells is the layer of fluid that surrounds them. Even for organisms that get their oxygen from air, oxygen must first dissolve in the layer of extracellular fluid covering the gas exchange surface before it can cross plasma membranes and enter the body.

Small, uncharged molecules, such as oxygen and carbon dioxide, pass directly through the phospholipid bilayer. They therefore diffuse into or out of cells along their concentration gradient. In contrast to the many nutrients that are actively taken up by organisms, neither oxygen nor carbon dioxide is actively pumped across membranes.

The rate of diffusion of a molecule across a membrane depends on the size and maintenance of the concentration gradient, and also on properties of the membrane itself. The amount of a particular molecule transferred per unit time depends on the membrane's permeability to the molecule, the available surface area of the membrane, and the thickness of the membrane (the distance of diffusion).

Efficient gas exchange surfaces

For efficient gas exchange:

- The surface area should be as large as possible. There is a greater total exchange across a large surface than across a small one.
- The barrier to be crossed (such as cells membranes and fluid layers) should be as thin as possible and should consist of a material that allows the gas to pass through the barrier easily.
- There should be an adequate supply of the gas being transferred. If the respiratory surface is not adequately ventilated, the rate of exchange drops.
- There should be efficient removal of the substance after transfer. Oxygen is carried away from the respiratory surface, usually by blood. Inadequate blood flow past the respiratory surface will allow oxygen to accumulate, so that further transfer is slowed down.

In most large animals, energy is used to ventilate the respiratory surface and to circulate blood past its inner surface. The efficient supply and removal of oxygen maintains a high concentration gradient across the exchange surface, and, therefore, a high rate of diffusion. Energy expenditure is most economical when the rates of ventilation and blood flow to the respiratory tissue are matched. For example, when you begin to exercise you need more oxygen. You breathe more heavily and your heart rate increases. Ventilation and blood flow to the lungs are still matched, but each is at a higher level in order to supply more oxygen.

Breathing air

Oxygen is absorbed from the environment by the respiratory system and transferred to the cells via the circulatory system.

The key steps in the process of human respiration occur at the following sites (see Figure 4.4.18):

- nose and throat—Air is drawn in through the nasal cavity and passes into the pharynx (the back of the throat). Breathing through the nose is preferable to breathing through the mouth because the air is filtered, moistened and warmed in the nasal passages.
- airways—From the pharynx, air passes into the airways: the trachea, paired bronchi and branching bronchioles. The trachea and bronchi are lined with cells covered in **cilia** and secrete mucus (Figure 4.4.19). Particles of dust or bacteria are trapped by this mucus and swept by the cilia back up to the pharynx and swallowed. The larynx, containing the vocal cords responsible for speech, is located at the upper end of the trachea.
- alveoli—Air enters the terminal air sacs, called alveoli, where gas exchange takes place. A constant supply of oxygen to cells is the most critical input for endotherms, such as mammals and birds, because they use energy to warm their bodies, and therefore need oxygen at a great rate for cellular respiration.

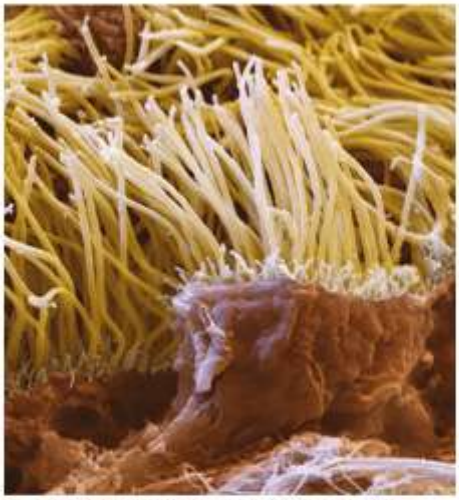


FIGURE 4.4.19 A cross-section through the cilia-covered epithelial cells of the bronchus (lung airway). The cilia are microscopic hairs that sweep trapped particles and mucus away from the gas-exchanging parts of the lungs and towards the throat, where the particles can be swallowed or coughed up.

Ventilation (breathing) is the active movement of the respiratory medium (air or water) across a gas exchange surface.

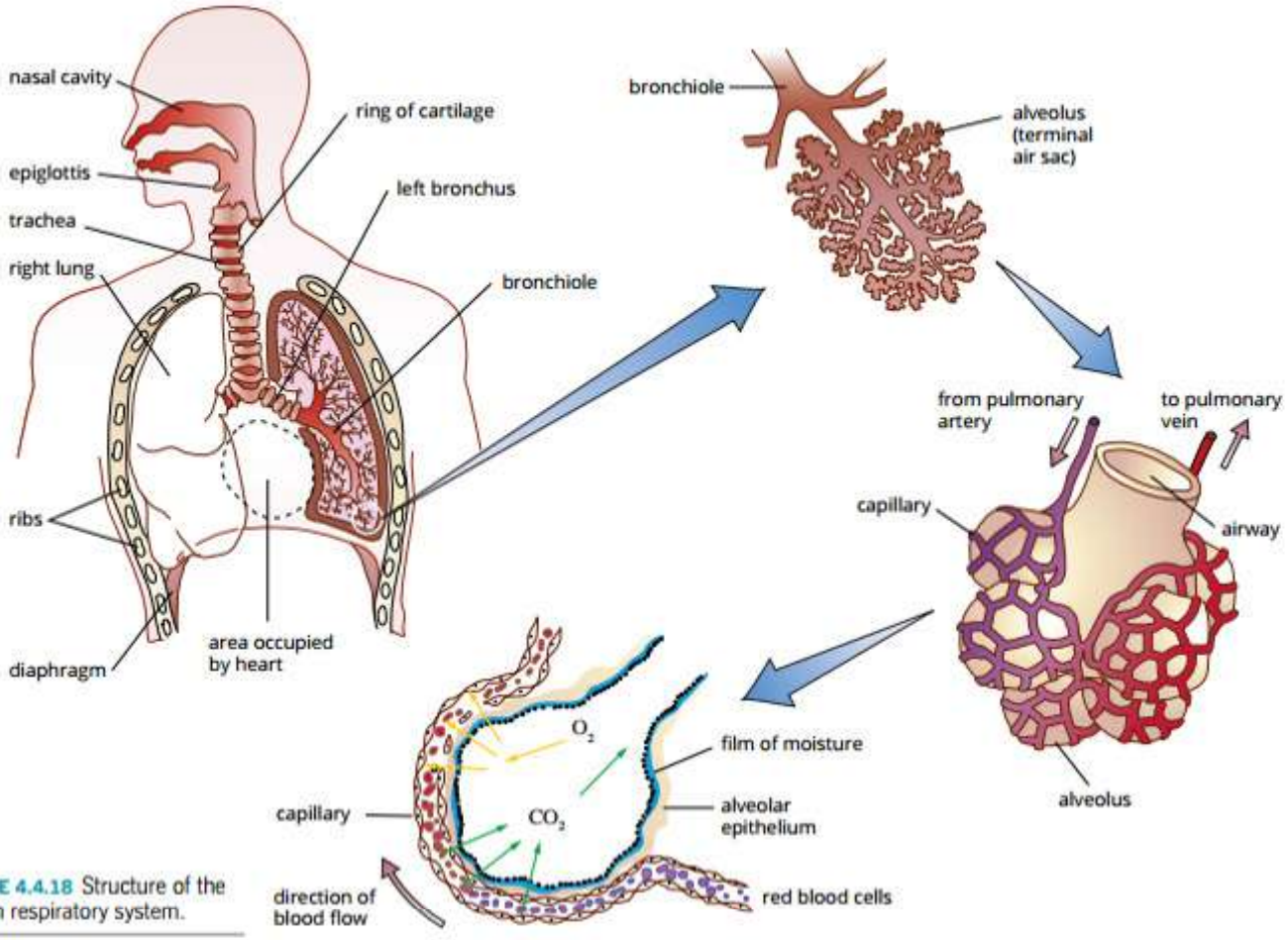


FIGURE 4.4.18 Structure of the human respiratory system.

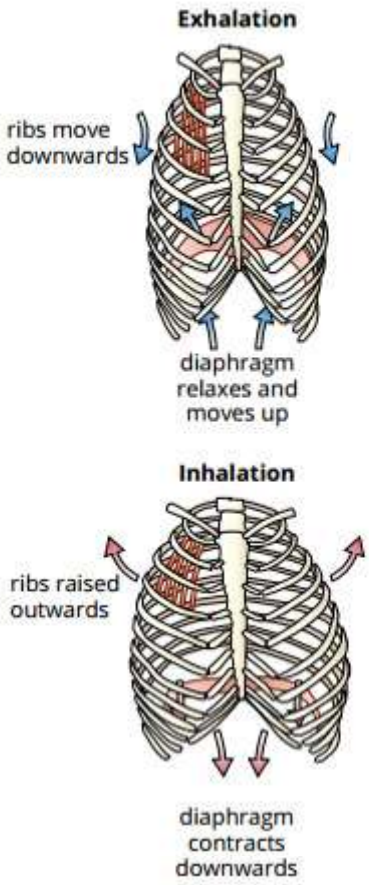


FIGURE 4.4.20 Mammals breathe by negative pressure ventilation. Raising the ribs and contracting the diaphragm increases the volume of the chest cavity and draws air into the lungs (inhalation). Relaxing these muscles causes the volume of the chest cavity to reduce and air is forced out again (exhalation).

The tissue of the alveoli shows all the features of efficient exchange organs. It provides a large surface area for gas exchange; the total surface area in most adults is between about 30 and 70 m^2. Each alveolus is lined with a very thin layer of flattened cells, called the alveolar epithelium (see Figure 4.4.18). This thin layer of cells is richly supplied with blood capillaries, facilitating diffusion of gases between the alveoli and the capillaries. Once oxygen enters the capillaries, it has entered the circulatory system, and the oxygenated blood is transported throughout the body.

There are two great advantages of breathing air. Ventilation with air requires much less energy than breathing water, which is heavy, and much more oxygen is available in air than is available in water. But animals that breathe air must have a large, moist gas exchange surface. The disadvantage of breathing air is that water evaporates continuously from this large, moist surface area. Respiratory surfaces are therefore a major site of water loss for all terrestrial organisms.

Enclosing the respiratory surface inside the body provides physical protection from the external environment and support for the respiratory membrane, and reduces water loss. But it increases the need for efficient ventilation of the gas exchange surface.

Lung ventilation

Mammalian lungs are contained in the chest cavity (the thorax), which is completely enclosed and under a small negative pressure that keeps the lungs expanded within the thorax. The floor of the chest cavity is the muscular diaphragm.

Mammals use a 'suction pump' mechanism to ventilate their lungs. The chest cavity is expanded by the contraction of the diaphragm downwards and the raising of the ribs. This expands the lungs and draws air in through the airways (Figure 4.4.20). Inhalation is always an active process (it requires energy). Exhalation, however, is normally the result of the elastic recoil of the thorax as it returns to its relaxed state. Forceful exhalation involves an active compression of the rib cage.

Tidal volume

Tidal volume is the volume of air moved in and out at each breath. Normal resting levels of inhalation and exhalation are much less than our **vital capacity**, which is the maximum volume of air that we can move into and out of our lungs. Tidal volume varies according to the need for oxygen.

Air moves tidally into and out of mammalian lungs through the same airways (Figure 4.4.21). This is not as efficient as one-way flow, because at the end of an exhalation there is still some 'stale' air left in the airways and in the alveoli. The next inhalation draws this stale air back into the lungs, so it is impossible to fill our lungs completely with fresh air. The volume of air left in the respiratory system at the end of exhalation is referred to as the residual volume.

Transporting gases

Carrying oxygen

Maintaining an oxygen concentration gradient across the lung surface requires efficient supply (through ventilation) and removal (by circulation) of the oxygen. But the amount of oxygen that dissolves in water (or blood, which is about 90% water) is very small.

The oxygen-carrying molecule haemoglobin increases the oxygencarrying capacity of the blood—that is, the amount of oxygen that it can carry. The most important feature of haemoglobin is that it can combine reversibly with oxygen.

Increasing the oxygen-carrying capacity of blood reduces the amount of energy that must be spent pumping blood. Because each millilitre of blood carries much more oxygen, an animal can have a much smaller volume of blood, and pump it around the body more slowly, while still supplying the same amount of oxygen to its cells.

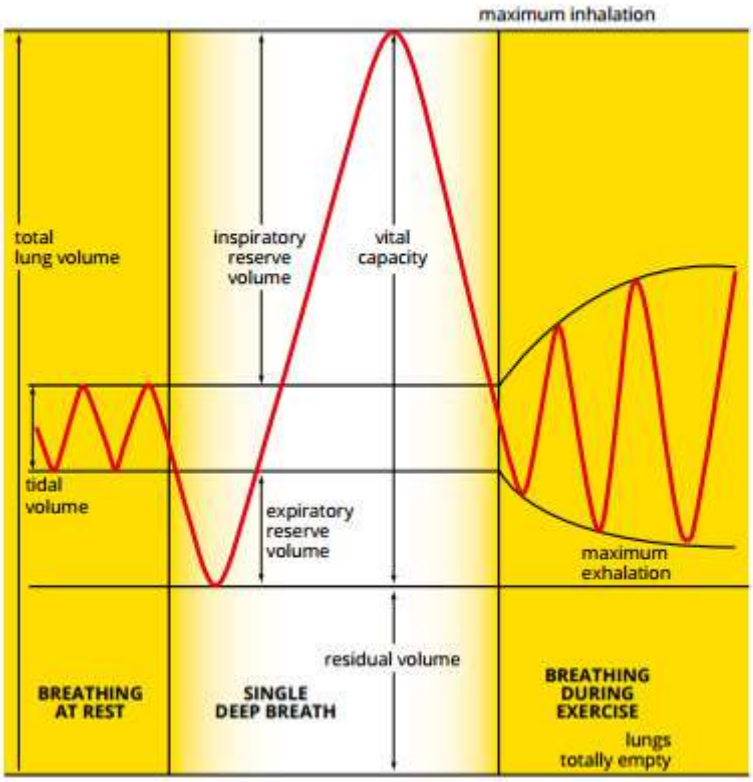


FIGURE 4.4.21 Lung ventilation in humans. During exercise, tidal volume increases. The extent of this increase is directly related to the increased use of oxygen, and is matched by an increased blood flow to the lungs.

BIOFILE

Human divers must breathe air at high pressure in order to inflate their lungs against the pressure of the outside water. This is because our chest muscles are not strong enough to expand the rib cage and inhale against water pressure at depths below about one metre.

FIGURE 4.4.22 A diver wearing high-pressure breathing apparatus.

Haemoglobin

Oxygen is relatively insoluble in blood: only 0.2 mL of oxygen gas dissolves in 100 mL of blood. The carrying capacity of mammalian blood is increased 100 times by the presence of the red respiratory protein haemoglobin (Hb), which is carried in red blood cells. Mature red blood cells are little more than plasma membranes filled with haemoglobin.

Haemoglobin is a complex protein containing iron. Four oxygen molecules can combine with each haemoglobin molecule (Figure 4.4.23). In areas of high oxygen concentration, such as in the blood in vessels in the lungs, haemoglobin combines with oxygen to form oxyhaemoglobin. In areas of low oxygen concentration, such as in exercising muscles, oxygen is released (dissociated) from the oxyhaemoglobin. The percentage of oxygen concentration in exercising muscles, tissues and lungs therefore varies. This relationship can be seen in Figure 4.4.24.

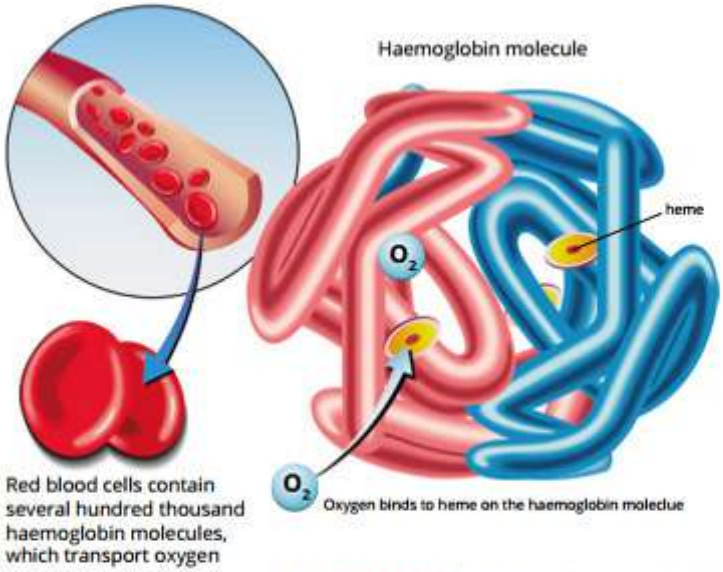


FIGURE 4.4.23 3D structure of a haemoglobin molecule. This molecule is responsible for binding oxygen molecules in red blood cells.

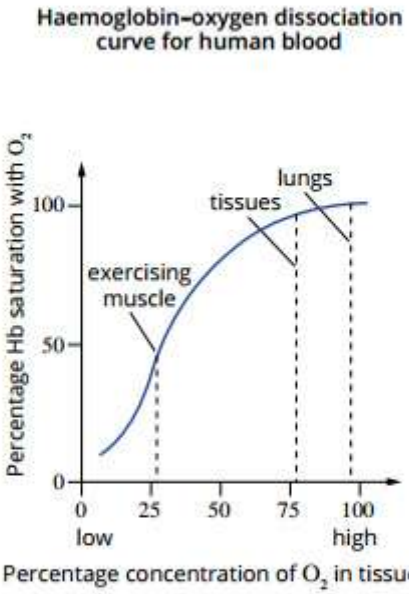


FIGURE 4.4.24 Haemoglobin–oxygen dissociation curve for human blood, shows the concentration of oxygen in different tissues in the body.

Oxygen in the tissues

In resting humans, haemoglobin is almost 100% saturated with oxygen in the lungs and about 75% saturated in tissues (Figure 4.4.24). This means that only about one-quarter of the oxygen carried by the blood throughout the body is taken up from capillaries and used by cells for cellular respiration. The remaining oxygen in the blood is a reserve, available for use when oxygen demand increases—for example, during exercise when blood oxygen saturation may drop to 25%. An adequate oxygen supply is so critical to our survival that it is necessary to have a considerable reserve for use during emergencies.

Our muscles are red because they also contain a form of haemoglobin, called myoglobin. Myoglobin carries a reserve store of oxygen that muscles can use for a limited period if the amount of oxygen in the blood suddenly decreases to a very low level. This situation could arise if a blood vessel were temporarily blocked, or during strenuous exercise. When blood supply is restored, the myoglobin oxygen store is immediately refilled from the blood. Myoglobin has a higher affinity for oxygen than haemoglobin and therefore can take oxygen from it. This also means that haemoglobin releases large amounts of its bound oxygen to exercising muscle before the myoglobin releases its store, making it a true emergency resource.

Anaemia

Anaemia is a condition in which there are insufficient red blood cells, or the quality of the red blood cells or the haemoglobin is low. The most common cause of anaemia is a deficiency of iron in the diet. Other causes include failure to absorb iron because of disease, heavy menstruation, and inherited disorders such as sickle cell anaemia (see Section 4.1).

Anaemia results in pale skin, tiredness, muscle weakness, headaches and problems with concentrations. Treatment is determined by the underlying cause, but can involve a change in diet, iron supplements, surgery, or (in extreme cases) oxygen therapy and blood transfusions.

Carrying carbon dioxide

Carbon dioxide, produced by cellular respiration, must be carried in body fluids to an external surface where it can be released to the environment. Because carbon dioxide combines with water to form an acid (carbonic acid) and cause a decrease in pH, it can be carried in solution only in limited amounts.

In mammals, about 7% of the carbon dioxide carried by blood is dissolved in the plasma. About 23% combines with haemoglobin molecules (forming carbamino-haemoglobin), but at a different site on the haemoglobin molecule to the site where oxygen binds. Carbamino-haemoglobin is still able to combine with oxygen. The remainder of the carbon dioxide produced in working tissues passes into red blood cells, where it is converted to hydrogen carbonate ions, and then passes out to be transported in the plasma.

When the blood reaches the lungs, the hydrogen carbonate moves back into the red blood cells where it is converted to carbon dioxide for release during breathing.

Malfunctions of the respiratory system

Although asthma, emphysema and pneumonia are unrelated human illnesses, some of their symptoms, such as tiredness and inability to exercise, are similar. The reason for this is that each of these illnesses interferes with at least one of the important features responsible for efficient gas exchange in the lung, leaving the cells unable to produce enough energy for their normal functions.

Asthma

Asthma is a condition in which the cells lining the airways (bronchi and bronchioles) are sensitive to foreign particles in the air, such as pollen. Small airways become swollen, filled with mucus and constricted (Figure 4.4.25). This reduces the space through which air can flow, causing an increased resistance to the flow of air into and out of the lungs. It is particularly difficult to breathe out. When the pressure on the lungs is increased to force air out, the narrowed airways that are causing the obstruction are also compressed.

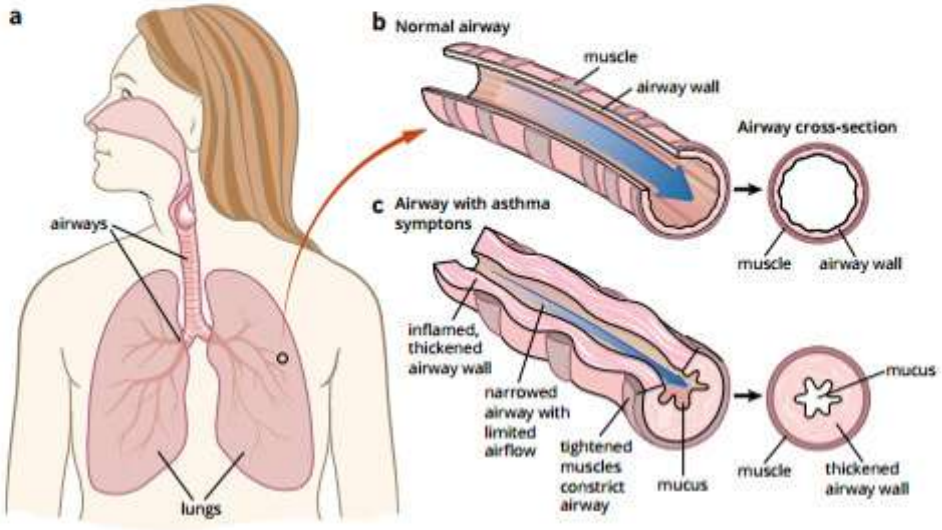


FIGURE 4.4.25 An overview of the respiratory system in humans (a), with a comparison of normal airways (b) and the inflamed airways during an asthmatic episode (c).

Emphysema

Emphysema is caused by the breakdown of the air sacs, reducing the lung surface area available for gas exchange, sometimes to less than one-quarter of that of healthy lung tissue (Figure 4.4.26b). It occurs mostly in old age and is becoming increasingly common, most likely as a consequence of smoking (Figure 4.4.27). As in asthma, there may be an increased resistance to airflow in the small airways, making breathing more difficult.

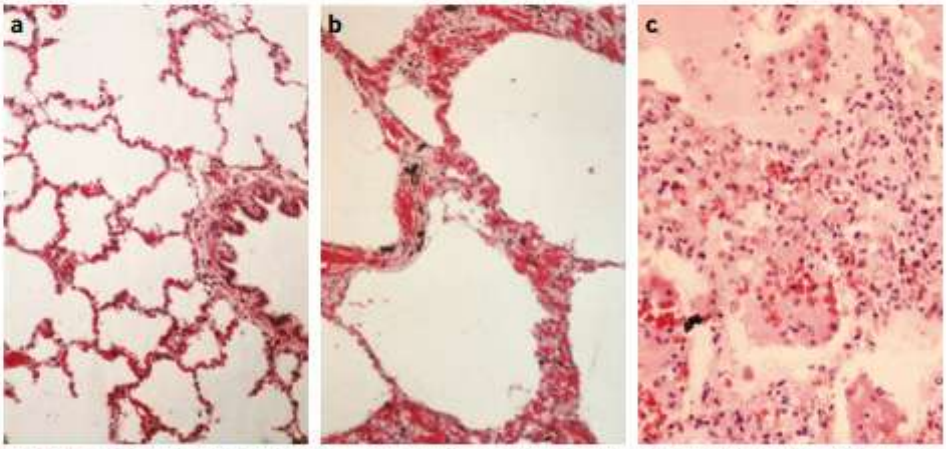


FIGURE 4.4.26 (a) Normal lung tissue has large air spaces and very thin membranes for efficient gas exchange. (b) In emphysema, the air sacs break down and the membranes become thicker. In this case the emphysema was associated with inhalation of coal dust (anthracosis), some of which can be seen as a black deposit in the lung tissue. (c) In pneumonia, large areas of the lung become filled with fluid and white blood cells. All photographs were taken at the same magnification.

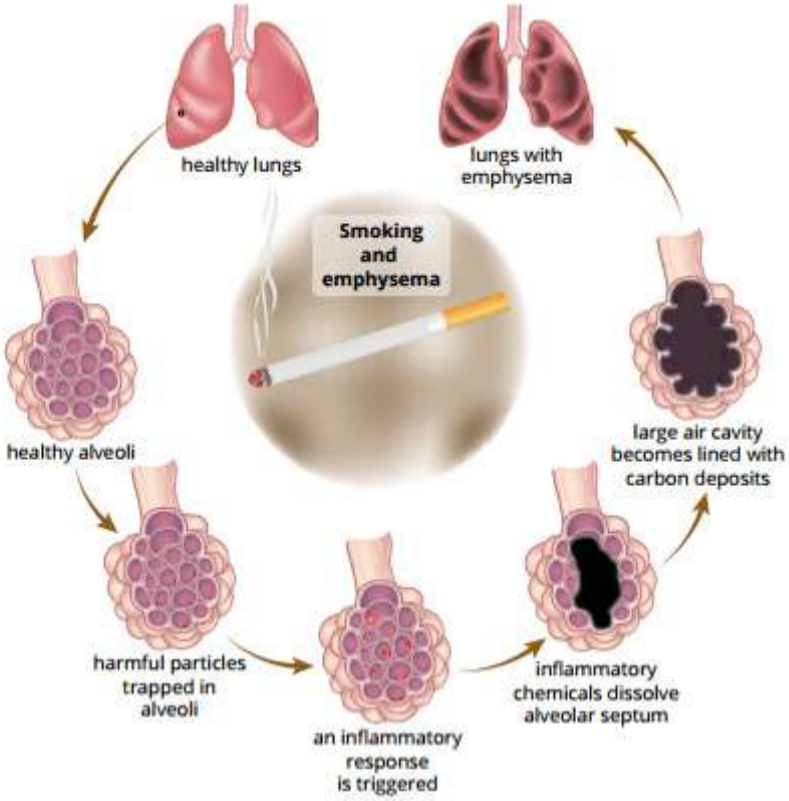


FIGURE 4.4.27 The stages of emphysema as a result of smoking. Emphysema is a progressive disease, with inflammation and breakdown of the alveoli worsening over time with exposure to cigarette smoke.

Pneumonia

Pneumonia is caused by an infection that causes the lung to become inflamed, and the air sacs (alveoli) become filled with white blood cells and fluid (Figure 4.4.28). This interferes with respiration because the fluid filling the air sacs reduces the area of lung surface in contact with air. The inflamed lung tissue is also swollen, so that oxygen has to diffuse further before it can enter the blood (Figure 4.4.28c).

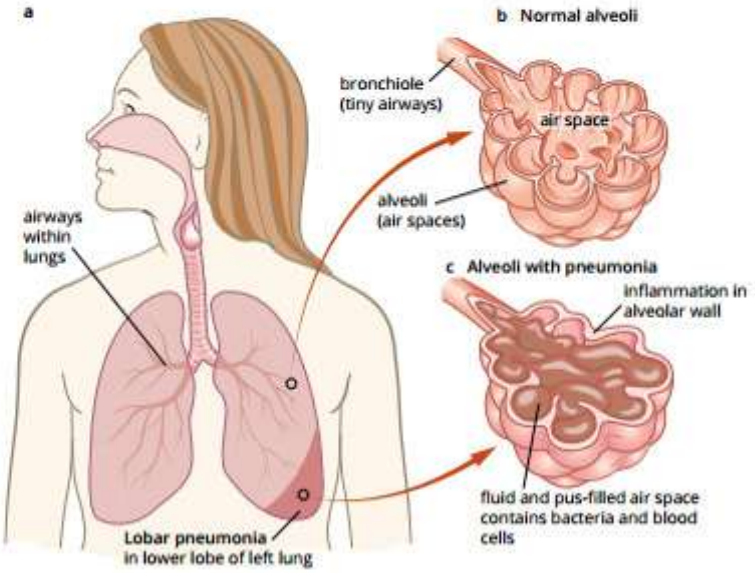


FIGURE 4.4.28 An overview of the respiratory system in humans (a) with a comparison of normal alveoli (b) and the inflamed, fluid-filled alveoli of someone with pneumonia (c).

OBTAINING NUTRIENTS: THE DIGESTIVE SYSTEM

Mammals are heterotrophs; unlike plants, they cannot make organic molecules from inorganic materials. So they must consume other organisms or their products to obtain organic molecules. As well as needing organic molecules to provide chemical energy, heterotrophs also require other organic molecules such as vitamins, amino acids and fatty acids. Their diet must also contain minerals and water.

Nutritional requirements

Carbohydrates and lipids

Carbohydrates are an important source of immediate energy for all living organisms. The monosaccharide glucose is broken down to produce ATP during cellular respiration. Animals store carbohydrates in the form of the polysaccharide glycogen.

Lipids are also an important energy store in animals, and they are required for cell membranes, hormones and vitamins.

Amino acids

Amino acids are required for protein synthesis. Animals cannot make all the amino acids they need, but they can change some amino acids into others. However, there are nine amino acids that cannot be made in this way (Table 4.4.3). These are called the essential amino acids because they must be included in the diet. Because amino acids are not stored, all required amino acids must be present in the blood for protein synthesis to proceed smoothly. This means that all essential amino acids should be eaten regularly to maintain their levels in the blood.

All nine essential amino acids are found in milk, eggs and meat. Wheat, corn, rice and other grains contain very little lysine. Beans, lentils and other legumes are rich in lysine but contain little methionine. So it is good to eat grains and beans together. Other sources with moderate to high amounts are shown in Table 4.4.3

Amino acid	Main sources
isoleucine	fish, cheese, seeds and nuts, lentils
leucine	grains, cereals, nuts, soybeans, lentils and beans, corn
lysine	fish, potatoes, lentils and beans
methionine	fish, soybeans, cottage cheese, yoghurt, pumpkin seeds, sesame seeds
phenylalanine	cheese, wheat germ, oatflakes
threonine	wheat germ, many nuts, beans and seeds
tryptophan	pineapple, yoghurt, bananas, unripened cheese
valine	soy flour, raw brown rice, cottage cheese, fish, seeds and nuts, lentils, mushrooms
histidine	meat and dairy products (infants cannot synthesise histidine, so they must obtain it from their diet).

TABLE 4.4.3 The nine essential amino acids.

Vitamins and minerals

Vitamins are a diverse group of organic compounds that are required in very small amounts for particular cell processes. They are not used to supply energy. Vitamins are synthesised by plants and by some simple animals and microorganisms. Mammals need 13 vitamins, and, like most animals, they must obtain them from their diet. Many vitamins are important because they are needed to make particular enzymes.

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Naming vitamins

Vitamins were named alphabetically (A, B, C, etc.) before their chemical structure was understood. This way of naming them is still used, although we now know their chemical formulae and dietary sources. We also know a great deal about their functions in the body.

Vitamins A, D, E and K are fat-soluble, and are therefore obtained from food containing fats and oils. The remaining nine vitamins (the B group and vitamin C) are water-soluble. Fat-soluble vitamins are stored in the liver, whereas excess water-soluble vitamins are excreted. This is why we need to constantly eat food containing vitamins B and C. Vitamin C is used up in the reaction in which it is involved, whereas the other water-soluble vitamins are recycled as they function. This is why the daily requirement for vitamin C is relatively large.

More than 20 **minerals** are also required in our diet. The main minerals required are calcium, phosphorus, magnesium, iron, sodium, potassium and iodine; others are needed only in trace (small) amounts. Mineral ions occur in the cytosol of cells, in structural components (such as bone) and in the molecules of many enzymes and vitamins.

A vitamin deficiency can be caused by an inadequate diet or poor absorption from the gut. Pernicious anaemia, for example, is a vitamin deficiency disease that is caused by the lack of a particular substance in gastric juices that is needed for the absorption of vitamin B12 from the intestine. In this case a huge intake of vitamin pills is not likely to remedy the problem.

In normal circumstances a healthy person eating a balanced diet should not require additional vitamin or mineral supplements (Table 4.4.4). An excessive intake of water-soluble vitamins should cause no direct harm because they are excreted rapidly in urine, but an excessive intake of fat-soluble vitamins can be dangerous. These are not excreted and are retained in the body. Even a fivefold excess may cause disease symptoms.

	Age	Body mass (kg)	Energy (kJ)	Protein (g)	Calcium (mg)	Iron (mg)	Thiamine (mg)	Niacin (mg)	Vitamin C (mg)
Females	14–18	55	5900	35	1050	8	0.9	11	28
Females	19–50	58	8400	37	840	8	0.9	11	30
Males	14–18	65	7600	49	1050	8	1.0	12	28
Males	19–50	70	11600	52	840	6	1.0	12	30
Pregnant women (trimesters 2 & 3)	18–35	68	9000	49	840	22	1.2	14	40
Lactating women	18–35	58	10800	54	840	6.5	1.2	13	60

TABLE 4.4.4 Some estimated average daily nutritional requirements of humans. Recommended daily intakes are higher than these values. (Adapted from 'Nutrient reference values for Australia and New Zealand', 2005.)

In normal circumstances a well-balanced diet is also the best way of providing good nutrition during pregnancy. An additional intake of vitamins and minerals can be detrimental. For example, an excessive intake of calcium during pregnancy may result in premature calcification of the developing baby's bones.

Digestion is the breakdown of food into a form that can be used by an organism for metabolism. This involves physical and chemical breakdown.

Food must be digested

Organisms are composed of many different types of complex organic molecules. When eaten as food, these molecules are too large to be simply absorbed into an animal's body. Regardless of the type of animal, food molecules must be small enough to pass across plasma membranes into the cells lining the gut. This is the purpose of digestion—to rapidly break down organic food into molecules small enough to be able to pass through membranes and into cells.

The food you eat does not become part of your body until it has been absorbed by the cells lining the walls of your intestine. The digested food then passes into the bloodstream and is carried throughout the body. If food is not absorbed, it continues through the intestine and is passed out again as faeces (**egestion**).

Do not confuse egestion with **excretion**. Excretion refers to the removal of substances that were once part of the body, and occurs largely in the kidneys.

Physical breakdown

Digestive enzymes can only act on the outside surface of food. If food is swallowed in large pieces, the enzymes have a relatively small surface area to work on. Unless the digestive system is extraordinarily long, most of the food would remain undigested. Given the relationship between surface area and volume (see Section 2.3), digestion is much faster if food is in small pieces and the enzymes have a proportionally larger area to act upon.

So it is important to have a mechanism for breaking down large food into pieces to increase its surface area. Animals have developed a variety of structures to break down food physically—for example, the teeth of vertebrates, which break food into pieces small enough to be swallowed (Figure 4.4.29).

To improve the efficiency of digestion, this physical breakdown should take place before chemical digestion is completed. In contrast to chemical digestion, physical breakdown does not chemically change food molecules.

Bile is important in the physical breakdown of fats, but it is not an enzyme. Bile is produced by the liver and released into the small intestine where it acts like a detergent to emulsify fats—breaking up large fatty masses into small droplets. This increases the surface area of fats available for digestion by lipases.

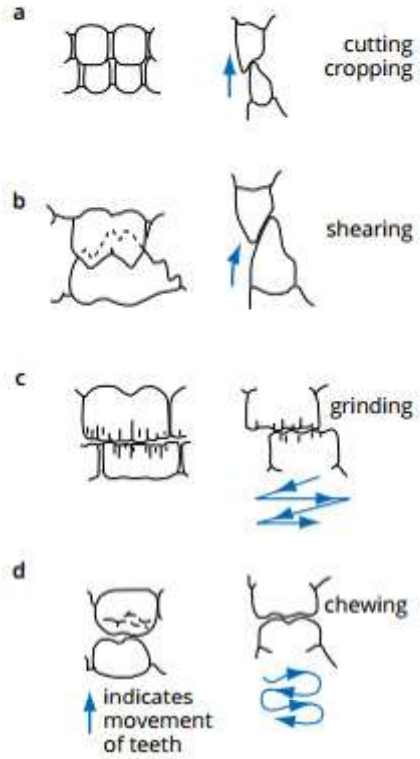


FIGURE 4.4.29 In mammals, the tooth structure is adapted for the mechanical breakdown of different types of foods. (a) Incisors are typically used for cutting and tearing. (b) Carnivores have large powerful cheek teeth that shear through tough sinews and bones. (c) Herbivores have molars that grind fibrous plant foods. (d) Omnivores, such as you, have molars that roll and crush a variety of foods.

Chemical digestion

The process of breaking apart complex molecules into simple molecules is called chemical digestion, and is carried out by the action of enzymes. Enzymes are important in digestion because they greatly increase the rate of breakdown of food molecules.

Most digestive enzymes split food molecules by the process of **hydrolysis** (from Greek *hydro* water and *lysis* split). This means they split the food molecule at a particular point by adding a water molecule. There are three main kinds of digestive enzymes (Figure 4.4.30):

- amylases, which act on carbohydrates
- proteases, which act on proteins
- lipases, which act on lipids.

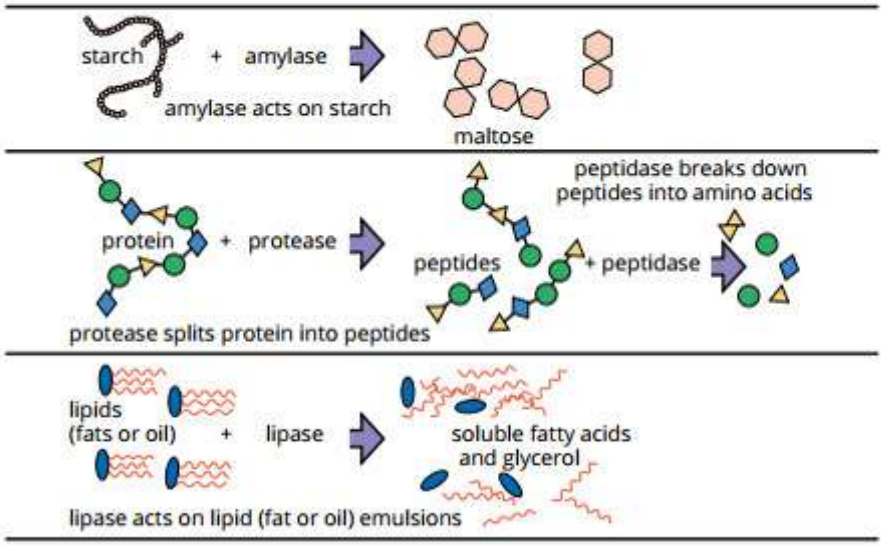


FIGURE 4.4.30 Digestion involves the splitting of food molecules into components small enough to pass across plasma membranes and into the body. Enzymes used in digestion are often named according to the substance on which they act, with the common ending –ase. For example, protease digests proteins and lipase digests lipids.

Digestive enzymes are manufactured by specific cells in the gut wall, and by the salivary glands and the pancreas. Many very large food molecules can be broken down only by several enzymes acting one after the other. In this case, the different enzymes are produced at appropriate sites along the digestive system.

The importance of pH

Because enzymes are proteins, they are sensitive to changes in the pH of a solution (Figure 4.4.31). Altering the pH changes the shape of protein molecules, which in turn alters their chemical properties. The change in shape alters the way that an enzyme binds with the molecule upon which it acts. Enzymes, therefore, have certain pH ranges over which they operate best. Different regions of the gut have different pH values that are most suitable for enzymes found in that region.

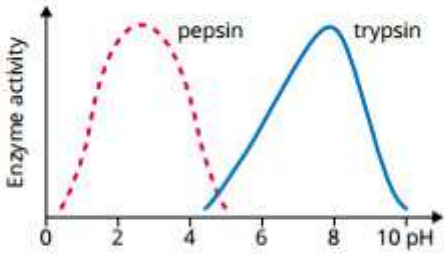


FIGURE 4.4.31 Pepsin and trypsin are both enzymes that digest proteins, but they have very different pH requirements. Pepsin is released in the stomach and is most active in its acidic environment. Trypsin is most active in the slightly alkaline small intestine.

Extracellular digestion

Chemical digestion can be extracellular or intracellular. Extracellular digestion occurs when, for example, cells release enzymes into the lumen (central cavity) of the small intestine. There, enzymes split the food molecules and the resulting smaller molecules are absorbed. Sea stars turn their stomach inside out and release enzymes directly onto the animal they have trapped. Carnivorous plants and fungi also release enzymes to break down their food before absorbing it. In each of these examples, digestion is extracellular because it takes place outside cells. Sometimes, digestive enzymes are located on the actual surface of cells. As the food is digested into smaller molecules, the molecules pass immediately into the cells. Mammals and most other animals rely on some form of extracellular digestion.

In contrast, many protozoans and invertebrate animals, such as mussels, sea jellies and free-living flatworms, use **intracellular digestion**. Their cells engulf small pieces of food into a membrane-bound food vacuole within the cell. Enzymes are released into the vacuole, the food is digested, and the resulting small molecules pass through the vacuole membrane and into the cytosol.

Features of effective digestive systems

In one sense, the digestive systems of all animals must be effective, otherwise the animals would not exist. For each animal, their digestive system adequately provides for their needs.

Large animals, including vertebrates, require higher levels of energy and nutrients for their normal activities. Because mammals are endothermic (animals that maintain a stable body temperature, usually higher than their environment), they require a lot of energy to maintain their body temperature. They therefore need digestive systems that can efficiently extract large amounts of energy and nutrients from food resources, and these systems are found in more active animals. Characteristics of these highly efficient digestive systems include:

- effective mechanisms for capture and preliminary handling of food
- appropriate physical breakdown of food
- a one-way gut with separation of tasks along its length
- efficient transport and storage of ingested food
- efficient sequential release of digestive enzymes
- an adequate surface area for maximal absorption of nutrients and water
- efficient egestion of unwanted materials.

Digestive systems in mammals

All mammals need food and water, but different species (such as cows and dogs) have different food requirements, feeding behaviours and digestive systems. Cows are slow-moving and spend much of the day eating grass and chewing. In contrast, dogs are energetic and active, and may spend only 5 or 10 minutes each day gulping down food. Dogs and cows have many other differences that relate to their eating habits. Their teeth are very different, and cows have much larger and more complex intestines than dogs (Figure 4.4.32 and 4.4.33).

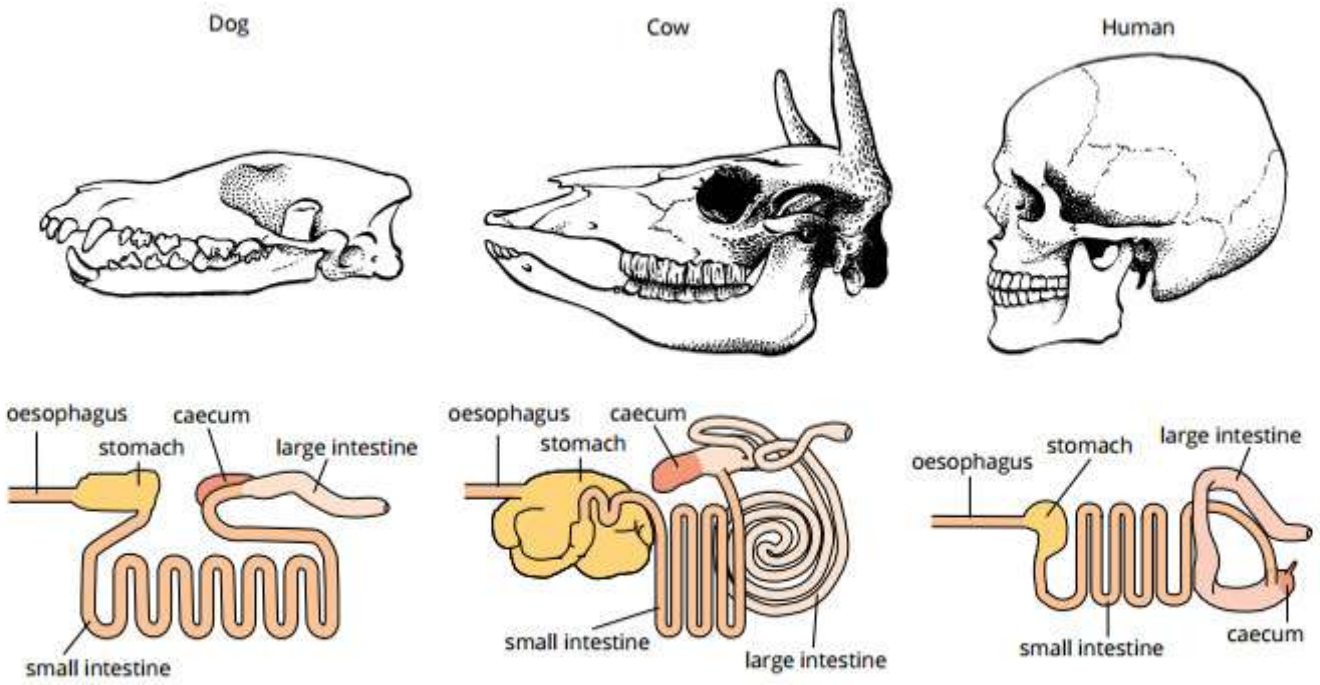


FIGURE 4.4.32 Skulls and digestive systems of the dog (a carnivore), the cow (a herbivore) and the human (an omnivore). Scientists studying fossil jaws, or even a few fossil teeth, can suggest the likely feeding behaviour and diet of the particular mammal species because teeth are modified in different species to suit the type of food that is eaten.

The feeding behaviour, teeth and digestive systems of cats and dogs are similar, but in guinea pigs and rabbits they are more like those of cows. One common factor is diet: cats and dogs eat meat, whereas cows, guinea pigs and rabbits eat plants.

Humans are different again. Our teeth are unlike those of dogs or cows—we are not very good at chewing bones or grass! Our preferred foods include both meat and plant material, and we often cook our food first.

Humans spend about 30 to 90 minutes each day eating, although the social aspects of eating may extend this time. The human digestive system is proportionally longer than that of a dog, but shorter than that of a cow.

Cows, dogs and humans are examples of animals with three different dietary patterns. Animals that eat only plants, such as cows, rabbits, kangaroos and koalas, are herbivores (Figure 4.4.33a). Herbivores typically spend much of the day eating. Carnivores, including dogs and cats, consume animals (Figure 4.4.33b). They spend much less time eating; sometimes animals in the wild, such as lions, may not eat for days between meals. Humans, on the other hand, are omnivores (from Latin *omnivorus* eating everything), because they eat both plant and animal foods.

Animal matter has a much higher proportion of extractable energy per gram than plant matter. The carnivore gut produces all the enzymes needed for the complete digestion of meat. Digestion is quicker and more efficient. Digestive systems are shorter and simpler in carnivores than in herbivores.

The reason for the difference in feeding behaviour between herbivores and carnivores is clear. Plant material must be repeatedly ground by the teeth to expose as much surface area as possible for enzyme action and to release the contents from broken cells. As a food, it provides much less energy than meat and it takes a long time to extract that energy.

FIGURE 4.4.33 (a) The skull of a kangaroo, a herbivore. (b) The skull of a Tasmanian devil, a carnivore.

Humans are omnivores

The digestive system in mammals has the principle function of digesting and absorbing food. In other words, the digestive system breaks down food, making it simple enough to pass across cell membranes and be useful to cells.

Before food passes into the digestive system of a mammal, it is physically broken into pieces by the teeth. Mucus is secreted to protect the lining of the gut and to lubricate food for easier passage. The food then moves along the gut past a series of digestive enzymes that sequentially break down the various compounds for absorption. Proteins are broken down to amino acids, fats and lipids to fatty acids and glycerol and complex carbohydrates such as starch to simple sugars. Useful substances, such as water, are absorbed, leaving unwanted and undigested substances to be eliminated in the faeces.

The main regions of the human digestive system are the mouth and mouth cavity, oesophagus, stomach, small intestine, large intestine, rectum and anus (Figure 4.4.34). The salivary glands, pancreas and liver are digestive glands that develop as outgrowths of the digestive system.

Key steps in the process of digestion in humans occur at the following sites (see Figure 4.4.34):

- mouth—Teeth mechanically break food into small pieces. Saliva lubricates food and enzyme amylase digests starch into **maltose**.
- epiglottis—This flap, at the entrance to the larynx, prevents food from entering the trachea and respiratory system, directing it down the oesophagus. The epiglottis is also associated with the gag and cough reflex.
- oesophagus—Food travels down this tube to the stomach, aided by muscular contractions (peristalsis).

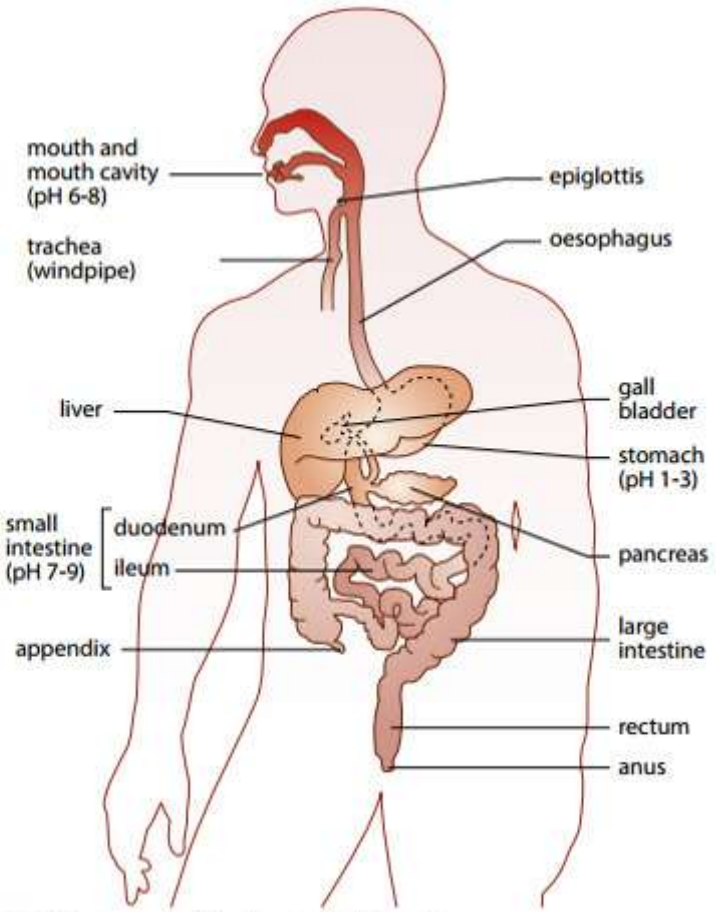


FIGURE 4.4.34 Components of the human digestive system.

- stomach—Protein-digesting enzymes (proteases) and gastric juices are secreted by the stomach to aid in food digestion. Peristalsis of the stomach muscles further breaks the food down and pushes it through the digestive system.
- liver—The liver has important roles in regulating metabolism, toxin removal and processing nutrients. It stores excess glucose as glycogen (a polysaccharide or carbohydrate) for later conversion back to glucose when needed for energy. The liver is also the site of bile is production, for the breakdown of fats.
- gall bladder—Stores and concentrates bile before releasing it to the small intestine.
- pancreas—Digestive enzymes are produced in the pancreas and activated when the food reaches the duodenum (first part of the small intestine). The pancreas also produces the hormones insulin and glucagon, which regulate sugar levels in the blood, and sodium bicarbonate, which neutralises stomach acids in the food.
- small intestine—The primary function of the small intestine is to absorb nutrients and minerals from food. Enzymes produced in the pancreas and the small intestine and bile from the liver and gall bladder further breakdown food products to facilitate nutrient and water absorption. The small intestine's many blood vessels absorb the nutrients and waste products of digestion and deliver them to the circulatory system.
- large intestine—Water is absorbed with soluble compounds like vitamins and minerals; undigested food leaves the body as faeces.

Structure of the small intestine

The principal organ of absorption is the small intestine. 'Small' refers to the diameter of this part of the intestine. The small intestine is long and has a large surface area, making it well suited for absorption. The internal surface area is further increased by millions of tiny folds called villi, and also by the presence of many microvilli on the exposed surface of the epithelial cells lining the lumen (Figures 4.4.35 and 4.4.36).

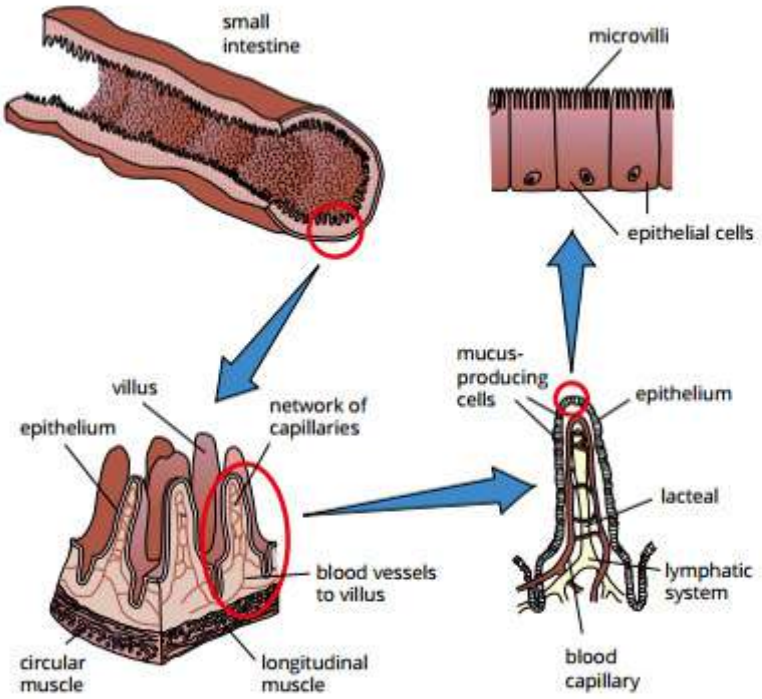


FIGURE 4.4.35 The internal surface of the human intestine, showing the villi and microvilli.

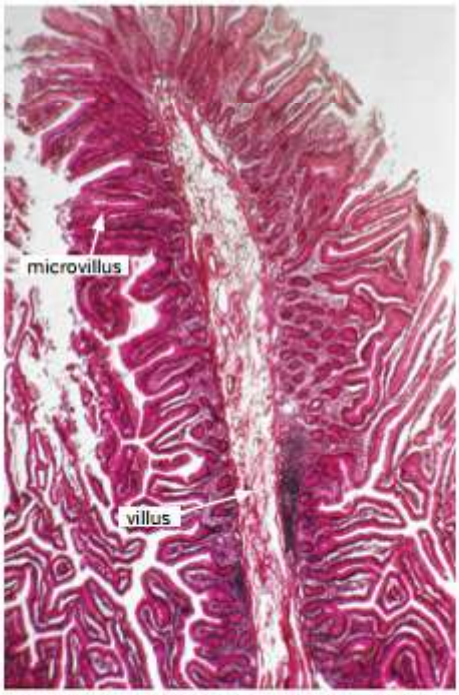


FIGURE 4.4.36 Cross-section of a villus (plural villi) from the small intestine. Villi are finger-like projections from the wall of the small intestine that increase the surface area for more efficient absorption of nutrients. Villi are covered in microvilli, which further increase the surface area for absorption.

Absorption in the small intestine

The epithelial lining in the small intestine is only one cell thick, allowing a rapid transfer of nutrients to the many blood and lymphatic vessels beneath the surface, which transport nutrients away to the body tissues. Nutrients pass through the lining of the small intestine by facilitated diffusion or active transport, along or against the concentration gradient.

Lipid-soluble molecules, which are the products of fat digestion (fatty acids and glycerol), diffuse easily through the membranes of the epithelial cells along a concentration gradient. They then reassemble into fats before passing into the lacteals. Lacteals are capillaries of the lymphatic system near the intestine and have a milky appearance because of their high fat content after a fatty meal. Lipid-soluble vitamins also pass through the intestinal epithelium by passive diffusion.

Water-soluble molecules, including amino acids, simple sugars (monosaccharides such as glucose), and water-soluble vitamins and minerals pass through the membranes of the epithelial cells by active transport and facilitated diffusion. This can occur down or against a concentration gradient, ensuring that these essential nutrients are absorbed quickly.

Most of the water (90–95%) that enters the small intestine is also absorbed. This absorption is passive. Water diffuses across the lining of the intestine osmotically as the products of digestion are absorbed.

Blood leaving the intestine passes first into the liver through the hepatic portal vein, where absorbed nutrients can be removed and stored in the liver, before passing into the general venous circulation.

Herbivores utilise cellulose

Cellulose is the main component of plant cell walls, but its molecules are too large to be absorbed without digestion. Although many species of animals are herbivores, only a few can make the enzyme cellulase that is needed to digest cellulose. To get around this problem, herbivores have a symbiotic partnership, called mutualism, with bacteria that can produce cellulase. The bacteria live in the gut of the animal. They receive shelter and free nutrients for themselves, and in return convert cellulose into simpler molecules that can be absorbed by the gut. The bacteria also supply important vitamins such as the B group and vitamin K.

The environment inside the gut is warm and wet but there is little or no oxygen, so the breakdown of cellulose must occur anaerobically by **fermentation**. Because of this, the part of the intestine in which the breakdown of cellulose occurs is sometimes called a fermentation chamber.

In herbivorous mammals, fermentation takes place in different parts of the intestine in different species, with varying degrees of efficiency. Generally, herbivorous mammals belong to either of two groups—hindgut or foregut fermenters.

Hindgut fermenters

In hindgut fermenters, fermentation occurs in the caecum (an enlarged pouch where the small and large intestines join), or the first part of the large intestine (the wombat, Figure 4.4.37a), or both (the koala, Figure 4.4.37b). Both of these are located after the small intestine, which is the region where most absorption takes place. This arrangement limits the advantage obtained from the symbiotic relationship, because the products of their digestion are not completely absorbed.

Horses are hindgut fermenters, and the relative inefficiency of their system can be seen by the fact that horse faeces contain large amounts of undigested plant material. Some hindgut fermenters, such as possums and rabbits, overcome this problem by producing two types of faeces. One of these comes directly from the caecum at night and is reingested so that it can go through the intestine again. This means that the vitamins and products of cellulose digestion from the bacteria are available for absorption from the small intestine.

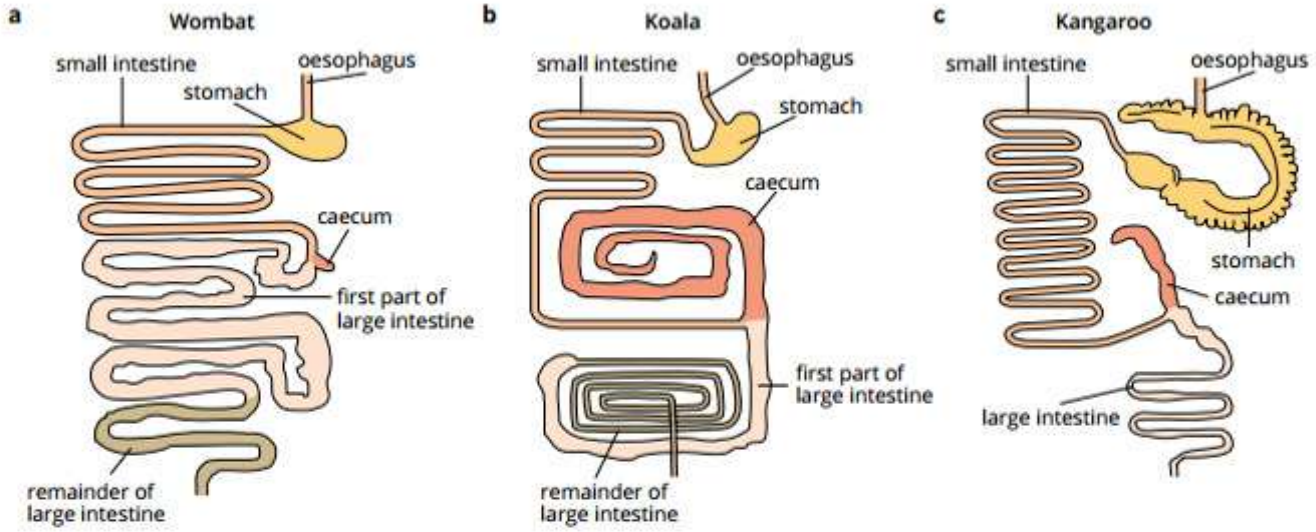


FIGURE 4.4.37 (a) Wombats, (b) koalas and (c) kangaroos are herbivores and use symbiotic bacteria for the digestion of cellulose. Wombats and koalas are hindgut fermenters whereas kangaroos are foregut fermenters.

Foregut fermenters

In the foregut fermenters (Figure 4.4.37c), the fermentation chamber is located before the stomach. In ruminants such as cattle and sheep, it is called the rumen. Food can be regurgitated back into the mouth for further physical breakdown (rumination), then returned to the rumen for continued chemical breakdown by bacteria. This regurgitated food is called cud.

Foregut fermentation has the obvious advantage that the products of digestion by microorganisms are available for absorption along the entire length of the small intestine. Kangaroos and wallabies are the only marsupial foregut fermenters.

Ruminant digestion has some drawbacks. The complete digestion of plant material in the rumen by microorganisms can take a long time—hours or even days, with constant regurgitation and chewing of the cud. If the quality of food is very low (that is, mostly cellulose and not much fresh, young plant growth) an animal may be starved of food that is digested enough for absorption, even though the animal has a very full rumen.

Food and energy storage in mammals

When food is not available, an animal's body draws on its own stores to meet its nutritional and energy needs. Energy storage is clearly essential for carnivores, which eat intermittently depending on the availability of prey.

Herbivores often have to travel considerable distances to find new and adequate supplies of the plants that they eat, when seasons change or if they have overgrazed an area. In winter, food generally becomes scarce for both herbivores and carnivores. In very cold climates some mammals (usually small species) resort to hibernation to survive the winter (Figure 4.4.38). In each of these situations, the ability to store nutrients and energy reserves is essential for survival.

When needed, carbohydrate stores in the liver and muscles (glycogen) are used first and most easily, but their capacity is limited. Humans usually have enough glycogen stored to last for 12 to 48 hours of moderate activity. The capacity for storage in fat tissue (adipose tissue) is virtually unlimited. In a person of healthy weight, there is enough fat stored in tissues to allow normal energy consumption to continue for 3 to 7 weeks. As a last resort, the more limited protein stores of body tissues are used to provide energy after other stores are depleted.

BIOFILE

Saving up for winter

Mountain pygmy-possums (*Burramys parvus*) are Australia's only hibernating marsupials. They live in alpine areas in Victoria and hibernate under the snow during winter. Adults weigh only about 45 grams (equal to two Tim Tams) but they double their weight before entering hibernation by feeding on Bogong moths (*Agrotis infusa*) in spring and summer.

Mountain pygmy-possums need a thick blanket of snow for insulation during their hibernation period, but climate change and reduced snowfall means that they may be exposed to low temperatures for longer periods. This could cause their winter fat stores to run out before the end of their hibernation, causing them to starve.

FIGURE 4.4.38 The mountain pygmy-possum (*Burramys parvus*) is Australia's only hibernating marsupial. They accumulate fat stores before entering hibernation for 5-7 months every year.

BIOFILE

Cold sheep

Freshly shorn sheep need about 25% more food to produce enough energy to maintain their body temperature, because without their fleece, their insulation against heat loss has been greatly reduced.

FIGURE 4.4.39 Shorn sheep.

Unlike carbohydrates and fats, amino acids cannot be stored in animal tissues, so the full range of amino acids needed for building proteins must be available in an animal's diet. Proteins are assembled in cells by linking amino acids in a specific order. If the next amino acid required is not available, the synthesis of that protein molecule cannot continue until the required amino acid arrives.

This has consequences for strict vegetarians because, unlike meat, individual plants do not normally contain the full range of essential amino acids. However, by eating an appropriate combination of plant foods at the same meal, such as beans (which are a good source of the amino acids isoleucine and lysine, but deficient in tryptophan) and rice (which is deficient in isoleucine and lysine, but a good source of other essential amino acids), a balanced diet can be obtained. A meal of rice and beans together is as good a source of protein as eggs or meat.

Energy reserves

In contrast to plants, animals have only a limited capacity to store carbohydrates. The storage carbohydrate in animals is **glycogen**, which, like starch, is a large molecule made from glucose subunits. In humans about 300 g of glucose is stored as glycogen in the liver and muscles. This is enough to provide the energy for about half a day at a moderate level of activity. The remainder of our energy reserves are stored as fats.

Animals use fats rather than carbohydrates as their main form of energy reserves because:

- Almost 25% more ATP is produced (per carbon atom) from fats compared with carbohydrates.
- Fat is almost 50% lighter (per carbon atom) than carbohydrate.
- Stored carbohydrates attract and bind water molecules, increasing their weight by 200 to 500%; fats do not.
- One gram of carbohydrate or protein provides up to 17 kJ of energy. One gram of fat provides 39 kJ of energy.

An average 70 kg male human stores about 11 kg of fat, which provides enough energy to last about a month without eating food. The same amount of energy stored as carbohydrate could weigh more than 100 kg. Some of the chemical processes that take place in living organisms use up energy, while other processes release energy. For energy balance, energy input (eating) must equal energy output (usage). If the amount of food eaten provides more energy than is used, the excess energy is stored as chemical energy (e.g. in fat or glycogen). If the energy content of food is less than required, the balance is made up from stored energy reserves or by breaking down body tissues.

Energy requirements in humans

In animals, the amount of energy that is needed each day depends on factors such as basal metabolic rate, body size, activity level and environmental temperature. Metabolism is the name for the sum of all these processes, and metabolic rate is a measure of the overall energy requirements of an organism. Basal metabolic rate refers to the amount of energy required to maintain basic functions in a resting, unstressed animal per unit time. Basal metabolic rate varies greatly between species. Mammals have a much higher basal metabolic rate than some other vertebrates because they use energy to maintain a constant body temperature. Basal metabolic rate does not include the extra energy required for activity or for maintaining a warm body temperature in a cold climate.

In humans and other mammals, metabolic rate is affected by:

- body composition (the proportion of fat or bone to muscle)—Muscle tissue uses energy at a faster rate than does fat tissue, so more muscle means a greater energy requirement.
- level of activity—Different levels of physical activity account for large differences in metabolic rate. Individuals also vary in the amount of energy they use to carry out a particular activity.

- gender—Men use energy at a higher rate than women, mainly because on average they have a lower fat-to-muscle ratio than women.
- age—Metabolic rate increases during periods of growth, such as childhood and adolescence, levels off during adulthood (except during pregnancy and breastfeeding when it increases by about 25% and 60% respectively) then declines during later years, mainly because of decreased physical activity and changes in body composition.

Malfunctions of the digestive system

Coeliac disease

Coeliac disease affects both children and adults. It is a condition in which the villi of the small intestine are damaged (Figure 4.4.40) by the body's immune system in response to gluten, the protein found in wheat, rye, barley and other cereals. The damaged villi will repair themselves if affected individuals follow a gluten-free diet.

FIGURE 4.4.40 Damaged villi caused by coeliac disease.

Liver disease

People who drink alcohol excessively are prone to severe and often fatal liver disease. Medical evidence indicates that the addition of vitamins to alcoholic drinks, while good for nutrition, will not prevent chronic liver damage.

Alcohol is a toxic substance. The special enzymes that are needed to break it down are found in the liver. Because the biochemical pathways in the liver cells of a heavy drinker are involved with removing alcohol, the cells cannot carry out their normal levels of cellular respiration. Substances that should have been broken down for energy are converted to fats instead, and these fats accumulate in the liver.

For a while the situation is reversible, but then the cells filled with fat start to die, causing alcoholic hepatitis. This is followed by cirrhosis, which is the formation of scar tissue in the liver (Figure 4.4.41). Finally, death may occur when the liver is unable to carry out its normal functions.

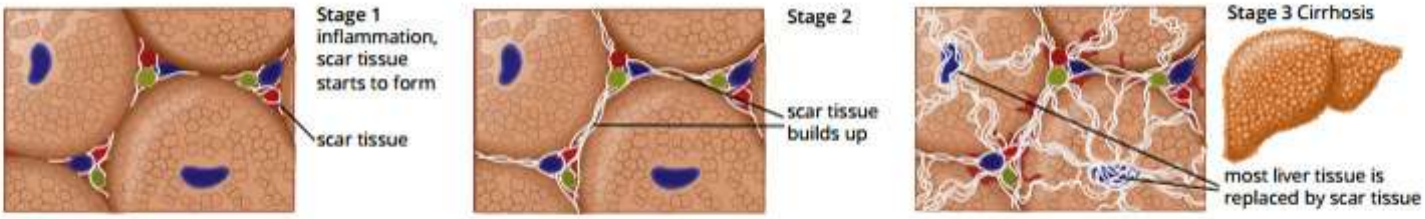


FIGURE 4.4.41 The stages of scar tissue formation (cirrhosis) in the liver. Tissue inflammation (Stage 1), followed by cell death, leads to scar tissue build up (Stage 2). Scar tissue replaces healthy tissue and eventually causes cirrhosis of the liver (Stage 3). Excessive alcohol consumption can cause this form of liver damage.

REMOVING WASTES: THE EXCRETORY SYSTEM

As cells function, they produce substances that are no longer useful to them. The accumulation of these waste substances, such as carbon dioxide from respiration and nitrogenous wastes from protein breakdown, can prevent cells from functioning properly.

In mammals, the function of the kidneys is to excrete nitrogenous wastes. Excretion usually involves the loss of water and is therefore closely linked to water balance in terrestrial animals. This system works closely with the circulatory system, filtering waste products from the blood stream and collecting them in urine.

For heterotrophs, it is sometimes inevitable that toxic substances are absorbed from the food they eat; these toxic substances must also be excreted. Excretion is the removal of substances that once formed part of the body of the organism. (This is different from egestion, which is the removal of undigested food from the gut in faeces.)

The internal environment of animals is extracellular fluid, which is quite separate from the external environment and has a highly regulated composition. Salts form ions in solution. The concentrations of certain ions in cells held within narrow limits. Some of these ions are also important for regulating the pH of body fluids, which must be at a suitable pH for enzymes and other molecules to function efficiently.

In animals the removal of wastes and toxic substances, and the control of pH, ion concentrations and water balance, are carried out mainly by excretory organs. These processes vary with the activity of the animal and the external conditions.

The nature of wastes

During normal activity, animal cells break down and replace carbohydrates, lipids and proteins, producing waste products that usually cannot be used by the body.

Carbon dioxide

When carbohydrates or lipids are broken down during cellular respiration to release energy, carbon dioxide and water are produced (see Section 3.2). These are released into the surrounding environment across respiratory membranes, which in mammals are in the lungs. Water produced during cellular respiration is incorporated into body fluids, and excess water is expelled from the body.

Nitrogenous wastes

Protein consists of amino acids, which contain nitrogen. When proteins are broken down, the nitrogenous parts are split off and the remainder of the molecule is converted into carbohydrates or lipids, which can be used for energy. The remaining nitrogenous wastes must be removed from the cell, because they can become toxic.

The first nitrogenous waste to be formed from the breakdown of protein is ammonia. Ammonia can be converted into urea or uric acid (Figure 4.4.42), but this process requires energy. Neither urea nor uric acid are of any further use to most animals. A few animals, such as sharks, are adapted to maintain high levels of nitrogenous wastes, particularly urea, within their body to aid in water balance.

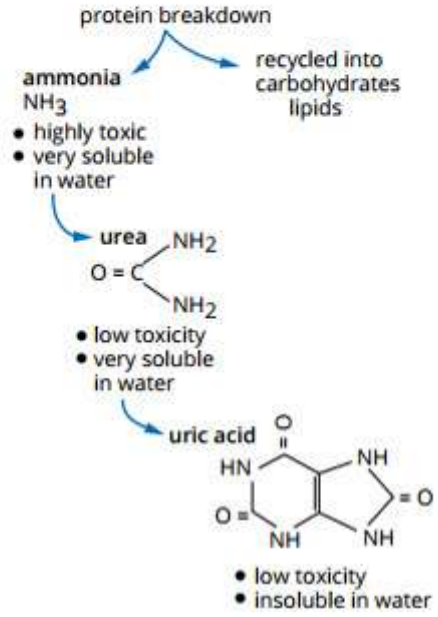


FIGURE 4.4.42 Three important nitrogenous wastes produced from the breakdown of proteins in animals. Mammals excrete their nitrogenous wastes in the form of urea.

Excretory mechanisms in mammals

Kidneys

The kidneys of all vertebrates, from fishes to mammals, function by filtering blood, then reabsorbing useful substances and secreting unwanted ones. Blood is filtered through blood vessel walls to form a primary filtrate that has the same composition as plasma, except that the large proteins have been filtered out. Most of the useful substances in the primary filtrate are reabsorbed as it passes through the kidney tubule. Some unwanted substances may be secreted into the fluid in the tubule before it passes out of the kidney to the bladder. These processes regulate the concentration of different salts in the blood, including those salts that are responsible for maintaining the pH of body fluids within closely controlled limits.

Mammals are able to conserve water by producing urine that is more concentrated than body fluids. The ability to produce concentrated urine is related in some mammals to the degree of water stress experienced in their normal environments. Desert-adapted mammals are able to excrete highly concentrated urine (Figure 4.4.43).

FIGURE 4.4.43 Desert-dwelling animals such as the bilby (*Macrotis lagurus*) can produce highly concentrated urine, which minimises water loss.

The liver prepares wastes

The **liver** performs many different functions and has a central role in the maintenance of a stable internal environment. In addition, it is responsible for preparing various substances for excretion. It detoxifies a variety of harmful chemicals such as alcohol and some drugs. It is also responsible for breaking down amino acids to release ammonia, which it then converts largely into urea. The waste products from these processes travel in the bloodstream to the kidneys for excretion.

The liver also destroys worn-out red blood cells, producing bile pigments from the breakdown of haemoglobin. Bile pigments, along with bile salts, which emulsify fats as part of digestion, are stored in the gall bladder before they are released into the lumen of the intestine. Bile pigments are one of the few substances excreted into the gut.

The mammalian kidney

Mammals have two kidneys at the back of the abdominal cavity. Blood flow to the kidneys is always kept high, because they are so important in maintaining the stability of the internal environment. Although kidneys are only about 1% of body tissue, they receive approximately 25% of the body's blood flow.

Blood enters the kidney from the aorta through the renal artery, and leaves through the renal vein. Blood vessels branch throughout the kidney in a complex fashion (Figure 4.4.44). Urine, formed in the kidneys, drains via the **ureters** into the **bladder**, for storage, until an appropriate time for release through the **urethra**.

BIOFILE

Urea

Urea is a larger molecule than ammonia and also contains carbon and oxygen. It is much less toxic than ammonia and is highly soluble in water, but converting ammonia into urea requires energy. So although urea is less toxic, an animal spends more energy excreting urea instead of ammonia.

Land vertebrates need to conserve water. Mammals excrete their nitrogenous waste largely in the form of urea, but their kidneys are capable of regulating and minimising water loss. This strategy is a successful adaptation to life on land.

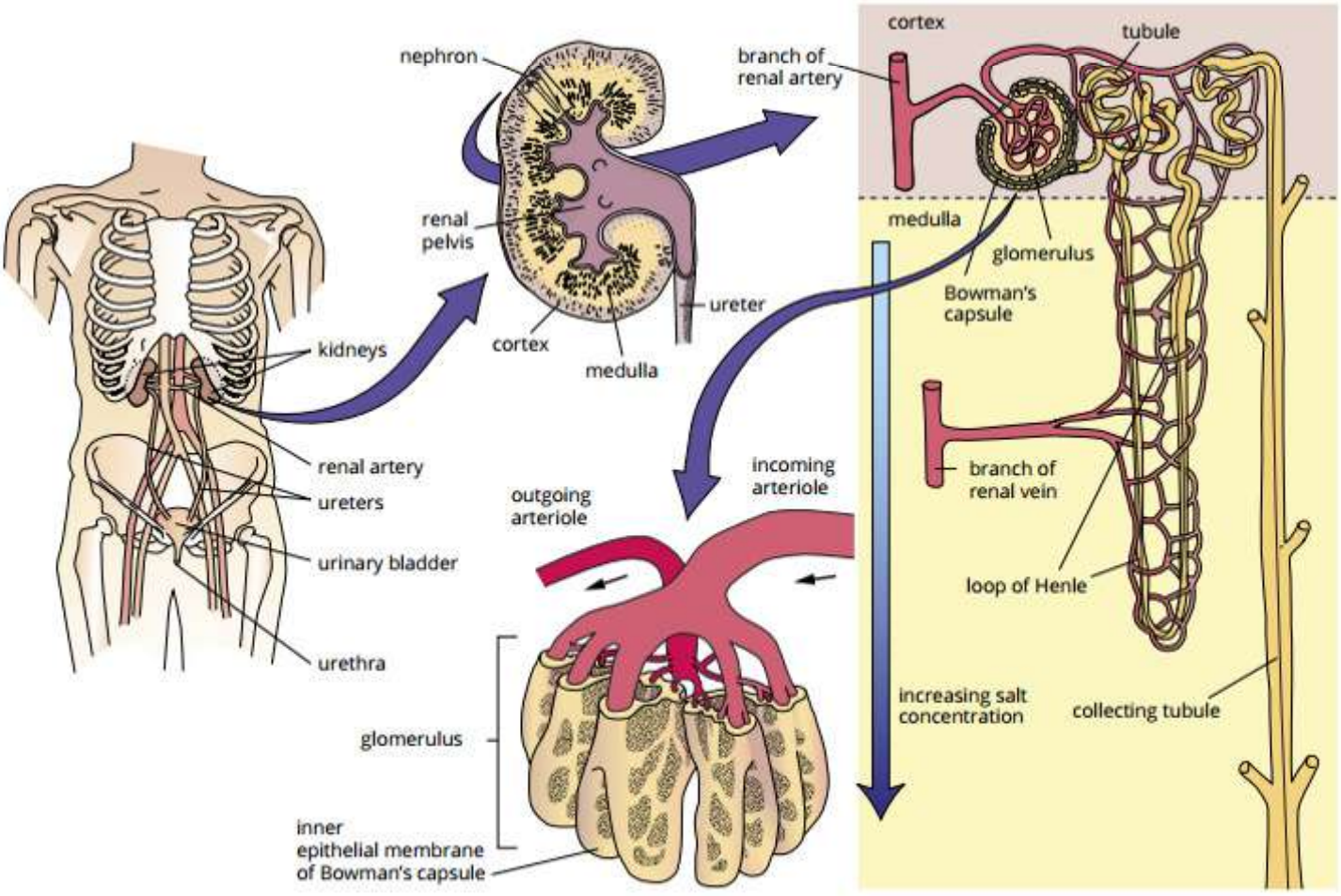


FIGURE 4.4.44 The structure of the human excretory system.

The functions of the mammalian kidney are carried out by **nephrons**, which are the functional units of the kidney. There are approximately one million nephrons in a human kidney, and their combined function carries out the work of the kidney. A nephron is composed of a **Bowman's capsule** surrounding a glomerulus, and a tubular region consisting of the proximal convoluted tubule, **loop of Henle** and distal convoluted tubule that leads into a collecting tubule (Figure 4.4.44). The formation of urine involves passive filtration, selective **reabsorption** and **secretion**, and the passive removal of water.

The nephron is very closely associated with blood vessels, particularly the **glomerulus**, which is a clump of looping capillaries embedded in the Bowman's capsule, and networks of capillaries wrapped around the remainder of the tubule.

There are two distinct regions in the kidney: the outer cortex and the inner medulla. Glomeruli are located in the cortex (Figure 4.4.44).

Filtration

Filtration occurs across the glomerulus into the Bowman's capsule. The high pressure of blood in the glomerular blood vessels forces fluid through the walls of glomerular capillaries and into the Bowman's capsule (Figure 4.4.44).

Only small molecules and water can pass through the wall membranes; blood cells and large blood proteins remain behind in the glomerular capillaries. This primary filtrate has the same composition as blood plasma, without large proteins.

If red blood cells or large proteins are found in urine, this indicates that the normal filtration mechanism has broken down and blood is leaking from the glomerulus into the Bowman's capsule. This may occur as a result of damaged glomerular blood vessels, or very high blood pressure.

Reabsorption

Approximately 99% of the primary filtrate—including salts, glucose, amino acids and water, but only half or less of the urea—undergoes reabsorption along the length of the nephron. Virtually all amino acids and glucose are reabsorbed in the convoluted tubules by active transport against a concentration gradient. The presence of glucose or amino acids in urine therefore indicates a possible kidney malfunction. Specific salts, particularly sodium chloride, are also actively reabsorbed. These active processes consume a lot of energy.

Water is reabsorbed from the urine passively, along an osmotic gradient. The mechanism by which the kidney is able to produce concentrated urine involves the loop of Henle. A large amount of sodium chloride pumped out of the loop of Henle is retained in the medullary region of the kidney, producing a very high salt concentration. The osmotic concentration within the kidney therefore increases considerably from the outer cortex to the medulla. When the urine finally passes down the collecting tubules towards the ureter, it passes through this region of high salt concentration. Because the collecting tubule is permeable to water, but not to salt, water passes from the collecting tubule back into the kidney and into blood vessels. As a result, the urine becomes concentrated. Antidiuretic hormone (ADH) from the pituitary gland increases the permeability of the collecting tubule to water, increasing reabsorption of water and causing urine to become concentrated.

Secretion

Secretion is the active removal (excretion) of particular substances by the cells of the tubule wall. Ammonium, potassium and hydrogen ions are actively secreted into the convoluted parts of the tubules. Various dyes and drugs such as penicillin and aspirin are also eliminated by tubular secretion. These substances are added to the filtrate as it passes through the nephron.

Malfunctions of the excretory system

Kidney failure

Kidney failure occurs when the kidneys can no longer effectively remove waste products and maintain the fluid levels of the body. The causes of kidney failure include high blood pressure, diabetes, polycystic kidney disease (Figure 4.4.45), swelling of the nephrons (glomerulonephritis), and some medications.

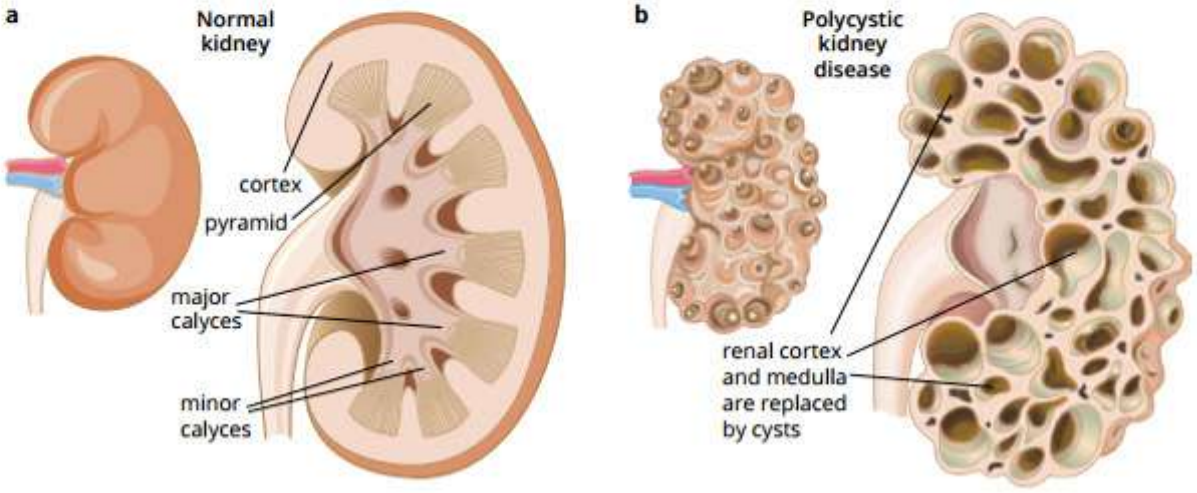


FIGURE 4.4.45 Comparison of a healthy kidney (a) and a kidney with polycystic kidney disease (b). Polycystic kidney disease is a genetic condition that causes kidney malfunction and may eventually lead to kidney failure.

It can occur at any age and results in the retention of wastes in the blood and imbalance of salts in the internal environment, which prevents proper cell function. Kidney failure may develop suddenly (acute kidney failure), leading to death within a few days if not treated, or there may be a slower progressive loss of kidney function until the remaining kidney tissue is unable to carry out the normal function of the kidney (chronic kidney failure).

Kidney transplants are now extremely successful and can offer a permanent solution to total kidney failure. However, there are always many people waiting for suitable donor kidneys. While they wait, these people depend on dialysis, which has been used for over 70 years to keep patients with kidney failure alive.

Dialysis is the diffusion of small solute molecules through a partially permeable membrane. (This is different from osmosis, which is the diffusion of water through a partially permeable membrane.) Small molecules are free to diffuse through the dialysing membrane, but larger proteins and cells do not. This is similar to the filtration stage of normal kidney function.

4.4 Review

SUMMARY

Mammalian transport systems

- Mammals have two transport systems: the blood circulatory system and the lymphatic system.
- The blood circulatory system:
  - consists of the heart, veins, arteries, capillaries and blood
  - transports nutrients and oxygen to all cells in the body and transports metabolic wastes away from all cells in the body
  - has two sequential circulation pathways: pulmonary circulation (transports blood to and from the lungs) and systemic circulation (transports blood to and from the rest of the body).
- The lymphatic system:
  - consists of lymph vessels, lymph nodes and organs, such as the thymus and spleen
  - transports a colourless liquid called lymph
  - transports lymph in one direction, from the tissues to the heart
  - has several functions, one of which is returning extracellular fluid containing proteins that have leaked out of the capillaries back into the circulatory system.
- Systems work together. In mammals the circulatory system interconnects with systems such as the digestive, respiratory and excretory systems. For example, the respiratory system absorbs oxygen from the environment, and the oxygen is then transferred to cells throughout the body by the circulatory system.
- Systems can malfunction and the malfunction can occur at any level of the system. This may have biological consequences for the whole organism. For example, Marfan syndrome is a disorder caused by a defective glycoprotein, resulting in weakened connective tissue. Weakened connective tissue can cause malfunctions in tissues and organs throughout the body. In the heart, weakened tissue can lead to aortic aneurysms (stretching and bulging of the aorta) or aortic dissection (tearing in the aorta).

The respiratory system

- Organisms must exchange oxygen and carbon dioxide with their environments to maintain cellular respiration and photosynthesis.
- Efficient gas exchange requires a large, moist surface area, a thin barrier, and an adequate supply and removal of the transferred gas.
- The mammalian respiratory system consists of the pharynx, trachea, bronchi, bronchioles and alveoli.
- Lung ventilation involves tidal inhalation and exhalation of air using a suction pump mechanism.
- Malfunctions of the respiratory system include asthma, emphysema and pneumonia.

The digestive system

- Mammals are heterotrophs. They must consume other organisms or their products to obtain organic molecules.
- The purpose of digestion is to rapidly break down organic food into molecules small enough to be able to pass through membranes and into cells.
- Chemical digestion involves breaking apart complex molecules into simple molecules by the action of enzymes (amylase, protease and lipase).
- Physical breakdown of large food into smaller pieces increases the surface area available for enzyme action and increases the efficiency of digestion.
- When food is not available, an animal's body draws on its own stores to meet its nutritional and energy needs.
- Mammals can store excess carbohydrates and fats, but not amino acids. Lipids store more energy by weight than carbohydrates.
- For energy balance, energy input (eating) must equal energy output (usage).
- The amount of energy that is needed each day depends on factors such as basal metabolic rate, body size, activity level and environmental temperature. In mammals, body composition, activity levels, sex and age also affect basal metabolic rate.
- Malfunctions of the digestive system include coeliac disease and liver disease.

The excretory system

- Excretion is the removal of substances that once formed part of the body of the organism.
- In animals, removal of waste and toxic substances, and control of pH, ion concentrations and water balance, are carried out largely by excretory organs, such as the kidney.
- Proteins are broken down into carbohydrates or lipids, which can be used for energy, and nitrogenous wastes, which must be removed from the cell, because they can become toxic.
- The nephron is the functional unit of the mammalian kidney.

- The three main stages of urine formation are filtration, reabsorption and secretion.
- Malfunctions of the excretory system include polycystic kidney disease and glomerulonephritis.
- A nephron consists of a Bowman's capsule (surrounding a glomerulus) leading into a tubular region (proximal convoluted tubule, loop of Henle and distal convoluted tubule) and then into the collecting tubule.

KEY QUESTIONS

1 What system in multicellular organisms provides cells with nutrients and removes wastes from the cell?

2 Describe the two pathways through which blood is circulated in mammals.

3 Match each of the following heart structures with its function.

Structure	Function
aorta	deoxygenated blood is pumped by the right ventricle and flows to the lungs
left atrium	deoxygenated blood returns from the body to the right atrium
left ventricle	oxygenated blood is pumped from the left ventricle and flows to the rest of the body
pulmonary artery	oxygenated blood returns from the lungs to the left atrium
pulmonary veins	receives deoxygenated blood from the right atrium and pumps it to the lungs
right atrium	receives deoxygenated blood returned from the body
right ventricle	receives oxygenated blood from the left atrium and pumps it to the rest of the body
venae cavae	receives oxygenated blood from the lungs

4 What are the fluid and cellular components of blood?

5 Which two forces result in filtration of fluids into and out of capillaries? In which direction do each of these exert pressure, and what impact does this have on fluid filtration in capillaries?

6 Describe how the circulatory system supports the functions of the digestive system in mammals.

7 What is the name of the protein that binds with oxygen in red blood cells? What condition can result if this protein is deficient?

8 Outline the functions of the lymphatic system.

9 Blood is a liquid tissue containing glucose, urea, plasma proteins and other components. List the other components of blood.

10 Describe the features and functions of the circulatory system and the lymphatic system.

11 Arrange the following structures in the respiratory system in order, from the largest in diameter to the smallest.
alveolus, trachea, bronchiole, bronchus

12 Outline the features of the alveoli that make them highly effective for gaseous exchange.

13 What are two differences between the digestive systems of herbivores and carnivores?

14 The small intestine is a site of absorption.
a Describe the features of the small intestine that make it well suited to its absorptive role. Use diagrams to illustrate your answer.
b What is different about the absorption of the products of fat digestion compared with the absorption of other products?

15 Relate the relative sizes of the stomach, small intestine, caecum and first part of the large intestine of hindgut fermenters to foregut fermenters.

16 What is the difference between foregut fermentation and hindgut fermentation?

17 **a** From a nutritional point of view, what is the problem for hindgut fermenters?
b How do some hindgut fermenters overcome this problem?

18 **a** Name the structural and functional unit of the kidney.
b Describe the function of the glomerulus, Bowman's capsule, proximal and distal convoluted tubule, the loop of Henle and the collecting tubule.

19 Explain why it is important that the permeability to water of the collecting tubule of the mammalian kidney can be regulated.

20 Explain the process of ultrafiltration.

Chapter review

04

KEY TERMS

active transport
aerobic
alveoli
amino acid
ammonia
amylase
angiosperm
antidiuretic hormone (ADH)
aorta
arteriole
artery
atrium
autotroph
basal metabolic rate
bile
bladder
blastula
Bowman's capsule
caecum
capillary
carbohydrate
carnivore
Casparian strip
cell differentiation
cell replication
cell specialisation
cellular respiration
cellulose
chemical digestion
cilium
closed circulatory system
cohesive bond
colony
connective tissue
coronary circulation
cytokinesis
daughter cell
diastole
diffusion
digestion
digestive enzyme
ectoderm
egestion
egg
embryo
endoderm
endotherm
epidermis
epiglottis
epithelial
essential amino acid
evolution
excretion
extracellular digestion
extracellular matrix
fermentation
filtration
gamete
gene expression
germ layer
glycogen
glycoprotein
guttation
haemoglobin
herbivore
hydrolysis
intracellular digestion
lacteal
larynx
lignin
lipase
lipid
liver
loop of Henle
lumen
lymph
maltose
maltose
meristem
mesoderm
metabolic rate
metabolism
mineral
mitosis
multicellular
myoglobin
nephron
nitrogenous waste
omnivore
open circulatory system
organ
organism
osmosis
oxygen-carrying capacity
peristalsis
phloem
photosynthesis
plasmodesma
plasmodium
protease
protein
pulmonary vein
reabsorption
root hair
root pressure
rumen
secretion
sink
source
sperm
starch
stem cell
stoma
symbiosis
syncytium
system
systole
tidal volume
tissue
tracheid
translocation
transpiration
transpiration stream
urea
ureter
urethra
uric acid
valve
vascular bundle
vascular plant
vascular tissue
vein
ventilation
ventricle
venule
vertebrate
vital capacity
vitamin
xylem
xylem vessel
zygote

KEY QUESTIONS

1 Why is the colonial theory thought to be the most likely mechanism by which multicellular organisms evolved and what evidence is there to support it?

2 Match each of the following specialised cells with its function.

epidermal cell	carries oxygen around the body
guard cell	protects against pathogens
meristem cell	carries signals around the body
muscle cell	prevents water loss and regulates gas exchange
nerve cell	allows movement of body parts
red blood cell	barrier against environmental stressors
white blood cell	gives rise to specialised cells

3 Describe the process of cell differentiation and specialisation, mentioning at least five key terms from above.

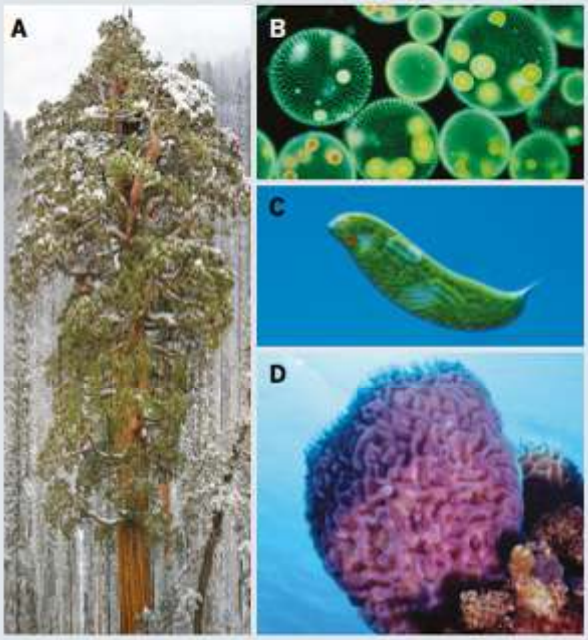
4 Which organisms are multicellular (M) and which are unicellular (U)?

a paramecium (protist)
b bat (mammal)
c earthworm
d amoeba (protist)
e diatom (protist)
f human
g yeast (fungi)
h eucalypt tree (plant)
i salmonella (bacterium)
j grasshopper.

5 List five advantages of being multicellular.

6 Referring to your answers in question 5, explain how being multicellular provides each of these advantages compared to unicellular organisms.

7 Identify the image that represents:
- **a** a single cell
- **b** a simple colony
- **c** a multicellular organism without tissues
- **d** a multicellular organism with tissues, organs and organ systems.

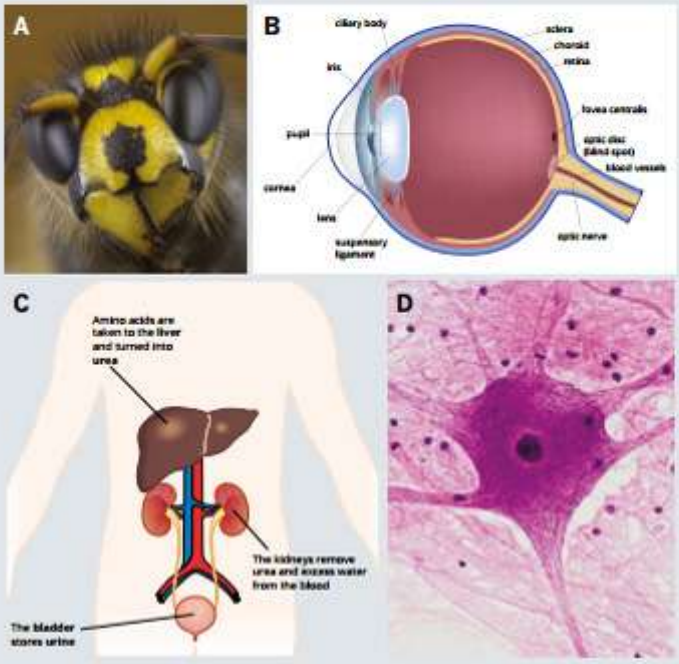


8 **a** Explain how a tree is killed by ringbarking.
- **b** How does unintentional ringbarking occur, and how can it be treated?

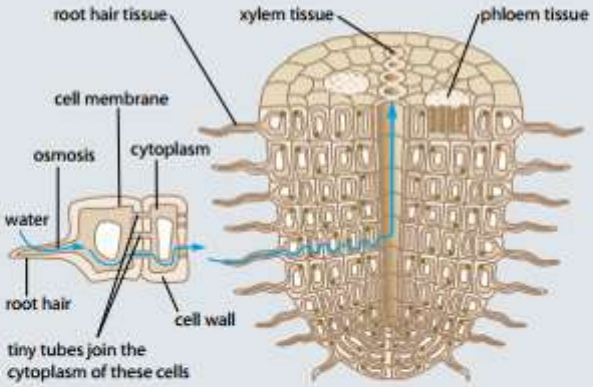
9 In autumn, the leaves of deciduous trees change colour and eventually fall. The change in colour is due to the movement of nutrients out of the leaves for storage. This involves:
- **A** xylem and phloem
- **B** only the xylem
- **C** only the phloem
- **D** diffusion

10 Define each of the levels of organisation in multicellular organisms.

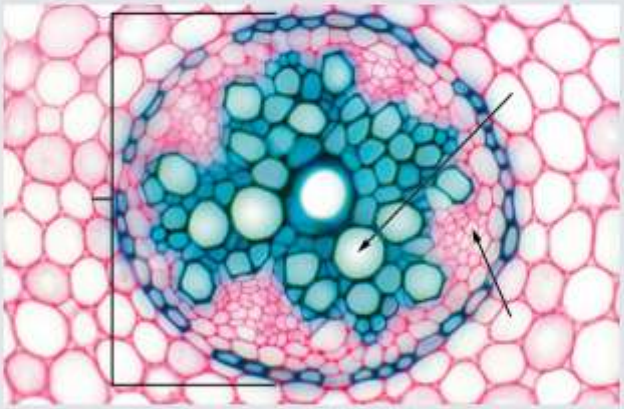
11 State the level of organisation that each of the following illustrations shows: tissue, organ, system or organism.



12 Describe the pathway of water absorption in the diagram of plant root tissue below.



13 The image below is a cross-section of the root of a buttercup plant viewed under a light microscope. Label the parts of the root.



14 An experiment was conducted to determine the effects of applying a sticky gel onto a leaf on the rate of transpiration. The graph below shows the results of the experiment.

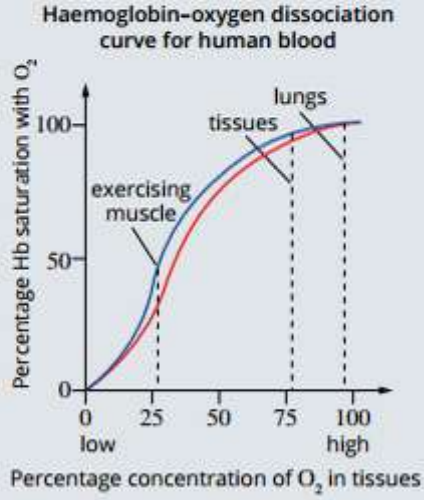
Match each line labelled on the graph to the correct experimental condition from the list below.

- **A** no gel applied
- **B** gel applied to the lower side of the leaves
- **C** gel applied to the upper side of the leaves
- **D** gel applied to the lower side and the upper side of the leaves

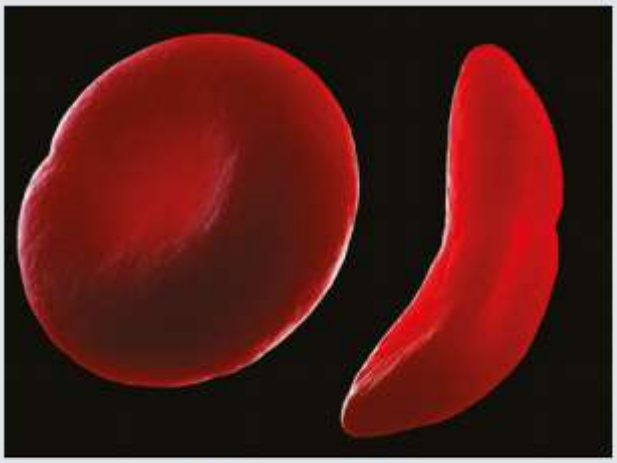
15 Discuss some of the adaptations that plants living in harsh environments, such as deserts, have developed to achieve water transport.

16 Which side of the heart has thicker muscular tissue, and why? How does this affect the blood pressure in the different areas of the heart?

17 Using the information in the following graph, discuss the relationship between oxygen, haemoglobin and the circulatory system.



18 Sickle cell disease is a red blood cell disorder. People with sickle cell disease have abnormal haemoglobin in their red blood cells. As a consequence, the red blood cells become sickle-shaped and inflexible.



Based on your understanding of the functions of red blood cells, what are the effects of having sickle-shaped red blood cells on the functioning of the circulatory system?

19 A common problem for passengers on a long plane trip is that, upon arrival, their feet have become so swollen that they will not fit into their shoes. Airlines recommend exercises to help reduce this problem.

- **a** Explain what causes feet to swell during air travel.
- **b** How could exercise help?
- **c** Deep vein thrombosis is a major concern for long-distance travellers. Explain why clots are likely to form and how this can be prevented.

20 Identify three specialised cells in the respiratory system and state their functions.

21 Coeliac disease causes the destruction of the villi cells. Which one of the following is most likely to happen to people with coeliac disease?

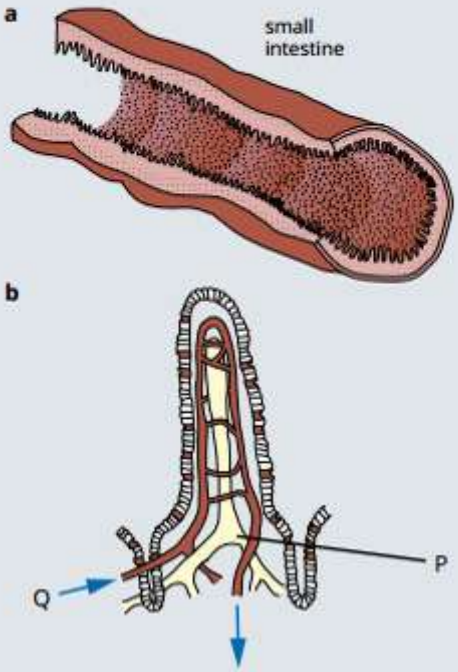
A damage in the oesophagus caused by increase in acid reflux
B incomplete digestion of proteins
C increased levels of glucose in blood
D poor absorption of calcium

22 Which one of the following statements relating to fermentation in herbivores is true?

A In foregut fermenters, cellulose is digested in the caecum.
B Fermentation in the gut requires oxygen.
C The rumen is located between the oesophagus and the stomach.
D All native Australian mammals are hindgut fermenters.

23 Figure a below shows a cross-section through the small intestine. Figure b shows a longitudinal section through a villus.

a Using figures a and b, outline three ways in which the structure of the small intestine is related to its function of absorbing products of digestion.
b Referring to figure b, identify structure P and state its function.
c The arrows in figure b indicate the direction of blood flow. State how the composition of blood entering from Q would be different from blood leaving R.



24 The table below shows the relative concentrations of urea, glucose, amino acids, salts and proteins in the primary filtrate and urine of mammals as a percentage of the concentration in blood plasma.

Substance	Primary filtrate (%)	Urine (%)
Urea	100	700
Glucose	100	0
Amino acids	100	0
Salts	100	200
Proteins	0	0

a What is the explanation for each value, for both primary filtrate and urine?
b Suggest how the values would be different in persons suffering from diabetes, or from kidney damage due to a heavy blow.

REVIEW QUESTIONS

How do organisms function?

Multiple choice questions

1 A student observes and draws an amoeba. The length of the drawing is 100 mm. The actual length of the amoeba is 100 µm. What is the magnification of the drawing?

A 0.001
B 1
C 100
D 1000

2 Which of the following would not be visible using a light microscope?

A nucleus
B chloroplast
C vacuole
D ribosome

3 Which of the following is an example of a eukaryotic cell?

A a fungal cell
B a bacterium
C an enzyme
D a virus

4 Which one of the following lists organelles that are found in both animal and plant cells?

A mitochondria, nuclei and chloroplasts
B mitochondria, Golgi apparatuses and chloroplasts
C ribosomes, chloroplasts and nuclei
D mitochondria, Golgi apparatuses and nuclei

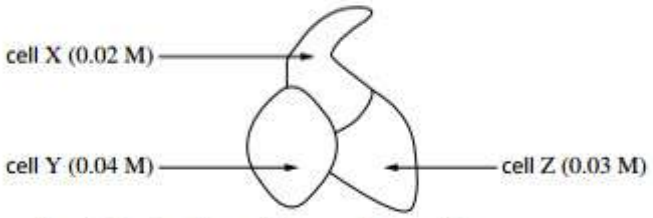
5 What are organelles?

A small structures found in the cytoplasm of cells that have multiple functions
B membrane-bound structures that are found near the nucleus of all cells
C specialised structures found inside cells that have a specific function
D membrane-bound structures only found in eukaryotic cells.

6 Which of the following is required for osmosis to occur?

A a fully permeable membrane
B a partially permeable membrane
C ATP
D an enzyme

7 Three cells X, Y and Z containing different solute concentrations were placed next to each other, as shown in the following diagram. (M is a unit of measurement of solute concentration. A higher value means a higher solute concentration.)



In which direction will osmosis occur?

A from X to Y only
B from X to Y, X to Z and Z to Y
C from Y to Z only
D from Y to Z and Z to X

8 Potassium cyanide blocks the production of ATP in cellular respiration, causing a decrease in the ion concentration in the cell. If potassium cyanide is taken into a cell, which of the following statements is true?

A Ions will enter the cell by active transport.
B Ions will enter the cell by diffusion.
C Ions will enter the cell by osmosis.
D Ions will not enter the cell.

9 Which of the following is required for facilitated diffusion but not passive diffusion to occur?

A membrane-bound enzymes and channel proteins
B ATP and channel proteins
C a concentration gradient only
D channel proteins and a concentration gradient

10 Which of the following groups correctly shows the energy sources of photoautotrophs, chemoautotrophs and heterotrophs?

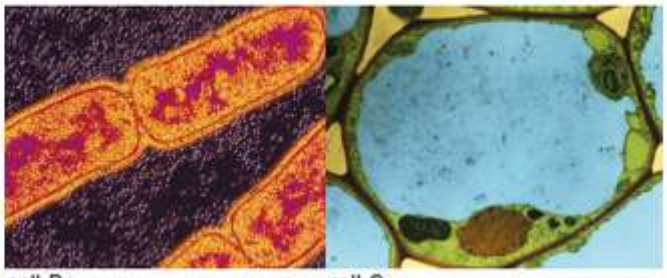
	Photoautotrophs	Chemoautotrophs	Heterotrophs
A	light	light	inorganic compounds
B	light	inorganic compounds	organic compounds
C	inorganic compounds	light	organic compounds
D	inorganic compounds	inorganic compounds	inorganic compounds

11 Which of the following statements about cellular respiration in plants is true?

- **A** It occurs only at night.
- **B** It occurs only in green leaves.
- **C** It occurs independently of photosynthesis.
- **D** It requires light energy from the Sun.

Short answer questions

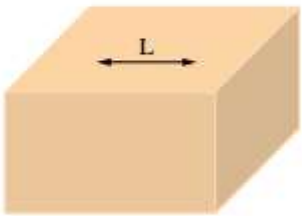
12 The following images show the transmission electron micrographs of two cells, P and Q.



cell P cell Q

- **a** Which of the images shows a prokaryote? Give reasons for your answer.
- **b** On each figure, draw an arrow and label the structures where DNA can be found.
- **c** Name two features in cell Q that are not visible in cell P.

13 To investigate the effect of surface area to volume ratio on the rate of diffusion, a student prepared different sizes of agar cubes containing phenolphthalein. The agar cubes were then suspended in a 4% sodium hydroxide solution for 10 minutes. When sodium hydroxide diffuses into the agar, the agar turns pink. After 10 minutes, the agar cubes were cut in half and the length of the colourless area (L) was measured. The illustration shows a cross-section of an agar cube.



The following table shows the results of the experiment.

Length of cube side (cm)	Surface area of cube (cm^2)	Volume of cube (cm^3)	Surface area to volume ratio of cube	Length of colourless area, L (cm)	Volume of colourless area (L × L × L) (cm^3)	Percentage diffusion (%)
1.0				0.0		
1.5				0.4		
2.0				0.8		
2.5				1.8		

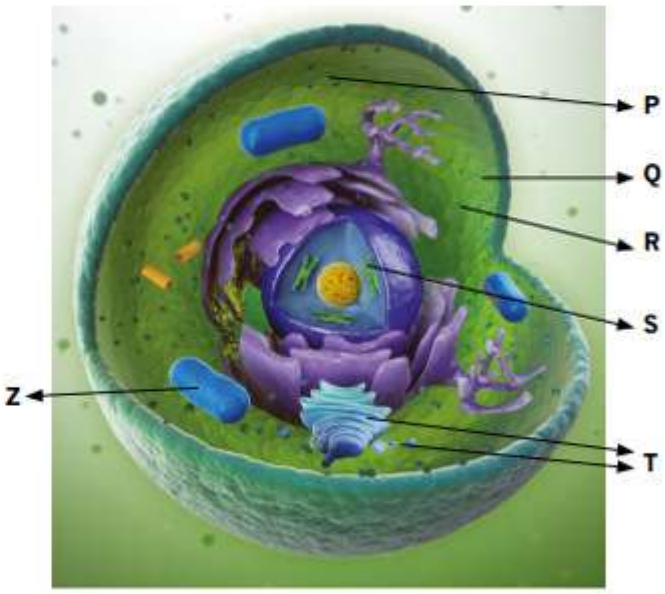
Surface area of cube = 6 × length of cube × length of cube

Volume of cube = length of cube × length of cube × length of cube

$$\text{Percentage diffusion} = \frac{\text{Volume of cube} - (\text{Volume of colourless area})}{\text{Volume of cube}} \times 100$$

- **a** Calculate the volume, surface area, surface area to volume ratio, and percentage diffusion of each cube, and complete the table.
- **b** Use graph paper to plot a graph of percentage diffusion against surface area to volume ratio. Include a best fit curve in the graph.
- **c** Using the graph you plotted in part b, describe the relationship between surface area to volume ratio and diffusion in an agar cube.
- **d** Which size cube was the most effective for maximising diffusion?
- **e** Provide an explanation for your answer to question d.
- **f** A large surface area is essential for quicker diffusion into the cell. Using the results from the experiment, explain why there is a limit to the size individual cells can grow.
- **g** Suggest how the reliability and validity of this experiment can be improved.

14 The following is a three-dimensional image of an animal cell.



a Identify structures P, Q, R, S and T.

b What is a key feature of structure Q? How does this feature relate to its function?

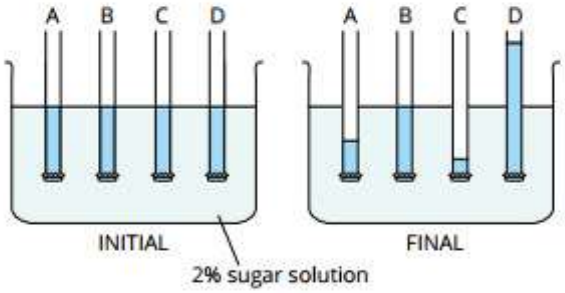
A transmission electron micrograph of structure Z is shown in the following figure. Structure Z is where most aerobic respiration occurs.

c Identify structure Z.

d Write the word equation for aerobic respiration.

e Structure Z requires oxygen to carry out aerobic respiration. Explain how oxygen from the blood eventually enters structure Z.

15 Four tubes contain solutions with different sugar concentrations. One end of each tube is covered by a semi-permeable membrane. The tubes are placed in a tank containing a 2% sugar solution and are left until the fluid levels are stable, as shown in the diagram. What were the original concentrations of solutions A, B, C and D? Explain your reasoning.



16 A student performed an investigation to model the selectively permeable nature of a cell membrane. She placed distilled water in two bags made from dialysis tubing. (The pores of dialysis tubing are smaller than starch molecules.) She then weighed the bags and recorded their masses. Next, the student placed one of the bags (bag A) in a beaker of distilled water. She placed the second bag (bag B) in a 10% w/v solution of starch. After one hour, the student weighed the bags again.

a Draw a labelled diagram of the experimental apparatus.

b Name the dependent variable in this experiment.

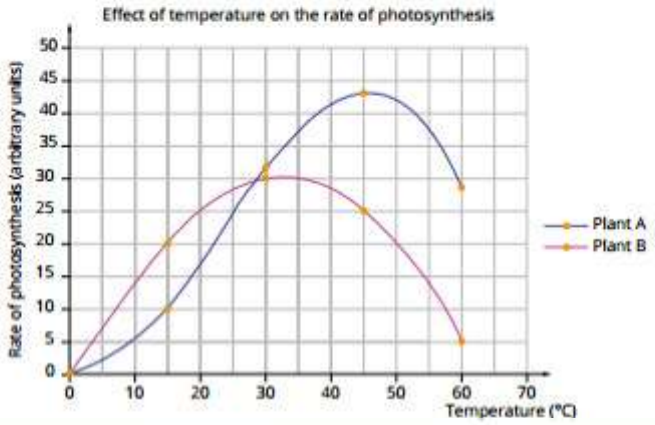
c Predict the student's results and explain your prediction.

17 **a** Write the word equation for photosynthesis.

b In which organelle does photosynthesis take place?

c Outline how oxygen is produced during the process of photosynthesis.

18 Scientists investigated the effect of temperature on the rate of photosynthesis on two different plants, plant A and plant B. The graph shows the results of the experiment.

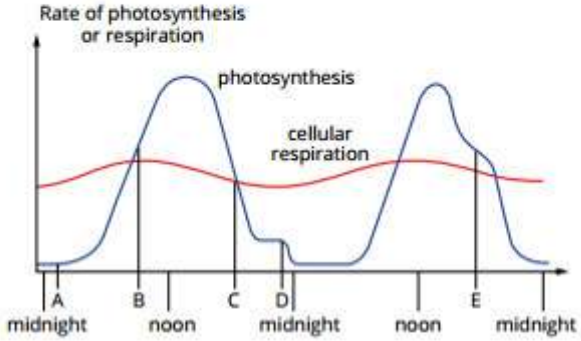


a Describe the similarities of the effect of temperature on the rate of photosynthesis on plant A and plant B.

b Explain why did the rate of photosynthesis falls beyond 50 °C.

c Which plant is more suited for a desert environment? Explain your answer.

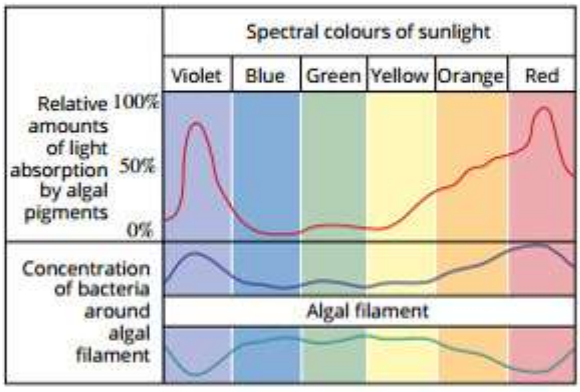
19 The following graph shows the rates of photosynthesis and cellular respiration for an indoor plant that receives plenty of natural light through a large window.



a State whether there is a net oxygen uptake or output at each of these times: A, B, C, D, E.

b Suggest what change in the plant's environment might have caused the rate of photosynthesis shown at times D and E.

20 In an experiment, a photosynthetic algal filament was placed in a solution containing aerobic bacteria. The filament was then exposed to different spectral light colours along its length. The following diagram indicates the distribution of bacteria around the algal filament after one hour.



a Describe the distribution of bacteria after one hour.

b Explain why aerobic bacteria were used in the experiment. (Hint: What photosynthesis product do they require?)

c What does the distribution of bacteria indicate about the relationship between spectral light colour and the rate of photosynthesis?

21 A student investigated the effect of varying types of sugar solutions (glucose, lactose, fructose, maltose and sucrose) on the rate of anaerobic respiration in yeast. The student hypothesised that the rate of respiration in yeast will be the highest for glucose. The steps in the experiment are described below.

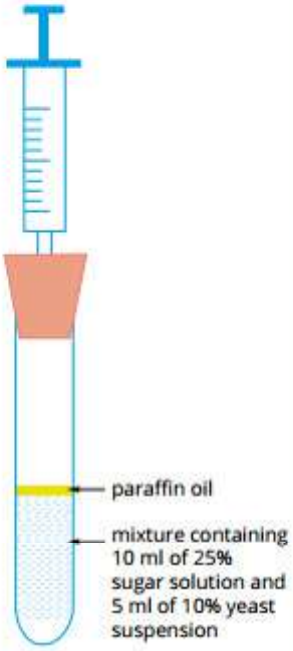
Step 1: 10 mL of fructose solution (25% concentration), 5 mL of yeast suspension (10% concentration) and three drops of paraffin oil were added to a test tube and mixed thoroughly.

Step 2: The test tube was sealed with a rubber stopper with a syringe attached, as shown in the diagram at right.

Step 3: After 15 minutes, the volume of gas collected in the syringe was recorded.

Step 4: Steps 1 to 3 were repeated four more times.

The experiment was then repeated using four other sugars: glucose, lactose, maltose and sucrose. The results are shown in the table below.



Sugar	Set 1	Set 2	Set 3	Set 4	Set 5	Mean
fructose	1.4	1.4	2.0	2.6	5.4	
glucose	9.0	8.2	7.0	8.6	8.8	
lactose	0.0	0.0	0.0	0.0	0.0	
maltose	2.8	3.2	3.0	3.0	6.2	
sucrose	7.4	7.0	7.0	6.6	6.8	

a Define anaerobic respiration.

b Write the word equation for the anaerobic respiration of yeast.

c Explain the purpose of the paraffin oil in this experiment.

d Calculate the mean for the experimental results and complete the table.

Using a suitable graph paper or software, plot a graph of volume of gas produced against type of sugar.

e Which type of sugar resulted in the:

i highest rate of respiration?

ii lowest rate of respiration?

f Was the student's hypothesis supported by the experimental results?

g Suggest a suitable control for the experiment.

22 The following image shows a scanning electron micrograph of a root.

a Identify structures P and Q.

b Explain how cell R is specialised in its function.

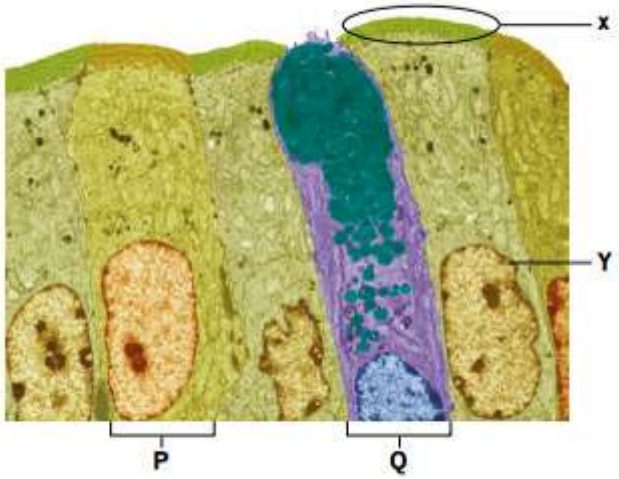
c The root is an organ. Using the root as an example, outline how the cells are organised to form an organ.

d Outline how structure P is involved in the transport and eventual loss of water.

23 The following table shows three specialised cells from three organ systems. Information about disorders of these systems is given. Using your knowledge of organ systems, complete the table with information about the function of the cell and how the cell is involved in each disorder.

	Red blood cell	Ciliated epithelial cell lining trachea and bronchi	Epithelial cell lining small intestine
			
Organ system			
Specialised cell structure		presence of cilia on surface facing the airway	
Specialised cell function		rhythmic waving or beating motion to sweep mucus, particles and microbes out of airways	
Disorder of the system	haemolytic anaemia: abnormal breakdown of red blood cells	chronic obstructive pulmonary disease (COPD): can be caused by cigarette smoke, which damages ciliated epithelial cells	coeliac disease: damage to villi (finger-like projections) in the small intestine
How cell is involved in the disorder			

24 The following electron micrograph shows some of the cells in the mammalian digestive system.



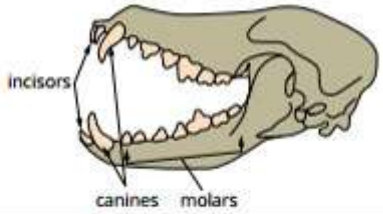
a Name structures X and Y.

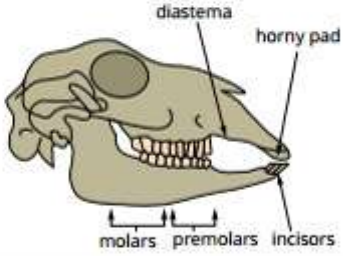
b Identify the types of cells labelled P and Q.

c Outline the function of cell Q.

d In which part of the digestive system was this image taken? Explain your answer.

25 The following table summarises the difference in the length of the digestive tract to the body length for two organisms, organism A and organism B. The skulls of the two organisms are also shown.

Organism A	
	
Ratio of body length to entire digestive tract	1 : 7
Ratio of body length to small intestine	1 : 6

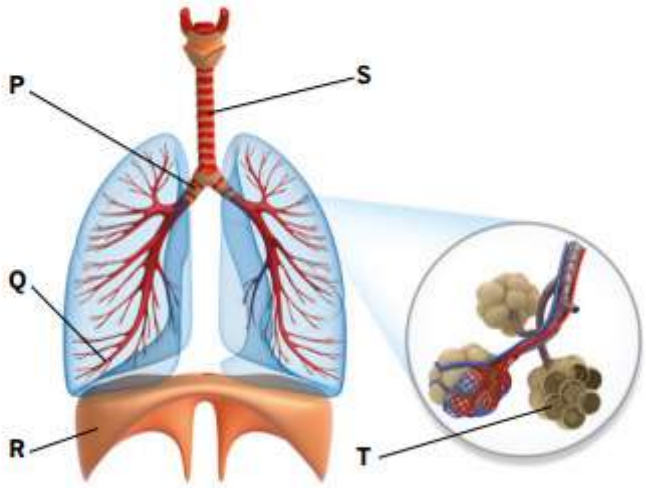
Organism B	
	
Ratio of body length to entire digestive tract	1 : 27
Ratio of body length to small intestine	1 : 25

a One role of teeth in mammals is to break food into smaller pieces. Explain the benefit of this.

b Describe the diet organism B would have.

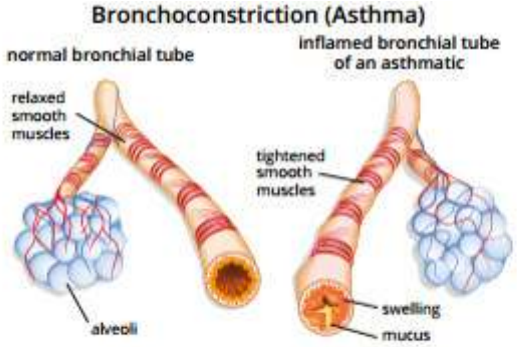
c Explain the difference in the length of the digestive tracts of the two animals.

26 The following figure shows the structure of the human respiratory system.



Identify structures P, Q, R, S and T.
Describe how the movement of the rib cage and diaphragm results in air moving into T.

27 The figure below shows a normal bronchus and a bronchus during an asthma attack.

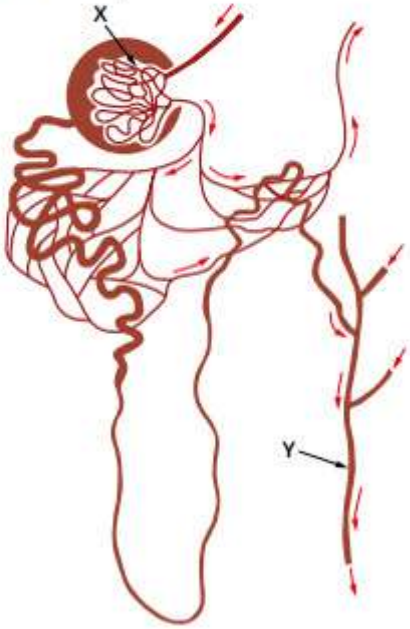


a What symptoms will a person have during an asthma attack?

b Explain the reason for the symptoms listed in question **a**.

c Asthma interferes with one important component of the gas exchange process. How does this happen?

28 The following diagram represents a nephron from a mammalian kidney.



a State the function of a kidney in the excretory system.

b Identify at least two differences that would be expected between the fluid at locations X and Y in a healthy person.

c Explain these resulting differences.

29 The following table compares the relative thickness of three major blood vessels.

Blood vessel	Mean diameter (mm)	Mean wall thickness (mm)
X	4.0	1.0
Y	0.008	0.0005
Z	5.0	0.5

a Identify the types of blood vessels represented by X, Y and Z.

b Explain the differences in diameter and wall thickness between the three blood vessels.

CHAPTER

05 Survival through adaptations and regulation

Living organisms can survive, grow and reproduce only in surroundings that provide adequate levels of nutrients, water, oxygen and carbon dioxide, and suitable physical conditions such as light and temperature. The range of conditions in which an organism can survive is called its tolerance range. Organisms function most efficiently when these conditions are within narrower limits, called the optimum range.

In this chapter you will examine some of the ways in which organisms regulate and maintain functionality of their internal environment, while overcoming the challenges of survival and reproduction in their ever-changing external environment.

Key knowledge

- the structural, physiological and behavioural adaptations that enhance an organism's survival and enable life to exist in a wide range of environments
- successful adaptations as models for biomimicry to solve human challenges.
- how regulation of factors is needed to maintain a relatively constant internal environment, explained by the stimulus–response model and the use of homeostatic mechanisms, including feedback loops
- factors regulated by homeostatic mechanisms in humans, including temperature, blood glucose and water balance
- malfunctions in homeostatic mechanisms that result in diseases, including type 1 diabetes and hyperthyroidism in humans

5.1 Adaptations

Organisms have different features that enable them to survive and reproduce in different environments. These features have evolved in response to various environmental factors and are known as **adaptations**. Adaptations can enable animals and plants to live in extreme environments, access resources and mates, defend themselves and their territory, and communicate and interact with their own and other species (see Figure 5.1.1).

Adaptations can be classified into three broad categories:

- structural (morphological or anatomical)
- physiological (functional)
- behavioural.

Adaptations are characteristics that increase the likelihood of survival and reproduction of an organism in a particular environment. They have a genetic basis and are passed on from generation to generation. Adaptations are the result of the evolutionary process of natural selection, in which those organisms that are best suited to their environment survive and reproduce, passing on their advantageous adaptations to their offspring. While adaptations help individual organisms survive, they are also critical for the survival and reproduction of populations and species.

In this section you will learn about the different types of adaptations in plants and animals and how theses adaptations enable organisms to exist in a broad range of environments.

FIGURE 5.1.1 Panther chameleons (*Furcifer pardalis*) of Madagascar have evolved a spectacular coloured skin that can change to signal aggression, territorial and mating behaviour as well as mood. Specialised layers of chromatophores in the skin enable the colour change to occur.

CHALLENGES TO ADAPTATION AND SURVIVAL

To live in a particular habitat, an organism must have access to the basic requirements necessary for growth. These requirements are usually met by the organism's environment, which consists of:

- abiotic factors—non-living components of an environment such as water, temperature, pH, and salinity
- biotic factors—living components of an environment, such as bacteria, fungi, plants and animals.

The adaptations of organisms enable them to overcome challenges in their environment, such as cold temperatures, excess salinity, lack of water and the threat of predation.

STRUCTURAL ADAPTATIONS

Structural adaptations are anatomical or morphological features that help organisms survive in a specific environment. They are the physical characteristics that relate to body size and shape that increase the likelihood of the organism's survival in a particular environment.

Structural adaptations of plants

Water is essential for photosynthesis. Therefore, a large number of structural adaptations that we observe in plants reduce water loss caused by salinity, heat and wind in the environment. Some of these adaptations include:

- reduced leaf surface area
- fewer **stomata**
- stomatal hairs that create a humid microclimate
- sunken or protected stomata
- thick, waxy cuticle
- extensive root systems
- rolled leaves
- leaves orientated away from the Sun.

Plants that grow in dry, hot environments are known as xerophytes (from Greek *xeros* dry and *phyton* a plant). Some of their adaptations are discussed in more detail below.

FIGURE 5.1.2 An SEM of the sunken stomata of a needle leaf of the coastal Sitka spruce (*Picea sitchensis*).

General adaptations to dry environments

Cacti are well-known examples of xerophytes. Xerophytes have adaptations that conserve moisture and prevent the leaf temperature from rising too much. They also have an increased tolerance to desiccation (drying). Some of the adaptations of xerophytes are shown in Figures 5.1.2 and 5.1.3.

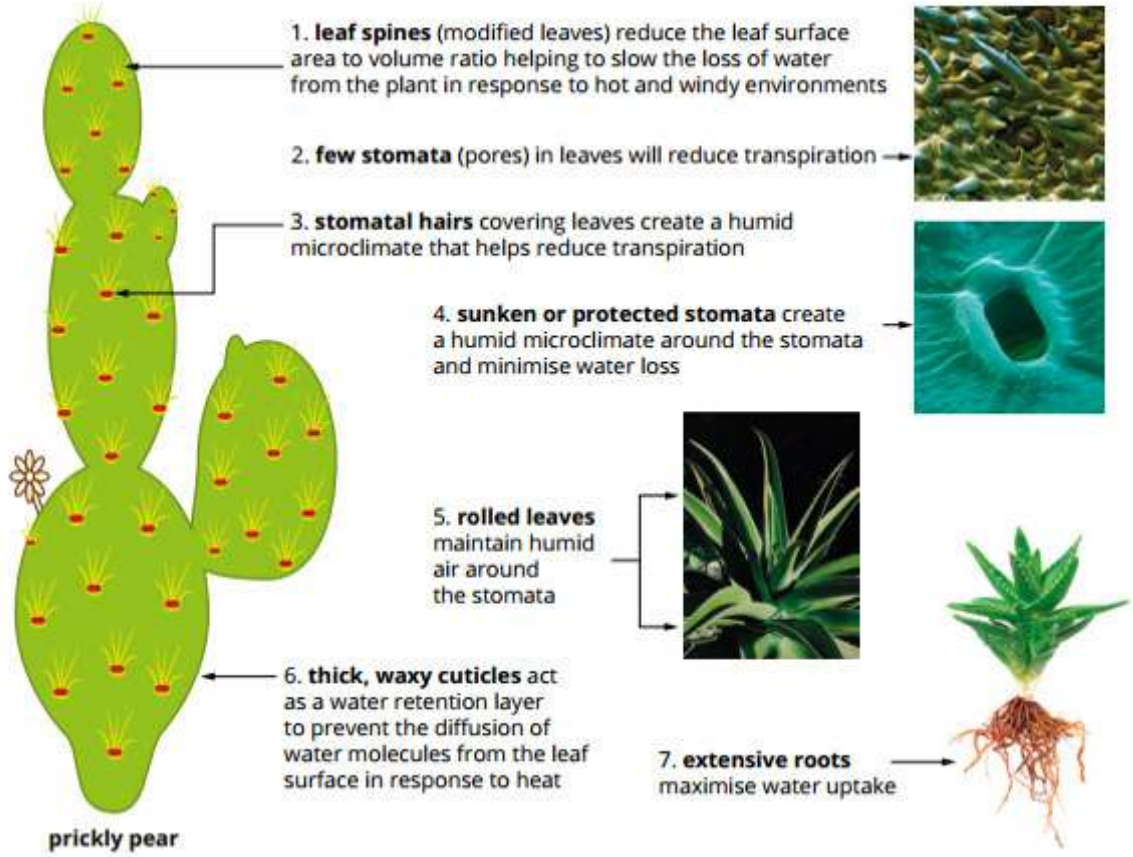


FIGURE 5.1.3 Plants that live in harsh, dry environments such as deserts, have evolved adaptations that enable them to conserve water.

Rolled leaves

Marram grasses (*Ammophila* species) are xerophytes that grow well in the salty, sandy soils of coastlines (Figure 5.1.4a). When conditions are hot and dry, thin-walled bulliform (bubble-shaped) cells partially collapse, causing the leaves to roll inwards, reducing water loss. Hairs on the inside of the rolled-up leaf trap moisture, creating a humid microclimate (Figure 5.1.4b). This humidity reduces the concentration gradient between the outside and inside of the leaf, which reduces transpiration. Because of this and other adaptations, these grasses have been used to stabilise sand dunes that are prone to erosion.

Leaf orientation

Eucalypt trees also have structural features that enable them to survive in hot, dry environments. They have hard leaves with waxy cuticles on both sides to reduce water loss. In many species the leaves also hang vertically, which reduces the amount of direct sunlight they receive (see Figure 5.1.5) and so reduces transpiration and water loss.

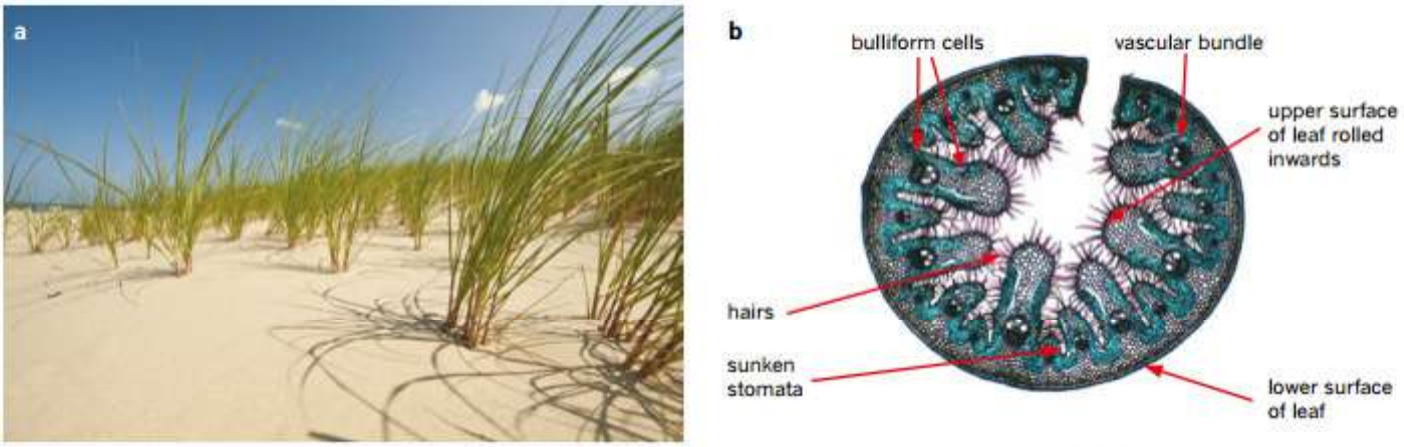


FIGURE 5.1.4 (a) Marram grasses (*Ammophila* species) grow well in the salty, sandy soils of coastlines. They have adaptations that allow them to survive in this dry, salty environment. (b) One of these adaptations is leaf rolling. This enables the plant to trap moisture and reduce water loss.

FIGURE 5.1.5 The leaves of this adult eucalypt tree are hanging downwards, reducing their exposure to sunlight. This adaptation reduces transpiration in hot, dry climates.

BIOFILE

Lithops

Lithops is a genus of succulent plants that live in dry, rocky environments in southern Africa. They are called stone plants or pebble plants because of their stone-like appearance. This appearance helps them to blend in with their surroundings, so they are less likely to be eaten by herbivores. Another unusual feature of *Lithops* is that most of the leaves grow underground. While this adaptation helps to reduce water loss, it also makes it difficult for the leaves to access vital sunlight. To overcome this problem, this plant has developed a unique structural adaptation. *Lithops* have evolved translucent tissue on their leaf tips that allows sunlight to be magnified through to the chloroplasts that are deep within their underground leaves. *Lithops* can also tolerate a diverse temperature range from a minimum temperature of –16.4 °C to a maximum of 68.7 °C. The enzymes in this plant have a broad functional temperature range to enable it to survive in these extremes.

FIGURE 5.1.6 *Lithops* or stone plants have a unique structure to cope with their dry environment.

Structural adaptations of animals

All animals have evolved structures that enable them to survive in their environment. Adaptations to abiotic factors such as temperature and water availability, as well as biotic factors such as predators, prey and competitors, are critical for survival in any environment.

Some examples of structural adaptations include:

- thick fur and blubber (fat) to insulate against cold
- bright feathers to help attract mates
- large ears to increase heat loss
- small ears to reduce heat loss
- webbed feet and flippers for swimming
- spines for protection against predators
- patterned body coverings for camouflage.

Further examples of structural adaptations in animals are discussed below.

Body coverings

The emperor penguin (*Aptenodytes forsteri*) has many structural adaptations to cope with life in the harsh Antarctic climate. Penguins have four layers of thick, scale-like feathers, creating a windproof coat (Figure 5.1.7). They also have thick blubber to keep them warm while swimming in the icy ocean. Juvenile penguins have soft down for insulation, which is a more effective insulator on land than the adult feathers but of little use in the sea. They must moult before they can swim. Penguins and other animals in cold climates tend to have bodies with a small surface area to volume ratio to assist them in conserving body heat.

FIGURE 5.1.7 The emperor penguin (*Aptenodytes forsteri*) has mastered living in extremely cold environments. The thick layer of feathers and blubber are two of many important adaptations that make this lifestyle possible.

Vascular body parts

Some adaptations of animals in hot, dry climates include large ears, long tails or a long body. When the extremities are highly vascular, it enables the animals to release heat efficiently and keep their bodies cool. The fennec fox (*Vulpes zerda*) of the Negev Desert is an example of a desert dweller with highly **vascularised** ears (see Figure 5.1.8).

Highly vascularised tissues contain many blood vessels.

FIGURE 5.1.8 The fennec fox (*Vulpes zerda*) has highly vascularised ears that allow it to release heat rapidly, lowering the body temperature in the extreme desert heat.

PHYSIOLOGICAL ADAPTATIONS

Physiological adaptations pertain to the functioning of an organism at the different levels of organisation, from biochemical to cell, tissue, system and organism level.

Physiological adaptations in plants

Plants inhabit an incredible range of environments, from the hottest deserts to high mountain peaks, fast-flowing rivers and even the coastal intertidal zone. So they need an equally impressive range of adaptations to cope in what are often stressful conditions. Physiological adaptations play an important role in enabling plants to meet environmental challenges.

Crassulacean acid metabolism (CAM)

Crassulacean acid metabolism, also known as CAM photosynthesis, is an example of a physiological adaptation that enables greater efficiency in water storage and use in plants. It is most commonly found in plants living in dry environments, such as succulent plants in deserts. Some xerophytes and some plants adapted to saline conditions can minimise water loss during the heat of the day by using the CAM metabolic pathway.

In CAM plants the stomata open only at night to collect carbon dioxide. Rather than using the carbon dioxide immediately, as non-CAM photosynthesising plants do, it is stored as malic acid in cell vacuoles. During the day the malic acid is transported to the chloroplasts, where it is used to produce the carbon dioxide needed for photosynthesis (see Figure 5.1.9, page 214). By storing the carbon dioxide required for photosynthesis at night, the plant is able to close its stomata during the heat of the day to reduce water loss. This physiological adaptation allows plants to survive in environments of extreme heat and aridity.

The range of environmental conditions in which an organism can survive is called its tolerance range.

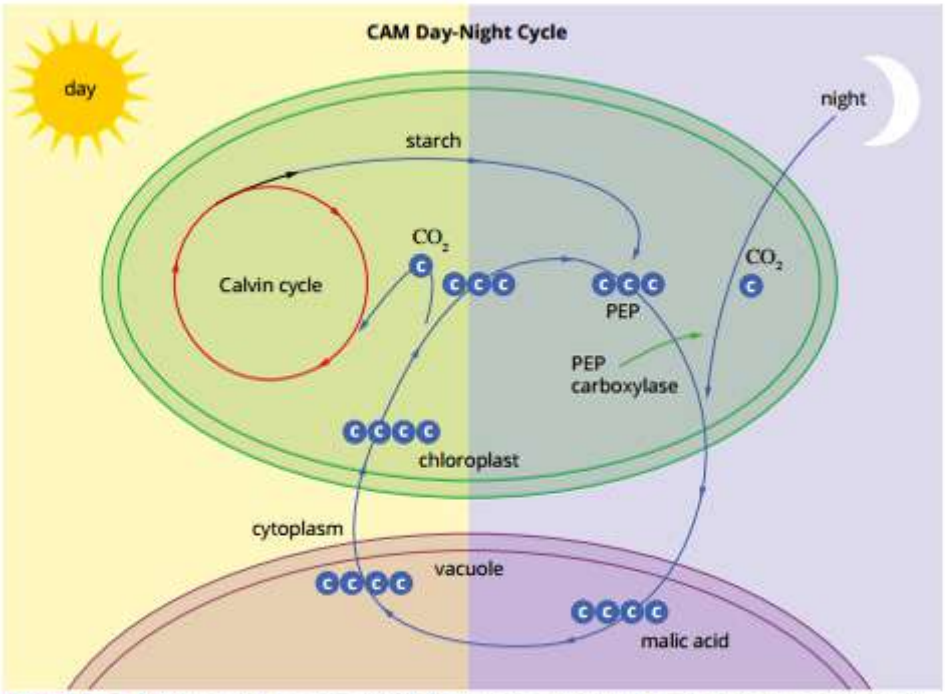


FIGURE 5.1.9 A summary of the complex CAM metabolic pathway of some plants in hot and dry or saline environments. This metabolic pathway enables the plants to absorb and store carbon dioxide at night to avoid losing precious water during the day.

FIGURE 5.1.10 Physiological adaptations, such as increasing solute concentrations, producing frost-inhibiting proteins and changing cell membrane composition, allow some plants to survive in extremely cold climates.

FIGURE 5.1.11 *Arthrocnemum indicum* is a coastal halophyte adapted to living in a highly salty environment. This species is able to control salt levels by increasing water uptake.

Frost tolerance

Extreme cold can be very damaging, and even lethal, to plants that are not adapted to cope with such conditions. Ice crystal formation inside cells causes plant cell membranes to burst, killing the cells. Cold temperatures can also decrease enzyme activity and change the fluidity of cell membranes, both of which effect a wide range of physiological processes in the plant. To overcome these problems, plants living in cold climates have evolved strategies that enable them to tolerate freezing temperatures (Figure 5.1.10).

A high concentration of solutes such as sugars and salts lowers the freezing point of water. Plants that can accumulate high concentrations of these solutes in their leaves are therefore less likely to be damaged by freezing temperatures.

Some plants produce proteins that reduce the risk of cell damage from freezing. **Antifreeze proteins** inhibit the growth and recrystallisation of ice crystals by binding to them. **Dehydrin proteins** bind to water molecules inside the cell, changing the structure of the water and stabilising the cell membrane.

In addition to adjusting solute concentrations and producing proteins to tolerate freezing, plants can also change the lipid composition of their cell membranes to optimise functionality in cold temperatures.

Regulation of salinity

Salinity is a major problem for many agricultural crops. In many areas, over-irrigation of agricultural land has resulted in highly saline soils, which most food crops cannot tolerate. Saline soils disrupt water and nutrient uptake by the roots, suppressing plant growth. When salt enters the plant's cells, it causes ion imbalance, inhibiting metabolic processes, and eventually leads to cell death. Plants living in saline environments such as coastal dunes, salt marshes or salt lakes have evolved physiological mechanisms to cope with the salinity (Figure 5.1.11). Plant species that can survive high salinity are known as halophytes (from Greek *halos* salt and *phyton* plant). These plants use a variety of mechanisms to exclude or regulate the concentration of salt in their tissues.

Some physiological adaptations that plants have evolved to cope with salinity are:

- Compartmentalisation of ions within the cells and tissues of the plant by transporting excess salt to vacuoles or old tissue. This avoids the toxic accumulation of salt in the cytoplasm.
- Excluding salt at the roots and leaves by:
  - shedding leaves that are overloaded with salt
  - excreting salt from salt glands
  - pumping salt out of the roots
  - controlling transpiration to avoid excess salt being delivered to the shoots from the soil
  - balancing the rate of growth with the uptake of soluble ions to maintain a constant salt concentration in tissues
  - increasing water uptake to dilute salt concentrations in tissues.

Physiological adaptations in animals

Animals display an astounding diversity of physiological adaptations. With these adaptations some species are able to overcome extreme conditions and exploit seemingly uninhabitable environments.

Examples of physiological adaptations in animals include:

- the ability to produce concentrated urine to conserve water in desert animals such as the spinifex hopping-mouse
- venom production for prey capture or defence, such as most snakes, wasps, spiders, many marine animals, and even some mammals such as the platypus
- colour changes in response to sunlight for thermoregulation, as in Namaqua chameleons
- shivering to maintain body temperature when cold, in endothermic animals (including humans).

Further examples of physiological adaptations in animals are discussed below.

Camouflage

Camouflage enables many organisms to blend in with their environment. This adaptation has many advantages, but it is particularly useful for avoiding predators or for capturing prey. One of the most amazing examples of camouflage is seen in the common octopus, *Octopus vulgaris* (Figure 5.1.12). This octopus can change colour and texture to match its underwater environment, blending in with corals, sand or kelp to hide itself from predators and prey.

The common octopus has specialised colour-changing cells called **chromatophores** that enable it to change colour to match its surroundings. Physiological mechanisms move pigment to and from the cells and change their reflection to produce the effect. In addition, tissues under the octopus's skin can create textures to match its environment.

Heat exchange for cooling

Heat exchangers work in different ways in different animals. In desert ungulates such as the gemsbok oryx (*Oryx gazella*), a **heat exchanger** is used to keep the brain cool (Figure 5.1.13a, page 216). If the oryx is dehydrated and can no longer afford to lose water, it stops sweating. This causes its body temperature to rise, sometimes as high as 43 °C. If blood at such high temperatures entered the brain, the animal would die. To avoid this, the arterial blood travels through a network of smaller arteries that intertwine with a network of veins before it enters the brain. This network of veins and smaller arteries is called the **carotid rete system** (Figure 5.1.13b, page 216).

Enzymes catalyse metabolic reactions only within certain temperature ranges. They denature (break down) at high temperatures and are inactive at low temperatures.

BIOFILE

Tasting bitterness

The ability to detect a bitter taste is an adaptation that has evolved in humans. Approximately 75% of people have the gene that enables them to detect a substance called phenylthiocarbamide (PTC), which registers a bitter taste. The other 25% of people do not register the bitter taste of PTC or bitterness in other similar tasting foods. This adaptation is thought to have evolved to help humans avoid poisonous foods, many of which have a bitter taste.

FIGURE 5.1.12 The common octopus (*Octopus vulgaris*) uses specialised cells called chromatophores to camouflage itself.

The venous blood in the carotid rete system has travelled through the nasal sinuses and has been cooled using evaporative cooling in the nostrils. As the cooler blood from the nostrils passes in the opposite direction to the warmer blood from the body, the heat flows from the hotter to the cooler blood. This process is known as countercurrent heat exchange. This cools the blood entering the brain by several degrees, enabling the animal to survive in extreme heat and drought.

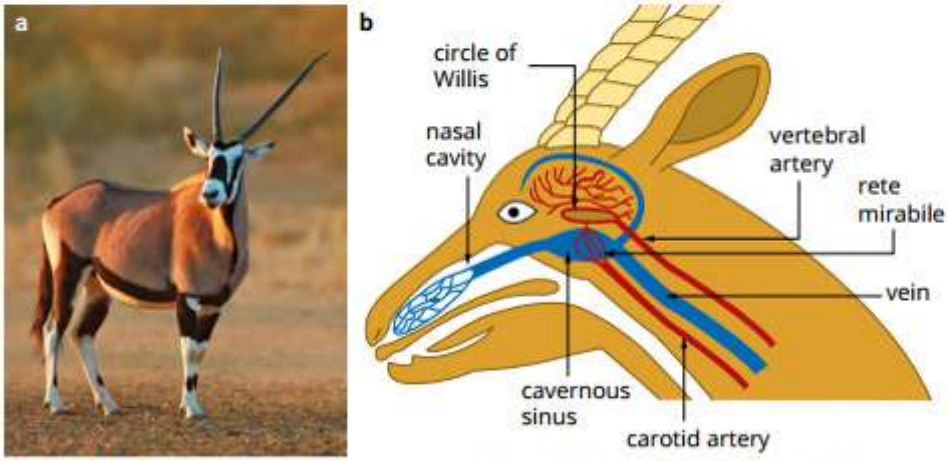


FIGURE 5.1.13 (a) A gemsbok oryx (*Oryx gazella*) in the Kalahari desert, South Africa. (b) The oryx's carotid rete system cools the hot arterial blood from the body before it enters the brain.

Heat exchange for heating

Countercurrent heat exchange also occurs in animals living in extremely cold climates, to reduce heat loss and maintain body temperature.

Penguins have heat exchangers in their flippers, feet and tails. These extremities have a relatively large surface area and are exposed to the cold, so they lose heat quickly. Blood from the feet flows back to the heart through veins close to the arteries. The warm blood in the arteries transfers heat to the veins so that blood moving back towards the heart is warmed, maintaining the penguin's body temperature (Figure 5.1.14). The blood travelling to the feet is cooled, so heat loss is minimised.

The diameter of the arteries flowing through the feet is also reduced to decrease the flow of blood to the extremities and further reduce heat loss. In this way the cells in the feet receive oxygen and nutrients and remain warm enough to function, but less heat is lost to the environment.

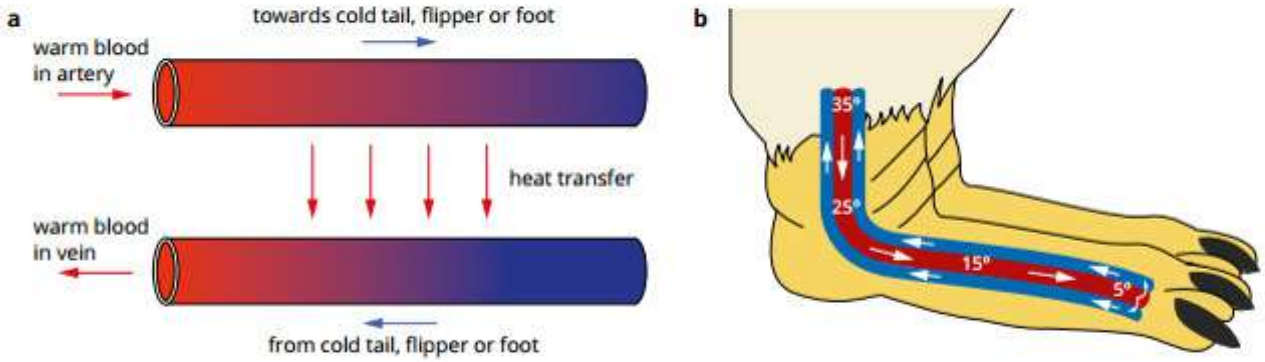


FIGURE 5.1.14 The heat exchange mechanism in the circulatory system of penguins ensures that heat loss at the extremities is minimised, while the core body temperature is maintained.

Antifreeze proteins

Some fish that inhabit very cold water, such as the Antarctic cod (*Notothenia coriiceps*), manufacture a type of protein that prevents tissue from freezing. These antifreeze proteins, similar to those produced by plants, circulate in the blood of the fish and prevent the growth of ice crystals, keeping their blood liquid (Figure 5.1.15).

FIGURE 5.1.15 Antarctic cod (*Notothenia coriiceps*) use a variety of physiological mechanisms to survive extreme cold. One of these mechanisms is the production of antifreeze proteins.

BIOFILE

Diving in the deep

Some diving mammals, such as the crab-eater seal (*Lobodon carcinophagus*) (Figure 5.1.17), can stay submerged at depths of 430 metres for over ten minutes. Diving mammals are able to store oxygen much more efficiently than other mammals. Some seals can store 70% of their oxygen in their blood; humans can store only 51%. These larger oxygen stores are possible because of increased levels of haemoglobin in the blood and myoglobin in muscles (haemoglobin and myoglobin are proteins that bind to oxygen), along with larger blood volumes in these animals.

Diving mammals are also able to carry out anaerobic respiration. They have a high tolerance for lactic acid build-up, so their muscles can still function efficiently when oxygen stores have been depleted. These animals also have excellent control over their organs, reducing blood flow to those that are not needed for immediate survival, such as the digestive organs, while conserving precious oxygen for vital organs such as the heart and brain. This also reduces the work of the heart, slowing the heart rate dramatically and further conserving oxygen.

FIGURE 5.1.17 Crab-eater seals (*Lobodon carcinophagus*) are able to dive to depths of 430 metres, remaining submerged for over ten minutes. They have a range of physiological adaptations that make this possible.

BIOFILE

Sweating: an efficient cooling mechanism

Humans are one of the few animals that produce sweat to cool down. Adults can sweat up to 4 litres per hour during vigorous exercise. Even when not exercising, this physiological adaptation plays an important role in thermoregulation through evaporative cooling. When warm sweat (which is about 99% water, with sodium chloride and some other substances) comes into contact with cooler air, it evaporates, carrying heat away and lowering your body temperature. It does this through a process of energy (and therefore heat) transfer.

FIGURE 5.1.16 Sweating is an important physiological adaptation in humans. It uses evaporative cooling to regulate the body's temperature and prevent overheating.

Torpor

FIGURE 5.1.18 A pair of greater mouse-eared bats (*Myotis myotis*) hibernating in a cave.

Torpor is a physiological state in which the metabolic rate is lowered to save energy. This enables an organism to cope with environmental stresses such as extreme cold or heat or decreased food or nutrient availability, and can occur over short or long periods.

A long period of torpor is often called dormancy. Hibernation, brumation and aestivation are different forms of prolonged torpor:

- **Hibernation** is prolonged torpor that occurs in winter. Over summer and autumn the animal builds up a thick layer of body fat that will provide them with energy during the hibernation period in winter. During hibernation the animal can decrease its body temperature and heart rate to conserve energy. Hibernation occurs mostly in mammals, but some species of birds also hibernate. Bears, bats and squirrels are examples of animals that hibernate (Figure 5.1.18).
- **Brumation** is similar to hibernation but involves different metabolic processes. Reptiles such as snakes and lizards undergo brumation. Brumation is triggered by decreases in air temperature and daylight hours. It begins just before winter and can last between one and eight months. How long a reptile remains in brumation depends on the air temperature and the size and age of the animal. Once brumation begins, the reptile eats less or not at all, but wakes regularly to drink.
- **Aestivation** is prolonged torpor in hot and dry conditions. Examples of aestivating animals are snails, frogs, crocodiles, tortoises, lungfish and some birds.

FIGURE 5.1.19 The green-striped burrowing frog (*Cyclorana alboguttata*) aestivates for up to nine months of the year underground.

Green-striped burrowing frogs (*Cyclorana alboguttata*) (Figure 5.1.19) inhabit semi-arid to arid regions of eastern Queensland and northern New South Wales. These frogs spend up to nine months of the year in aestivation. During this time they live underground in small burrows and do not eat. Research has shown that during this time they can reduce their metabolic rate by up to 80%. This allows them to survive these underground periods just on their store of body fat.

Torpor is an example of both a behavioural adaptation (retiring to a cave or seeking shelter and going to sleep) and a physiological adaptation (the slowing of the heart, breathing and metabolic rates associated with periods of torpor).

Bioluminescence

Bioluminescence is a physiological adaptation in which light is produced by an organism to attract attention, frighten enemies or lure prey. Bioluminescence is a form of chemiluminescence, which involves the release of light energy following a chemical reaction. Fireflies (Figure 5.1.20), deep sea fish and sea jellies are some of the organisms that are bioluminescent, producing the chemicals luciferin (a pigment) and luciferase (an enzyme). The luciferin reacts with oxygen to create light. The energy system for bioluminescence is highly efficient, with no excess heat being produced.

FIGURE 5.1.20 Fireflies, also known as lightning bugs, regulate flashes of light from their abdomen by controlling the amount of oxygen admitted to the bioluminescent organ. The flashing lights enable fireflies to signal their presence to one another, which is particularly important during the mating season.

BIOLOGY IN ACTION

The soldiers that glowed in the dark

The Battle of Pittsburgh Landing

In just two days during the spring of 1862, the Battle of Pittsburgh Landing during the American Civil War saw over 16000 soldiers wounded and more than 3000 killed. Medics were not prepared to deal with the overwhelming number of men that needed medical attention, and untreated wounds contaminated with dirt and shrapnel were the perfect breeding ground for bacteria. The soldiers' immune systems were weak after months of poor diet and living conditions, and infections soon ravaged the camps. During this time little was understood about the biology of microorganisms, and antibiotics had not been developed. Infections that are easily treated today took many soldiers' lives.

As soldiers waited for days in the muddy fields for medics to help them, some of them noticed something strange about their wounds: as night fell, their wounds began to glow. Even more peculiar, those with glowing wounds were found to have a faster healing rate and a better chance of survival. The apparent healing powers of the strange illumination earned it the name Angel's Glow.

The science of glowing soldiers

The cause of Angel's Glow remained unknown until 139 years later, when 17-year-old Bill Martin visited the battlefield in 2001. When he learnt about the glowing wounds, he asked his mother (a microbiologist researching luminescent bacteria) what might have caused it. She told Bill to do an experiment to find out, so he and his friend, Jon Curtis, investigated a bioluminescent bacterium, *Photorhabdus luminescens*. They thought that the life cycle of the bacterium might hold clues about what caused the soldiers' wounds to glow.

Photorhabdus luminescens bacteria live in the gut of parasitic worms called nematodes. These nematodes burrow into the bodies of insect larvae (Figure 5.1.21) living in the soil and move into their blood vessels. Once inside the larva, the nematode ejects the bacteria, which begin to produce toxins that kill the insect larva, along with antibiotics that kill any other microorganisms living inside the insect larva. *Photorhabdus luminescens* emits a soft blue glow while they, and their nematode host, consume the remains of the larva. The glowing bacteria in the insect corpse attract other insects, making the search for the next host easier. Once the larva has been consumed, the nematode ingests the bacteria again, allowing them to recolonise the worm's gut and hitch a ride to the next host (see Figure 5.1.22).

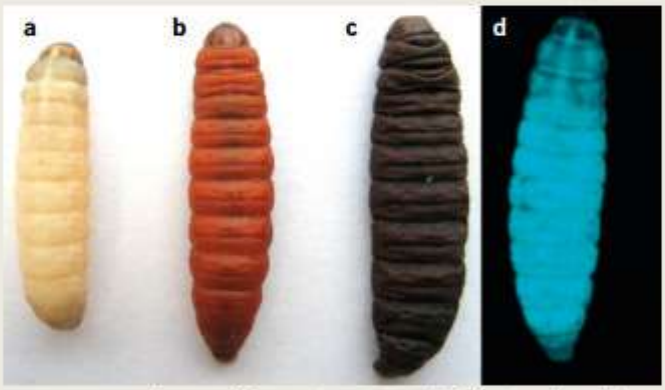


FIGURE 5.1.21 Larvae of the greater wax moth (*Galleria mellonella*) infected with *Photorhabdus luminescens*: (a) not infected; (b) 24 hours after infection; (c) 48 hours after infection; and (d) bioluminescence in a larva caused by infection with *Photorhabdus luminescens*.

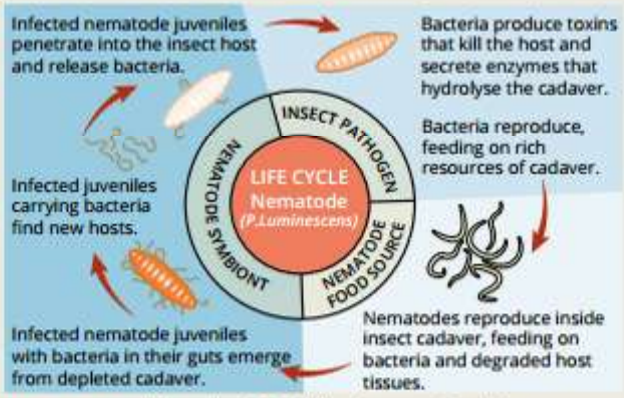


FIGURE 5.1.22 Life cycle of the bioluminescent bacteria, *Photorhabdus luminescens*.

Historical records of the battle revealed that the weather and soil conditions at that time would have been ideal for *Photorhabdus luminescens* and the nematodes. Although human body temperatures are not ideal for the bacterium, Bill and Jon calculated that the cold overnight temperatures that the soldiers were exposed to would have lowered the soldiers' body temperatures enough to be suitable for the bacterium.

Bill and Jon hypothesised that the host nematodes colonised the soldiers' wounds from the soil. Neither *Photorhabdus luminescens* nor the nematodes are particularly infectious to humans and would have eventually been destroyed by the soldiers' immune systems. However, antibiotics produced by the bacteria would have killed any pathogenic bacteria in the soldiers' wounds, helping them avoid infection. *Photorhabdus luminescens* not only made the soldiers glow, but also may have saved their lives.

Adaptations for movement in plants

Although plants do not have muscles or a nervous system like animals, they can still move in response to their environment. In most cases the mechanisms for plant movement are controlled by chemicals such as hormones, or by **turgor pressure**, both of which are physiological adaptations. Plants can undergo two types of movement in response to environmental stimuli. One is called tropism and the other is called nastic movement.

Tropism

FIGURE 5.1.23 The growth of these seedlings towards the light is an example of tropism.

Tropism is plant growth in response to an environmental factor such as gravity, light or water (Figure 5.1.23). The response depends on the direction of the **stimulus**—the plant will either grow towards (positive tropism) or away from (negative tropism) the stimulus. Tropisms are controlled by hormones such as auxin, gibberellin, ethylene and cytokinin.

Types of tropisms include:

- **phototropism**: growth in response to light
- **geotropism** or **gravitropism**: growth in response to gravity
- **chemotropism**: growth in response to chemicals
- **thigmotropism**: growth in response to touch
- **hydrotropism**: growth in response to water concentration.

Nastic movement

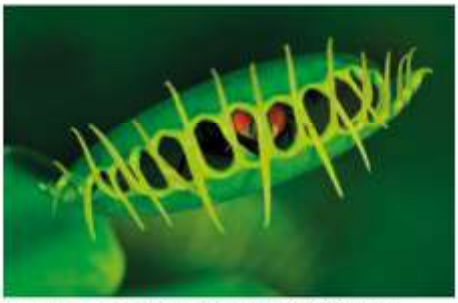


FIGURE 5.1.24 The Venus flytrap (*Dionaea muscipula*) uses mechanosensors (hairs) on the leaf surface to trigger cell pores to open in the lower side of the leaf. Water rushes into these cells, causing them to expand and forcing the trap to close.

Nastic movement is a movement of plant tissue in response to an environmental stimulus (but not in the direction of the stimulus). This allows a plant to adapt to changes in its environment by changing its orientation. Some nastic movements in plants are:

- **thigmonasty**: movement in response to touch
- **photonasty**: movement in response to a change in light intensity
- **thermonasty**: movement in response to a change in temperature.

Thigmonastic movements include the rapid opening and closing of plant parts in response to touch, such as those observed in the Venus fly trap, *Dionaea muscipula* (Figure 5.1.24). The Venus fly trap is a carnivorous plant that is adapted to low levels of nitrogen in the soil. It obtains nitrogen by trapping prey such as flies, which it attracts by secreting a sweet sap. When a fly touches the tiny hairs (mechanosensors) on the leaves, an electrical signal is sent to the centre of the trap. This signal opens pores in the trap's lower layer of cells, allowing water to rush in from the cells in the upper layer of the trap. The rapid change in pressure (turgor) causes the cells on the lower side of the trap to expand, forcing the trap to snap shut (Figure 5.1.25), trapping the fly inside. Enzymes released by the plant then digest the insect. About one third of the **ATP** in the cells is used up in each movement. This is why after repeated touches a leaf will not respond until its energy reserves have been replenished.

FIGURE 5.1.25 A bloodroot plant (*Sanguinaria canadensis*) displaying photonastic movements on a cloudy morning. In low light this plant closes its leaves and flowers.

The flowers and leaves of many plants respond to changes in light intensity, opening during the day and closing at night or on cloudy days (Figure 5.1.25). This is an example of photonasty.

An example of thermonastic behaviour is the opening and closing of tulips in response to air temperature. The petals open as the air temperature rises and close when the temperature falls. This behaviour allows the pollen to be exposed only in warmer weather, when pollinators are more likely to visit the flower, and protects it during cooler weather. As in the thigmonastic movement of the Venus fly trap, this movement is a result of turgor pressure.

Plants that are capable of rapid movement rely on internal changes in turgor. Changes in turgor are usually initiated by contact with objects outside the plant. The cells involved are parenchyma tissue of the cortex or specialised swellings (pulvini) at the base of leaves or leaflets. Some movements may be very fast, occurring in less than a second.

Behavioural adaptations of animals

Behavioural adaptations in animals that help them to survive in extreme environmental conditions include:

- seeking or leaving shade or shelter
- evaporative cooling to lower temperature
- huddling to maintain body temperature
- migration.

Seeking or leaving shade or shelter

Many desert animals have behavioural adaptations that are very important in regulating the rate of heat exchange with their environment. An example is the central netted dragon (*Ctenophorus nuchalis*). To raise its body temperature, this lizard emerges from under a rock and basks in the sunshine, spreading itself out at right angles to the Sun's rays. To lower its body temperature or reduce the rate of increase in body temperature, the lizard orientates its body parallel to the Sun's rays, minimising the exposed surface area, or simply retreats beneath a rock or into a burrow (see Figure 5.1.27).

Some animals such as desert snakes and tortoises adopt nocturnal behaviour during summer to prevent overheating. They move only in the cooler evening, avoiding the extreme heat of the day. Animals may also seek shelter to increase their body temperature when it is cold or windy.

Evaporative cooling

Evaporative cooling is used by many land animals to lower their body temperature by releasing heat into the environment. Although it is a physiological adaptation it is achieved by behavioural adaptations, such as:

- panting or licking limbs
- spraying water on the body
- wallowing in mud or water
- mouth gaping
- gular fluttering
- urohydrosis.

Panting or licking limbs enable animals to release heat effectively using evaporative cooling. For example, kangaroos lick their paws, and animals such as dogs, gazelles and foxes pant. The fennec fox (*Fenecus zerda*) has been observed panting at a rate of 690 times per minute after chasing prey. The rate of panting is proportional to the amount of air flowing over the tongue. If animals can flatten their tongue, increasing surface area, while increasing their panting rate, then the cooling effect is greater. Sometimes even penguins have to pant. In warmer weather, they also hold their flippers out of the water so that both surfaces are exposed and can release heat via evaporative cooling.

BIOFILE

Trigger plant

Trigger plants (*Stylidium* species) have one of the fastest movements in the plant world. The flowers have a structure called a column (the trigger), where the male anthers as well as the female stigma are located. When triggered by the touch of an insect, the column flicks back against the insect's body, depositing or picking up pollen from its back (Figure 5.1.26a/b). This mechanism ensures cross-pollination between plants. Some other plants have similar mechanisms in which the stamens are pulled in towards the centre of the flower, usually hitting the pollinator (Figure 5.1.26c).

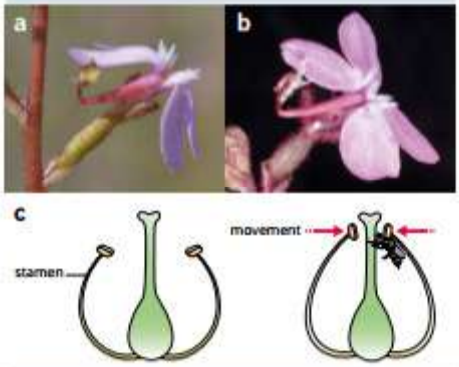


FIGURE 5.1.26 (a) The column of a trigger plant flower before it is triggered. (b) The column after it has been triggered. (c) In some plants, the touch of a pollinating insect can cause the stamens to the pulled rapidly inwards, depositing pollen on the insect.

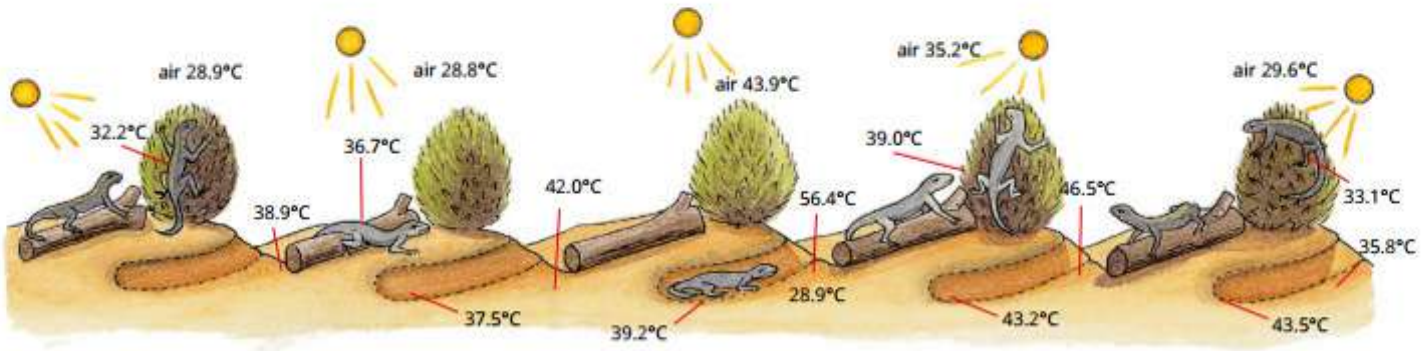


FIGURE 5.1.27 The central netted dragon (*Ctenophorus nuchalis*) has adapted its behaviour to desert conditions, regulating its temperature throughout the day by seeking shade or basking in sunlight.

FIGURE 5.1.28 A female African elephant (*Loxodonta africana*) splashes water over her body, making use of evaporative cooling to control her body temperature. Mud remaining on the elephant's skin provides protection against solar radiation.

Spraying water on the body is commonly seen in elephants (Figure 5.1.28) but is also a behaviour used by many other animals.

Wallowing in mud or water is a very common behaviour. Animals such as pigs, elephants, rhinoceroses and deer wallow in mud; the wet mud acts like sweat to cool the skin. Animals such as hippopotamuses, tapirs, bison, horses and cattle wallow in water to cool down.

Mouth gaping is seen in many animals, such as crocodiles and alligators (Figure 5.1.29), when air moves across the moist surface of an open mouth. It uses evaporative cooling from the membranes inside the mouth to reduce the temperature of blood being supplied to the brain.

Gular fluttering is a cooling behaviour in which birds flap membranes in their throat to increase evaporation from the moist buccal (mouth) region; as the air temperature increases, birds increase the amount of gular fluttering.

Urohydrosis is a cooling behavior exhibited by some birds, including vultures and storks. They urinate on their legs, creating an evaporative cooling effect.

FIGURE 5.1.29 A saltwater crocodile (*Crocodylus porosus*) opens its mouth to allow water to evaporate from its moist tongue.

BIOFILE

Wallowing in mud is cool

Wallowing in mud has many advantages for animals, including skin maintenance, camouflage, parasite control, protection from solar radiation, and social play. One of the more common reasons is thermoregulation. Many animals, such as hippopotamuses, elephants and pigs wallow in mud to lower their body temperature. Like sweating, the evaporation of the water in the mud cools the animal's skin by carrying heat away from the body. It can cool the animal's body by up to 2 °C, making it more efficient than sweating. Wallowing in mud has an advantage over water, too; the water in the mud evaporates more slowly than water alone, keeping the animals cooler for longer (Figure 5.1.30).

FIGURE 5.1.30 A pig wallows in mud to cool down.

Huddling

Huddling is used by many animals, such as penguins, to cope with cold temperatures (Figure 5.1.31). Thousands of emperor penguin chicks may huddle together for warmth in the spring, when they begin to develop their adult plumage. By huddling, penguins decrease the surface area of the group exposed to the harsh environment. They continually rotate the animals on the outside, each taking a turn in the freezing cold winds.

FIGURE 5.1.31 Emperor penguin chicks huddling together for warmth.

Migration

Some animals move extremely long distances each year to inhabit a different area. This type of seasonal pattern of relocation is known as migration. The purpose of migration is usually to seek better food availability, or to move to a better site for breeding along with suitable climatic conditions. Birds navigate their migratory paths using the position of the Sun and Moon, as well as topographical details and cues from the Earth's magnetic field. Migration is an innate behaviour prompted by cues from the environment, such as the length of daylight. These cues are closely coordinated with an animal's biological clock and trigger biological responses, such as increased feeding before migration.

BIOLOGY IN ACTION

Adaptations of mangroves

Mangroves grow in the intertidal zone on shallow, muddy shores (Figure 5.1.32). This environment presents them with constantly changing and challenging conditions that they need to adapt to, including:

- fluctuating salinity levels with the movement of the tide or from freshwater entering a tidal river
- lack of oxygen for their roots because they are growing in waterlogged soil
- boggy, unstable soil that makes anchorage difficult
- seed dispersal in an aquatic environment.

FIGURE 5.1.32 Mangroves grow in the constantly changing and challenging environment of the intertidal zone.

Getting rid of salt

Mangroves have three methods of ridding themselves of salt: exclusion, excretion and accumulation. Some mangroves exclude salt by actively pumping it out across membranes at their root surface. Other mangroves, including Ceriops (in Queensland) and Avicennia (which grows as far south as Victoria), also have salt-excreting glands on their leaves (Figure 5.1.33).

FIGURE 5.1.33 Salt crystals on a mangrove leaf. The salt was excreted in solution through specialised salt glands, and evaporation formed the crystals. This physiological adaptation allows the plant to regulate internal salt concentration.

Specialised roots

Oxygen normally enters roots through lenticels, which are rough spots consisting of loose, corky tissue through which gas exchange can occur. Mangroves have evolved a range of aerial roots, all of which have lenticels. These aerial roots include peg roots, pneumatophores and stilt roots. Pneumatophores increase the surface area exposed to the air at low tide for maximum oxygen uptake. These types of aerial roots, together with cable roots that spread laterally, also help stabilise the plant in the soft mud (Figure 5.1.34). The cable roots have a mat of fine, hair-like roots that absorb nutrients and water.

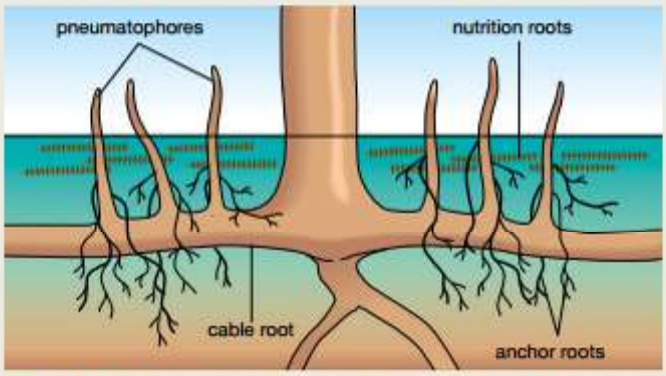


FIGURE 5.1.34 The structure of the root system of a typical mangrove plant, showing cable roots and pneumatophores.

Seed dispersal

The seeds of mangroves are buoyant and are adapted for dispersal by water. Some mangroves are viviparous. Viviparity in botany (plant science) means that the seed germinates and the young plant starts to develop while still attached to the parent plant. When the germinating seed falls into the water it already has a developing root system (Figure 5.1.35). This enables it to quickly anchor itself before it can be washed away by wave action.

FIGURE 5.1.35 Mangrove seeds have adaptations that enable them to disperse in their aquatic environment. In some species the seeds already have a developing root system before they leave the parent plant, and the seeds of most species can float in water.

BIOMIMICRY

Biomimicry (also called biomimetics) involves mimicking or copying structures or systems found in nature to develop new materials or products. Biomimicry is divided into three main areas: form, process and systems.

Form biomimicry

Form biomimicry is the imitation of shape or structure. Form biomimicry is not a new discipline. For example, in the 1920s aircraft designers copied the shape of a gull's wing in an attempt to build a more stable glider. The following are modern examples of biomimicry.

The invention of Velcro

In 1941, after a hunting trip in the European Alps, Albert de Mestral, a civil engineer, became curious about the burdock seeds caught in his socks and in the fur of his dog. When he viewed the seeds under a microscope he saw that they were covered in tiny hooks (Figure 5.1.36a) which became entangled in the fibres of his socks. These structures inspired him to develop a fastening design that mimicked the hooks from the burr and the loops in clothing (Figure 5.1.36b). He tested various natural materials such as cotton, as well as synthetic material such as nylon. Eventually he created Velcro, and his patent was granted in 1955.

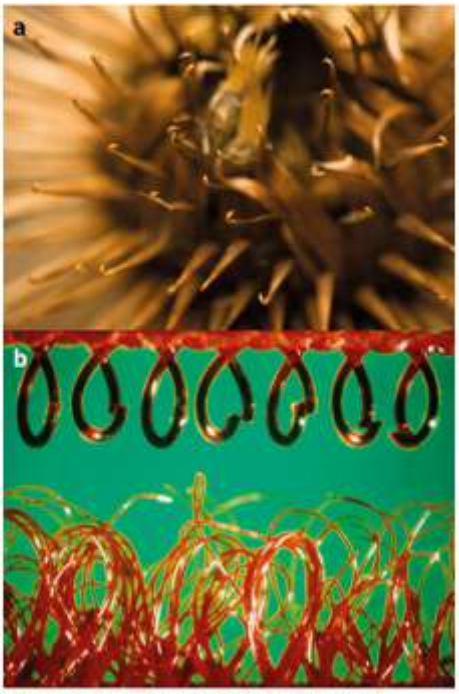


FIGURE 5.1.36 (a) A magnified view of a burdock (*Arctium lappa*) seed. (b) A magnified image of Velcro, showing the separated hooks and loops.

Bullet train design

When the Shinkansen bullet train travelled through a tunnel at high speed (up to 300 km/hour), air pressure changes resulted in a deafening sonic boom when it left the tunnel. Eiji Nakatsu, an engineer and keen birdwatcher, knew that kingfishers could perform a perfect splashless dive into water to catch fish. He used this knowledge to improve the design of the bullet train. A round beak would send shock waves in all directions (like the train as it left the tunnel). But the kingfisher's long, streamlined beak allows the water to flow past the beak rather than be pushed in front of it, which greatly reduces the impact when it hits the water (Figure 5.1.37a,b).

Another source of noise was the pantograph, which is the structure on top of the train that receives electricity from overhead wires. Engineers tackled the problem using inspiration from the feathers of owls, which have almost silent flight. The engineers adapted a similar design, consisting of many small vortices, thus reducing the sound on the main part of the pantograph.

These biomimicry design solutions allow the train to travel more quietly. The beak-like nose of the train also has the additional benefits of increasing speed by 10% and reducing electricity use by 15% (Figure 5.1.37c).

FIGURE 5.1.37 (a,b) A kingfisher's long, streamlined beak allows it to dive for fish without creating a splash. (c) The Shinkansen bullet train's nose shape is modelled on the kingfisher's beak. The streamlined shape solved the problem of sonic booms when the train travels through tunnels at high speed.

Sharklet technology

The skin of a shark is made up of thousands of microscopic, overlapping scales that have grooves along their surface called dermal denticles (Figure 5.1.38a). They create uneven surfaces and small forces that prevent algae and barnacles from attaching and growing on the shark's skin. Sharklet is an artificial material inspired by shark skin (Figure 5.1.38b). The texture of this material inhibits bacterial growth and has enormous potential for reducing infection rates in hospitals.

Another application for this material is in eye cataract surgery, which often results in a clouding of the replacement lens. The clouding is caused by migration of epithelial cells onto the newly implanted intra-ocular lens (IOL). Another operation is often required to clear these cells away. The implantation of a Sharklet membrane with the IOL eliminates the need for this surgery to correct the lens, because the texture on the membrane inhibits cell migration. Sharklet material can also be used at catheter sites to prevent infection, and for keeping medical devices clean.

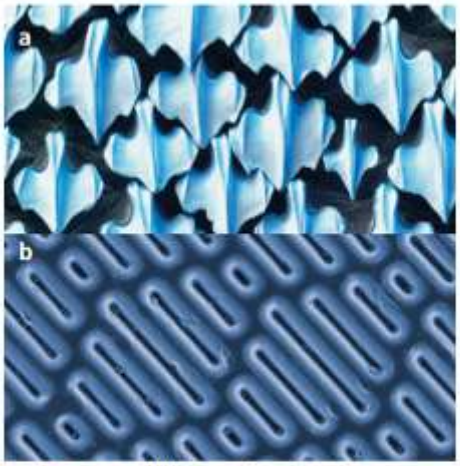


FIGURE 5.1.38 (a) A scanning electron micrograph of shark skin, showing the dermal denticles. (b) Sharklet is an artificial material inspired by the dermal denticles of shark skin. This material has many applications in medicine because of its ability to prevent bacterial growth on its surface.

Hypodermic needle

Scientists at Kansai University in Japan have developed a hypodermic needle to reduce the pain of injections, inspired by the jagged surface and internal tubular structure of the mosquito proboscis (Figure 5.1.39). The uneven surface of the needle reduces contact with nerves in the skin, while a tiny internal tube is used to deliver drugs or take blood.

FIGURE 5.1.39 Mosquitoes feed on blood through a specialised structure called a proboscis.

Process biomimicry

Process biomimicry involves imitation of behaviours or a series of operations. For example, engineers and mathematicians are developing algorithms based on the communication behavior of ants and bees. Using this approach, control boxes that attach to electrical appliances have been developed to communicate with one another and monitor and regulate the appliances' energy use. In a way similar to hive communication systems, signals are sent out across the whole network of appliances, and energy management decisions are made according to the status of the entire system.

Systems biomimicry

Systems biomimicry involves mimicking processes that work together to manage materials or energy. Systems biomimicry is a relatively recent development that is being used mainly to solve engineering problems, particularly those involving energy use. For example, designers looking to increase the efficiency of wind turbines were inspired by the movement of humpback whale flippers through the water. Their fins have bumps called tubercles, which improve lift and reduce drag.

Portcullis House, United Kingdom

The architects who designed Portcullis House, a seven-storey building in London, created an air-conditioning system modelled on termite mounds. The temperature of termite mounds is maintained within a range of one degree, without the use of energy. They achieve this through a series of funnels and cool, moist underground chambers. The outside air flows into the funnels, is cooled in the chambers and distributed throughout the mound. Warm air is then released through the top of the termite mound (Figure 5.1.40a).

The heating and cooling system in Portcullis House uses a series of chimneys and vents (Figure 5.1.40b) that allow fresh air to enter the building. This air is warmed in winter by solar radiation and cooled in summer by groundwater. This system has been so effective that there is no need for traditional air conditioning or heating. Portcullis House uses only 25% of the energy used in traditional office buildings.

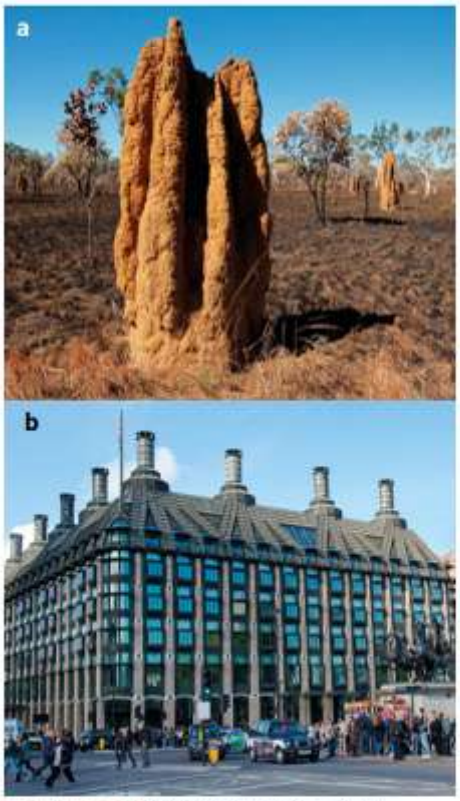


FIGURE 5.1.40 (a) A large termite mound in Kakadu National Park, Australia. The temperature inside the termite mound is maintained within a one degree range. (b) The design of the passive heating and cooling system in Portcullis House in London was inspired by the temperature regulation system in termite mounds.

5.1 Review

SUMMARY

- An adaptation is an inherited characteristic that increases the likelihood of survival and reproduction of an individual organism in a particular environment.
- There are three main types of adaptation: structural, physiological and behavioural.
- Structural adaptations are anatomical or morphological body parts that help an organism to survive in its environment.
- Examples of structural adaptations of plants are:
  - reduced leaf surface area
  - fewer stomata
  - stomatal hairs to create a humid microclimate
  - sunken or protected stomata
  - thick, waxy cuticle
  - extensive root systems
  - leaf shape: rolled leaves; reduced surface area
  - leaves orientated away from the Sun.
- Examples of structural adaptations of animals include:
  - thick fur and blubber (fat) which insulates against cold
  - bright feathers or skin to help to attract mates
  - large ears to increase heat loss
  - small ears to reduce heat loss
  - webbed feet and flippers for swimming
  - spines for protection against predators
  - patterned body coverings for camouflage.
- Physiological adaptations pertain to the functioning of the animal at biochemical, cellular, tissue, organ and whole organism levels.
- Examples of physiological adaptations of plants are:
  - CAM
  - frost tolerance
  - salinity tolerance
  - drought tolerance.
- Examples of physiological adaptations of animals include:
  - the ability to produce concentrated urine
  - counter-current heat exchange mechanisms
  - dormancy, hibernation, torpor and aestivation
  - production of venom or poisons
  - ability to withstand high temperatures
  - sweating
  - shivering to maintain body temperature
  - production of antifreeze proteins to prevent freezing.
- A behavioural adaptation is how an organism acts or moves in response to its environment.
- Examples of behavioural adaptations of plants include:
  - phototropism
  - geotropism
  - chemotropism
  - hydrotropism
  - thigmotropism
  - nastic movements.
- Examples of behavioural adaptations of animals include:
  - huddling for warmth
  - panting, licking skin, wallowing and gular fluttering to lose heat
  - seeking shade or sunlight
  - nocturnal activity
  - burrowing
  - making themselves look bigger.
- Biomimicry is an approach to the innovation and design of products that is modelled on structures and systems found in nature.

KEY QUESTIONS

1. Describe how adaptations are beneficial to the survival of an individual organism and to a species.
2. What are the three main types of adaptations in animals and plants?
3. List and describe two adaptations from each of the three main types described in Question 2, and state whether they are found in plants or animals.
4. What environments would each of the adaptations you mentioned in Question 3 be suited to? Explain your answers.
5. What is biomimicry? Can you think of an example of biomimcry that isn't mentioned in this book?

5.2 Regulatory mechanisms in animals and plants

Organisms and cells are constantly experiencing changes in their environment. These changes to the internal and external conditions can adversely affect the survival, growth and function of the organism. The **internal environment** of an organism must always remain within tolerable limits, even when conditions in the **external environment** fluctuate widely. When a change occurs in the external environment, an adjustment must be made to the internal environment.

Living organisms rely on their external environments to provide adequate levels of nutrients, water and oxygen and suitable physical conditions, such as light and temperature. Organisms have a range of mechanisms that allow them to adapt to changing conditions while maintaining a stable internal environment when external conditions fluctuate (see Figure 5.2.1). If an organism is not able to adapt to its external environment, it will suffer cellular damage and possibly death when conditions change.

In this section you will look at how animals and plants regulate their internal environments to maintain stability at the organ, tissue, cellular and intracellular level to sustain life of the organism.

MAINTAINING EQUILIBRIUM

Homeostasis

Homeostasis is the maintenance of variables in a system within certain limits. When an organism is healthy and functioning well, its systems are in homeostasis. Homeostasis is achieved by a variety of mechanisms that work to keep internal environments constant. This maintains conditions at an optimum level when the internal or external environment changes.

Homeostasis is achieved by **negative feedback loops**: **receptors** detect a change in the internal environment, and **effectors** work to reverse the direction of the change to achieve equilibrium. (In positive feedback loops, the effectors work to maintain and enhance the direction of the stimulus; therefore positive feedback is not usually involved in maintaining homeostasis.) Complex multi-cellular animals maintain the equilibrium of their internal environment by detecting and responding appropriately to changes in the external and internal environment.

Animals coordinate the activities of their cells, tissues and organ systems so that **responses** occur in an integrated and controlled manner. Detecting and responding to a stimulus requires an effective internal communication system. Communication in animals is achieved by hormonal and nervous system mechanisms, which transmit information between different parts of the organism, and also translate environmental disturbances into signals that can be interpreted and responded to. For example, the iris of the human eye detects light and responds by dilating or constricting to regulate the amount of light that enters the eye (see Figure 5.2.2).

Regulation usually involves the coordination of a number of systems, such as circulatory, respiratory, immune, digestive and excretory systems, along with the behavioural response of the organism.

The two most important systems in maintaining homeostasis in animals are the endocrine system (hormone) and the nervous system. Physiological and behavioural responses to environmental change that are carried out by both the endocrine (hormone) and nervous systems include:

- short-term and long-term regulation of growth
- maturation and reproduction
- homeostatic regulation of the internal environment.

The nervous system also provides rapid responses to:

- produce efficient coordinated movement to detect and avoid predators
- find and capture prey.

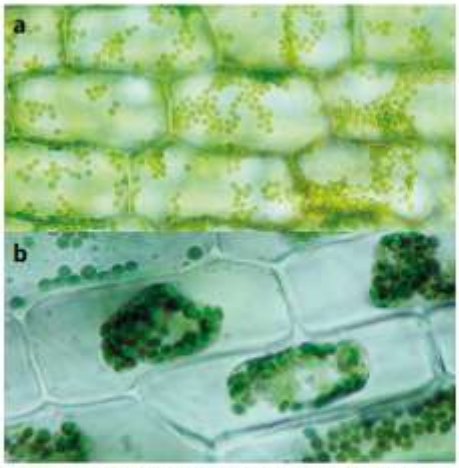


FIGURE 5.2.1 The internal cellular environment of the freshwater Canadian pondweed, *Elodea* sp., responds to changes in the external environment using osmosis. (a) In fresh water, chloroplasts move freely through the cytoplasm, as solute concentration is equal in both the internal and external environments. (b) When the cells are exposed to a salty environment, water leaves the cell by osmosis and the cell membrane contracts, clumping the chloroplasts in the middle of the cell. Because *Elodea* is a freshwater plant, it does not have the regulatory mechanisms to survive in a saltwater environment.

The internal environment of a multicellular organism is the watery extracellular fluid that surrounds the cells of a multicellular organism, which is often highly regulated.

The external environment of a multicellular organism is the environment immediately surrounding an organism as well as the interior of the respiratory, digestive and urogenital tracts.

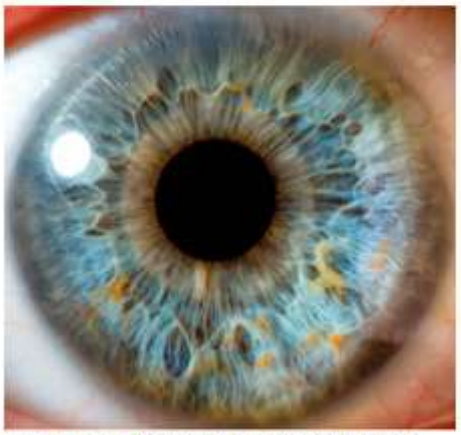


FIGURE 5.2.2 The iris is a pigmented muscle that responds to a light stimulus by dilating and constricting to regulate the amount of light entering the eye.

Homeostasis comes from Greek *homoios* and *stasis*, meaning 'staying in the same place'.

These regulatory systems are the most developed in mammals, which are able to maintain a relatively stable internal environment in the face of changing conditions.

Although in many ways hormonal systems and nervous systems appear distinctly different, they share one common feature: they both involve **chemical communication**. In both systems, signals are passed from one cell to the next by the release of specific molecules, known as hormones and neuro-transmitters. Hormones are released from glands or other tissues, and neurotransmitters are released from nerve endings. These molecules exert their effects by highly specific interactions with a receptor on, or within, the responding or target cell.

Feedback loops

Feedback loops may involve the endocrine and nervous systems working together to regulate the internal environment.

Negative feedback loops promote stability in the internal environment and maintain homeostasis by responding to changes in the body and adjusting the variables to their original or optimal state. They are stimulus–response mechanisms in which the response produced reduces the effect of the original stimulus by reversing its direction. For example, if the concentration of a substance in the blood is too high, a negative feedback loop will lower the concentration. If the concentration is too low, a negative feedback loop will increase the concentration. Most feedback loops in biological systems are negative.

Negative feedback loops are called negative because the information produced by the feedback causes a reversal of the size or effect of the stimulus. Negative feedback loops maintain stability through the action of the nervous or hormonal systems, or both acting together.

An example of a negative feedback loop is the regulation of blood sugar levels by **insulin**. When blood sugar levels are high, receptors detect the change and the pancreas secretes insulin. This lowers the blood sugar levels until homeostasis is reached, at which point the pancreas stops releasing insulin.

A negative feedback loop acts as follows (see Figure 5.2.3):

- The system is in a stable state.
  1. A change (**stimulus**) occurs.
  2. The change is detected by an appropriate **receptor**.
  3. The receptor sends a signal to a control centre (hypothalamus or transmission molecules).
  4. The control centre sends a signal to an appropriate **effector** or a specific effector cell, tissue or organ.
  5. The effector responds to the signal.
- The original state is restored.

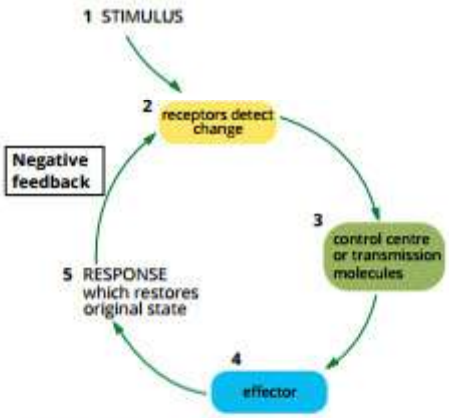


FIGURE 5.2.3 When the response reduces the initial stimulus or disturbance, it is operating as a negative feedback mechanism.

In the **control centre** information from sensory receptors is received and compared with a set-point (the optimal value for the functioning of that organism). This information is processed with other information about the state of the organism, and an appropriate response is initiated.

Regulation therefore involves fluctuations around the set-point. The size of the fluctuations depends on:

- the sensitivity of the receptor
- the tolerance of the control centre to variation from the set-point
- the efficiency of the effector.

Some features of the internal environment, such as blood **glucose** levels, can vary considerably; others, such as body temperature in mammals, are tightly controlled.

In contrast to negative feedback loops, **positive feedback loops** force an organism out of homeostasis by maintaining the direction of the stimulus, and sometimes increasing the stimulus. An example of a positive feedback loop is uterine contractions during childbirth. The hormone oxytocin stimulates the uterus to contract, causing pain.

Rather than the nervous system signalling the endocrine system to lower the oxytocin and reduce the pain, more oxytocin is produced to stimulate stronger contractions. The contractions work to push the baby into the birth canal and continue until the baby is born.

Hormones are a diverse group of compounds that act as intercellular messengers to regulate cell functions.

HORMONAL (ENDOCRINE) PATHWAYS

Hormonal control systems are found in all animals and plants, with varying levels of complexity among organisms. **Hormones** are signalling molecules that are responsible for the communication between organs and tissues to regulate physiological and behavioural processes. They are commonly involved as the response arm in negative feedback control mechanisms. Hormones modify the activity of certain cells as a result of interaction with specific receptors. They are involved in the control of various metabolic functions, including rates of chemical reactions in cells, transport of substances across plasma membranes, the secretion of other hormones, and the growth of cells.

Mode of action

In plants and animals, hormones are synthesised by specialised cells (either in the endocrine glands or other tissues in animals) and are transported to where they are needed via the circulatory system (in animals) or by diffusion (in both plants and animals) through the extracellular fluid.

Hormones transmit signals to target cells by altering specific biochemical reactions in these cells. Target cells are those that possess a specific receptor for a particular hormone. Hormones exert their effects either directly by passing through the plasma membrane into the cell, or indirectly by interacting with a receptor on the surface side of the cell. They are effective in low concentrations.

Specificity

Hormonal communication is specific for two reasons. Firstly, a particular stimulus will only affect a specific group of hormone-secreting cells. Secondly, although hormones may pass throughout an organism, only those cells that possess specific receptors are capable of responding to the hormone. For example, a sudden shock causes the release of **adrenaline** from the adrenal gland. Only those cells that have adrenaline receptors in their plasma membrane, such as muscle cells of the heart and blood vessels, can respond to the adrenaline circulating in the blood.

While a few animal hormones affect most cells in the body, most hormones affect specific organs, and often only one type of cell within that organ.

Signal speed

Hormonal effects are generally slower than nervous responses, longer in duration, and often affect cells that are widely distributed throughout the body. The passage of a signal along a hormone pathway is slower because the hormone is moved indirectly in the blood or relies on diffusion through the extracellular fluid to reach the target cells.

Types of hormones

There are three main groups of hormones:

- peptide hormones
- protein or amino acid derived hormones
- steroid hormones (hormones synthesised from cholesterol).

Hormones interact with cells in various ways. The way that a cell 'reads' a hormonal message depends on whether the hormone can pass through the plasma membrane (see Figure 5.2.4).

Peptide hormones consist of a chain of amino acids (polypeptide chain). These hormones are water-soluble and cannot pass through the plasma membranes of cells. Because of this, the receptors for these hormones are found on the surface of target cells. Examples of peptide hormones are oxytocin, growth hormone and follicle-stimulating hormone (Figure 5.2.4; Table 5.2.1).

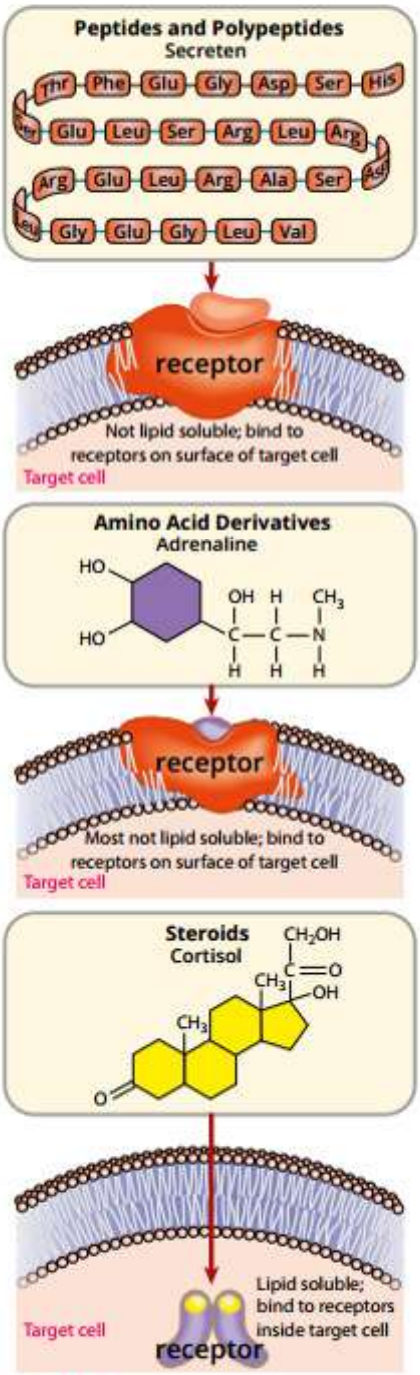


FIGURE 5.2.4 The three types of hormones (peptides and polypeptides–top, amino acid derivatives–middle, and steroids–bottom) interact with the plasma membrane of cells differently because of differences in their chemical structure.

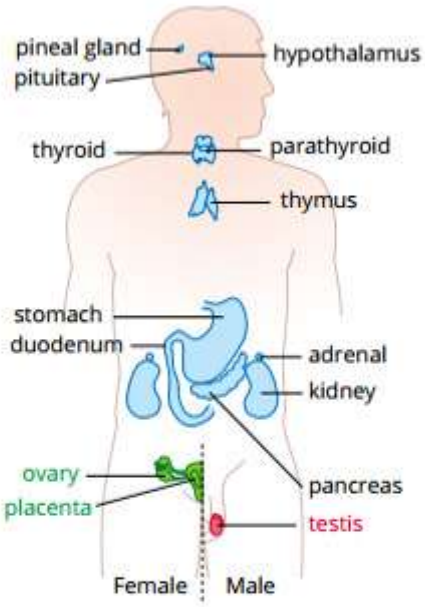


FIGURE 5.2.5 The major endocrine glands of the human body.

Amino acid derived hormones are water-soluble and cannot pass through membranes. Instead they bind to a specific receptor in the plasma membrane, triggering physiological responses within the cell. Examples of protein hormones are adrenaline and melatonin.

Steroid hormones, which are derived from fatty acids, are small and lipid-soluble. They easily pass through membranes into the cytoplasm, where they bind specifically to receptor molecules. They then pass into the nucleus where they act directly on particular genes. Examples of steroid hormones are testosterone and oestrogen.

Endocrine glands

Animals usually have specialised cells for producing hormones. In more complex animals (vertebrates, insects, crustaceans and some molluscs), these cells are often clustered into discrete organs called endocrine glands (Figure 5.2.5).

Initially, the term 'hormone' was restricted to the regulatory products of discrete endocrine glands that are released into circulating blood and that exert their action at a distance from the site of their secretion. However, it is now evident that hormones are secreted by a wide variety of tissues that are not necessarily organised into endocrine glands, and that they are able to reach their site of action by simple **diffusion**. Mammals have many major hormones (Table 5.2.1) and many more molecules thought to act as minor hormones.

Gland	Hormone	Hormone type	Target	Function
adrenal cortex	• glucocorticoids • mineralocorticoids	• steroid	• many cell types • kidney tubes	• Promotes synthesis of glucose. • Regulates reabsorption of salts.
adrenal medulla	• adrenaline (epinephrine)	• amino acid derivative	• heart, blood vessels, liver, fat	• Increases cardiac output, mobilises glucose, prepares body for action.
anterior pituitary	• adrenocorticotrophic hormone (ACTH)	• peptide	• adrenal cortex	• Promotes release of adrenal cortex hormones.
	• growth stimulating hormone (GSH)	• peptide	• bone, muscles	• Promotes protein synthesis and growth.
	• follicle stimulating hormone (FSH)	• peptide	• ovaries	• Promotes development of follicle and secretion of oestrogen.
	• luteinising hormone (LH)	• peptide	• ovaries	• Promotes ovulation, development of corpus luteum, and secretion of progesterone.
	• prolactin	• peptide	• mammary glands	• Stimulates milk secretion.
	• thyroid stimulating hormone (TSH)	• peptide	• thyroid	• Promotes production and release of thyroxine.
hypothalamus	• several releasing hormones	• peptides and amino acid derivatives	• anterior pituitary gland	• Controls release of anterior pituitary hormones.
ovary	• oestrogen	• steroid	• reproductive tract, body generally	• Promotes menstrual cycle, development of female features and behaviour.
	• progesterone	• steroid	• uterus	• Prepares uterus for, and maintains, pregnancy.
pancreas	• insulin	• peptide	• muscles, liver, fat	• Lowers blood glucose concentration.
	• glucagon	• peptide	• liver, fat	• Raises blood glucose concentration.
parathyroid	• parathyroid hormone	• peptide	• bone, kidneys	• Raises blood calcium concentration.
posterior pituitary	• oxytocin	• peptide	• mammary glands	• Causes release of milk.
	• antidiuretic hormone (ADH)	• peptide	• kidney	• Promote reabsorption of water from the collecting tubule.
pineal	• melatonin	• amino acid derivative	• brain	• Daily and seasonal cycles.
testis	• testosterone	• steroid	• reproductive tract, body generally	• Development of masculine features and behaviour.
thyroid	• thyroxine	• amino acid derivative	• most cells	• Regulates cellular metabolic rate.

TABLE 5.2.1 Hormones produce by the major human glands, showing their target organs, and functions.

The pituitary gland

The pituitary gland is a small gland at the base of the brain (Figure 5.2.6). In humans it is about 1 cm in diameter and weighs only about 0.5 grams. It plays an important role in endocrine regulation in vertebrates. Recent research has shown that the pituitary gland consists of two distinct parts, called the anterior and posterior pituitary glands.

The pituitary gland secretes hormones involved in the regulation of growth, lactation, reproduction, skin pigmentation, fat tissue, kidney function, and the activity of the thyroid and adrenal glands (see Figure 5.2.7). It lies immediately below, and is connected to, the **hypothalamus**, a region of the brain that receives information from all parts of the body (Figure 5.2.6). The hypothalamus is a collecting centre for information about the body's condition, such as food and water satiety (sense of fullness), smell, pain and arousal. This information is used to regulate the release of hormones from the pituitary gland. The hypothalamus produces releasing hormones, which control the release of some hormones from the pituitary gland.

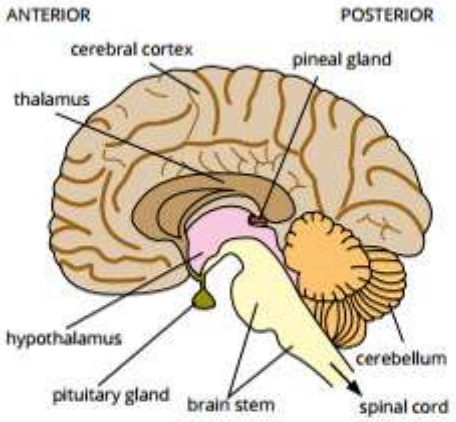


FIGURE 5.2.6 The human brain is subdivided into regions that are associated with particular functions. The pituitary gland (green) lies immediately beneath the hypothalamus (pink).

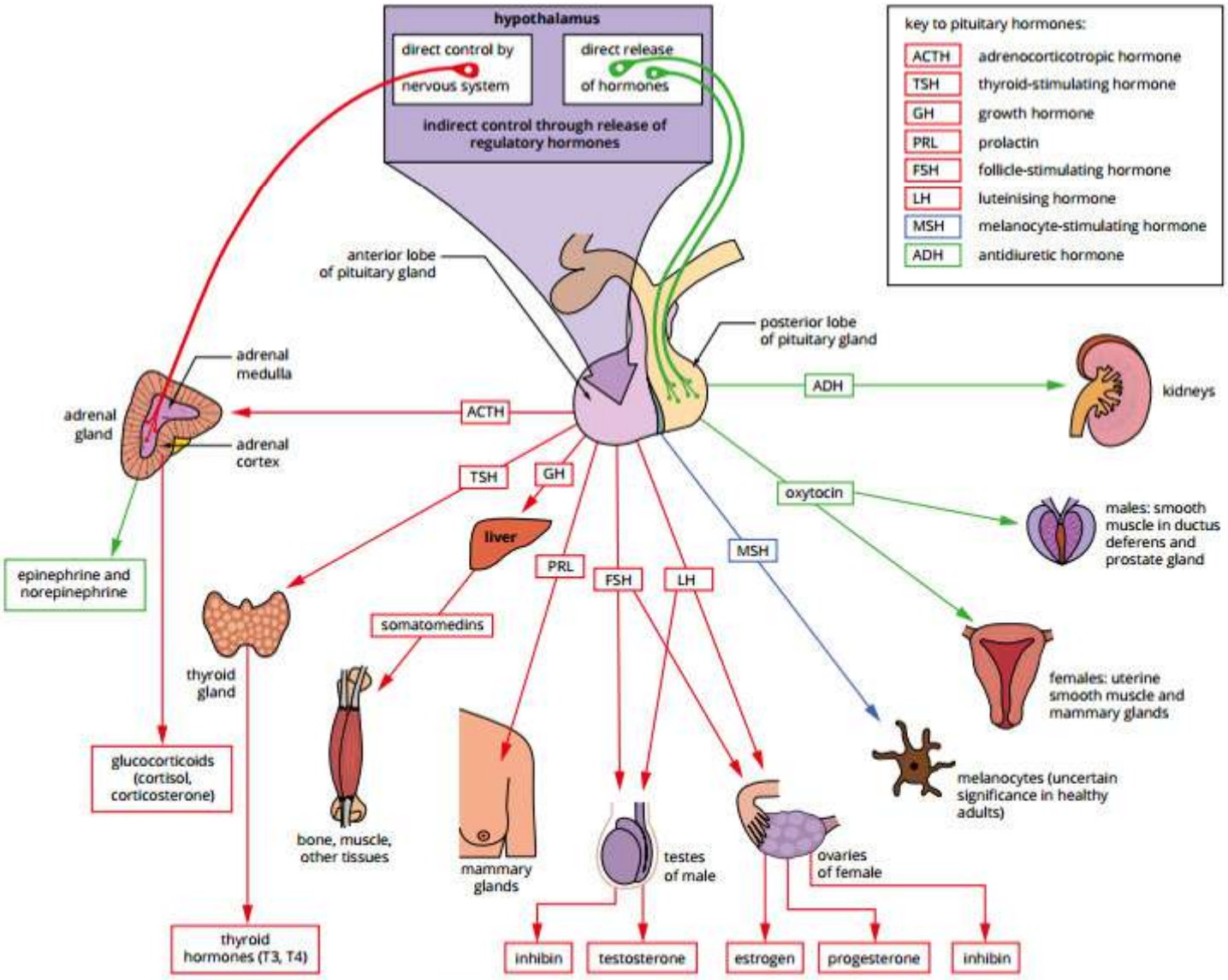


FIGURE 5.2.7 The pituitary gland is responsible for the secretion of many hormones that are important for growth, reproduction and metabolism in vertebrates.

Several pituitary gland hormones act to regulate secretion from other glands, including the thyroid, adrenal glands, ovaries and testes. The sequence of hormones involved in the release of thyroxine from the thyroid gland is shown in Figure 5.2.8.

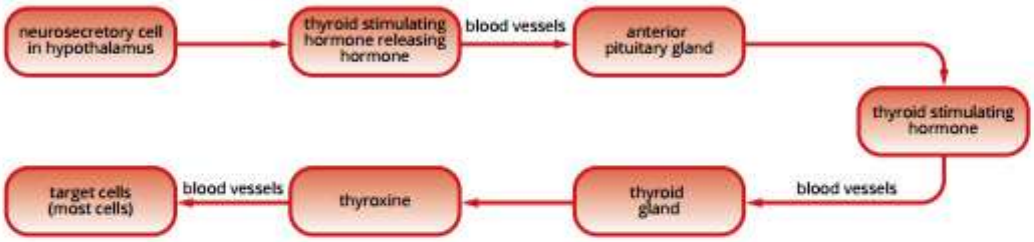


FIGURE 5.2.8 The sequence of hormones involved in the release of thyroxine from the thyroid gland.

BIOFILE

New insights into the pituitary gland

As scientists have learnt more about the function of the pituitary gland, what was once thought to be a clear distinction between the endocrine and nervous system has become increasingly blurred. Some of the hormones released from the pituitary gland are actually produced in nerve cells and released into the circulatory system from nerve endings.

The posterior pituitary gland releases hormones into the circulatory system that are produced in nerve cell bodies in specific regions of the hypothalamus. They are packaged into vesicles and then pass down axons into the posterior pituitary, where they are released. The specialised neuronal cells that produce and release these hormones are called neurosecretory cells.

The anterior pituitary gland produces several important hormones that are released in response to hormones released by the hypothalamus. The hormones from the hypothalamus travel in small blood vessels to the anterior pituitary, where they trigger the release of anterior pituitary hormones into the circulation.

BIOLOGY IN ACTION

Biorhythms and the pineal gland

All vertebrates have a pineal gland. The pineal gland can detect and respond to light, although in mammals it is much deeper within the brain and does not sense light directly. But it does receive internal messages from the eyes about the brightness of light.

The pineal gland produces the hormone melatonin, but when it receives internal messages from the eyes that light levels are too high, it stops releasing melatonin. So levels of this hormone circulating in the blood normally increase during the night and decrease during daylight, allowing animals to sense the time internally. The pineal gland therefore functions like an internal 'biological clock'.

Humans have daily patterns of temperature, alertness and other functions. These rhythmic patterns continue in the absence of the normal daylight cues. Jet travel from one time zone to another disrupts these internal rhythms, producing the symptoms of jet lag, which include disorientation, sleepiness and wakefulness. Similar problems are experienced by shift-workers. Melatonin or bright light can synchronise these internal rhythms, which has led to the use of melatonin as a 'jet-lag pill'. Alternatively, spending a day out in the bright sunlight will also help to reset your biological clock.

In animals living at higher latitudes with long winter nights and short summer nights, levels of melatonin can indicate seasons (Figure 5.2.9). In winter, when the nights are long, levels of melatonin in the blood are high most of the time. In summer, melatonin levels are lower most of the time. These differences can control seasonal rhythmic activities such as reproduction, and the development of reproductive organs and winter coats.

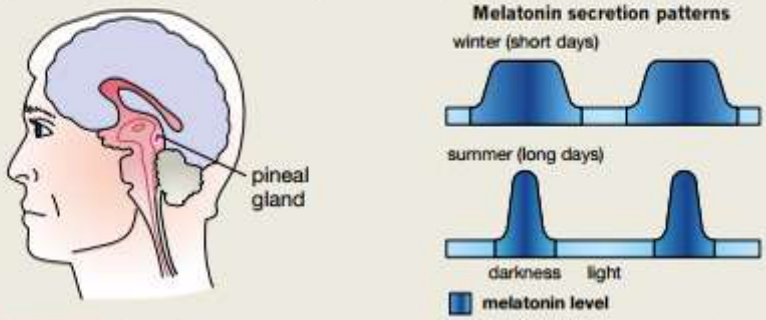


FIGURE 5.2.9 The pineal gland secretes the hormone melatonin in darkness. Because long and short nights produce different patterns of melatonin secretion, animals can tell what season it is.

NERVOUS SYSTEMS

Animals receive information about their environment and respond to external stimuli though the network of neural pathways that makes up the nervous system. The nervous system works closely with the endocrine system to respond to environmental changes and regulate the internal environment.

The rapid responses characteristic of most animals are brought about by the nervous system. Nervous systems typically involve a more direct pathway of communication between parts of the body than hormonal responses.

The **neuron**, also called nerve cell, is the functional unit of nervous systems. Neurons are specialised cells with structures that enable rapid transmission of information between cells (Figure 5.2.10). There are three basic functional classes of neurons (Figure 5.2.10a):

- Efferent (motor) neurons: transmit information from the central nervous system to the tissues and organs (effector cells)
- Interneurons: connect neurons within the nervous system
- Afferent (sensory) neurons: communicate information from tissues and organs to the central nervous system.

These different types of neurons have different structures but are made up of the same basic components: one or more dendrites, a cell body and an axon (Figure 5.2.10b). Branching dendrites receive signals from other cells, and transmit these to the cell body. A single axon conducts a signal from the nerve cell body to nerve endings, which form synapses with other cells. Neurons are also grouped into classes based on their structure: multipolar neurons have two or more dendrites that are separate from the axon; bipolar neurons have a single dendrite; and unipolar neurons have just one extension from the cell body, made up of an axon and dendrite.

The basic structure and function of neurons is very similar across all groups of the animal kingdom (Figure 5.2.11). In fact, much of what we know of the function of mammalian nerves comes from studies of frog neurons and giant neurons found in squids.

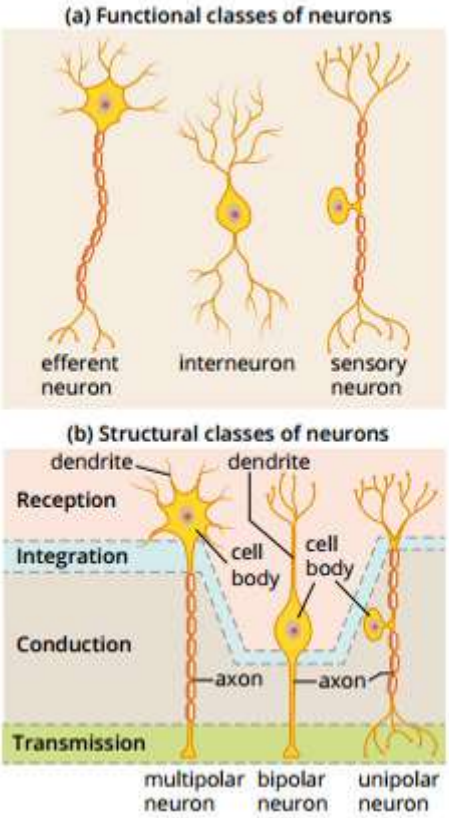


FIGURE 5.2.10 Different types of neurons vary in structure in order to serve their function and can be divided into classes based on their function (a) or their structure (b).

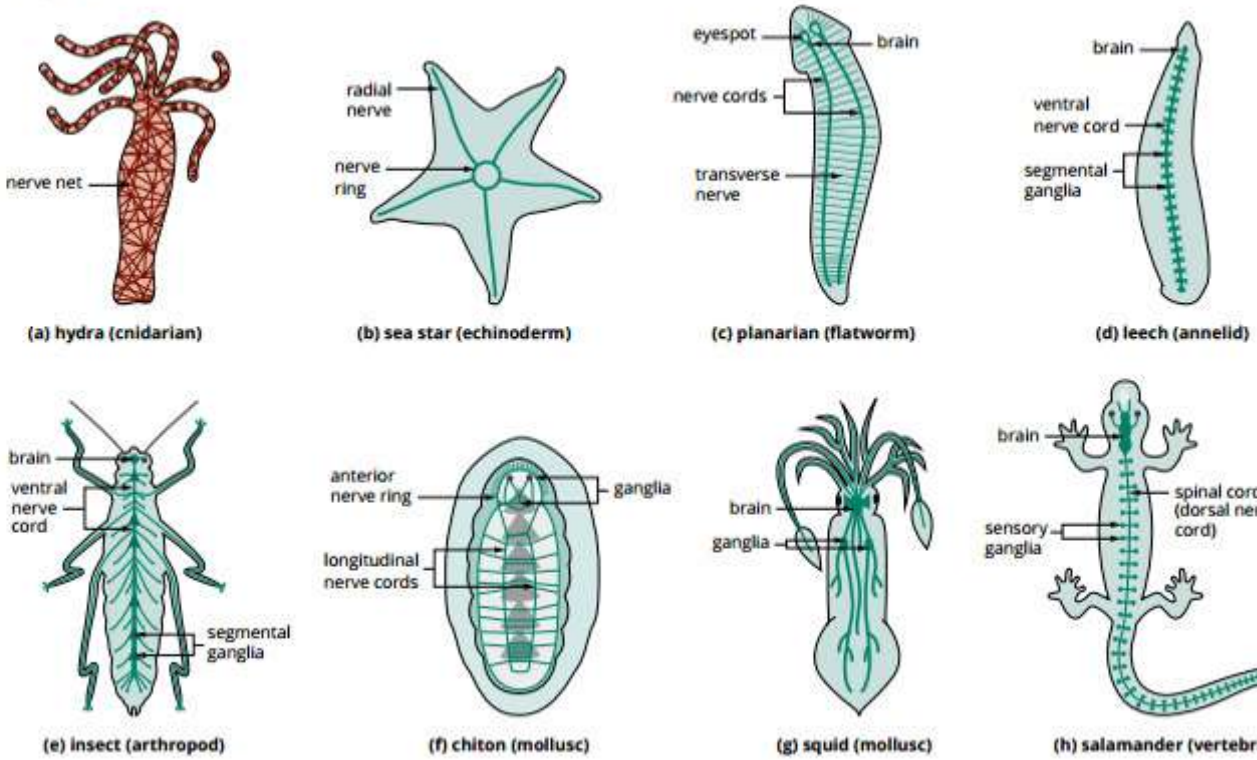


FIGURE 5.2.11 Nervous systems range from simple nerve nets in cnidarians (sea jellies and anemones) and sea stars, to complex networks of nerves connected to a brain in other invertebrates, and a brain and spinal cord in vertebrates.

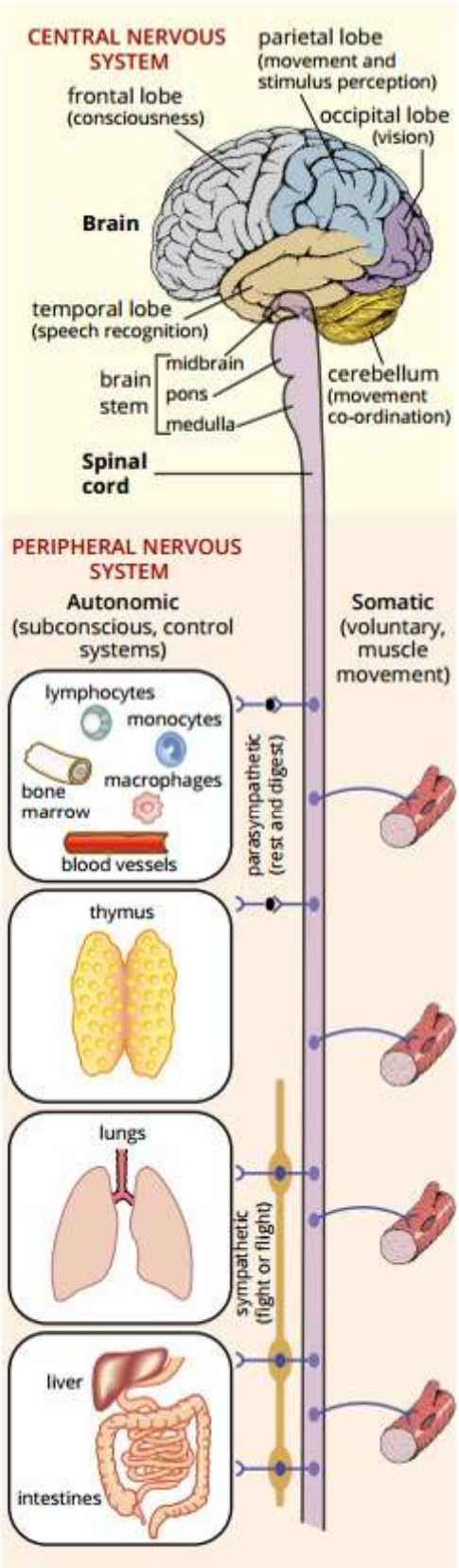


FIGURE 5.2.12 The nervous system of vertebrates consists of a brain and a spinal cord. The central nervous system (CNS) is made up of the brain and spinal cord, while the peripheral nervous system (PNS) is a network of nerves that branch throughout the body and send signals to and from the CNS.

In nervous systems, nerve cells connect to form pathways between receptor cells and responsive organs, sometimes via a central organ such as the brain or spinal cord. For example, when sensory cells detect an environmental disturbance, a signal is generated that passes as an electrical message along two or more neurons to reach particular effector cells, such as muscle or gland. Chemical transmitters communicate from sensory cell to nerve cell, between nerve cells, and from nerve cell to the effector cell that produces the response.

Neural response pathways are highly specific. Receptor cells are sensitive to specific environmental disturbances: the 'wiring' of neuronal pathways is direct, and to respond, effector cells must possess specific receptors. Because of the directness of the pathway, and the speed of conduction along nerve fibres, control by nerves is usually extremely rapid and short in duration, and the response is precisely located.

Nervous responses require more energy than hormonal responses. Hormones are carried to their target cells in the circulatory system, while in nervous systems, the passage of signals along nerve axons requires considerable energy to re-establish the balance of ions across the axon membrane after each signal.

Neurons establish steep concentration gradients of ions across their cell membranes to enable an electrical impulse or action potential to occur. Establishing these gradients uses active transport, which requires a large amount of energy. Therefore neurons need many mitochondria and a large supply of glucose.

In simple animals, such as sea jellies and hydra, the nervous system is a network of nerves that link sensory receptors in the skin to muscle cells (Figure 5.2.11). The evolution of animals led to the development of organised nervous systems composed of coordinating groups of nerve cells connected to pathways of sensory (from receptor) and motor (to muscle or gland) nerve fibres.

More complex animals have nerve cells grouped together to form one or more structures similar to small 'brains' (known as ganglia), which can receive and coordinate information from sensory cells in all parts of the body in order to produce an appropriate response.

As animals evolved, locomotion became more efficient, with movement always in the direction of one end of the organism. It was therefore an advantage to have sense organs concentrated at the front (anterior) end because that end is the first to meet the new environment, and to have the coordinating brain close to these sensory receptors—in other words, to have a head. Bundles of nerve fibres pass from the anterior brain to innervate (form a functional connection with) muscle and sensory cells in more distant parts of the body (Figure 5.2.9). In vertebrates, coordination occurs largely in the brain and spinal cord, which are known as the **central nervous system** (CNS). Information is relayed to and from the CNS by neurons lying outside the CNS, which make up the **peripheral nervous system** (PNS).

The CNS is made up of the brain and, in vertebrates, the spinal cord. This system has a major role in controlling the activity of the other organs. It does this by communicating with the peripheral nervous system. The PNS is made up of the system of nerves which branch throughout the body to and from the receptors and effectors. These are nerves that originate in the CNS and connect to all body parts, along with nerves that originate in the organs and connect to the CNS (Figure 5.2.12).

Reflex responses

The ability to detect and quickly respond to changes in the internal and external environments is fundamental to the survival of all animals. Some responses to stimuli happen very quickly. If you put your hand on a hot stove or tread on a pin, your body will react in a rapid and coordinated way to move away from the painful stimulus. Pain is what you feel as a result of excessive stimulation of sensory receptors in the skin. But, before you are aware of the pain, you have pulled your foot or hand away. This is an example of a rapid, unconscious response called a reflex. This kind of reflex protects the body from further injury. The contraction and dilation of the iris described previously (Figure 5.2.2) is also a reflex response.

Stimulation of the sensory receptors in the skin sends a message along nerves to the spinal cord, where the message is passed on to nerves that stimulate the muscles involved in withdrawing your hand (see Figure 5.2.13) or pulling away your foot. At the same time, other nerves in the spinal cord carry the message up to your brain and you become aware of the pain.

A reflex is the simplest type of nervous response in an animal, and it may involve just two or three cells. A sensory neuron detects a change and sends a signal, perhaps via another neuron, to an effector cell, which produces a response. The response is unconscious and automatic; it is not modified because of information received from other parts of the body. The nerve net of a sea jelly produces only reflex responses. Reflex responses are also important in highly complex animals, such as vertebrates, because they occur rapidly and unconsciously—for example, defensive reactions and changes in posture.

The knee-jerk (stretch) reflex is an example of the simplest form of reflex in mammals, and involves only two neurons. It is known as a monosynaptic reflex. Most reflexes are polysynaptic and involve one or more additional neurons called **interneurons** (see Figure 5.2.14) in the central nervous system, between the sensory and motor nerves, as in the withdrawal reflex.

If you concentrate, you can increase or decrease your knee-jerk response. You can also repress the reflex that would cause you to remove your hand from a painful or uncomfortable stimulus. This indicates that there is a connection from the brain that can consciously override the automatic response. You can consciously send signals down the spinal cord to prevent the reflex stimulation of muscles by the sensory nerves. For example, most people do not pull away when being given an injection.

Reflexes are also involved in homeostatic regulation of systems such as the circulatory system. For example, the baroreceptor–heart rate reflex helps maintain blood pressure in mammals. An increase in blood pressure increases the stretch on baroreceptors in major arteries, causing an increase in impulse activity from these sensory neurons. This leads to a reflex decrease in heart rate and a consequent decrease in blood pressure.

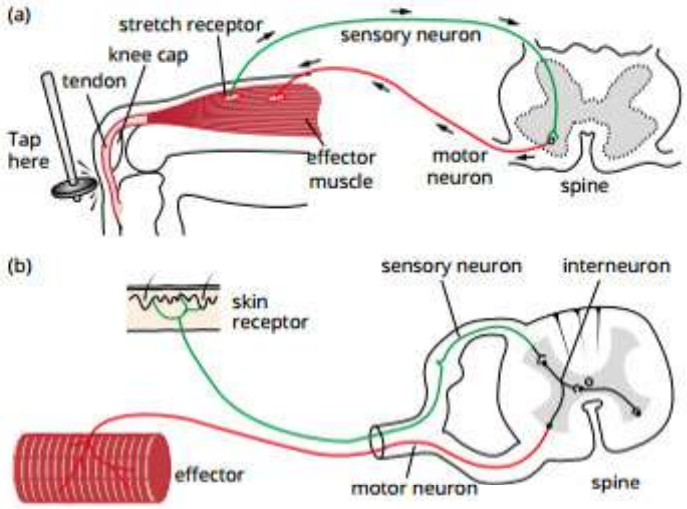


FIGURE 5.2.14 (a) The knee-jerk response is an example of a monosynaptic reflex. It is used most frequently by doctors to detect potential damage to motor areas of the central nervous system. (b) The withdrawal reflex, triggered by pain receptors in the skin, involves interneurons.

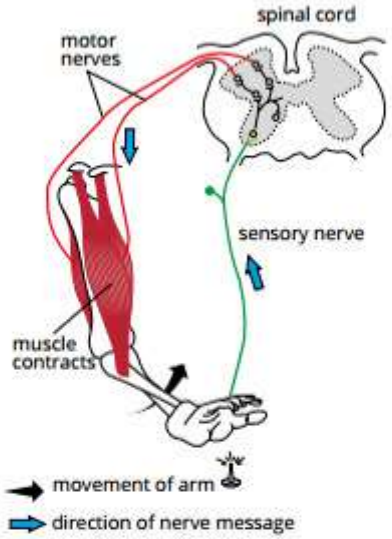


FIGURE 5.2.13 The pathway involved in the reflex withdrawal of the hand in response to a painful stimulus.

BIOFILE

Maintaining posture

Reflex muscular responses are occurring all the time. The unconscious maintenance of our posture is the response to a lot of information from ears, eyes, joints and muscles. Standing on one foot for a while can be tricky, but try it with your eyes shut and you will realise the importance of visual information.

Stretch receptors in muscles and tendons provide information about the length of muscles and the precise positions of joints (proprioceptors). This information is used in the unconscious maintenance of posture. Imagine you are standing at attention and then slowly sway forward. This stretches your calf muscles a little and stimulates calf muscle stretch receptors. When these receptors are gently stretched, they send signals back to the spinal cord and are passed on to nerves that cause the calf muscle to contract a little more. This pulls you slightly backwards, towards a position of balance. Tiny reflex adjustments like this are occurring all the time in the muscles that control posture.

An interneuron is a neuron that transmits information from one neuron to another.

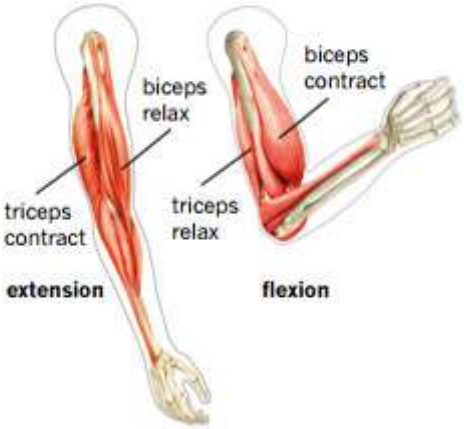


FIGURE 5.2.15 Extension (straightening) of the arm involves the biceps muscle relaxing and the triceps muscle contracting. The opposite action of flexion (bending) of the arm at the elbow joint involves the biceps muscle contracting, while the triceps muscle relaxes.

Interneurons and integration

When interneurons are added to a pathway, the opportunity for coordination and integration increases. Consider, for example, the movements of joints that operate by the action of opposing sets of muscles: one set causes flexion (bending), the other causes extension (straightening). Your elbow is flexed by the action of the biceps muscle, and extended by the triceps muscle (Figure 5.2.15). When a muscle is stimulated to contract, such as in a reflex response, interneurons in the spinal cord also carry a message inhibiting the contraction of the opposing muscle. This prevents, for example, both the biceps and triceps from contracting at the same time, which would put the elbow under severe strain.

Many reflexes need to be even more complex. There is a withdrawal reflex of the leg similar to the withdrawal reflex of the hand in response to pain (Figure 5.2.13). If you tread on a nail, however, you cannot simply withdraw your foot; if you did, you would fall over. You must first shift your weight onto the other foot. In this situation, interneurons also carry instructions to the muscles of the opposite leg, making it brace to take your weight as you lift the painful foot.

At a more complex level, increased numbers of interneurons in the nervous system provide more opportunity for synapses between neurons, thus allowing increased integration of information received from all parts of the body. In fact, 97% of human neurons are interneurons.

BIOFILE

Fight or flight?

When you get a fright or experience excessive stress, your body sets off a series of mechanisms to prepare you to cope with the threat. This is called the 'fight or flight' response. It is a primitive, automatic response that enables your body to act quickly in dangerous situations. Fortunately, modern humans rarely find themselves in life threatening situations, however this automatic response can't always distinguish between real and perceived threats.

When your body perceives a threat, your hypothalamus activates both the sympathetic nervous system and the adrenal-cortical system. The sympathetic nervous system puts your body into alert mode and sends a rapid signal to the adrenal cortex, which releases the stress hormones epinephrine (adrenaline) and norepinephrine (noradrenaline). These hormones, along with dozens of others, circulate through the body, triggering different responses in different organs: your heart beats faster, breathing becomes rapid, muscles tense up, non-essential systems (e.g. the digestive system) slow down, pupils dilate to let more light in and energy release in the form of glucose increases. When the threat is perceived to be so great that your brain is overwhelmed, you might not be able to respond. This is what someone is experiencing when they have stage fright.

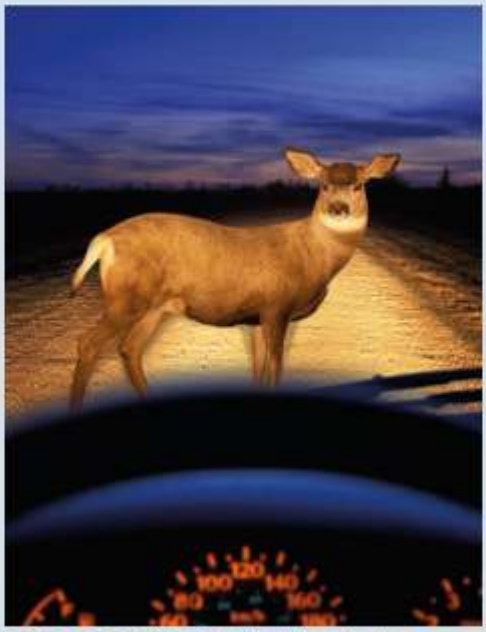


FIGURE 5.2.16 Animals often 'freeze' rather than flee when confronted by an oncoming car's headlights. This is a response to being overwhelmed and confused by the blinding lights.

Processing stimuli

After a stimulus has been detected by a receptor, a message is sent along the axon of the receptor cell to the processing centre of the nervous system. In complex animals, this processing centre is the CNS (brain and spinal cord). Different regions of the brain are associated with particular functions:

- The cerebral cortex (cerebrum) has areas associated with motor activity, sensory input, speech, sight and hearing.
- The hypothalamus receives information relating to the wellbeing of the body, and functions in maintaining homeostasis.
- The cerebellum is involved in the coordination of muscular activity, including posture, balance and movement.
- The brainstem has centres associated with the control of the heart, blood vessels and lung ventilation.

As well as coordinating information from all parts of the body to produce appropriate responses, the brain stores information so that responses can take into account past experiences and learned information (memories).

The PNS includes sensory nerves, which carry information towards the CNS, and motor nerves, which carry signals to effector organs such as muscles and glands. The motor component of the PNS can also be subdivided into somatic (voluntary) and autonomic (involuntary) systems. The voluntary nervous system involves functions over which you have voluntary control, such as movement of the body by skeletal muscles.

The **autonomic nervous system** (Figure 5.2.17) includes nerves involved in unconscious responses, such as constriction of pupils, secretion from glands and heart rate changes. It conveys signals to smooth muscle (internal organs), heart muscle and glandular tissues, and regulates the activities of the digestive, cardiovascular, excretory, respiratory and endocrine systems (Table 5.2.2, page 238).

The autonomic nervous system consists of two major subdivisions (sympathetic and parasympathetic) that work in similar but often opposite ways, as well as the **enteric nervous system**. In general, the **sympathetic division** increases energy use and prepares the body for action in emergency situations by increasing the heart and metabolic rate (the so-called 'fight or flight' response). The **parasympathetic division** enhances activities that conserve energy, such as digestion and slowing the heart rate. The enteric nervous system is the third part of the autonomic nervous system. It is an extensive network of nerve cells (and reflexes) within the wall of the gut that coordinate the functions of the gut.

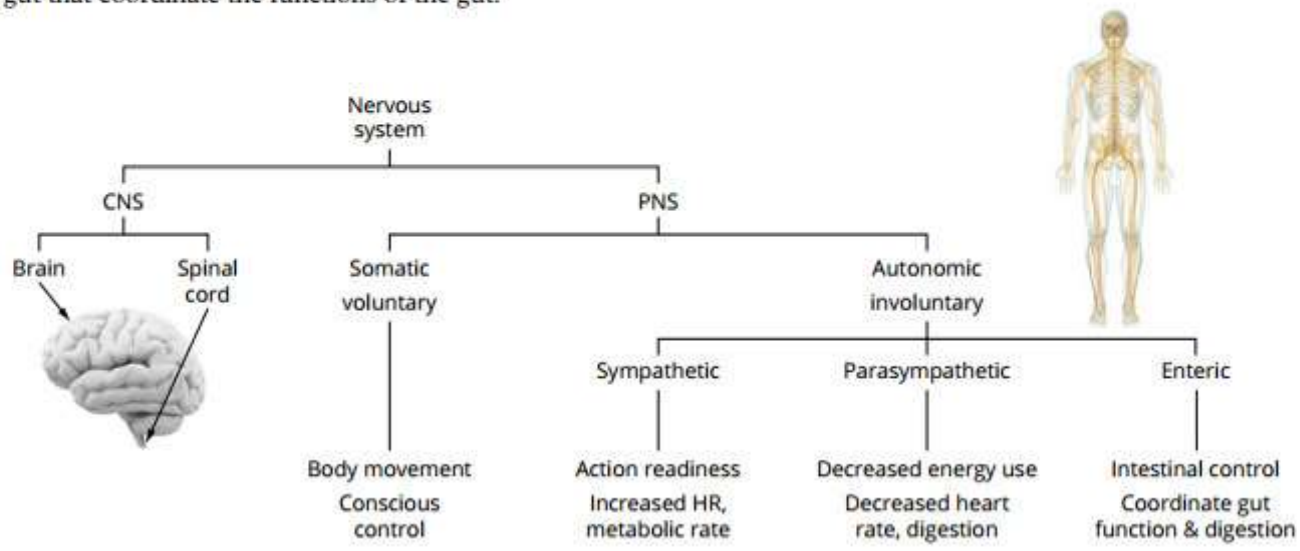


FIGURE 5.2.17 Components of the central nervous system (CNS) and peripheral nervous system (PNS).

The correct balance of activity in different divisions of the nervous system, along with their interactions with the endocrine system, are central to maintaining homeostasis.

System/role	Function/description
cardiovascular system	Controls the rate and strength of the heartbeat and the distribution of blood to different organs by changing the diameters of arteries.
digestive system	Controls mixing and movement of food through the gut and secretion of digestive enzymes in various regions of the gut.
respiratory system	Controls the diameter of major airways of lungs and the secretion of mucus over respiratory surfaces.
excretory system	Promotes emptying of bladder and controls rate of production of urine by the kidneys.
reproductive system	Controls contraction of various parts of the reproductive tract in males and females, and thus the passage of eggs, sperm and embryos.
metabolic regulation	Controls the formation and release of hormones affecting overall metabolism.
temperature regulation	Controls cutaneous blood flow and sweating.
eye function	Controls the diameter of the pupil to regulate incoming light, secretion of tears and focusing of the lens.

TABLE 5.2.2 Roles of the autonomic nervous system.

Detecting external and internal stimuli

Animals have sensory receptors to detect aspects of their environment that may affect their ability to survive and reproduce. The types of sensory receptors present, and their sensitivity, differ substantially between animals, and are related to the way they have adapted to their environments. For example, a wombat has less visual acuity for distinguishing small objects than an eagle, dogs use chemical scents much more than humans, and some moths have chemoreceptors that can detect a single molecule of pheromone. Some animals respond to different parts of the energy spectrum. For example, snakes can detect infrared radiation, bees see ultraviolet light and platypuses can detect weak electric currents.

In humans, the five senses (vision, hearing, taste, smell and touch) are perceived through sense organs (eyes, ears, tongue, nose and skin) that collect and process sensory information. Receptors that detect external stimuli are known as **exteroreceptors**. These are usually located close to the surface of the body and detect stimuli such as pain and pressure. Some receptors detect internal states, such as blood pressure and blood chemistry (e.g. oxygen and carbon dioxide levels), and these are known as **interoreceptors** or visceral receptors. From a functional point of view, the types of sensory receptors involved in these senses can be classified as **photoreceptors** (vision), **chemoreceptors** (taste, smell, communication), **mechanoreceptors** (hearing, balance, pressure, touch) and **thermoreceptors** (temperature) (Table 5.2.3).

Receptor type	Examples	Received stimuli
mechanoreceptors	pressure (touch) receptors:	
	skin (see Figure 5.2.23): • Meissner corpuscle	light touch
	• Pacinian corpuscle	heavy touch
	proprioreceptors:	
	• muscle spindles	movement, position of the body
	• Golgi cells	gravity
	• joint receptors	movement with ligaments
	labyrinth in the vertebrate ear:	
	• sacculus and utriculus	gravity and linear acceleration
	• semicircular canals	angular acceleration
	• ciliated cells in the cochlear duct	sound waves
chemoreceptors	taste buds, olfactory epithelium	specific chemical compounds
thermoreceptors	• thermoreceptors in blood-sucking insects and ticks • pit organs in pit vipers • nerve endings and receptors in the skin and tongue of many animals	heat
electroreceptors	organs in the skin of some fish	electric currents in water
photoreceptors	• eyespots • ommatidia in arthropods • rods and cones in the retina of the vertebrate eye	light energy

TABLE 5.2.3 Receptor types and their functions in complex animals.

EXTENSION

Sensory receptors

Photoreceptors

Vision

Photoreceptor cells that contain light-sensitive pigments appeared very early in animal evolution. Light interacts with the pigment and produces an electrical signal in a sensory nerve. The most primitive type of eye consists of a small patch of light-sensitive receptors that acts as a light-detecting organ and cannot form images (for example the planarian eye-spot shown in Figure 5.2.18).

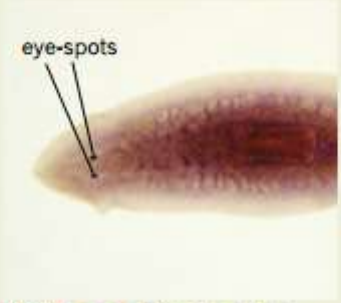


FIGURE 5.2.18 Planarians have simple light-sensitive receptors, called eye-spots, that help them detect and move away from light.

Optical systems that focus light to form an image arose much later in evolution and in fewer groups of animals. Because it has more photoreceptors, an eye can detect greater variation in light intensity and therefore form more complex images. There are two types of eyes:

- Simple eyes are single-chambered eyes (Figures 5.2.19 and 5.2.20). Vertebrate eyes, including our own, use a lens, a cornea, or both, to form an image on the photoreceptors of the retina. A camera is constructed on the same principle.
- Compound eyes in insects consist of many ommatidia, which form images very different from what vertebrates see (Figures 5.2.19c,d and 5.2.20).

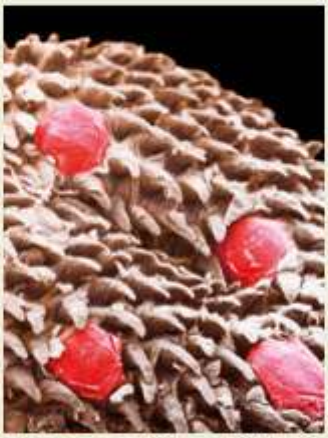


FIGURE 5.2.21 Coloured SEM of the surface of the human tongue. The scale-like projections are filiform papillae, which sense pressure. The red areas are fungiform papillae, which contain the taste buds.

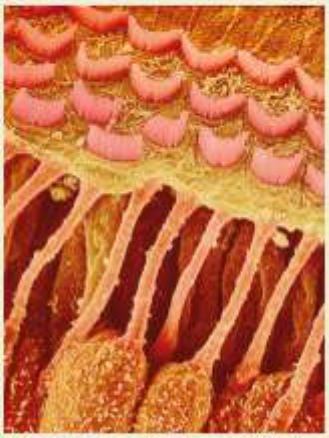


FIGURE 5.2.22 Coloured SEM of sensory hair cells in the cochlea. The inner ear converts sound waves into nerve impulses by stimulation of the stereocilia (the pink, crescent-shaped 'brushes') at the ends of the hair cells.

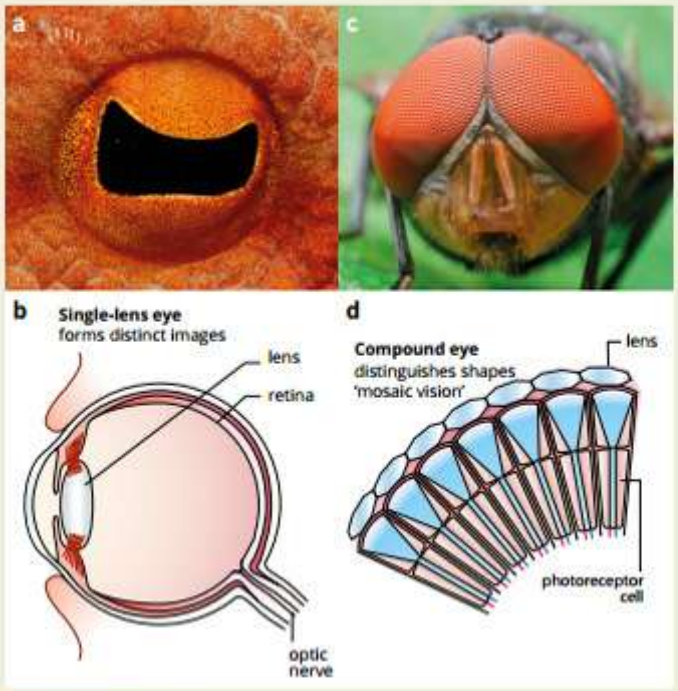


FIGURE 5.2.19 (a), (b) A single-lens eye, in this case an octopus eye, has a focusing lens and a retina that gives better resolution than insect eyes. (c), (d) The compound eye of an insect has thousands of individual detectors, each like a small eye.

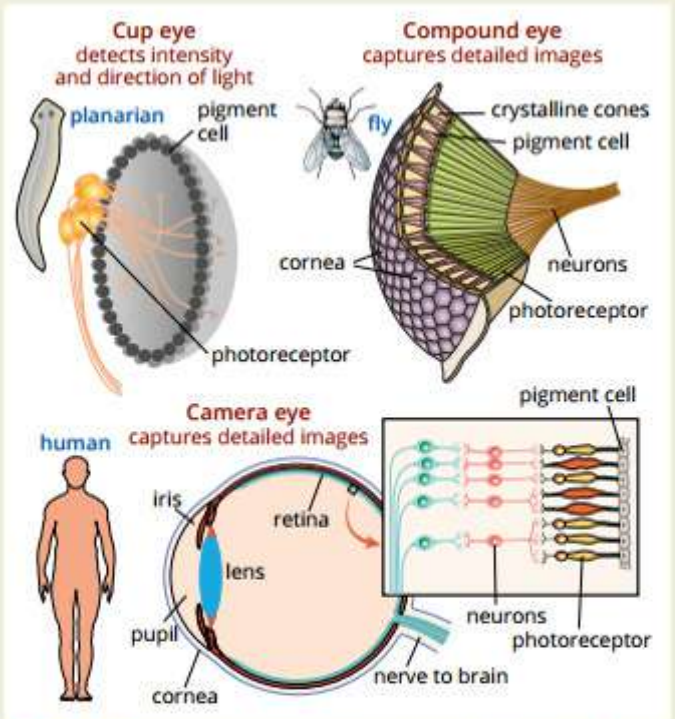


FIGURE 5.2.20 The simplest form of an eye is found in planarians and is capable of detecting the intensity and direction of light. Compound eyes and single-lens eyes are more complex, with a greater number of photoreceptors and connections to muscles and neurons. These structures allow the eye to detect greater variations in light intensity and capture detailed images.

Chemoreceptors

Taste and smell

Chemoreceptors are cells sensitive to different chemicals. They may be grouped inside structures that maximise the probability of detection. Terrestrial animals have specialised organs for olfaction (smell) to detect airborne chemicals, and taste to detect chemicals in food and drink (see Figure 5.2.21). Many animals also have receptors for specific chemicals emitted by prey or predators, or pheromone chemicals released by others of their species signalling sexual readiness.

Mechanoreceptors

Hearing

Sound travels as vibrations through air, water and solids. Animals detect sound using mechanoreceptors, which are sensory neurons that can detect minute vibrations. Vibration-sensitive neurons may be attached to larger vibrating structures that select and filter, and sometimes amplify the frequencies that are important to the animal. In human ears, vibrations are amplified by a system of bony levers (ossicles) and are then transmitted to a fluid-filled canal (cochlea) with sensory hair cells that have projections on the ends called stereocilia (Figure 5.2.22). Vibrations entering the inner ear displace the fluid that surrounds the stereocilia, causing them to bend, generating nerve impulses that travel to the brain along the auditory nerve. The inner ear can transmit information about the volume and pitch of a sound.

Touch and pressure

Cutaneous mechanoreceptors detect external stimuli, including pressure and touch (Figure 5.2.23). A range of receptors detect internal mechanical stimuli, including joint position, muscle tension, and tension in the walls of organs such as the lungs and stomach. Examples of mechanoreceptors are stretch receptors, which aid in proprioception (the unconscious perception of body positioning and movement). When you stand on one foot, the slight movements you feel in your ankles are a result of your body correcting its position because of the stimuli detected by these stretch receptors.

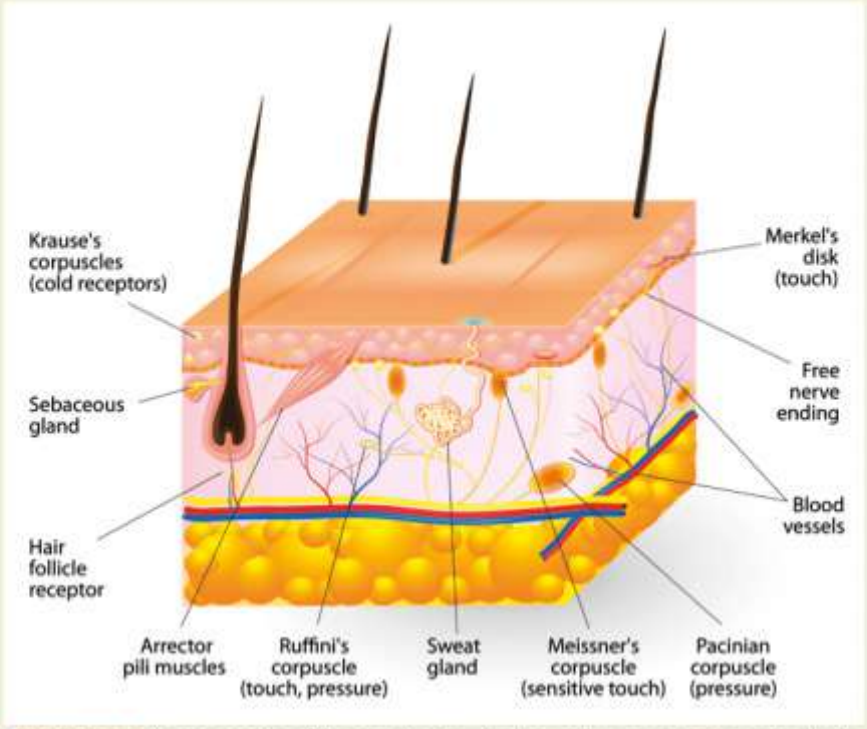


FIGURE 5.2.23 A cross-section of human skin showing the various receptors for pain, touch, pressure and temperature.

Pain

All animals with nervous systems avoid encounters with harmful external stimuli. It is not clear how complex a nervous system must be for an animal to experience something like the pain felt by humans. Some vertebrates can vocalise in response to certain stimuli that humans interpret as painful, and certainly behave as if their experience is similar. Although it is difficult to measure pain, most non-human animals have the same mechanisms of pain detection, similar pain-processing areas in the brain, and show similar pain-response behaviours as humans, indicating that their physiological experience of pain is likely to be similar to that of humans. The process of pain transmission is called nociception, and pain receptors (nociceptors) are found in most body tissues.

Thermoreceptors

Temperature

Thermoreceptors detect changes in heat energy (Figure 5.2.23). Thermoreception is complex and involves the detection of heat energy as well as changes in temperature. Different parts of the body have more receptors than others. The hand, for example has more thermoreceptors than the leg, which means that it is more sensitive to temperature changes.

5.2 Review

SUMMARY

Homeostasis

- Homeostasis is the maintenance of variables in a system within certain limits.
- Regulation in animals involves internal communication by the endocrine (hormone) and nervous systems to integrate and coordinate the activities of cells, tissues and organ systems.
- In both endocrine and nervous systems, signals are passed from one cell to the next by chemical communication.
- The nervous system provides rapid responses to produce efficient coordinated movement.

Feedback systems

- Hormone and nervous systems play important roles in negative feedback mechanisms that promote homeostasis in animals.
- Negative feedback loops are stimulus–response mechanisms that respond to changes in the body by adjusting variables back to their original or optimal state, reversing the direction of the stimulus.
- Most feedback loops are negative.
- Positive feedback loops are the opposite of negative feedback loops. They promote a process rather than reversing the effect of the stimulus.

The endocrine system

- Hormones are substances that carry messages between the cells of an organism to regulate the growth or activity of specific target cells.
- Hormones modify the activity of certain cells, called target cells as a result of interaction with specific receptors.
- Hormones are specific, effective in low concentrations and generally slower and more indirect than nervous responses.
- Because they are effective at low concentrations, and target cells have specific receptors, hormones can affect particular cells in widely separated tissues.
- Complex animals have endocrine glands (e.g. thyroid glands, gonads, and the anterior pituitary gland) that typically release hormones directly into the circulatory system.
- In vertebrates, the pituitary gland has a pivotal role in overall endocrine regulation. The pineal gland is involved in many biorhythms.

The nervous system

- The nervous system involves a more direct pathway of communication than hormonal responses. Control by nerves is generally rapid, short in duration, and precisely located.
- Nervous responses require more energy than hormonal responses.
- Highly organised nervous systems have a central coordinating group of neurons (CNS—brain and spinal cord), and peripheral pathways of sensory and motor nerve fibres (PNS).
- A rapid unconscious nervous response is called a reflex.
- The simplest type of nervous response in a mammal, a monosynaptic reflex, involves just two cells.
- More complex circuits that include interneurons enable more control.
- The brain has four main regions which all have specific functions:
  - cerebral cortex
  - hypothalamus
  - cerebellum
  - brain stem.
- The peripheral nervous system is composed of the somatic system and the autonomic (sympathetic, parasympathetic and enteric divisions) systems.
- Sensory receptors, often grouped into sense organs, monitor conditions in an animal's internal and external environment and provide information that enhances the animal's ability to survive and reproduce.
- The neuron is the functional unit of the nervous system and its basic structure and function are very similar across all groups of animals.
- Neurons are excitable cells. The three basic steps involved in their function are:
  - generation of an action potential
  - conduction of the action potential along axons
  - chemical transmission to another cell across a synapse.

KEY QUESTIONS

1 What is homeostasis and why is it important?

2 How do negative feedback loops function? Explain using an example.

3 Which two systems are the most important in regulating the internal environment of animals?

4 What are the two main types of hormones? Give an example of each and describe how they interact with cells.

5 Describe the two main parts of the vertebrate nervous system, and state the primary function of each part.

6 Which type of nervous system response protects the body from further pain and injury?

7 Complete the table below by placing each of the following stimuli next to the receptor that it responds to.

body position, temperature, internal stimulus, electrical current, touch and pressure, chemical stimulus, external stimulus, blood pressure

Receptor	Stimulus
baroreceptor	
chemoreceptor	
electroreceptor	
exteroreceptor	
interoreceptor	
mechanoreceptor	
proprioreceptor	
thermoreceptor	

8 Explain how hormones that circulate throughout the blood can act only on a specific type of target cell.

9 Name the types of neurons involved in a simple monosynaptic reflex, and outline their function.

10 Why is it beneficial for the neural circuit entering a body joint to contain interneurons?

11 Which section of the peripheral nervous system—somatic or autonomic—is involved in unconscious control of internal organs?

5.3 Homeostatic mechanisms in humans

FIGURE 5.3.1 Sweating results in evaporative cooling and is one of the human body's homeostatic mechanisms to regulate body temperature.

Metabolism in humans is controlled by a number of complex homeostatic mechanisms, as outlined in section 5.2. These regulatory mechanisms are essential for the maintenance and survival of organisms (Figure 5.3.1). Temperature, blood glucose and water balance are some of the most important factors that are regulated by homeostatic mechanisms and these will be explored in detail in this section.

THERMOREGULATION

Regulation of body temperature in humans involves a complex negative feedback pathway with several sensory inputs and many effector responses that act together to maintain a stable body temperature. The control centre for measuring the body temperature set-point (37 °C) is in the hypothalamus. A change in the temperature of the hypothalamus initiates regulatory responses that can reduce heat loss or initiate heat production or heat exchange (see Figure 5.3.2).

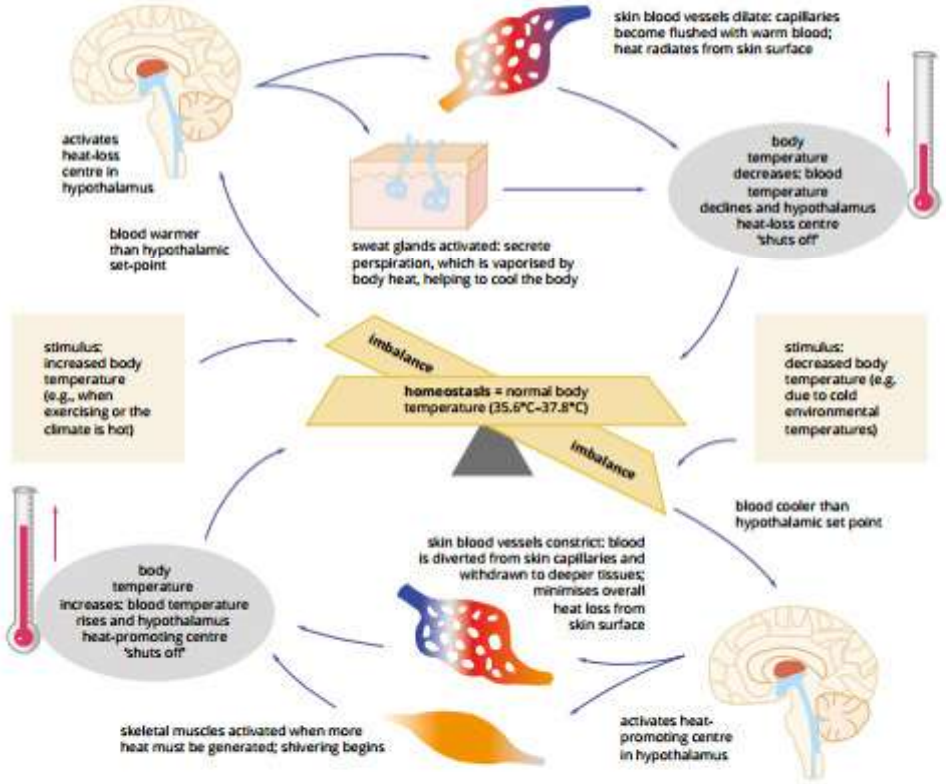


FIGURE 5.3.2 Thermoregulation in humans involves a range of regulatory mechanisms that function to maintain thermal homeostasis (normal body temperature) for optimal functioning of the organism.

Detecting temperature change

Regulation of temperature in humans is an example of the way different sensory receptors work together to produce an integrated response. Arterial blood has the most constant temperature. The relatively constant temperature of many other parts of the body indicates that they are well-supplied with arterial blood.

In **endotherms**, a group of temperature-sensitive cells in the hypothalamus act as misalignment detectors, triggering homeostatic responses if blood temperature deviates from the optimal temperature range, or set-point. Lowering or raising the temperature of the hypothalamus initiates regulatory changes in heat production or heat exchange.

Temperature receptors are also found in the skin. A decrease in environmental temperature detected by these receptors will initiate regulatory responses such as decreased blood flow to the skin to reduce heat loss, and behavioural changes such as moving into a warmer or more sheltered environment. These responses take place long before there has been any change in the internal temperature of the body. Skin temperature receptors act as disturbance detectors, detecting changes in the external environment and triggering responses before there is a change in core body temperature.

As the environmental temperature falls, disturbance detectors stimulate responses that reduce heat loss and increase heat production. The reverse occurs as environmental temperature increases. If the arterial temperature falls despite the regulatory responses that have been initiated, or if it rises because the responses made have been too effective, these changes will be detected by the misalignment receptors in the brain, which will fine-tune the temperature-regulating mechanisms.

The value of the disturbance detectors in the skin is to reduce fluctuations in arterial blood temperature, providing a more precise control around the set-point level than there would be if misalignment detectors (the brain's temperature receptors) alone were involved.

Heat loss

Organisms are constantly exchanging heat with their environment. This heat exchange occurs through four mechanisms (Figure 5.3.3):

- conduction—Occurs when the temperature of the organism and the environment are different. Heat exchange is a result of direct contact (e.g. a lizard basking on a warm rock).
- convection—Transmission of heat from a warmer region to a colder region, resulting from the movement of liquid or gas (e.g. heat moves from the inside of living organisms to the body surface by convection).
- radiation—Occurs all the time, without direct contact, regardless of temperature differences between the organism and their environment (e.g. heat radiating from dark coloured surfaces).
- evaporation—Heat loss by water evaporation. This occurs most rapidly when the air is hot and dry (e.g. sweating).

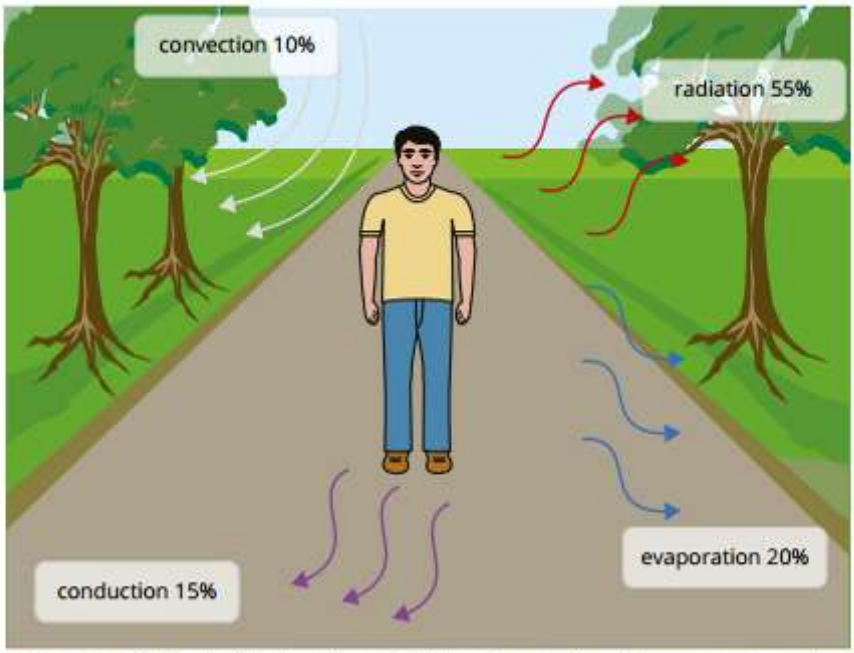


FIGURE 5.3.3 Methods of heat exchange with the environment and the average amount lost via each route in a human at rest.

BIOLOGY IN ACTION

Fever

A fever is an increase in your body temperature above the normal range or set-point and is a common symptom of an infection (Figure 5.3.4). Fever is one of your body's defences against infection, working to raise your body's internal temperature above the tolerable limits of the invading pathogens.

Pathogenic viruses and bacteria contain substances called **pyrogens**. An example of a pyrogen is the lipopolysaccharides found in some bacterial cell walls. Pyrogens induce fever by triggering your body's immune response, signalling the hypothalamus to increase your body's temperature.

The body responds to these signals from the hypothalamus by initiating a variety of warming activities in order to generate and retain heat. Peripheral blood vessels are constricted to reduce blood flow and heat loss through the skin. The reduction in blood flow to your skin makes you look pale and feel cold, even though your body is working to retain heat. If your body temperature is still too low, you might start shivering to generate more heat. Your body temperature will continue to increase until it reaches the new higher set-point of the hypothalamus. The fever is maintained until the invading organisms are eliminated and their effect on the hypothalamus ceases. The fever then makes you feel hot and flushed, and the mechanisms that were used to warm your body are reversed; blood vessels dilate, shivering stops and sweating works to cool your body back to the normal temperature range.

A body temperature above 41.5 °C is considered extremely high and requires immediate medical attention. Extreme fevers are known as hyperpyrexia and are most commonly caused by a haemorrhage inside the skull. Some infections and sepsis (blood infection) may also lead to hyperpyrexia.

FIGURE 5.3.4 (a) Thermal scanning cameras are used to monitor the skin temperature of passengers arriving at airports. Raised skin temperature can be an indicator of fever from illnesses such as influenza and Ebola. Such cameras have been used widely to screen for carriers of various epidemic influenzas, such as bird flu and swine flu, to prevent the global spread of the viruses. (b) Teams in airports around the world were equipped with thermal guns to measure the temperatures of travellers from Liberia, Sierra Leone and Guinea in an effort to prevent an Ebola pandemic in 2014.

Responding to cold

In section 5.1 you looked at examples of physiological, behavioural and structural adaptations of a variety of animals and plants to cold, such as hibernation, huddling and large ears.

In humans a number of nervous and endocrine responses occur rapidly to reduce heat loss from the body and increase heat production when the body becomes too cold.

The following voluntary and involuntary responses reduce heat loss from the human body:

- **vasoconstriction** (constriction of the blood vessels in the skin)—This reduces heat loss from the skin, as the amount of blood moving close to the exposed surface is reduced.

- **piloerection**—This is the constriction of the piloerector muscles around hair follicles ('goose bumps'), which increases the insulating effect of the hairs (Figure 5.3.5). This response has a minimal effect in humans but in animals with thick fur, the layer of trapped air increases significantly and reduces heat loss from the body.
- seeking shelter—Seeking a warmer place with less exposure to harsh winds and cold temperatures will maintain body heat for longer.
- changing body shape or decreasing surface area (e.g. curling up to make yourself small)—This reduces the area exposed to the cold and reduces the rate at which heat is lost from the skin.
- putting on more clothes—Clothes trap a layer of air (which is the best insulator). Some fabrics are better than others at trapping air and increasing insulation.

The following responses increase heat production in the human body:

- voluntary movement—During physical effort, the amount of heat produced by the muscles is increased (Table 5.3.1).
- **shivering thermogenesis**—The production of metabolic heat is increased through shivering. This involuntary movement of the muscles generates especially large amounts of heat. Shivering thermogenesis is stimulated by adrenaline.
- **non-shivering thermogenesis** in brown fat (brown adipose tissue or BAT)—Increased cellular activity in BAT, which is a tissue specialised for heat production, causes the tissues to warm up. The heat produced is carried to other parts of the body in the blood. Brown fat contains a huge number of mitochondria (which give it its brown colour), fat-metabolising enzymes and an extensive vascular network. Brown fat is capable of high rates of aerobic metabolism using a pathway, which breaks down fats to produce large amounts of heat, but little ATP.
- increasing **metabolism** (the rate of cellular respiration)—Metabolic processes in the internal organs are the main source of heat when the organism is at rest (Table 5.3.1). In humans, around 60% of the energy released during cellular respiration is transformed into thermal energy. In humans, the overall metabolic rate, and therefore the rate of heat production, is controlled by hormones.
- TRH (thyrotropin releasing hormone) secretion by the hypothalamus—TRH acts on the anterior pituitary to secrete TSH (thyroid stimulating hormone). As the name suggests, TSH acts on the thyroid gland to release thyroid hormones, tri-iodothyronine (T3) and thyroxine (T4) (Figure 5.3.6). T3 and T4 hormones regulate metabolic processes, increasing heat production and body temperature.

The amount of T3 and T4 in the bloodstream is regulated by the pituitary gland via a negative feedback loop; if there is too much or too little T3 or T4, the pituitary gland reduces or increases the amount of TSH it secretes. This mechanism allows a very delicate regulation of the level of thyroid hormones in the blood.

Organs	Participation in heat production at rest (%)	Participation in heat production during physical effort (%)
brain	16	2
internal organs	56	22
skeletal muscles	15	73
other organs	13	3

TABLE 5.3.1 Major sources of heat production in humans. Metabolic processes in the internal organs are the main source of heat when a person is at rest. During physical activity, the heat generated in the muscles increases.

FIGURE 5.3.5 A close-up of a human forearm with goose bumps. The contraction of blood vessels and small muscles (arrectores pilorum) that are attached to the base of each hair follicle pull the hair into an upright position. In this position the skin resembles plucked goose skin.

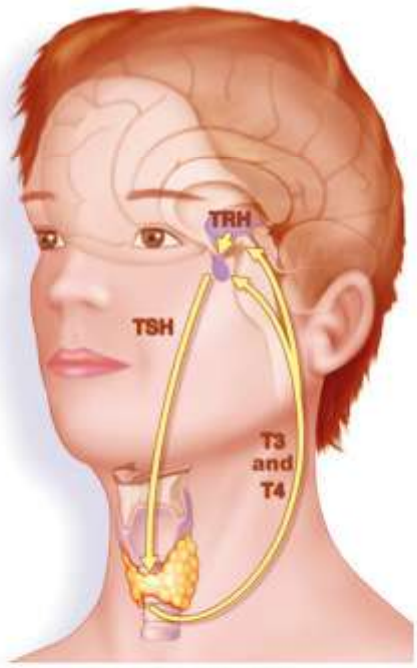


FIGURE 5.3.6 The thyroid is a gland that produces hormones that stimulate cellular respiration. The hypothalamus releases TRH, which stimulates the secretion of TSH by the pituitary gland, which in turn stimulates production of T3 and T4 hormones by the thyroid. The increase in cellular respiration creates thermal energy.

Responding to heat

Sweating

Evaporative cooling is a very effective way of losing heat energy from the body. A change of state from liquid to gas is an endothermic process; that is, it requires an input of energy. In evaporative cooling of the skin, this energy comes from your body, in the form of heat energy.

Humans have two types of sweat glands: eccrine glands and apocrine glands. The function of apocrine glands is thought to be mainly scent or pheromone production while the eccrine sweat glands function to control body temperature. These glands are distributed over much of the body and release sweat onto the skin surface via pores when your body temperature rises. These glands extend just below the surface of the dermis and secrete odourless sweat that is high in electrolytes and sodium. In humans, the rate of sweat secretion increases from almost zero in cold conditions to about 1.5 litres per hour in a hot environment. After about six weeks' acclimatisation to heat this can increase to 4 litres per hour, which means a much greater evaporative cooling capacity is possible.

Other responses

Some other voluntary and involuntary ways that your body responds to heat are as follows:

- Slowing the rate of cellular respiration in internal organs, which decreases heat generation thus decreasing body temperature.
- Covering your body with water (Figure 5.3.8). Spraying water on your skin produces the same evaporative cooling effect as sweating.
- Swimming or bathing in cool water, which causes heat loss through conduction across the skin. Evaporative cooling also occurs when you are out of the water and your skin is still wet.
- Vasodilation (dilation of the blood vessels in the skin). Dilation means more blood is sent to the extremities. Heat is lost to the environment by radiation and convection (especially if it is windy).
- Changing your body shape to increase its surface area, e.g. by standing with your arms and legs outstretched.
- Removing clothing, which reduces the insulating effect of clothing layers and allows heat to escape from the skin.
- Moving out of the sun into shade.
- Decreasing activity.

BIOFILE

Rosy cheeks

Children often have rosy cheeks in cold weather. This is a result of increased blood flow to the cold tissues following **vasodilation** (opening of the blood vessels). Cold-induced vasodilation functions to warm parts of the body that have been exposed to the cold. By increasing the blood to the exposed area, the risk of injury from extreme cold is reduced. As vasodilation allows heat to escape the body, it can be maintained only for short periods in cold conditions. If the body does not warm up after a while, vasoconstriction occurs to minimise heat loss.

FIGURE 5.3.7 Rosy cheeks from exposure to cold are caused by the dilation of blood vessels (vasodilation). Vasodilation increases blood flow to exposed skin to counteract the cold.

BIOFILE

Apocrine glands

The apocrine glands are associated with hair follicles and are mainly in the armpits and groin. These glands extend deep into the dermis and secrete proteins and fats into canals of the hair follicles. The sweat secreted by apocrine glands is usually thicker than that secreted by the eccrine glands, and is the source of 'body odour'.

FIGURE 5.3.8 Long-distance runners spray water on their skin to take advantage of evaporative cooling. This enables their bodies to work at maximum efficiency, and helps to prevent them from becoming dangerously hot.

BIOLOGY IN ACTION

Heat stress and sweating: a double-edged sword

By Professor Mark Febbraio

Humans are different from most other mammals in terms of how they deal with heat stress. When we exercise, only about 25% of chemical energy is transferred to mechanical work with the rest transferred to heat. In order to lose heat, humans sweat.

Blood flow is diverted to the skin, where it gives up the heat required for sweat to evaporate, and the blood then returns to the heart at a cooler temperature. While this is an efficient means of getting rid of excess body heat, it can cause problems, the major one being heat cramps. Extensive sweating can lead to large amounts of water loss and electrolyte (salt) deficits, particularly for sodium. When an athlete exercises in warm weather, the extensive and repeated sweating and the consequent sodium deficit can lead to dehydration, electrolyte imbalance and muscle fatigue. All of these factors contribute to heat cramps and reduce the ability of muscles to regulate their contractions.

One of the most famous athletes to suffer with heat cramps was the former world number one tennis player, Pat Rafter (Figure 5.3.9). In my laboratory we measured his sweat rates, body temperature and heart rates, and took blood and sweat samples on both the treadmill and tennis court. Rafter was most efficient in dissipating heat from his body because he was extremely fit and a profuse sweater. In fact his sweat rate was about 3.0 litres per hour when most adults sweat about 1.0 litre per hour. This was good because it kept his body temperature down, but along with the water that he was losing he also lost a huge amount of salt. His sweat sodium concentration was high and this led to a progressively reduced sodium concentration in the blood. To remedy this, Rafter had to drink large amounts of fluids with extra sodium during training and match play to combat the problem. In addition, while others should avoid salting their food because of the risks associated with hypertension, it was almost essential for Rafter, and excessive sweaters like him, to salt their meals. Sweating is a very efficient way of ridding the body of excess heat, but the fluid and electrolytes that are lost in sweat must be replaced.

FIGURE 5.3.9 (a) Former number one ranked tennis star, Pat Rafter, suffered from heat cramps for most of his playing career. His very high sweating rate caused him to lose huge amounts of salt. (b) Pat Rafter undergoes tests in the University of Melbourne's Exercise Physiology and Metabolism Laboratory, observed by Professor Mark Febbraio (front right).

Professor Febbraio is a former triathlete and a leading researcher in the field of metabolism. He is a Senior Principal Research Fellow of the National Health and Medical Research Council and is the head of the Diabetes and Metabolism Division at the Garvan Institute of Medical Research in Sydney. His expertise is keenly sought to develop optimal strategies for managing elite athletes.

CONTROL OF BLOOD GLUCOSE LEVEL

FIGURE 5.3.10 Blood glucose levels can be tested by pricking the finger and placing a small drop of blood on a piece of absorbent material, which is tested by an electronic device. The person pictured here has a BGL of 6.4 mmol/L.

Blood glucose level (BGL), sometimes called blood sugar level, is the concentration of glucose in your blood. This level is constantly changing in your body and is tightly regulated by homeostatic mechanisms. Glucose is the main source of energy for your body's cells. Eating carbohydrates and doing physical activity will change blood glucose levels throughout the day. The more carbohydrates you eat, the more insulin you will produce. Glucose is stored in the body in the form of a polymer called **glycogen**. When the body needs glucose, the glycogen is broken back down into usable glucose for cellular respiration, which is the energy-producing reaction in cells. If BGL is not maintained within its optimal range, **hyperglycaemia** (BGL too high) or **hypoglycaemia** (BGL too low) can develop, leading to a range of long-term health problems, such as diabetes (Figure 5.3.10).

Detecting blood glucose level

Cells in the pancreas detect changes in BGL. Blood glucose concentration is regulated so it remains within a range of about 3.5–8 mmol/L. A deviation from these levels in either direction will result in a response by clusters of specialised cells in the pancreas, called the islets of Langerhans (Figure 5.3.11). These cells detect blood glucose levels and release insulin and **glucagon** to maintain blood glucose levels within the normal range.

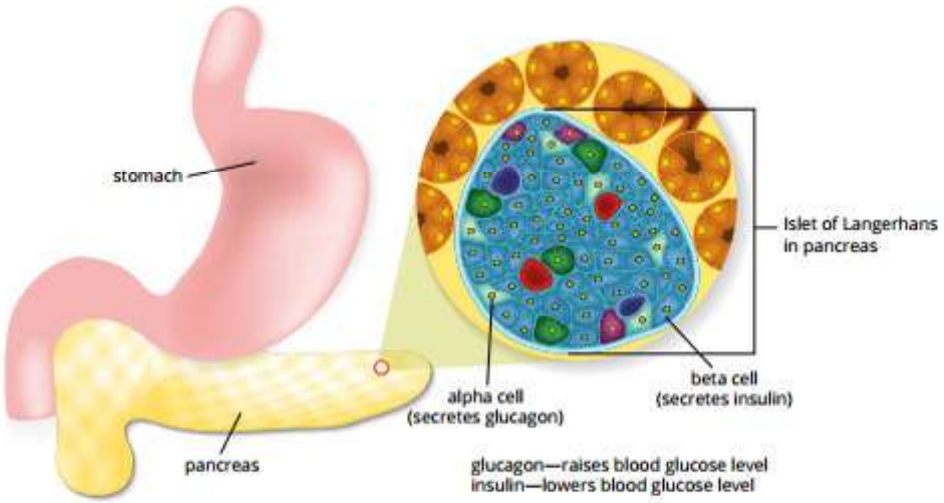


FIGURE 5.3.11 Groups of specialised cells in the pancreas, called the islets of Langerhans, detect blood glucose levels and secrete either insulin (from beta cells) or glucagon (from alpha cells) to maintain blood glucose levels within the normal range.

BIOFILE

Carbohydrates and blood glucose levels

Simple carbohydrates consist of only one or two sugar molecules (monosaccharides and disaccharides). Because of this they can be rapidly digested and absorbed, raising blood glucose levels quickly. Some sources of simple carbohydrates are table sugar, soft drinks and lollies. These foods provide a short burst of energy but contain very little nutrition.

Complex carbohydrates (polysaccharides) are starches made up of longer chains of sugars, and take longer to break down and absorb. Foods such as white bread and cakes contain refined starches, while unrefined starches are found in whole grain foods, such as brown rice and wholemeal bread, and starchy vegetables. Foods that contain unrefined complex carbohydrates provide a steady energy supply, minimising spikes in blood glucose levels, and also provide beneficial nutrients and fibre.

There are also glucose-sensing neurons in the hypothalamus in the brain. Scientists believe that these glucose-sensing neurons play a key role in food intake, thus helping to regulate blood glucose concentrations.

Responding to high blood glucose levels

When glucose levels rise above about 5 mmol/L, the islets of Langerhans in the pancreas release insulin (Figure 5.3.11). Insulin increases the conversion of glucose to glycogen, fats or fatty acids for storage in the liver and skeletal muscles. The overall effect of insulin is to lower BGL (see Figure 5.3.12).

Responding to low blood glucose levels

When glucose levels fall below about 5 mmol/L, the islets of Langerhans in the pancreas release glucagon (Figure 5.3.11). Glucagon is a hormone that stimulates the conversion of glycogen to glucose, which raises BGL (Figure 5.3.12). Adrenaline also raises BGL by its actions on fat cells and the liver.

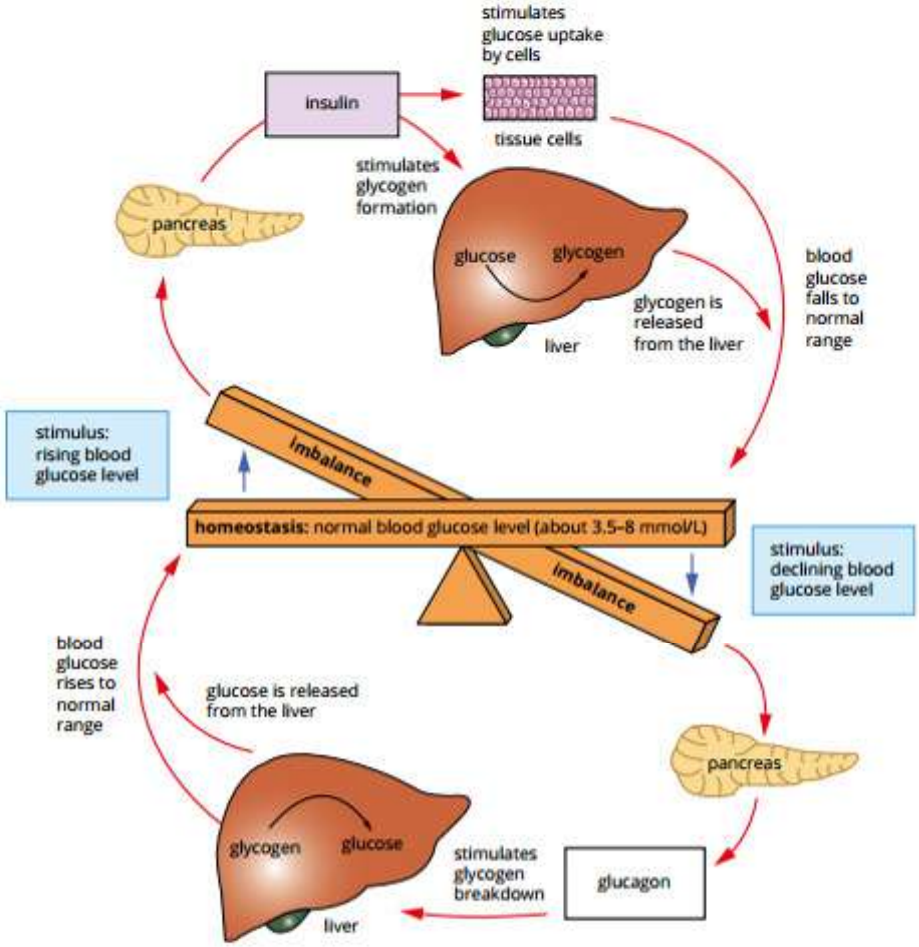


FIGURE 5.3.12 The regulation of blood glucose level (BGL) by insulin and glucagon. When BGL is too high, insulin is secreted by the beta cells in the pancreas. This stimulates glucose uptake and storage as glycogen in the liver, reducing BGL. When BGL is too low, glucagon is secreted by the alpha cells in the pancreas. This stimulates glycogen breakdown and the release of glucose from the liver, increasing BGL to within the normal range.

BIOFILE

Glycogen storage

It is often said that glycogen is synthesised and stored in the liver, but this is only partly true. Most glycogen is actually synthesised and stored in skeletal muscle cells. The human liver can store about 100 grams of glycogen, whereas skeletal muscle can store about 500 grams. When the glycogen-storing capacity of the body is full, excess glucose is stored mainly as triglycerides (fats).

OSMOREGULATION

Some animals maintain water balance simply by living in environments where fresh water is freely available. Others can regulate the composition of their internal environment, allowing them to live in drier or saltier environments.

Maintaining water balance is necessary to control salt concentrations. Salts form ions in solution, and cells require the concentrations of ions to be held within narrow limits for biochemical processes to occur efficiently (Figure 5.3.13). Some ions (such as the hydrogen carbonate ion) are also important for regulating the pH of body fluids, which must be at a suitable pH for enzymes and other molecules to function efficiently. Maintaining the correct concentrations of ions is achieved by regulating both water and salt balance.

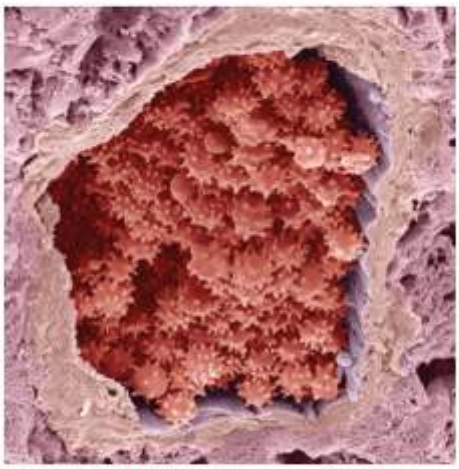


FIGURE 5.3.13 The maintenance of constant osmotic pressure in the blood is important because it prevents red cells from dehydrating or bursting. This SEM of a section through an arteriole shows crenate (wrinkled) red blood cells caused by dehydration, which distorts the red blood cell.

BIOFILE

Effects of dehydration

The effects of dehydration can range from mildly uncomfortable to life-threatening. The following table shows the typical symptoms of dehydration in humans. The progressively worsening symptoms are typical of those experienced by someone without sufficient water in a hot, dry environment, such as a person lost in a desert.

Percentage of water volume lost	Symptoms
0	no symptoms
1	thirsty but not uncomfortable
2	uncomfortably strong thirst
3	dry mouth, fatigue, stumbling, headache, irritability
4	strong fatigue, nausea, lack of concentration
5	decision-making and coordination strongly impaired, sleepiness
6	reduced ability to sweat, rapid, pounding heartbeat, tingling and numbness in fingers and toes
7	fever, confusion, dry skin, inability to stand
8	dizziness, laboured breathing, extreme fatigue
9	muscle spasms, delirium
10	blood circulation impaired, kidney failure
> 10	unconsciousness, likely general organ failure and death

TABLE 5.3.2 Progressive symptoms caused by dehydration.

Osmolality is a measure of the concentration of particles (such as sodium and chloride ions) that affect osmosis.

Water balance involves regulating the intake and loss of both water and salts. In organisms, net movement of water occurs as a result of **osmosis**, which is regulated by solute concentrations. Water moves across a semi-permeable membrane from regions of lower solute concentration (higher concentration of free water molecules) to regions of higher solute concentration (lower concentration of free water molecules).

The amount of water lost or gained throughout the day differs between individuals and depends on the amount of exercise, temperature, humidity, food and fluid intake. Urination rather than water intake is a better indicator of whether an individual has good water balance. A healthy person with adequate hydration would usually urinate four to eight times per day, and the urine would be pale yellow.

Water gain and loss

The total volume of fluid taken into the body depends on diet and activity levels, and typically varies from about 2 to 16 litres. The minimum water requirement for fluid replacement in a 70 kg person in a cool climate is about 3000 mL per day. Of this, about 400–600 mL is obtained by eating, and about 400 mL is produced by aerobic respiration. (This is called metabolic water because it is produced in cellular respiration.) The remainder of about 2000–2200 mL must be obtained by drinking. (Review the equation for cellular respiration in Section 3.2, page 118.)

For this person, water will be lost mainly in urine (500–1500 mL per day), evaporation from the respiratory system (400–800 mL per day), sweat (100–800 mL per day), and faeces (100–200 mL per day).

Salt gain and loss

Salt intake varies greatly depending on diet. The three major salt groups in the human diet are sodium salts, potassium salts and calcium salts.

Daily sodium salt intake (mostly as sodium chloride) ranges from about 1 to 10 grams per day, mainly in bread, meat and processed cereal products. Highly processed foods usually contain more sodium salts than unprocessed foods. The recommended daily intake for Australians is 1.6 grams.

Daily potassium salt intake (mainly potassium chloride and potassium citrate) ranges from about 2.0 to 4.0 grams per day. The recommended daily intake for Australians is 4.7 grams. Highly processed foods usually have a much lower potassium salt content that unprocessed foods.

Daily calcium salt intake (mainly in dairy foods and green vegetables) is up to about 2.4 grams per day. The recommended daily intake for Australians is 1.0–1.3 grams, depending on age.

Salts are lost mainly in urine but also in sweat and faeces. The kidney filters excess salts from the blood and excretes them into the urinary system. However, most salts are reabsorbed into the blood plasma for recirculation to tissues.

Hormonal control of water balance

Water and solute concentration are monitored by **osmoreceptors** in the hypothalamus and **baroreceptors** in the atria of the heart. Osmoreceptors are sensitive to blood solute concentrations, while baroreceptors detect changes in blood pressure, which is an indication of the volume of blood. Collectively, these receptors detect the solute concentration in blood and extracellular fluid. The unit of measurement used for these blood solute concentrations is osmolality, because they contribute to osmotic effects on cells.

Because cell membranes are permeable to water, the osmolality in the extracellular fluid is about the same as it is in the intracellular fluid (cytosol). Changes in the osmolality of the extracellular fluid will therefore affect cytosol concentrations, which can cause problems with cellular metabolic reactions. Compared to extracellular fluid, the cytosol of cells is high in potassium and magnesium and low in sodium and chloride ions.

Antidiuretic hormone (ADH), also called vasopressin, regulates water reabsorption. It is synthesised in the hypothalamus and transported to the posterior pituitary gland, where it is stored (Figure 5.3.14). When osmoreceptors in the hypothalamus detect an increase in the osmolality of the blood, a signal is sent to the posterior pituitary gland, and ADH is released.

ADH acts on the kidneys to increase the permeability to water of the distal tubules and collecting ducts. The collecting ducts run through the medulla of the kidney, which has high salt levels (and therefore a higher osmotic potential). This causes the absorption of water from the tubules back into the blood by osmosis, decreasing urine output; the urine becomes more concentrated and has a darker yellow colour. As the blood returns to a normal concentration, negative feedback stops the production of ADH.

Conversely, if the osmoreceptors detect a decrease in osmolality (e.g. if too much water has been taken into the body), ADH release will be stopped. This reduces the reabsorption of water and consequently increases urine volume; the urine becomes more dilute and has a paler yellow colour (Figure 5.3.14).

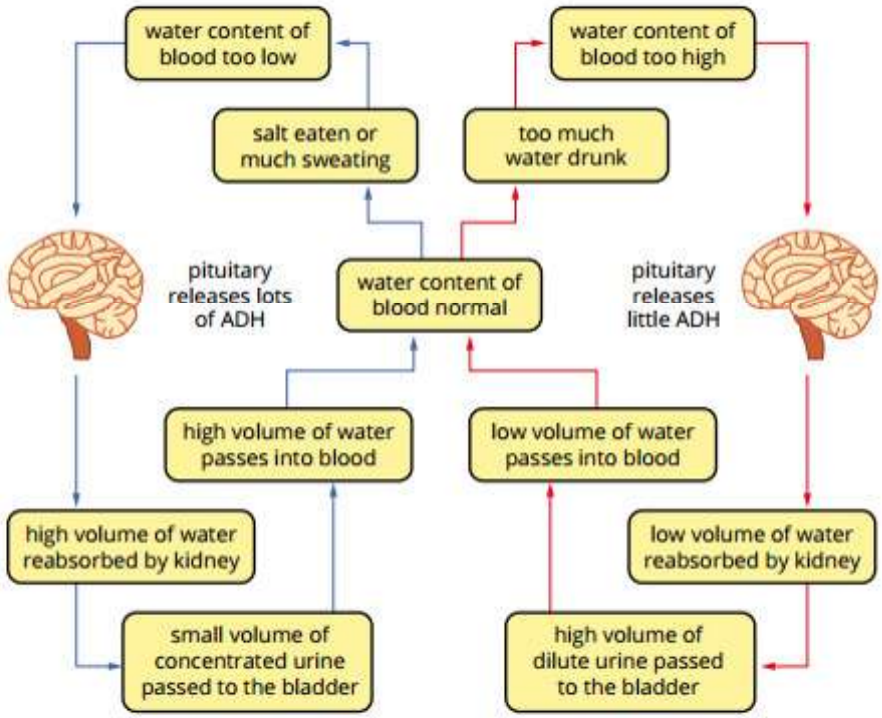


FIGURE 5.3.14 Hormonal control of water balance by antidiuretic hormone (ADH).

A number of substances such as nicotine, alcohol and narcotics can interrupt the feedback control of water balance in the body. This can also occur because of pain, stress or hypothermia (lowered body temperature).

Changes in blood osmolality or blood pressure also stimulate counteracting response. Initially an enzyme called **renin** is secreted from the kidneys in response to these changes (Figure 5.3.15). Renin then triggers a series of reactions involving other hormones that results in the release of **aldosterone** from the adrenal glands situated above the kidney. Aldosterone simultaneously regulates sodium and potassium levels by increasing potassium excretion into the urine and causing sodium reabsorption into the blood. This causes more water to be drawn into the blood by osmosis, thus increasing blood volume and pressure.

A lack of aldosterone can result in low sodium levels, high potassium levels and high acid levels in the blood. These are potentially dangerous conditions. People with an aldosterone deficiency suffer from Addison's disease and must take a synthesised hormone called fludrocortisone acetate.

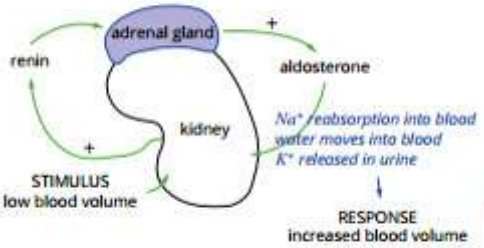


FIGURE 5.3.15 Hormonal control of sodium and potassium levels by renin and aldosterone.

EXTENSION

Water balance in the kidneys

The primary functions of the kidneys are filtration of blood, reabsorption of useful substances into the blood plasma, and secretion of wastes in urine. They use the principles and processes of osmosis, passive diffusion and active transport of water and solutes down or against concentration gradients, as outlined in Section 2.4 (page 100). The nephron is the basic structural and functional unit of the kidney. An average human kidney contains 800 000 to 1.5 million nephrons.

In biological systems water moves passively along concentration gradients. The kidney is able to produce concentrated urine, thereby reducing water loss, via the counter-current arrangement of the loops of Henle, and of blood vessels in the medulla of the kidney (Figure 5.3.16).

Cells forming the ascending arm of the loop of Henle actively pump sodium chloride out of the tubular fluid and into the medulla (Figure 5.3.16b-A). This increases the salt concentration in the medulla. In the descending arm of the loop of Henle, sodium chloride diffuses along a concentration gradient from the medulla into tubular fluid (Figure 5.3.16b-B). This increases tubular sodium chloride concentration, so that there is more sodium chloride to be actively removed when the fluid passes up the ascending arm. This further increases the medullary salt concentration. In this way, sodium chloride is recycled around the loops of Henle, resulting in the production of a high concentration of salt in the medulla of the kidney.

Tubular fluid continues through the nephron and into the collecting duct (Figure 5.3.16b-C), which passes back through the medulla and into the pelvis of the kidney. The wall of the collecting duct is permeable to water but not to salt, so as tubular fluid passes through the collecting duct, water diffuses into the medulla along the osmotic gradient. In this way tubular fluid becomes concentrated as it passes along the collecting duct.

It might be expected that blood flowing through the medulla would pick up and carry away any excess salt in the medulla and prevent the development of a high salt concentration. This does not occur because there is a similar counter-current arrangement of blood vessels in the medulla, called the vasa recta (Figure 5.3.16b-D). The salt concentration in blood increases as it flows down through the increasing salt concentration of the medulla, and then decreases as it passes back out again, thus maintaining the high salt concentration. When blood is too concentrated, ADH acts to increase the reabsorption of water in the collecting duct.

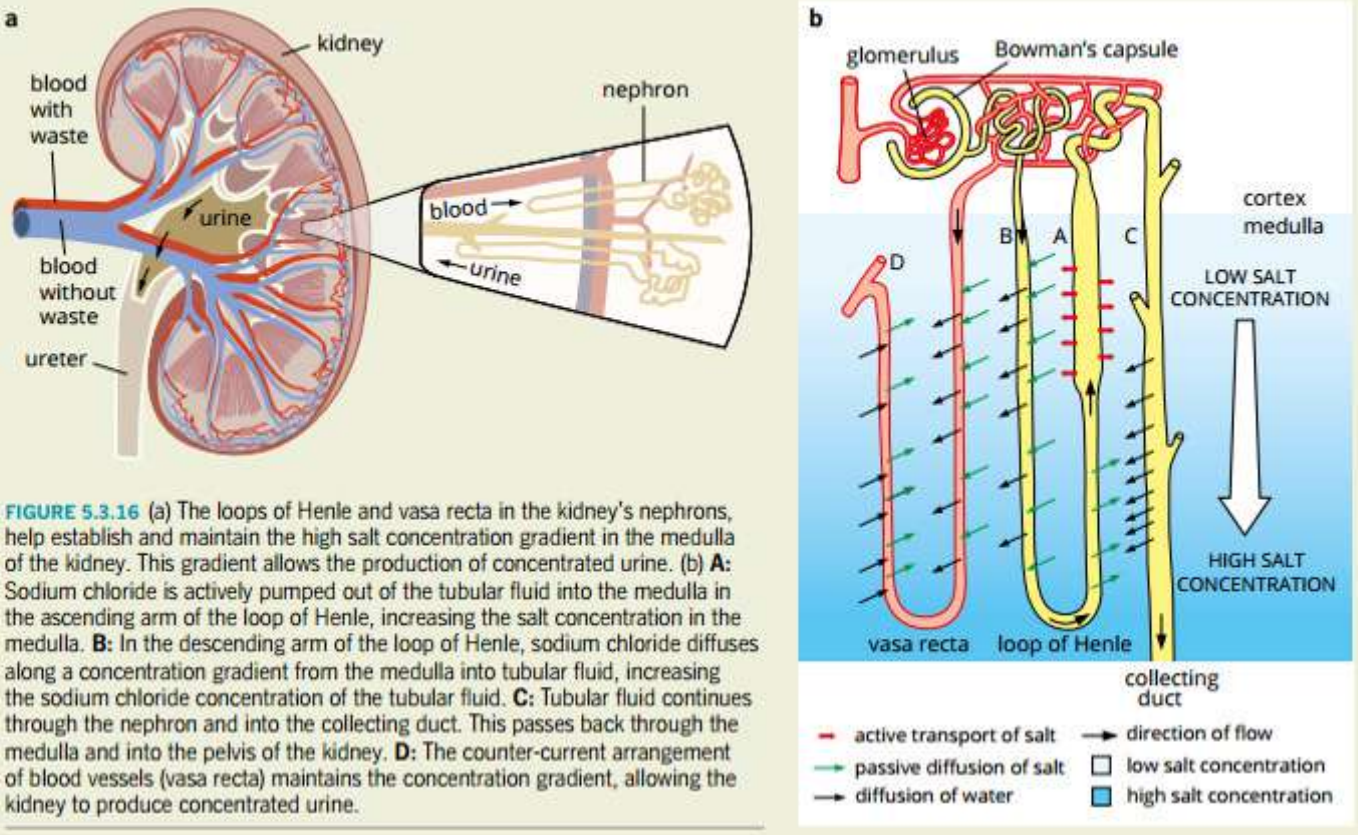


FIGURE 5.3.16 (a) The loops of Henle and vasa recta in the kidney's nephrons, help establish and maintain the high salt concentration gradient in the medulla of the kidney. This gradient allows the production of concentrated urine. (b) **A:** Sodium chloride is actively pumped out of the tubular fluid into the medulla in the ascending arm of the loop of Henle, increasing the salt concentration in the medulla. **B:** In the descending arm of the loop of Henle, sodium chloride diffuses along a concentration gradient from the medulla into tubular fluid, increasing the sodium chloride concentration of the tubular fluid. **C:** Tubular fluid continues through the nephron and into the collecting duct. This passes back through the medulla and into the pelvis of the kidney. **D:** The counter-current arrangement of blood vessels (vasa recta) maintains the concentration gradient, allowing the kidney to produce concentrated urine.

5.3 Review

SUMMARY

Temperature control

- A change in the temperature of the hypothalamus initiates regulatory responses that can involve heat production or heat exchange.
- Temperature receptors are found in the skin and the hypothalamus.
- Heat is lost from the body by:
  - conduction
  - convection
  - radiation
  - evaporation
- Responses to the cold involve reducing heat loss as well as producing heat.
- The responses to reduce heat loss are:
  - vasoconstriction
  - piloerection
  - behavioural changes like putting more clothes on or seeking shelter
- The responses to generate heat are:
  - voluntary movement
  - shivering thermogenesis
  - non-shivering thermogenesis
  - increasing rate of cellular metabolism
- The responses to heat are:
  - sweating or perspiring
  - covering your body with water
  - vasodilation
  - behavioural adaptations like removing clothing, seeking shade, increasing surface area and decreasing physical activity.

Control of blood glucose

- Blood glucose levels are detected by receptor cells in the pancreas and neurons in the hypothalamus. The normal fasting BGL is 4–6 mmol/L.
- When glucose levels rise:
  - insulin is released from the beta cells in the islets of Langerhans in the pancreas. Insulin causes a decrease in BGL by acting on a number of tissues to:
    - increase conversion of glucose to fat in fat cells
    - increase uptake of glucose in muscle and fat cells
    - increase conversion of glucose to the storage compound glycogen for storage in the liver.
- When glucose levels decrease, glucagon is released from alpha cells in the islets of Langerhans which stimulates the conversion of glycogen to glucose.
- Adrenaline acts on
  - skeletal muscle and the liver to increase breakdown of glycogen to glucose
  - fat cells to increase fat breakdown for energy.

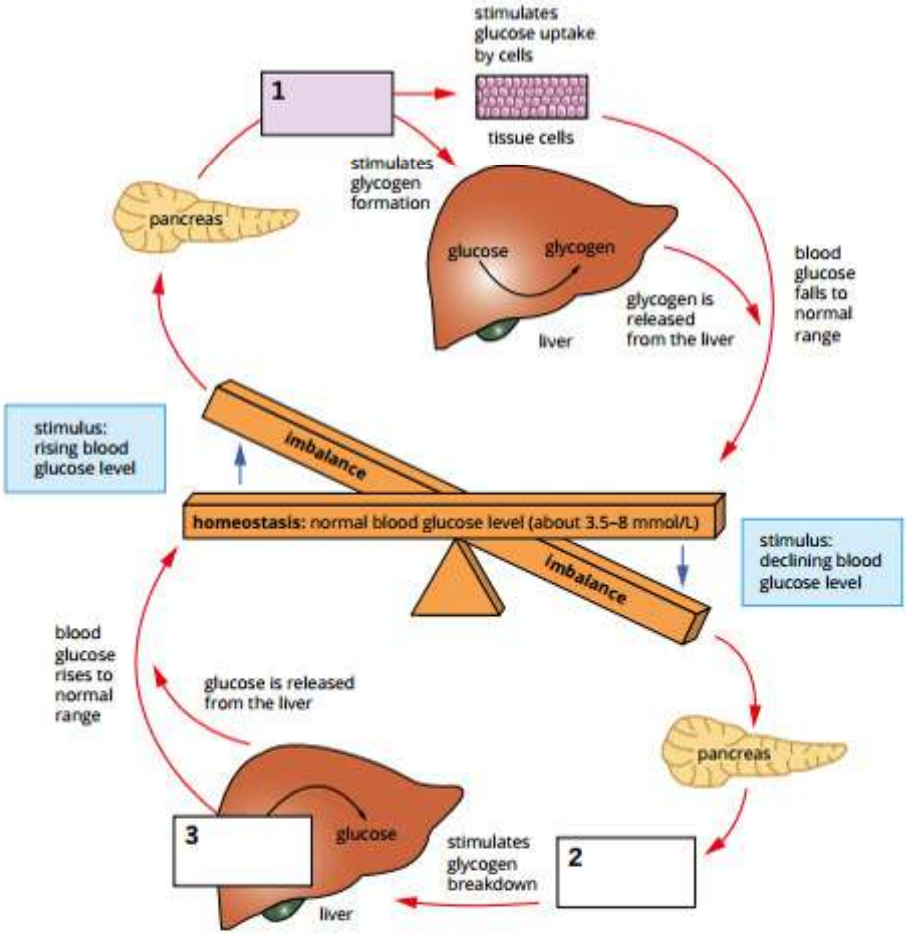
Water and salt balance

- Water enters body cells throughout the day from:
  - drinking
  - eating
  - cellular respiration.
- Salt is gained from our diet.
- Water is lost from the body mainly:
  - as urine
  - in faeces
  - across the skin
  - from the lungs.
- Salt is lost through:
  - the skin
  - kidneys
  - faeces.
- Osmoreceptors in the hypothalamus and baroreceptors in the atria of the heart detect the osmolality of the blood.
- An increase in osmolality causes:
  - release of ADH from the pituitary
  - ADH acts on the kidney to increase water absorption back into the blood.
- As a result:
  - osmolality of the blood decreases and volume increases
  - urine concentration increases and volume decreases.
- A decrease in osmolality causes:
  - decrease in ADH levels
  - urine volume will increase
- Low blood volume stimulates the secretion of aldosterone:
  - Renin is secreted from the kidneys
  - Renin causes release of aldosterone
  - Aldosterone causes absorption of sodium into the blood
  - Aldosterone causes potassium excretion into the urine
- As a result of this multiple hormone action:
  - blood volume increases
  - blood pressure increases.

5.3 Review *continued*

KEY QUESTIONS

1. How do organisms exchange heat with their environment? Explain each of the four methods of heat exchange using examples.
2. What are three mechanisms humans use to produce heat?
3. What are three mechanisms humans use to lose heat?
4. What is the main role of insulin, and how does it do this?
5. Describe the role of glucagon in glucose homeostasis.
6. Provide labels for points 1, 2 and 3 on the diagram below to explain the regulation of blood glucose levels in the human body.
7. **a** What does osmolality measure?
   b Which two receptors detect changes in osmolality in the blood?
8. What is ADH and what is its role?
9. What change in the blood acts as a stimulus for ADH release?
10. Describe how negative feedback is involved in ADH action and water balance.



5.4 Malfunctions in homeostatic mechanisms

The regulation of the internal environment, and thus the functionality and health of your body, is maintained by homeostatic mechanisms. These mechanisms are extremely sensitive to changes in internal conditions. However, homeostatic mechanisms can malfunction because of factors such as genetic disorders, ageing, poor nutrition, insufficient physical activity or exposure to harmful substances.

A malfunction in a homeostatic mechanism causes an imbalance and a subsequent oversupply or undersupply of substances to cells. Many diseases are associated with malfunctions in homeostatic mechanisms.

Hormonal balance plays a key role in regulating the internal environment. The endocrine system makes, stores and releases hormones that act as chemical messengers that trigger and direct functions in the body. The endocrine system controls vital functions in growth and development, metabolism, reproduction and tissue repair, among many others. Malfunctions in the endocrine system often lead to a disruption in a homeostatic mechanism, which can have an adverse effect on the body (Figure 5.4.1).

Diseases of the endocrine system fall into three groups:

- **hypersecretion** (oversupply) of hormones
- **hyposecretion** (undersupply) of hormones
- cancers of endocrine glands.

Examples of diseases of endocrine glands include diabetes, Graves' disease, Cushing's disease, gigantism, cretinism, Addison's disease and hyperthyroidism. In this unit you will explore type 1 diabetes and hyperthyroidism in detail.

A disease is any condition that impairs, or has the potential to impair, the normal functioning of the body.

FIGURE 5.4.1 The world's tallest person, Sultan Kösen from Turkey, meets the world's smallest person, Chandra Bahadur Dangi from Nepal. Sultan's gigantic height (251 cm) is the result of a tumour that affects his pituitary gland, leading to excess production of growth hormone. Chandra's small stature (55 cm) is a result of a genetic disorder known as MOPD type 1.

TYPE 1 DIABETES

Type 1 diabetes is caused by a malfunction of the pancreas, which leads to a deficiency in insulin secretion. It is an **autoimmune** condition in which the body's immune system destroys the insulin-producing beta cells in the islets of Langerhans in the pancreas (Figures 5.4.2 and 5.4.3). Insulin is essential for breaking down glucose to provide energy for the body. Treatment of type 1 diabetes involves artificially increasing the insulin supply by injections or an insulin pump.

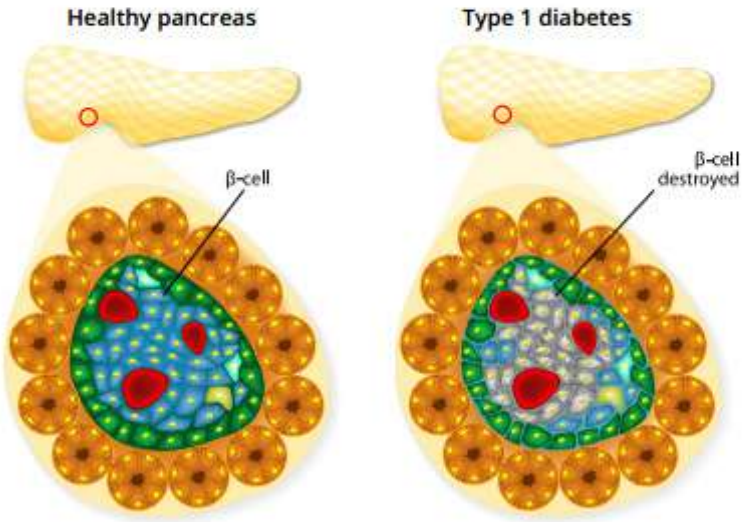


FIGURE 5.4.2 In type 1 diabetes, beta cells in the islets of Langerhans are destroyed. This means that the pancreas cannot secrete enough insulin to convert glucose to glycogen, and blood sugar levels can increase to dangerous levels.

An autoimmune disorder occurs when a person's immune system mistakenly targets the body's own cells. Antibodies that attack the body's cells are called autoantibodies. Examples of autoimmune disorders are type 1 diabetes, Graves' disease and multiple sclerosis.

BIOFILE

Diabetic complications

People with type 1 diabetes are at risk of several serious and even fatal conditions. In the short term, ketoacidosis (the release of ketones into the blood for energy production when insulin is not available) can lead to severe dehydration, vomiting, blurred vision and fainting. In extreme cases the person may become comatose.

Long-term risks include heart failure, vision impairment and possibly blindness, obesity, slow wound healing, skin infections, nerve damage causing a loss of sensation in the limbs, and insufficient blood supply to the hands and feet.

Injecting too much insulin, or over-exercising after injecting insulin, can result in dangerously low blood sugar levels (hypoglycaemia). This can result in a rapid loss of consciousness if not treated promptly. The usual first aid treatment is drinking fruit juice or sucking on a lolly such as barley sugar to boost blood sugar glucose quickly (Figure 5.4.4). This can be followed by more substantial carbohydrates once the patient is more alert.

FIGURE 5.4.4 First aid for hypoglycaemia usually involves drinking fruit juice or sucking on a sweet lolly to boost glucose levels quickly.

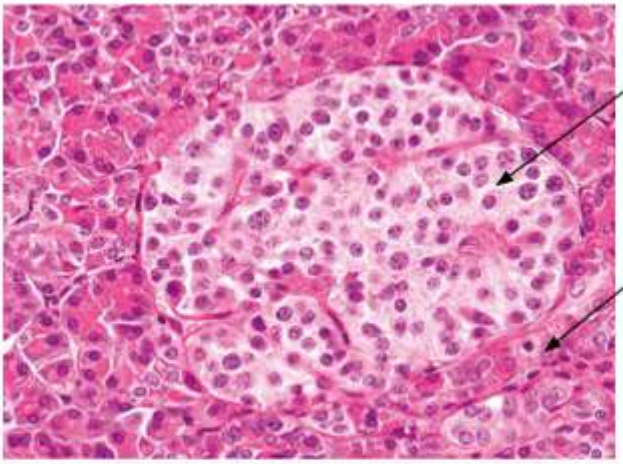


FIGURE 5.4.3 Micrograph of the islets of Langerhans, a cluster of pancreatic cells that regulate blood sugar levels by releasing insulin. The islets of Langerhans are surrounded by enzyme-producing acinar cells.

The onset of type 1 diabetes symptoms often occurs in childhood to early adulthood, and there is currently no cure or way of preventing the disease. People with type 1 diabetes must monitor their blood glucose levels (BGL) and inject or pump insulin into their bodies every day. Type 2 diabetes is also a disturbance of glucose homeostasis. In this disorder the pancreas still makes insulin, but the body cells do not respond. This form of diabetes often appears later in life, but is increasingly common in younger people, and is more common in those who are overweight or obese and have a sedentary lifestyle. It can usually be managed by diet, exercise and medication.

Cause of type 1 diabetes

Scientists are unsure what causes the beta cells in the islets of Langerhans in the pancreas to be destroyed in type 1 diabetes (Figure 5.4.2). There is some evidence for a link between the Coxsackie A and B4 viruses (which are common in children) and the onset of the autoimmune disease. Other childhood viruses, including enterovirus, mumps, polio and rubella, have also been suggested as triggers for type 1 diabetes. Without functioning beta cells, the body cannot secrete the insulin required to convert glucose to glycogen in the liver and to stimulate glucose uptake into muscle and fat. This causes blood glucose levels to increase to dangerously high levels.

Symptoms of type 1 diabetes

Insulin deficiency results in hyperglycaemia (high blood glucose levels) and accelerates the breakdown of fat for the body to use as energy. Symptoms of the disease include:

- glucose in the urine
- increased urine production
- excessive thirst
- excessive hunger
- ketosis
- weight loss
- fatigue
- blurred vision
- irritability
- muscle cramps
- skin infections
- delayed wound healing
- tingling or numbness in the feet.

Longer-term consequences are kidney and eye disease. All of these symptoms occur because of the elevated levels of glucose in the blood. Glucose is excreted in the urine because the raised blood glucose levels exceed the filtration capacity of the kidneys (normally the kidneys prevent glucose from entering the urine). Glucose escaping into the nephron tubules draws in more water, by osmosis, increasing the volume of urine produced. As a result, more frequent urination leaves the body dehydrated and feeling thirsty. The presence of glucose in urine is a simple test for diabetes (Figure 5.4.5).

Dehydration can lead to blurred vision as the lens loses moisture and the blood vessels are damaged. This can result in blindness if left untreated. The raised glucose levels in blood cause chemical reactions with molecules on the surface of neurons and cells lining the small blood vessels. The resulting damage to the body's nerves can result in loss of sensation in limbs, while damage to capillaries contributes to kidney malfunction and eye disease (diabetic retinopathy).

FIGURE 5.4.5 A dipstick test for glucose in urine. The pad is dipped in the urine, and the colour of the pad is checked against the chart. This gives an estimate of the glucose level in the urine. A high level is usually an indication of diabetes, although other conditions or the use of certain medications can cause high glucose levels.

Management of type 1 diabetes

Artificial insulin

As well as managing their diet, people with type 1 diabetes must receive insulin artificially. This is usually by injection (Figure 5.4.6a). Blood glucose levels are monitored by pricking a finger and testing a small drop of blood with a blood glucose meter or a chemical strip.

Alternatively, an electrode placed under the skin and connected to a continuous glucose monitoring device warns a person when their glucose level is reaching a high (or low) level. The monitor can be coupled to an electronic pump that delivers insulin when blood glucose levels reach a predetermined level (Figure 5.4.6b). An improved system called an 'artificial pancreas' is currently being tested in several countries, including Australia. This system uses a monitoring and feedback system to deliver insulin as the body requires it, in the same way that the pancreas produces insulin.

Transplants

Pancreas transplants from deceased donors are usually given to patients with serious complications from diabetes. Human pancreas cells can also be transplanted into a patient's liver, where they begin to produce insulin. This process is called pancreatic islet transplantation. Although it is still in the experimental stage, it may become widely available in the next few years. Recipients of pancreas or pancreatic islet transplants must take **immuno-suppressant drugs** for the rest of their lives to prevent their bodies from rejecting the transplanted organ. These drugs can have side effects such as high blood pressure, fatigue, and increased risk of bacterial and viral infections.

Gene therapy

Gene therapy, in which the gene that codes for insulin is inserted into the patient's cells, is a potential future treatment for diabetes. Trials in the USA have been successful in diabetic rats, targeting the liver because of the organ's regenerating ability. A major benefit of gene therapy is that patients would not require immunosuppressant drugs.

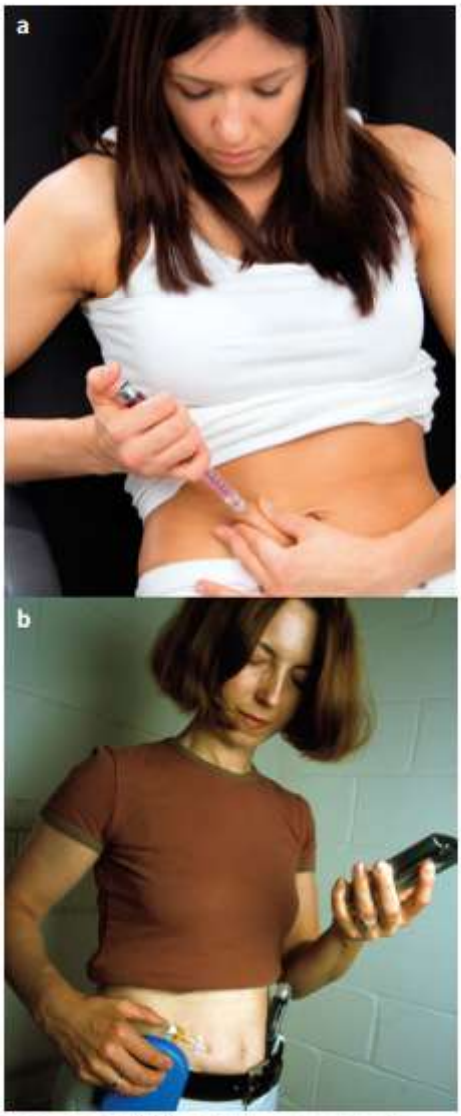


FIGURE 5.4.6 (a) A diabetic woman injecting insulin with an insulin pen, which delivers the correct dose of insulin. (b) This person is wearing a continuous glucose monitoring device and insulin pump. The monitor measures blood glucose levels and sends a signal to the pump when insulin is needed.

HYPERTHYROIDISM

Hormones secreted by the thyroid gland interact with cells throughout the body. They are responsible for regulating growth, development and metabolic rate, along with many other vital functions. Malfunction of the thyroid can therefore have widespread and serious effects on a range of organs and bodily functions (Table 5.4.1, page 260).

Hyperthyroidism is a condition in which excess amounts of the hormones triiodothyronine (T3) and thyroxine (T4) are secreted by the thyroid gland. T3 and T4 are made from an amino acid (tyrosine) and contain iodine. Blood tests for these hormones and thyroid stimulating hormone (TSH) are used to diagnose the condition. When T3 and T4 are oversupplied by the thyroid, a negative feedback message is sent to the hypothalamus to decrease the release of thyrotropin releasing hormone (TRH). This in turn decreases the synthesis of TSH from the pituitary gland.

A positive blood test for hyperthyroidism shows elevated levels of T3 and T4 and decreased TSH levels (see Figure 5.4.9). Thyroid malfunctions affect about 6–7% of the population. Hyperthyroidism occurs in about 2% of the Australian population. The disease most commonly affects people over the age of 60 and women are 5 to 8 times more likely to develop hyperthyroidism.

In hypothyroidism the thyroid produces less T3 and T4 than the body needs. Hypothyroidism also can have serious effects on health (Table 5.4.1).

Process or system affected	Normal physiological effects	Effects of hyperthyroidism	Effects of hypothyroidism
Basal metabolic rate (BMR)/temperature regulation	Promotes normal oxygen use and BMR; heat production via the digestion of food and thyroid hormones; enhances effects of sympathetic nervous system.	BMR above normal; increased body temperature, heat intolerance; increased appetite; weight loss.	BMR below normal; decreased body temperature, cold intolerance; decreased appetite; weight gain; reduced sensitivity to hormones produced by the adrenal glands.
Carbohydrate/lipid/ protein metabolism	Promotes glucose metabolism; mobilises fats; essential for protein synthesis; enhances liver's synthesis of cholesterol.	Enhanced breakdown of glucose, proteins, and fats; weight loss; loss of muscle mass.	Decreased glucose metabolism; elevated cholesterol/triglyceride levels in blood; decreased protein synthesis; swelling from excess fluid in tissues (edema).
Nervous system	Promotes normal development of nervous system in foetus and infant; promotes normal adult nervous system function.	Irritability, restlessness, insomnia, personality changes, bulging eyes (in Graves' disease).	In infants, slowed/deficient brain development, delayed development; in adults, mental dulling, depression, tingling sensations in the fingers and toes; memory impairment, hypoactive reflexes.
Cardiovascular system	Promotes normal functioning of the heart.	Increased sensitivity to adrenal gland hormones (e.g. adrenaline and dopamine) leads to rapid heart rate and possible palpitations; high blood pressure; if prolonged, heart failure.	Decreased efficiency of heart's pumping action; low heart rate and blood pressure.
Muscular system	Promotes normal muscular development and function.	Muscle atrophy and weakness.	Sluggish muscle action; muscle cramps; muscle pain.
Skeletal system	Promotes normal growth and maturation of the skeleton.	In children, excessive skeletal growth initially, followed by early epiphyseal closure and short stature; in adults, demineralisation of skeleton.	In children, delayed or slowed growth, skeletal stunting and retention of child's body proportions; in adults, joint pain.
Gastrointestinal (GI) system	Promotes normal GI motility and tone; increases secretion of digestive juices.	Excessive GI motility; diarrhoea; loss of appetite.	Depressed GI motility, tone, and secretory activity; constipation.
Reproductive system	Promotes female reproductive ability and lactation.	In females, depressed ovarian function; in males, impotence.	Depressed ovarian function; sterility; depressed lactation.
Integumentary system	Promotes normal hydration and secretory activity of skin.	Skin flushed, thin, and moist; hair fine and soft; nails soft and thin.	Skin pale, thick and dry; facial swelling (edema); hair coarse and thick.

TABLE 5.4.1 The major effects of thyroid hormones T3 and T4 in the human body. Hyperthyroidism results from an excess of T3 and T4 secreted from an overactive thyroid gland (hypersecretion). Hypothyroidism is a result of an underactive thyroid gland and insufficient levels of T3 and T4 (hyposecretion).

BIOLOGY IN ACTION

Brown fat and diabetes management

A study led by endocrinologist Dr Paul Lee at the Garvan Institute of Medical Research in Sydney is investigating the link between brown fat and diabetes. Brown fat is rich in mitochondria and plays an important role in generating heat in hibernating animals and babies. Cool environments promote the growth of brown fat, while warm environments suppress it. Dr Lee wanted to investigate how brown fat is regulated in humans, its role in metabolism, and how this influences blood glucose levels and diabetes.

In this research, study participants slept in temperature-controlled rooms for four months: 24 °C for the first month (the body does not have to work to produce or lose heat at this temperature), 19 °C for the second month, 24 °C for the third month and then 27 °C for the last month. Participants completed a 'thermal metabolic evaluation' at the end of each month.

As expected, brown fat increased during the cooler month (19 °C) and decreased during the warmer month (27 °C). The researchers also found that increased brown fat led to heightened insulin sensitivity. This means that people with more brown fat need less insulin to bring their blood glucose levels down. With increased efficiency in household heating over the last few decades, the average home temperature in the UK and USA has risen from 19 °C to 22 °C. This temperature change is enough to reduce brown fat production.

The researchers speculate that this shift in household temperature, along with unhealthy diets and lack of exercise, may have contributed to the rise in obesity in these populations. The findings from this research indicate that people with diabetes may be able to regulate their brown fat deposits, making themselves more sensitive to insulin and therefore less reliant on large doses of insulin. This research could also open new avenues for diabetes management.

BIOFILE

Insulin from microbes

Insulin for human use was once extracted from animals, mostly pigs, but it is now produced mainly by genetically engineered microbes. The gene that codes for insulin is inserted into yeast or bacteria (e.g. *Escherichia coli*), which are cloned to produce large quantities of insulin (Figure 5.4.7). These organisms are grown in culture and produce insulin on a large scale.

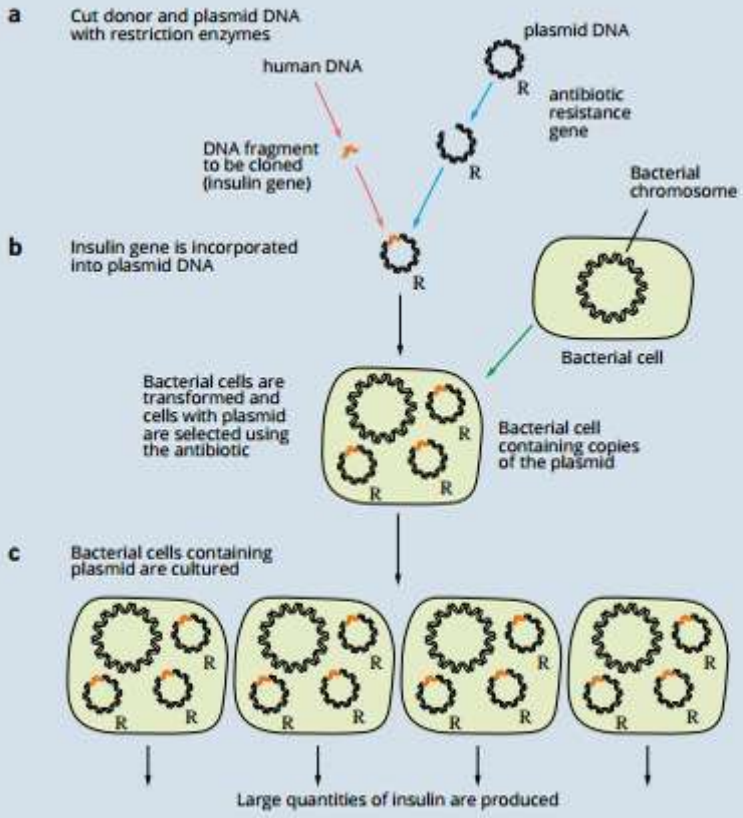


FIGURE 5.4.7 Cloning bacteria for the production of insulin involves three steps. (a) The gene responsible for insulin production is cut from human DNA using restriction enzymes. The plasmid DNA of a bacterium is cut with the same restriction enzymes. (b) The gene that codes for insulin is incorporated into the plasmid DNA of the bacterium. (c) Bacteria containing the insulin gene survive antibiotic treatment and are cultured to generate clones. The clones produce large quantities of insulin, which can then be harvested.

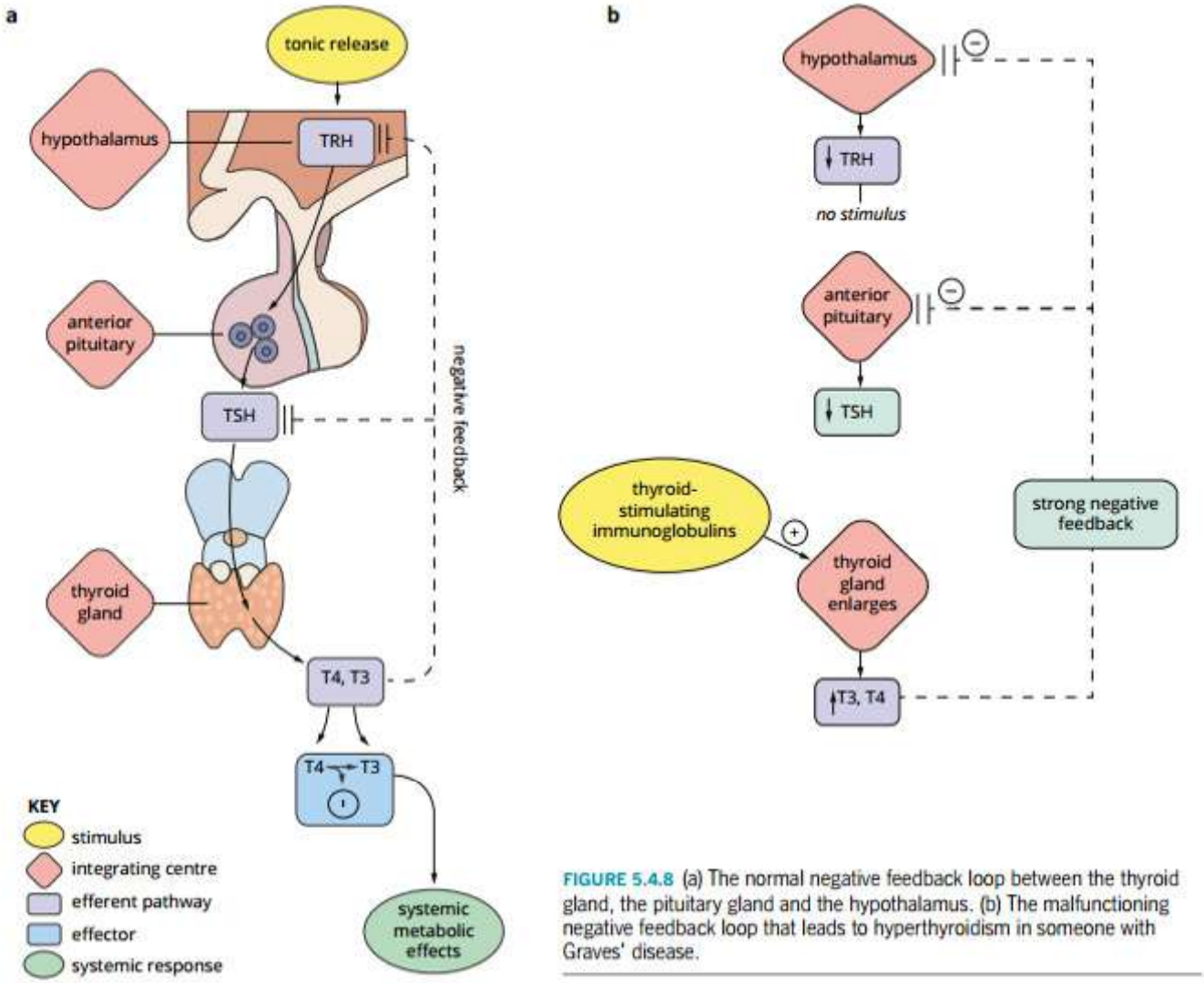


FIGURE 5.4.8 (a) The normal negative feedback loop between the thyroid gland, the pituitary gland and the hypothalamus. (b) The malfunctioning negative feedback loop that leads to hyperthyroidism in someone with Graves' disease.

Causes of hyperthyroidism

There are many causes of hyperthyroidism. The most common cause is an autoimmune condition called Graves' disease. In patients with Graves' disease, the immune system makes an antibody called thyroid stimulating immunoglobulin (TSI), which mimics TSH, stimulating the thyroid to make more T3 and T4 hormones than the body needs (Figure 5.4.8 and Figure 5.4.9). The trigger for the production of the antibody is unknown, but a combination of environmental and genetic factors are thought to contribute. Infection caused by some viruses and bacteria, stress, childbirth, excess iodine (through food or contrast dyes used for imaging) and some medications have been linked to the onset of Graves' disease. People with other autoimmune conditions such as type 1 diabetes, as well as smokers and those with tumours of the testes or ovaries, have a higher risk of developing the disease.

Symptoms of hyperthyroidism

The symptoms of hyperthyroidism can include some or all of the following:

- **goitre** (a visibly enlarged thyroid) or thyroid nodules (Figure 5.4.10a)
- weight loss
- rapid heartbeat (tachycardia)
- irregular heartbeat (arrhythmia)
- pounding of your heart (palpitations)
- increased appetite

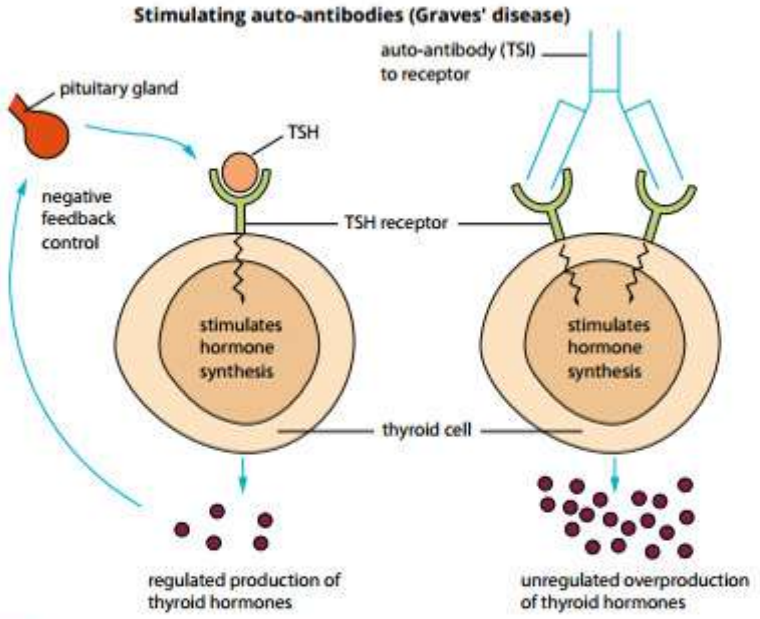


FIGURE 5.4.9 Thyroid stimulating immunoglobulin (TSI) acts on cells in the same way as thyroid stimulating hormone (TSH) to trigger the synthesis and release of T3 and T4. This results in an excess of these thyroid hormones and hyperthyroidism in people with Graves' disease.

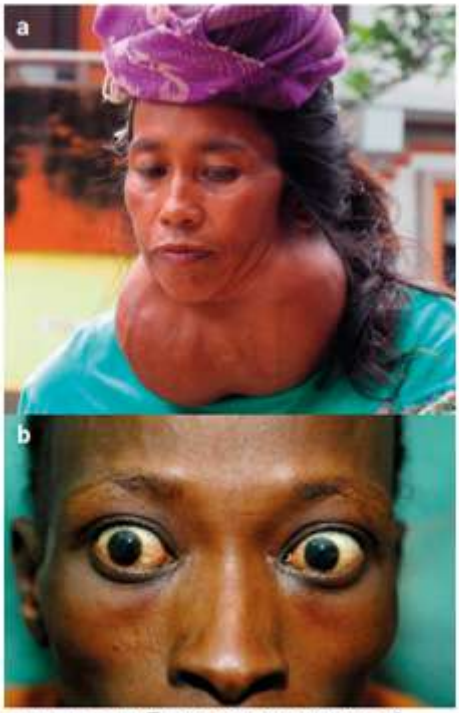


FIGURE 5.4.10 Two common symptoms of hyperthyroidism. (a) An enlarged thyroid gland, called a goitre. (b) In Graves' disease, bulging eyes result when thyroid stimulating immunoglobulin (TSI) produces inflammation and swelling of the soft tissues in the eye.

- nervousness, anxiety and irritability
- changes in bowel patterns (more frequent)
- fatigue, muscle weakness
- tremor—usually a fine trembling in your hands and fingers
- breast development in men
- bulging eyes (exophthalmos) (Figure 5.4.10b)
- nausea and diarrhoea
- sweating and heat intolerance
- changes in menstrual patterns
- increased sensitivity to heat
- light or absent menstrual periods
- trouble sleeping
- skin thinning, blushing, flushing or being itchy or clammy
- fine, brittle hair or hair loss

Management of hyperthyroidism

The symptoms of hyperthyroidism can be treated with drugs called beta-blockers, which act on the circulatory and nervous systems to slow down the increased heartbeats and tremors associated with the disease. However, these drugs do not have an effect on the thyroid itself.

Sometimes anti-thyroid drugs are prescribed to interfere with the thyroid's ability to make hormones. These drugs act on the thyroid gland to slow the production of hormones to normal levels and reduce or eliminate the symptoms. Only 20–30% of patients have long-term success in treating hyperthyroidism with anti-thyroid drugs.

Radioactive iodine treatment is the most widely used permanent treatment for hyperthyroidism. (Iodine is needed to make T3 and T4 hormones.) Thyroid cells are the only cells in the body that absorb iodine. Taken orally, the radioactive iodine (I-131) is absorbed by the thyroid cells. I-131 emits beta radiation, which kills thyroid cells.

Surgery is another permanent cure and involves the removal of all or part of the thyroid. Removal or destruction of the thyroid means the patient will suffer from hypothyroidism, and must take thyroid pills such as levothyroxine for the rest of their life.

BIOFILE

Hypothyroidism

In contrast, to hyperthyroidism, underactivity of the thyroid gland can cause hypothyroidism as a result of insufficient production of the thyroid hormones. Symptoms of this disease in adults are weight gain, lethargy, slow heart rate, hair loss and sensitivity to cold. In children, hypothyroidism can cause delays in growth and mental development. Babies are screened for this disorder a few days after birth. Raised levels of TSH in the blood indicate possible hypothyroidism. The main cause of hypothyroidism is lack of iodine in the diet, which is essential for the production of thyroid hormones. This deficiency can be resolved by adding potassium iodide to table salt. In countries where iodine deficiency is not a widespread problem, the most common cause of hypothyroidism is an autoimmune condition called Hashimoto's thyroiditis.

5.4 Review

SUMMARY

- Malfunctions in homeostatic mechanisms lead to imbalances and a subsequent oversupply or undersupply of substances needed by cells.
- Many diseases are associated with malfunctions in homeostatic mechanisms.
- The endocrine system is particularly important for maintaining homeostasis, and malfunctions in this system can affect the whole body.

Diabetes

- There are two types of diabetes: type 1 (genetic and may be caused by a virus) and type 2 (often late onset and related to lifestyle).
- The cause of type 1 diabetes is the autoimmune destruction of the insulin-producing beta cells in the islets of Langerhans. People with type 1 diabetes do not produce enough insulin. Without treatment, blood glucose concentration can rise to dangerous levels.
- Symptoms of type 1 diabetes include glucose in the urine, increased urine production, excessive thirst, weight loss, fatigue, blurred vision, irritability, muscle cramps, skin infections and delayed wound healing.
- Treatment and management of type 1 diabetes includes daily insulin supplements by injection or insulin pump, and a strictly controlled diet. Pancreas transplants may be required for people with serious complications caused by type 1 diabetes. Potential treatments include pancreatic islets transplants, an artificial pancreas and gene therapy.

Hyperthyroidism

- Hyperthyroidism is the over-secretion of the thyroid hormones triiodithyronine (T3) and thyroxine (T4).
- Symptoms of hyperthyroidism include goitre, weight loss, heartbeat irregularities, increased appetite, nervousness, changes in bowel movements, fatigue, tremor, bulging eyes, nausea, heat intolerance, changes in menstrual patterns, and hair loss.
- Treatment for hyperthyroidism involves the use of beta-blockers, anti-thyroid drugs or radioactive iodine I-131, or surgery.

KEY QUESTIONS

1. Discuss how malfunctions in homeostatic mechanisms can lead to disease, using an example.
2. Why do people with diabetes sometimes need to have sweet drinks or food?
3. Why does type 1 diabetes cause high blood glucose levels?
4. Explain how brown fat might be important in diabetes management.
5. How is thyroid disease diagnosed? How would blood test results differ between someone with hyperthyroidism and hypothyroidism?
6. Why do disruptions to homeostatic mechanisms of the thyroid gland affect so many different systems in the body?

Chapter review

05

KEY TERMS

adaptation
adrenaline
aestivation
aldosterone
antidiuretic hormone (ADH)
antifreeze proteins (AFPs)
autoimmune disorder
autonomic nervous system
baroreceptors
bilateral symmetry
bioluminescence
brumation
CAM photosynthesis
carotid rete system
central nervous system
chemical communication
chemotropism
chromatophore
control centre
dehydrin
diffusion
effector
endotherm
enteric nervous system
external environment
exteroreceptors
geotropism
glucagon
glucose
glycogen
goitre
halophyte
heat exchanger
hibernation
homeostasis
hormone
hydrotropism
hyperglycaemia
hypersecretion
hyperthyroidism
hypoglycaemia
hyposecretion
hypothalamus
immuno-suppressant drug
insulin
internal environment
interneuron
interoreceptor
metabolism
nastic movement
negative feedback loop
neuron
nocioreception
non-shivering thermogenesis
osmoreceptor
osmosis
parasympathetic division (nervous system)
peripheral nervous system
photonasty
phototropism
piloerection
positive feedback loop
proprioception
pyrogen
receptor
renin
response
shivering thermogenesis
stimulus
stomata
sympathetic division (nervous system)
thermonasty
thermoreceptor
thigmonasty
thigmotropism
tolerance range
torpor
tropism
type 1 diabetes
vascularised
vasoconstriction
vasodilation
xerophyte

KEY QUESTIONS

1 What are adaptations? Describe how they benefit individuals, populations and species.

2 Complete the following table, where S = structural (the way it is built), P = physiological (the way it functions) and B = behavioural adaptation.

Organism	Feature	S, P or B	Benefits to organism
Mangrove	pneumatophore		
Honey possum	long, brush-like tongue		
Kangaroo	sleeps in shade during the day		
Echidna	goes into torpor		
Saltbush	salt-secreting glands in leaves		

3 The ability of the male southern pygmy perch to change colour in the breeding season and establish a territory is best interpreted as a:
- **A** structural adaptation
- **B** behavioural adaptation
- **C** physiological adaptation
- **D** limiting factor in reproduction

4 Complete the following table with adaptations that animals and plants have to survive in these different environments.

Environment	Adaptation		
	Structural	Physiological	Behavioural
Desert			
Snow			
Salty soil or water			
Deep underwater			
Long, cold winter			
Intertidal zone			

5 Jack rabbits, which are often found in deserts, have disproportionately large ears that have a rich network of blood vessels close to the skin. Kangaroos have a special network of capillaries that lie near the surface of the skin on the inside of the forearms. On very hot days, kangaroos can often be seen licking their forearms.
State the type of adaptation and how this common feature might help each animal regulate its temperature.

6 Describe how an emperor penguin is adapted to life in the harsh Antarctic climate, mentioning at least one structural, one physiological and one behavioural adaptation.

7 Describe how CAM (crassulacean acid metabolism) photosynthesis is a beneficial adaptation for plants living in the desert.

8 Why is it important for an organism to be able to regulate its internal environment?

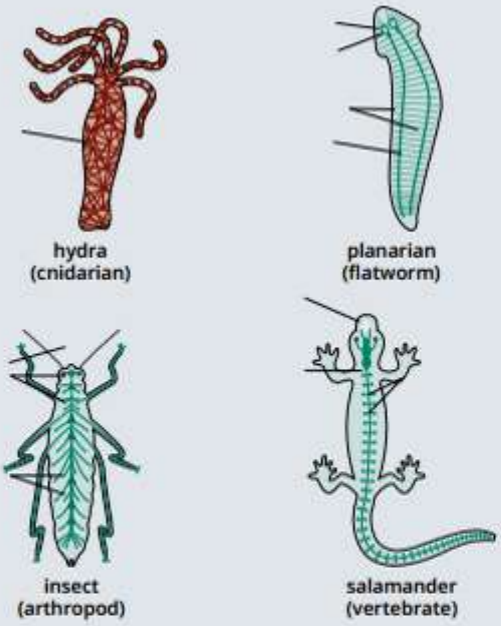
9 How do receptors and effectors maintain homeostasis?

10 Arrange the following terms from first to last in the order of their involvement in a physiological response: control centre, effector, receptor, response, stimulus.

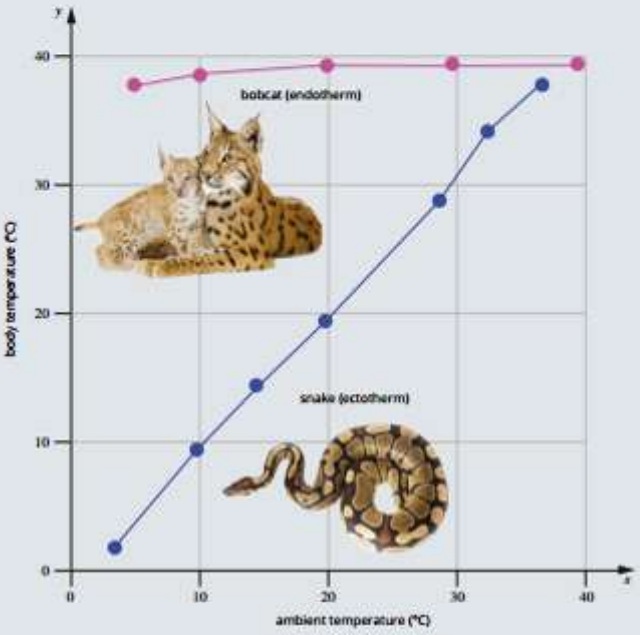
11 Indicate which statements are true or false.

- One hormone can affect every cell
- Hormones affect target cells
- Target cells contain receptors
- Receptors recognise hormones specific for them
- Receptors recognise groups of hormones that are specific for them, e.g. peptide hormones
- Receptors for steroid hormones are located in the cytoplasm and receptors for peptide hormones are located in the cell surface membrane

12 Label the parts of the nervous systems of these organisms.



13 Endothermic and exothermic animals regulate their body temperatures in different ways. Consider the following graph, which shows the body temperatures of a bobcat (pink line) and a snake (blue line) for different ambient environmental temperatures.

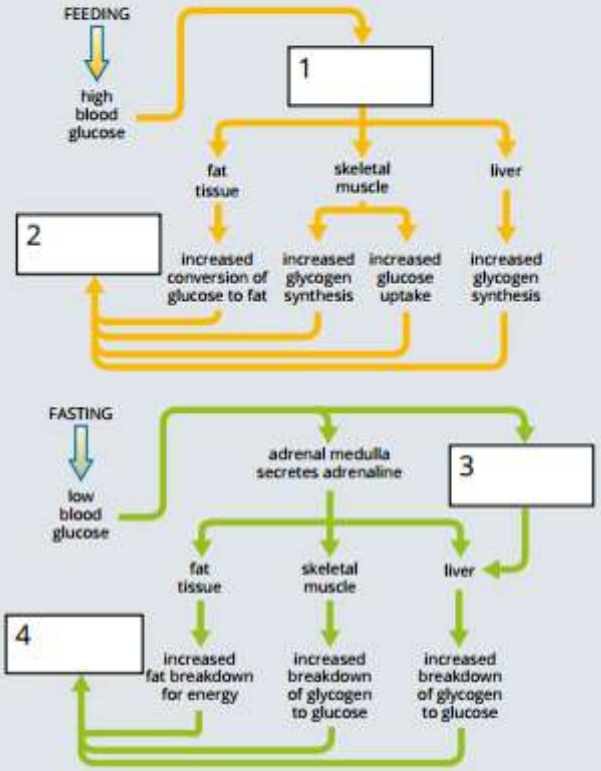


a When the ambient temperature is 30 °C, what is the body temperature of the snake?

b Why does the body temperature of the snake continue to increase as the ambient temperature increases, but the body temperature of the bobcat does not?

14 Describe the thermoregulatory mechanisms that occur during and immediately after a fever.

15 Provide labels for boxes 1, 2, 3 and 4 in the following diagram to complete the steps of the feedback mechanisms that regulate glucose levels in the blood.



16 What are the primary functions of the kidneys? Which structures in the kidney are responsible for these functions?

17 **a** Explain the principle of negative feedback in homeostasis.

b Using the aid of a diagram, explain how a decrease in body temperature can be brought back up again. In your diagram, draw and label an arrow to show where negative feedback occurs.

18 Diseases of the endocrine system fall into three groups. What are they? Provide an example of each.

19 Using either type 1 diabetes or hyperthyroidism as an example, discuss how chronic disease can occur when there is a malfunction of homeostatic mechanisms in the body.

CHAPTER

06 Organising biodiversity

In this chapter you will learn about the variety of living things on Earth. You will learn how to classify organisms into taxonomic groups. You will also look at the impact that humans are having on the ecosystems of the world, and explore strategies for conserving and managing the Earth's biodiversity.

Key knowledge

- classification of biodiversity, past and present, into taxonomic groups based on shared morphological and molecular characteristics, and naming using binomial nomenclature
- strategies for managing Earth's biodiversity to support the conservation of species and as a reservoir for the bio-prospecting of new food sources and medicinal drugs.

6.1 Classifying biodiversity

WHY CLASSIFYING ORGANISMS IS IMPORTANT

FIGURE 6.1.1 The mulga snake (*Pseudechis australis*) is the heaviest venomous snake in Australia.

Biologists spend considerable time classifying organisms by carefully examining them for features in common, grouping them and then naming the groups. Classification is not a new practice. Indigenous people around the world also have names for the organisms that they use or need to recognise. For example, the mulga snake (*Pseudechis australis*) is also known as kulipirri by the Ngarla people in Western Australia (Figure 6.1.1).

Taxonomy is the scientific discipline concerned with the naming and classifying of organisms. Taxonomists place organisms into groups known as taxa (singular: **taxon**) and give the organisms unique scientific names. Taxa include species, genera (singular: genus) and families. For example, *Aptenodytes forsteri* (the emperor penguin) is a species taxon. It belongs to the genus taxon *Aptenodytes* (the great penguins), which in turn belongs to the family taxon Spheniscidae (the penguins).

The scientific system of placing groups of organisms into taxa is called **biological classification** and this system enables us to understand the evolution and diversity of living things. By applying an internationally recognised system of classification, you can quickly obtain information about a particular organism; for example, whether it is a mammal or a fish, or whether it is a flowering plant or a fern. Because every taxon in a kingdom has a unique name, scientists know exactly what organism it is that they are talking about when they use the name.

RECORDING THE WORLD'S BIODIVERSITY

The **biosphere** is the region of the Earth inhabited by living things. It includes seas, lakes, rivers, soil and the lower atmosphere. Humans share the biosphere with millions of other species (Figure 6.1.2). This biological diversity, or **biodiversity**, is very important to our well-being because we use other species as sources of food, shelter and medicines. We are still discovering possible uses for many species. For example, mushroom corals (Figure 6.1.3) are exposed to the sun's radiation during low tides. Compounds that they secrete in their mucus act as an effective sunscreen, preventing them from damage during this time. Knowledge of these corals and the use of their compounds may help to protect people from skin cancer.

FIGURE 6.1.2 A coral reef in the Red Sea, showing the large diversity of organisms.

FIGURE 6.1.3 Mushroom coral (*Fungia fungites*). The mucus secreted by the coral is known to be useful as an effective sunscreen.

It is estimated that there are at least 8.7 million species of **eukaryotes** in the world today, but only 1.2 million of them have been named. About 7.5 million species of eukaryotes have yet to be described. Only by recording biodiversity will we know what organisms exist, at what rate they are becoming extinct, which habitats are most endangered and in need of protection or restoration, and which species and habitats can be used safely for the benefit of people.

A eukaryote is any organism whose cell contains a nucleus and other organelles enclosed within membranes.

BINOMIAL NOMENCLATURE

Common names are often used to refer to a group of similar organisms that have features in common. However, common names often mean different things to different people and can therefore be confusing. For example, the common name 'magpie' is used for the European magpie, the American black-billed magpie and the Australian magpie, but they are three very different birds (Figure 6.1.4).

FIGURE 6.1.4 Early European settlers gave the Australian magpie (*Cracticus tibicen*), shown here on the left, its common name because it reminded them of the European magpie, (*Pica pica*), shown on the right.

BIOFILE

When is a magpie not a magpie?

There are at least 17 different birds in the world that are called magpies, but only four of these are 'true' magpies. True (or Holarctic) magpies belong to the genus *Pica* in the family Corvidae, and are found only in the northern hemisphere. Oriental magpies are closely related to true magpies and are brightly coloured birds that inhabit eastern Asia. Azure-winged magpies are also closely related to true magpies and inhabit central Asia and southern Europe.

The Australian magpie (*Cracticus tibicen*) is not really a magpie at all. It is classified in the family Artamidae and is most closely related to currawongs, butcherbirds and wood-swallows. Our crows and ravens are more closely related to true magpies than our magpie is!

To avoid confusion when scientists communicate with each other, organisms are referred to by their scientific names, which are based on Latin. The scientific name of each species consists of two parts and is known as a **binomial**. The system of using a two-part name is called the **binomial system**. The binomial system was developed in the 18th century by Swedish botanist Carl **Linnaeus** (1707–1778).

In a binomial, the first part of the name is a generic name, or the **genus**. A genus is a group that includes one or more species (Figure 6.1.5).

The second part of a binomial is the **species** name (abbreviation 'sp.'). It is a specific descriptive name that is unique for each species within the genus. For example, *Agra sasquatch* and *Agra vation* are the scientific names for two different kinds of beetles. Both species belong to the same genus *Agra* (Figure 6.1.6).

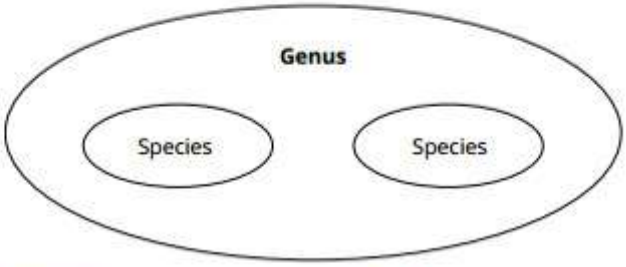


FIGURE 6.1.5 A genus is a larger group that includes one or more species within it.

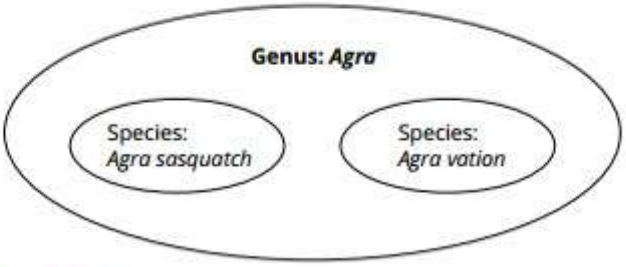


FIGURE 6.1.6 The species *Agra sasquatch* and *Agra vation* belong to the same genus *Agra*.

BIOLOGY IN ACTION

Identifying poisonous and beneficial animals

Blue-ringed octopus

Many poisonous animals are brightly coloured and easily recognisable. In Australia, some of the most venomous marine animals are the blue-ringed octopuses. These are commonly found in intertidal rock pools along the southern coastline. The most common and dangerous species is the southern blue-ringed octopus (*Hapalochlaena maculosa*). It is a small and usually inconspicuous animal with an arm spread of only about 6–8 cm, but it quickly develops characteristic brilliant blue rings on its tentacles when disturbed (Figure 6.1.7). The beak is at the centre of the body and the bite is almost painless, but can be lethal if enough venom is injected.

FIGURE 6.1.7 The southern blue-ringed octopus (*Hapalochlaena maculosa*), displaying the blue rings that give it its common name.

Box jellies

There are many species of box jellies (class Cubozoa). The sting of some species results in short-lived itching and mild pain (such as *Chiropsella bart*, Figure 6.1.8), but others such as *Chironex fleckeri* can deliver extremely potent venom that can cause extreme pain and, in some cases, death. So it is essential to be able to identify some of the species that have stings that are life-threatening to humans. The box jelly *Chironex fleckeri* (Figure 6.1.9) inhabits the tropical and subtropical waters of northern Australia and nearby islands.

Chironex fleckeri has a box-shaped bell 25 cm to 30 cm in diameter. The four corners of the bell may have up to 15 thick, flat tentacles, and each tentacle can be 3 metres or more in length. The tentacles are lined with nematocysts (stinging cells) that are used to kill fish and crustaceans. The nematocysts contain a venom that causes severe pain, nausea, vomiting and respiratory problems in humans. Death can result if a swimmer is badly stung by this sea jelly, even if medical treatment is available. It is not surprising that the seasonal occurrence of *Chironex fleckeri* is announced along with the weather report in the affected areas.

FIGURE 6.1.8 The box jelly, *Chiropsella bart*, is the size of a tennis ball. Its sting is not life-threatening to humans.

FIGURE 6.1.9 The box jelly, *Chironex fleckeri*, whose sting is potentially fatal to humans.

Orange roughy

The orange roughy, *Haplostethus atlanticus* (Figure 6.1.10), became a popular food fish in the late 1980s when large populations were discovered off western Tasmania and Victoria. However, the annual catch declined dramatically after a peak in 1990. This was probably because orange roughies live for a long time and only reach sexual maturity after about 25 years, so they tend to be caught before they have reproduced. It is also thought that trawling during the spawning period, when they are easiest to catch, disrupts their breeding cycle.

In 2006 the orange roughy fishery was closed to prevent further declines, and a recovery strategy is in place to allow the population to recover. However, a small incidental catch limit (in which orange roughy are not the target species but are still caught) is still allowed. Fishers have to be able to identify which fish species they are allowed to keep in a catch, and they must know how many of each species they are allowed to catch each year. The orange roughy can be identified by a dorsal fin with six spines and 15–18 soft spine-like rays, a bright red body (which fades to orange after death) and a row of 19–25 spiny scales (scutes) along the belly.

FIGURE 6.1.10 The orange roughy (*Haplostethus atlanticus*) is beneficial to humans as a food, but stocks have been declining since 1990.

The genus name always begins with a capital letter and the species name always begins with a lower case letter, even if it is named after a person or a place. When scientific names are typed they should be italicised, but they can be underlined instead.

The binomial system for naming species is concise and precise. Its international acceptance resulted in a great improvement in communication within the scientific community.

Only genus, species, subspecies and variety names are italicised or underlined. Names of families, orders, classes, phyla, kingdoms and domain are not.

Naming species

Since Linnaeus introduced the binomial classification, the species has been the basic unit in the classification of organisms. Traditionally, differences in the morphology (form and structure) of organisms have been used to divide organisms into species. However, not all biologists agree on the definition of 'species'.

In the 1940s biologist Ernst Mayr introduced a single concept of species for all organisms. This was based on the concept of **biological species**. According to this concept, members of a single species breed and produce offspring in the wild. Members of different species generally do not breed in the wild.

The term 'species' means a group of organisms that resemble each other more than they resemble members of other groups. A biological species refers to individuals that can breed among themselves and produce fertile offspring.

For example, house sparrows (*Passer domesticus*) breed with one another (Figure 6.1.11), but not with other species. Different species do not generally interbreed freely in nature, even when they are members of the same genus, although there are exceptions to this. However, species of many organisms do not reproduce sexually (e.g. bacteria, some insects and many protists undergo both sexual and asexual reproduction), so this criterion of a species is not relevant for those organisms.

FIGURE 6.1.11 House sparrows (*Passer domesticus*) freely breed with one another but not with other species.

BIOLOGICAL CLASSIFICATION

The Linnaean system of classification

Besides developing the binomial system, Linnaeus also grouped similar organisms into a **hierarchy**. The hierarchy places species into groups that are increasingly more inclusive. This system is known as the **Linnaean system**. The first grouping is built into the binomial, where species with the most similar characteristics are grouped together into the same **genus** (plural: genera).

For example, sugar gliders (*Petaurus breviceps*) are small possums with a relatively short head, grey fur and a membrane attached to their sides and limbs that allows the animal to glide from tree to tree (Figure 6.1.12). Sugar gliders belong to the same genus *Petaurus* as yellow-bellied gliders (*Petaurus australis*). Yellow-bellied gliders, as their name suggests, have yellowish fur on their belly (Figure 6.1.13). Although not identical to each other, sugar gliders and yellow-bellied gliders are so similar in size, shape and ability to glide that they can be put together to form a larger group of gliders, a genus.

FIGURE 6.1.12 A sugar glider (*Petaurus breviceps*) with limbs outstretched showing the membrane attached to its sides.

FIGURE 6.1.13 Yellow-bellied gliders (*Petaurus australis*) are similar in form and structure to sugar gliders, but features such as fur colour distinguish them as a different species.

BIOFILE

Splitters and lumpers

Taxonomists are often described as either 'splitters' or 'lumpers'. Splitters separate organisms into species on the basis of small differences. Lumpers group organisms together even when there are seemingly distinct differences. For example, splitters once separated the Australian magpie into seven different species, based on their geographical distribution and differences in the pattern of black and white feathers. Lumpers grouped them under one species because they thought these differences were not significant. Today we know the lumpers were right; all Australian magpies belong to one species, *Cracticus tibicen*. The other 'species' are now subspecies, such as *Cracticus tibicen dorsalis*, sometimes called the Western Australian magpie.

Similar genera are grouped together into a **family**, families are grouped into an **order**, orders are grouped into a **class**, classes are grouped into a **phylum** (plural: phyla), phyla are grouped into a **kingdom**, and kingdoms are grouped into a **domain** (Figure 6.1.14). At each level the difference between groups becomes greater; two species in the same genus will be much more similar than two families in the same order.

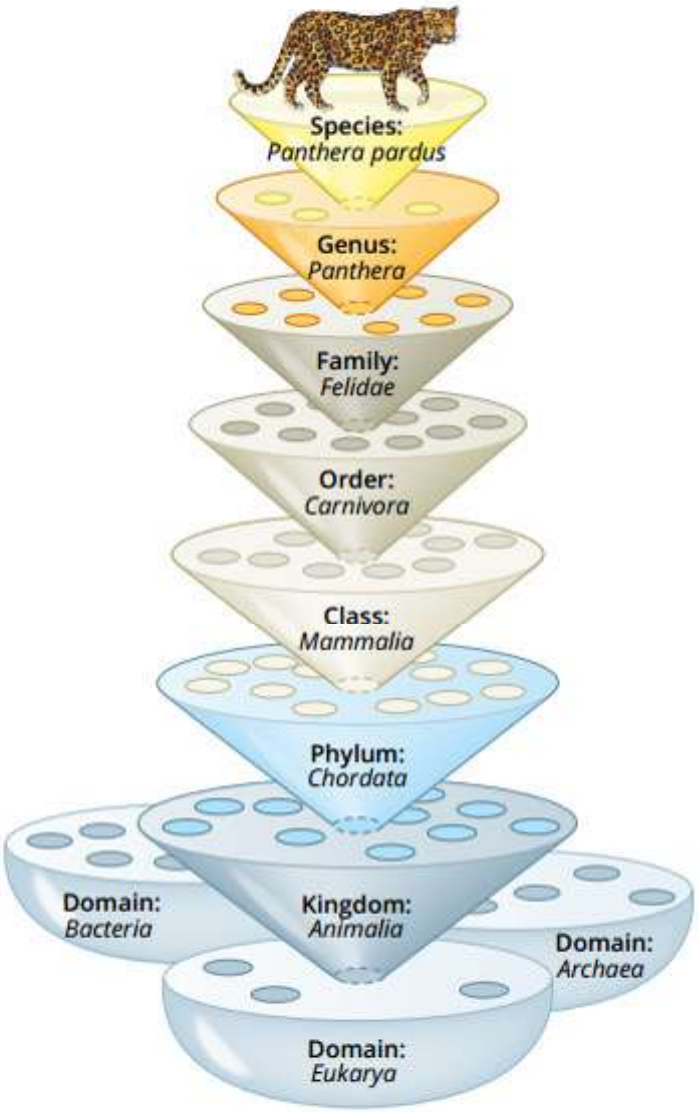


FIGURE 6.1.14 At each level in the Linnaean system, organisms are placed into groups that are more diverse. An easy way to remember the order of the groups is to use this mnemonic: Do Kings Play Chess On Fine Glass Surfaces?

EXTENSION

Subspecies and hybrids

Subspecies

Some species show variation in form between populations across their total geographic range. The differences may be slight, or the forms may intergrade and not be clear-cut. In these cases, taxonomists recognise **subspecies** to convey this information. Subspecies usually have different geographical distributions from each other. For example, the tiger (*Panthera tigris*) was once classified into eight subspecies based on geographical distribution.

Today the extant tigers are classified into six subspecies (Amur, Bengal, Indochinese, Malayan, South China and Sumatran) based on DNA studies. The remaining three subspecies—the Caspian, Javan and Bali tigers—have been hunted to extinction. All other subspecies are endangered and only a very small number of South China and Sumatran tigers survive, mainly in zoos. The Indian subspecies, known as the Bengal tiger (Figure 6.1.15), has the largest population, estimated to be less than 2500.

FIGURE 6.1.15 The Bengal tiger (*Panthera tigris tigris*) is a subspecies of tiger.

Hybrids

Although members of different biological species do not generally interbreed in nature, there are exceptions, such as hybrids, which can occur when closely related species are kept together in game parks or zoos (rather than natural habitats). The liger (the offspring of a male lion and a female tiger) and tigon (the offspring of a male tiger and a female lion) are examples of such hybrids. It is also apparent that many insects breed across species.

The offspring from cross-breeding of two species is called a hybrid. Many of the plants sold in your local nursery are hybrids. They are indicated by a cross in their name; for example, *Grevillea juniperina* x *victoriae* is a hybrid between *Grevillea juniperina* and *Grevillea victoriae*. The best-known animal hybrid is the mule, which is the hybrid offspring from a mating between a male donkey and a female horse (Figure 6.1.16). Most mules are sterile (unable to produce offspring).

FIGURE 6.1.16 A mule (on the left) and a horse (on the right). A mule is a hybrid between a male donkey and a female horse.

BIOFILE

Writing subspecies and varieties

Subspecies are recognised for animals, but varieties are not. The subspecies name is written immediately after the species name, as in the Bengal tiger *Panther tigris tigris* and the Sumatran tiger *Panther tigris sumatrae*.

Subspecies as well as varieties are recognised for plants. They are written using the abbreviations 'subsp.' and 'var.'. For example, *Zieria arborescens* subsp. *decurrens* is a subspecies of the forest zieria, and *Zieria aspalathoides* var. intermedia is a variety of the hairy zieria.

If you are writing names by hand you use an underline instead of italics.

BIOLOGY IN ACTION

Naming 'bush tucker'

For tens of thousands of years, Australian Aboriginal people have exploited an extensive range of native plants and animals for food, medicines and materials. They eat seasonal fruits, nuts, roots, vegetables, meats and fish, and, like other cultures, they named the organisms that they used, with different clans using different names.

When Europeans arrived they gave English names to Australian plants and animals. Since then scientists have named them according to the binomial system. Although the words used by Aboriginal people and scientists are different, the organisms that are recognised and grouped together under a given name are very similar (Table 6.1.1).

Australia's first European settlers did not benefit from the Aboriginal people's extensive knowledge of native plants and animals. Although surrounded by edible food, the settlers sometimes nearly starved, and a few who decided to 'eat and see' died. For example, eating the tempting cycad nuts (Figure 6.1.17) made settlers violently ill (fortunately preventing them eating enough to seriously harm themselves) and killed their pigs and cattle. But this nut was a staple in the diet of Aborigines from Arnhem Land, the Kimberleys and Cape York. The Yolngu people of north-eastern Arnhem Land call the cycad 'ngathu'. Aboriginal people were well aware of the toxic nature of the nuts and knew how to treat them for safe eating.

FIGURE 6.1.17 The ripe nuts of cycads are pounded, soaked and fermented to make bread. An Aboriginal name for cycads is ngathu; the scientific name for one cycad species is *Cycas armstrongii*.

Aboriginal name	English name	Scientific name	Use
ngathu	cycad	*Cycas armstrongii* *Cycas media*	nuts edible but highly toxic unless prepared properly
djalad	kurrajong	*Brachychiton diversifolium*	edible seeds in poisonous pods
djaburu	native grape	*Ampelocissus acetosa*	fruit eaten in season
bara	bush potato	*Operculina brownii*	tuber roasted on fire
jitama (gunu)	round yam	*Dioscorea bulbifera*	poisonous if not cooked and leached
ganguri	long yam	*Dioscorea transversa*	roasted, tastes like sweet potato
murunga	wild plum	*Terminalia ferdinandiana*	50 times more vitamin c than citrus fruit
ngaru	desert tomato	*Solanum petrophilum*	many Solanum species are important desert staples; others are highly poisonous

TABLE 6.1.1 Aboriginal, English and scientific names of some Australian plants.

Table 6.1.2 compares the group names for Leadbeater's possums, red kangaroo, agile wallaby and redback spider. The red kangaroo is more similar to the agile wallaby because both are in the genus *Macropus*. Leadbeater's possum, red kangaroo and agile wallaby share the same class (Animalia) as redback spiders but there are very little similarities in their form and structure.




Group	Leadbeater's possum	Red kangaroo	Agile wallaby	Redback spider
Kingdom	Animalia	Animalia	Animalia	Animalia
Phylum	Chordata	Chordata	Chordata	Arthropoda
Class	Mammalia	Mammalia	Mammalia	Arachnida
Order	Marsupialia	Marsupialia	Marsupialia	Araneae
Family	Petauridae	Macropodidae	Macropodidae	Theridiidae
Genus	*Gymnobelideus*	*Macropus*	*Macropus*	*Latrodectus*
Species	*Gymnobelideus leadbeateri*	*Macropus rufus*	*Macropus agilis*	*Latrodectus hasseltii*

TABLE 6.1.2 Sample classification of four organisms.

Phylogenetic classification

The Linnaean system of classification was based only on the morphological characteristics of organisms, especially their reproductive structures. It was created before scientists understood how organisms evolved. Once the theory of evolution became accepted by scientists, biologists began to analyse the likely evolutionary history (phylogeny) of organisms and use this information to classify them. This is known as phylogenetic classification.

Patterns of morphological or genetic characters (or both) can be represented in a branching diagram called a **phylogenetic tree**. The phylogenetic tree, which is like a family tree, is a useful way to show the evolutionary relationship between organisms, which is called a **phylogeny**.

For example, the sugar glider (*Petaurus breviceps*) and the yellow-bellied glider (*Petaurus australis*) belong to the same genus *Petaurus* and can be grouped together (Figure 6.1.18).

BIOFILE

Classification by post

The biological classification of an organism is like a global postal address that identifies a person (species) living in a house or unit or flat (genus) in a street (family) in a suburb (order) in a city or town (class) in a state or territory (phylum) in a country (kingdom) on a continent (domain).

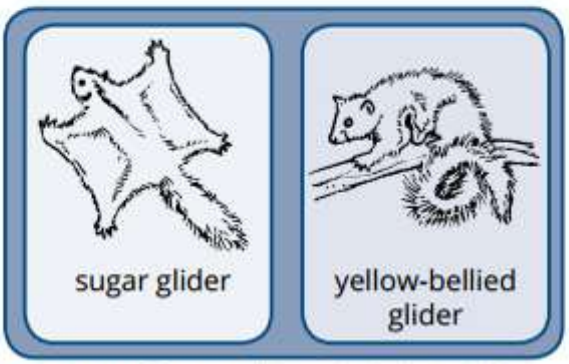


FIGURE 6.1.18 The sugar glider and yellow-bellied glider are similar morphologically and are placed into the same genus.

BIOFILE

The Madagascan fossa

The fossa (*Fossa fossana*) of Madagascar is a large, cat-like carnivore, closely resembling a small panther. It has a long, slender body, a short head, padded feet with retractable claws, a long tail and small rounded ears. Phylogenetic analyses based on morphology traditionally placed the fossa in the cat family, Felidae. However, recent DNA studies have shown conclusively that it is not a cat at all, and it is now classified in the family Eupleridae, along with several other native Madagascan carnivores.

FIGURE 6.1.22 The cat-like fossa, *Fossa fossana*.

Leadbeater's possum (*Gymnobelideus leadbeateri*) does not glide, but it shares many features with the sugar glider and yellow-bellied glider, so together they form a larger group of possums (Figure 6.1.19).

FIGURE 6.1.19 Leadbeater's possum (*Gymnobelideus leadbeateri*) does not glide, so it is not placed into the same genus as sugar gliders and yellow-bellied gliders.

The striped possum (*Dactylopsila trivirgata*), is part of an even larger group with these other animals. This pattern of groups can be represented by the Linnaean system (Figure 6.1.20) or using a phylogenetic tree (Figure 6.1.21). A phylogenetic tree is like a family tree. Each branch point shows the most recent common ancestor of the organisms. From the phylogenetic tree, it can be deduced that the sugar glider is the closest relative of the yellow-bellied glider, and that the common striped possum is the most distant relative. The tree, and the Linnaean classification, depict the evolutionary history of this group of possums.

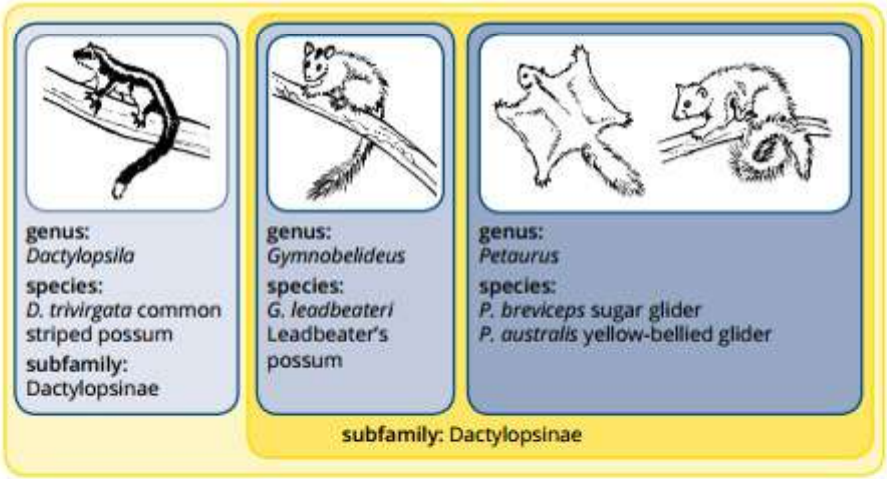


FIGURE 6.1.20 A classification of four possum species using the Linnaean system. The sugar glider and yellow-bellied glider are classified in the same genus.

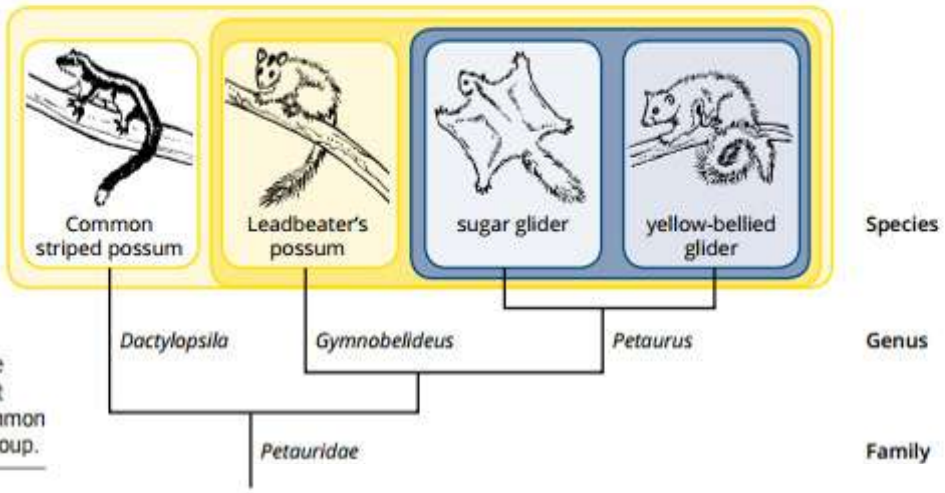


FIGURE 6.1.21 Using the Linnaean system, a phylogenetic tree can be constructed. From this tree it can be deduced that the sugar glider is the closest relative of the yellow-bellied glider, and that the common striped possum is the most distant relative in this group.

Sometimes a species might have been placed within a genus (or other group) of species to which it is not most closely related. For example, the house sparrow (Figure 6.1.24) was initially named *Fringilla domestica* by Linnaeus in 1758 because it has similar characteristics to other species in the genus *Fringilla*. But shortly after that the genus *Fringilla* was restricted to finches of the Old World, such as the common chaffinch *Fringilla coelebs* (Figure 6.1.25). So in 1760 Mathurin Jacques Brisson created the genus *Passer* for sparrows, and the house sparrow became *Passer domesticus*. If DNA or other new evidence indicates that such a mistake has occurred, the species may be reclassified to accurately reflect its evolutionary relationships with other species.

FIGURE 6.1.24 The house sparrow *Passer domesticus*.

FIGURE 6.1.25 The genus *Fringilla* includes three species: the common chaffinch, *Fringilla coelebs* (shown here), the blue chaffinch, *Fringilla teydea*, and the brambling, *Fringilla montifringilla*.

BIOLOGY IN ACTION

Scientific names are sometimes changed

Taxonomy is a field that is constantly evolving. Scientific names of species can change when scientific understanding of animal species and their evolutionary relationships change. For example, the genus *Felis* once included all small cat species. The genus has now been split into several genera to show the evolutionary differences between the species. For example, the bobcat of North America was once known by the scientific name *Felis rufus* but is now known as *Lynx rufus* (Figure 6.1.23).

FIGURE 6.1.23 The North American bobcat, *Lynx rufus*.

THE MAJOR GROUPS OF ORGANISMS: KINGDOMS AND DOMAINS

At the beginning of this chapter you learned that the Earth has a huge diversity of organisms. One of the challenges of modern biology is to discover the tree of life—how all these species are related and how all of the organisms that have existed on Earth evolved since life began.

Five kingdoms

In the 18th century, Linnaeus classified all living organisms into one of two kingdoms—Animalia and Plantae. Plants and animals certainly appear very different—animals move around and capture food, whereas most plants cannot move around and are green. In modern times, with the development of the techniques of biochemistry, cell biology and electron microscopy, other important and fundamental differences between organisms have been identified. These discoveries have led biologists to recognise other major groups of living organisms that have had to be placed in separate kingdoms. Until recently the most widely accepted system of classification recognised five kingdoms (Figure 6.1.26), which were the largest groupings of organisms:

- Protista (mostly unicellular organisms: eukaryotes)
- Plantae (land plants: eukaryotes)
- Fungi (fungi: eukaryotes)
- Animalia (animals: eukaryotes)
- **Monera** (bacteria: prokaryotes).

Although the five kingdom system of classification is sometimes still used, it has been largely replaced by a new system based on DNA evidence.

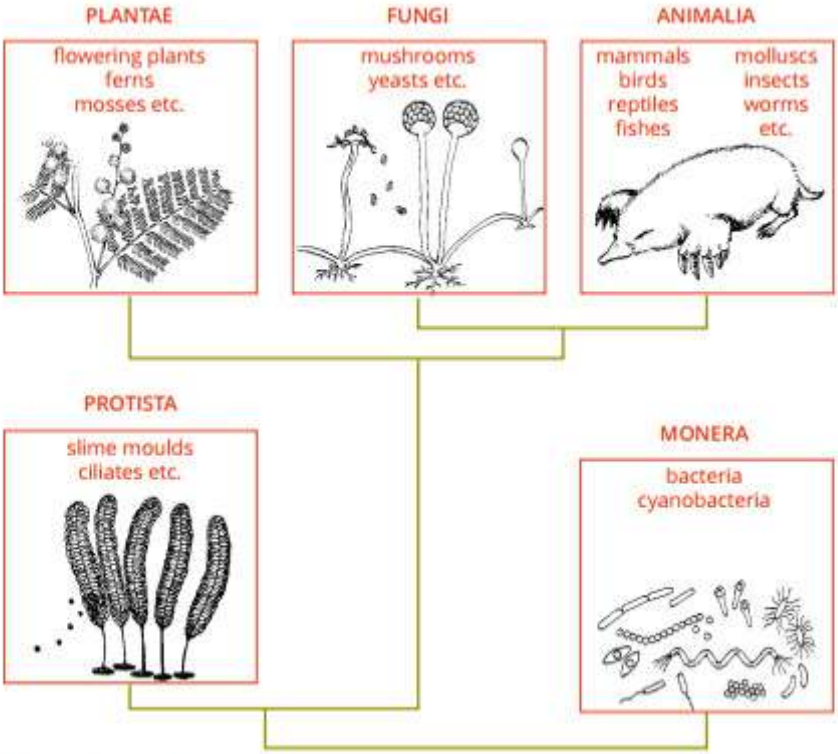


FIGURE 6.1.26 The five kingdoms of life.

Three domains

In the 1970s microbiologists Carl Woese and George Fox discovered two distinct lineages in bacteria, using DNA techniques that had only recently become possible. Woese went on to develop the theory that there are three major lines of evolution among living things, which he called 'urkingdoms'. Despite initial skepticism from leading biologists, more evidence gradually accumulated to show that Woese's theory was correct. By the 1980s it had become widely accepted, and is the system of classification that is used today.

The three-domain system recognises that there are two major lines of evolution among the bacteria, and that all eukaryotes (protists, plants, fungi and animals) are related to one another in another major lineage. The three major lineages are called domains (Figure 6.1.27). The old prokaryote kingdom of Bacteria is split into two domains, the **Bacteria** and **Archaea**, and the four eukaryote kingdoms are grouped together in the domain **Eukarya**.

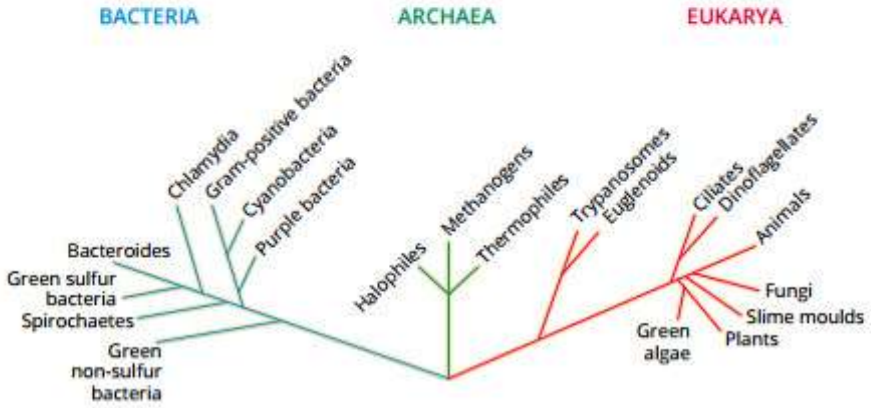


FIGURE 6.1.27 A phylogenetic tree showing the relationships of the major types of bacteria consisting of two major domains, Bacteria and Archaea. The other kingdoms form the domain Eukarya.

Bacteria

Bacteria are unicellular, microscopic prokaryotes (Figure 6.1.28). Fossil evidence has confirmed that bacteria were the first type of living organism on Earth, evolving about 3.5 billion years ago.

Bacteria have a very diverse cell chemistry (metabolism) and can survive in a great range of habitats and conditions. They play an important role in ecosystems because they break down many kinds of substances, including plant and animal remains and wastes. Bacteria include organisms that can fix atmospheric nitrogen into a form that other organisms can use.

Bacteria cause a wide variety of diseases for plants and animals, such as tomato wilt, citrus canker, tuberculosis, leprosy, tetanus, gonorrhoea, cholera and toxic shock syndrome. Some bacteria, however, can be used by humans to manufacture foods such as cheese and yoghurt, and medicines such as antibiotics, enzymes, drugs and even human insulin.

Prokaryotes are organisms with cells that do not have a membrane surrounding the nucleus and lack most organelles.

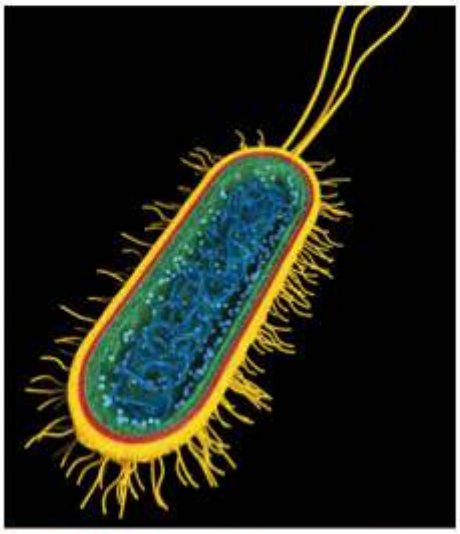


FIGURE 6.1.28 A model of the bacterium *Escherichia coli*, showing the lack of membrane-bound organelles.

Nitrogen fixation is the process by which nitrogen in the atmosphere is used to create nitrogen compounds that can be used by plants. It occurs only in some bacteria and archaea.

BIOLOGY IN ACTION

Bacteria: the most numerous organisms in the biosphere

Bacteria live on or in humans, other animals and plants, and in soil and water. They occur in environments of moderate temperature that are moist and low in salt, where sunlight or organic compounds are plentiful. Some bacteria can live with little or no oxygen—Eubacteria have many ways of extracting energy and fixing carbon. For example, they can use sunlight and carbon dioxide, reduce inorganic substances such as sulfide or ferrous ions, and even break down some plastics.

Gram-positive cocci (bacteria identified by their reaction to a particular stain) include *Staphylococcus* and *Streptococcus*, some of which can cause diseases in humans (Figure 6.1.29). Gram-negative bacteria include *Rhizobium leguminosarum*, which is an important associate of legume roots and fixes nitrogen (Figure 6.1.30) and *Escherichia coli*, a common inhabitant of human intestines. Cyanobacteria, once called blue-green algae (Figure 6.1.31) because they contain chlorophyll, often form dense mats in shallow estuaries, or toxic blooms in fresh water. They can also fix nitrogen.

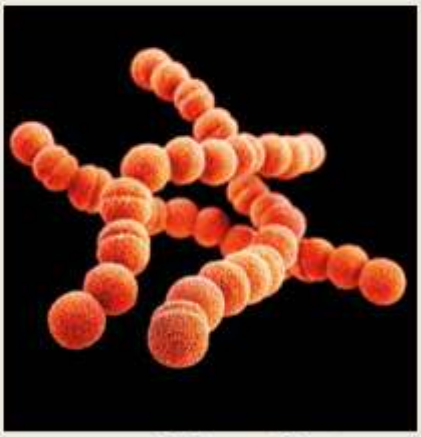


FIGURE 6.1.29 A 3D image of *Streptococcus pyogenes* bacteria.

FIGURE 6.1.30 A computer-generated model of a *Rhizobium leguminosarum* bacterium (coloured green) on the root hair of a pea plant, *Pisum sativum*. The bacterium fixes nitrogen to form compounds that can be taken up by other plants.

FIGURE 6.1.31 A light micrograph of a cyanobacterium belonging to the genus *Anabaena*.

Archaea

FIGURE 6.1.32 Morning Glory pool is a hot spring colonised by colourful thermophilic bacteria in Yellowstone National Park, Wyoming, USA.

Archaea include prokaryotic organisms that can live at high temperatures (thermophiles) (Figure 6.1.32), in acidic environments (acidophiles) or in very salty environments (halophiles). Although archaeans have evolved over billions of years, they have stayed within their specialised environments. Despite their name, archaeans evolved after bacteria and are the closest relatives of the eukaryotes.

Archaeans include methanogens, which use hydrogen gas and carbon dioxide to generate the energy needed to make sugars, releasing methane gas in the process.

Eukarya

This domain includes all eukaryotic organisms. They have cells that have membrane-bound organelles (for example a nucleus and mitochondria). They represent the vast majority of organisms we see each day. The Eukarya include the kingdoms Protista, Fungi, Plantae and Animalia.

Table 6.1.3 summarises the differences and similarities between the cells of the organisms in the four kingdoms in the domain Eukaryota.

Kingdom	Cell differentiation	Mitochondria	Chloroplasts	Cell wall
Protista	no (one cell type)	present or absent	present in some	present in some
Fungi	yes	present or absent	absent	present (chitin)
Plantae	yes	present	present	present (cellulose)
Animalia	yes	present	absent	absent

TABLE 6.1.3 A summary of the differences and similarities between the cells of the organisms in the four kingdoms in the domain Eukarya.

The kingdoms of Eukaryota

Protista

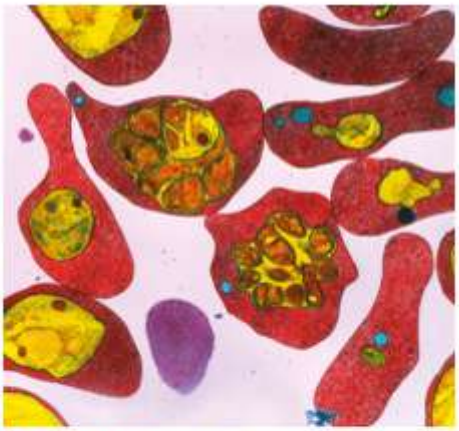


FIGURE 6.1.33 A coloured TEM of a section through a red blood cell infected with a malaria parasite (*Plasmodium* species), coloured green. The red blood cells appear misshapen because they are swollen by the presence of the parasite.

The kingdom **Protista** (consisting of 30–40 phyla) is a diverse group of eukaryotic organisms, including algae, diatoms, dinoflagellates, protozoans, water moulds and slime moulds. Most protists are unicellular but some are multicellular, such as seaweeds. Kelps (brown algae) belonging to the genus *Macrocystis*, are the largest seaweeds. *Macrocystis pyrifera* grows up to 60 metres long in Californian waters and *Macrocystis angustifolia* grows up to 10 metres long in the waters around Tasmania. Protists are a very diverse group. Some protists are plant-like, some are fungi-like and others are animal-like, making it difficult to classify protists based on morphology. For this reason, DNA sequencing will probably be a very important tool in the classification (and reclassification) of protists.

One defining characteristic of protists is that, unlike animals or plants, they do not contain more than one clearly differentiated functional tissue. They inhabit moist environments, including fresh water and salt water. Most are free-living, but some are parasites that cause diseases such as malaria (Figure 6.1.33).

i Autotrophs are able to synthesise their own food from inorganic substances (such as carbon dioxide and water) using light or chemical energy.

Plantae

The kingdom **Plantae** is the most conspicuous group of producer organisms on land. As with some protists and cyanobacteria, plants are autotrophs (self-feeders). They manufacture their own food by photosynthesis, using chlorophyll to capture light energy for the manufacture of glucose from carbon dioxide and water. The plant cell wall is made of the polysaccharide cellulose. Plants are multicellular and include small and structurally simple forms, such as mosses (Figure 6.1.35a) and liverworts (Figure 6.1.35b) and large and more complex forms, such as ferns (Figure 6.1.36) and seed plants. Living seed plants include cycads, ginkgo, conifers and flowering plants, but flowering plants dominate the landscape (Figure 6.1.37). Kingdom Plantae contains the largest and longest-living organisms on Earth.

BIOFILE

Giardia

Giardia species are parasites that can live in the intestines of humans and other animals. In humans *Giardia lamblia* causes abdominal cramps and diarrhoea. It is a unicellular protist that is identifiable by its two nuclei, flagella, and a disc on its ventral side that allows it to attach itself to its host's gut (Figure 6.1.34). Infection is spread by cysts from faeces in contaminated water. In 1998 *Giardia* was identified in Sydney water, possibly contaminated by flood water. Sydney residents had to boil drinking water to avoid contracting giardiasis.

FIGURE 6.1.34 A *Giardia* parasite.

FIGURE 6.1.35 (a) Lambtail moss, *Leucobryum aduncum*, and (b) golden pocketwort, *Schistochila brotheri*.

FIGURE 6.1.36 Kermadec tree-fern, *Cyathea kermadecensis*.

FIGURE 6.1.37 Some examples of living seed plants. (a) Burrawang, *Macrozamia communis*, an Australian cycad. (b) Ginkgo, *Ginkgo biloba*, native to China. (c) Huon pine (*Lagarostrobos franklinii*), a conifer native to Tasmania. (d) Brown stringybark, *Eucalyptus baxteri*.

BIOFILE

Tall and long-lived plants

The tallest flowering plant species in the world is the Australian mountain ash (*Eucalyptus regnans*), which can grow to over 100 metres in height and can live for about 400 years (Figure 6.1.38). The longest-lived tree species is a conifer, the giant redwood of California (*Sequoiadendron giganteum*), which can reach 4000 years of age (Figure 6.1.39).

FIGURE 6.1.38 The mountain ash (*Eucalyptus regnans*) of south-eastern Australia is the tallest of all flowering plants.

FIGURE 6.1.39 The giant sequoia (*Sequoiadendron giganteum*) of California is thought to live for up to 4000 years. It is the tallest plant in the world.

Fungi

The kingdom **Fungi** includes common organisms such as mould, mushrooms, yeasts, lichens and truffles (Figure 6.1.40). Fungi are a distinct group because they secrete enzymes over the surface of their food and absorb the breakdown products directly. They are non-motile (cannot move by themselves) like plants, but unlike plants they do not photosynthesise. The fungal cell wall is made of the polysaccharide chitin. The main body of a fungus is usually hidden in soil or in the tissue of their food source. Except for yeasts, fungi consist of minute thread-like structures called **hyphae** (singular: hypha). They reproduce by spores produced in fruiting bodies, e.g. a mushroom. Fungi, together with bacteria, are ecologically important in decomposing biological material, causing diseases and spoiling foods. Some fungi form a symbiotic relationship with algae, forming lichens (see Section 7.1); lichens are classified according to the fungal partner. Some fungi are important sources of medicines. Particular species (e.g. *Penicillium camembertii* and *Penicillium roquefortii*) are used to make different types of cheeses, and yeasts are important in brewing beer and making wine.

FIGURE 6.1.40 Examples of organisms found in the kingdom Fungi: (a) mould such as black bread mould (*Rhizopus stolonifer*), (b) mushrooms such as fly agaric (*Amanita muscaria*), (c) lichens such as coral lichen *Cladia retipora* and (d) truffles such as black perigord (*Tuber melanosporum*).

Animalia

Members of the kingdom **Animalia** are unable to synthesise their own food, so they are heterotrophs (that is, they feed on other organisms). The animal kingdom is an extremely diverse group of organisms, living in the sea, in fresh water and on land. All animals are multicellular. They include sponges, worms, molluscs, crustaceans, insects, spiders, sea stars, fishes, amphibians, reptiles, birds and mammals including humans. Most animals can move around to find food, nesting sites and mates. But many marine animals, such as coral polyps, mussels and barnacles, cannot. They obtain their food from the water flowing around them, and release their eggs or sperm into the water to reproduce.

BIOFILE

Pilobolus crystallinus: specialised dung fungus

Pilobolus crystallinus is a very specialised dung fungus that has evolved a way to shoot its spores away from the dung and onto nearby grasses, where it will be eaten by herbivores. Its 'shotgun' is a stalk swollen with cell sap, bearing a black mass of spores on the top. Below the swollen tip is a light-sensitive area. The light-sensitive area affects the growth of *Pilobolus* by causing it to face towards the Sun. As the fungus matures, water pressure builds in the stalk until the tip explodes, shooting the spores into the air. The spores fly away at almost 40 km/h, reaching a height of 2 metres and landing up to 2.5 metres away.

FIGURE 6.1.41 *Pilobolus crystallinus*, commonly known as the dung cannon or hat thrower.

Viruses: genetic parasites

The broad classification of organisms is based on cellular and metabolic differences, but viruses are not considered to be living organisms because they are not made up of cells. Viruses exist between the living and non-living world. They are very small and usually cannot be seen under a light microscope. An electron microscope is needed to study their structure (Figure 6.1.42). However, viruses are part of biodiversity on Earth. They transmit and transfer genetic information. They infect and invade cells and can have major impact on life. It is thought that viruses probably originated from cells.

Viruses are obligate intracellular parasites, meaning they must invade a living cell in order to replicate. They have two stages. The first stage, called a **virion**, enables the virus to infected another organism. A virion comes apart when it enters a cell of a suitable host, and the genetic material forms the second stage that can reproduce. Viruses cannot reproduce by themselves. Instead, the nucleic acid of the virus takes over the host's replication mechanisms, forcing the host cell to manufacture new copies of the virus.

Viruses are classified according to the type of genetic material (DNA or RNA), size, coat proteins and their host organisms. Virus classification and identification is important for monitoring the spread of damaging infections in crops and animals. For example, monitoring changes in human influenza viruses each year through DNA sequencing to identify new strains based on changes in the coat protein, is essential for developing the correct vaccine for each 'flu season'.

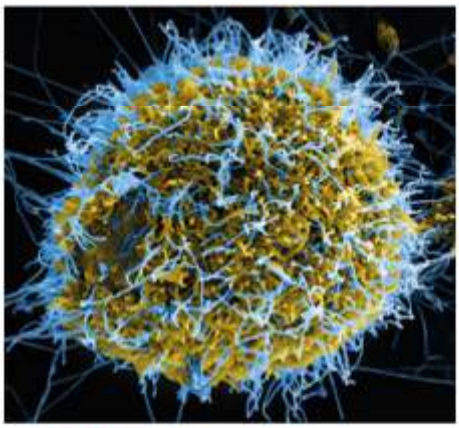


FIGURE 6.1.42 Coloured scanning electron micrograph (SEM) of ebola virus particles (blue) budding from an infected cell.

BIOFILE

Viruses that can be seen using a light microscope

Most viruses cannot be seen using a light microscope because of their small size. However, three genera of viruses can be seen: *Pandoravirus* (about 1 µm) (Figure 6.1.43), *Megavirus* (about 0.7 µm) (Figure 6.1.44a), and *Mimivirus* (about 0.6 µm) (Figure 6.1.44b). All three infect amoebas.

FIGURE 6.1.43 Pandoraviruses have been found in samples collected off the coast of Chile, and in a pond in Melbourne, Australia.

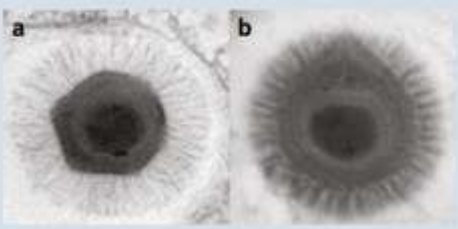


FIGURE 6.1.44 Electron microscope images of (a) *Megavirus* and (b) *Mimivirus*.

6.1 Review

SUMMARY

- Life on Earth consists of a great diversity of living organisms, which we call biodiversity. Each organism that is discovered is classified and given a unique scientific name so that it can be identified accurately.
- Classification is the grouping of organisms on the basis of features that they have in common.
- Taxonomy is the naming of these groups scientifically.
- Classifying and naming organisms:
  - enables effective communication between scientists all around the world because every organism has only one scientific name
  - enables us to group organisms in a hierarchy so features can be compared between and within different groups
  - enables quick and efficient identification of living things, which helps in other areas of biology such as conservation, ecology, pest control, toxicology, and medicine
  - enables scientists to learn about the evolutionary relationships between different organisms
  - enables us to recognise an organism that is beneficial, poisonous or dangerous.
- The scientific name of each species consists of two parts: genus and species.
- The system of using a two part name is called the binomial system. It was developed in the 18th century by Carl Linnaeus.
- The genus name always begins with a capital letter, and the species begins with a lower-case letter. The names are italicised when typed, or they can be underlined instead.
- The species is the basic unit of classification. Members of a single species are so similar to each other that they can breed and produce offspring that resemble one of the parents. Different species generally do not interbreed in the wild.
- Classification of organisms is based on morphological or genetic characteristics, or both.
- Biological classification is hierarchical: species are classified together into genera, genera into families, families into orders, orders into classes, classes into phyla and phyla into kingdoms.
- Characteristics of species can be used to construct a phylogenetic tree to show the evolutionary relationships between organisms.
- Genetic information from DNA analysis often causes species to be reclassified into a different group.
- Some classifications group organisms into three domains: Bacteria, Archaea and Eukarya. Eukarya includes the four eukaryote kingdoms Protista, Fungi, Plantae and Animalia.
- The classification most widely used includes the five kingdoms: Bacteria (Monera), Protista, Fungi, Plantae and Animalia.
- A virus is not an independent cellular organism (it is not made up of cells); it is an intracellular parasite composed of genetic material and protein. There is a whole classification system for viruses, based on DNA, size, capsid structure and host organism.

KEY QUESTIONS

1 Define 'biodiversity'.

2 List four benefits of classifying and naming organisms.

3 The scientific naming of species is based on a binomial system.
   - **a** What does 'binomial' mean?
   - **b** What classification groups are used in the name of a species?
   - **c** What conventions are used when writing the name of a species? Give an example.

4 Write a definition of 'species'.

5 In the Linnaean system of classification, what characteristics are used in the classification of organisms?

6 Rewrite the following list of taxon names from the most general taxon to the least general taxon: class, domain, family, genus, kingdom, order, phylum, species

7 What does a phylogenetic tree show?

6.2 Managing biodiversity

We rely on the biodiversity of the planet for our lives. We need to grow food, use timber as a building material and use plants to make an extensive variety of medicines and other products. Maintaining Earth's biodiversity is essential because it is a reservoir for bioprospecting new food sources and medicinal drugs. Bioprospecting is the exploration of biodiversity for new resources, such as chemical compounds and genetic material that has social or commercial value.

While there is a struggle for survival between species in an individual **ecosystem**, all are dependent on ecosystems functioning as a whole for survival. Our survival depends on ensuring that species and habitats are not lost as a result of how we use ecosystems, so we have to learn to use, manage, and at the same time conserve endangered species such as the bilby and their habitats.

WHY CONSERVE BIODIVERSITY?

Conservation of species

One of the key reasons for the conservation of species is what Harvard biologist Edward Wilson calls biophilia, which is our sense of connection to nature and all life. In addition, a common belief in many religions is that other living things are entitled to life, and this also forms the basis of a moral argument that we should protect biodiversity. Finally, a healthy biodiversity of organisms provides aesthetic, ecological and practical benefits for humanity.

Aesthetic value

People appear to need the beauty and harmony of natural landscapes of trees, mountains, lakes and wildlife (Figure 6.2.2). Our feelings for animals, for example, are easily aroused. We quickly learn to love koalas and pandas, and we feel a kinship with chimpanzees and endangered orangutans (Figure 6.2.3).

FIGURE 6.2.2 Scenes like this one of pink flowers growing on the side of a mountain at sunset evoke feelings of happiness and contentment in humans.

FIGURE 6.2.3 Seeing this orangutan with her baby in Borneo evokes positive feelings about the importance of maintaining biodiversity. Orangutans could become the first great ape to become extinct in the wild.

Ecological value

Plants, animals and microorganisms have ecological value. Plants are producers of food, and during photosynthesis they release the oxygen that we breathe. Plants also provide shelter and nest sites for animals. Animals in turn pollinate flowers, and many animals also disperse seeds (Figure 6.2.4). Predators keep prey numbers in check. All organisms depend on certain bacteria and cyanobacteria for nitrogen fixation in ecosystems. And without fungi and bacteria there would be no decomposition of dead matter.

BIOFILE

The endangered bilby

Before European settlement the bilby (*Macrotis lagotis*) occupied about 70% of mainland Australia. Today bilbies are found only in scattered, isolated populations in semi-arid to arid grasslands and acacia shrublands. Because of this the bilby is considered to be an endangered species and is protected by law. Bilbies have been bred in captivity recently and released into the wild in the Currawinya National Park in south-eastern Queensland.

FIGURE 6.2.1 The bilby (*Macrotis lagotis*).

FIGURE 6.2.4 The southern cassowary (*Casuarius casuarius*) is an important disperser of rainforest seeds in north-eastern Queensland. But continuing clearing and fragmentation of rainforest, and increased mortality from cars and dogs, have reduced cassowary numbers to perhaps as few as 2000, threatening the species with extinction.

BIOFILE

Protecting native species

In Victoria almost all native species are protected by law, and a special permit is required to collect plants or animals. In addition, the *Flora and Fauna Guarantee Act 1988* gives special recognition to species and communities that are threatened with extinction, and also processes that threaten native species.

The list of species that are threatened includes 384 plants, 77 birds, 39 mammals, 35 insects, 29 reptiles, 31 fish, 18 crustaceans, 12 frogs, 10 molluscs, 7 echinoderms, 2 lichens, 1 fungus, 1 cnidarian, and 1 earthworm.

The Act also lists 37 threatened communities of flora and fauna, and 42 processes that are considered to threaten endangered species, such as predation of native wildlife by foxes and cats.

FIGURE 6.2.5 Common heath (*Epacris impressa*) is Victoria's floral emblem.

Practical value

Organisms have practical values for humans (Figure 6.2.6). The following are examples of biological resources provided by organisms:

- Food—More than 600 species of finfish and shellfish are caught and sold in Australia for human consumption
- Medicines and drugs—About 25% of prescribed medicines contain natural plant compounds. Many other prescribed medicines are synthetic versions of natural compounds.
- Industrial materials, including wood, fibres, dyes, resins, gums, rubber and oil.
- Ornamental plant —More than 2500 Australian native plant species are listed as useful in horticulture.
- Crop pollinators—39 of the 57 global crops benefit from natural pollinators such as birds and insects.
- Breeding stocks and population reservoirs.
- Future resources—bioprospecting of new food and medicinal drugs.
- Engineering and design—Biomimicry is a new branch of science that studies the structure and function of organisms and applies this knowledge to solve practical problems.
- Plants for the restoration of waste land after mining.
- Diversity in genes, species and ecosystems—For example, diversity in genes and species can help to protect crops from devastating diseases, such as potato blight that cause a famine in Ireland in the 1840s.

FIGURE 6.2.6 (a) Blue mussels (*Mytilus galloprovincialis*) are commonly grown in aquaculture farms. (b) The tea tree oil from the tea tree plant (*Melaleuca alternifolia*) has antiseptic properties. (c) The blue banded bee (*Amegilla cingulate*) is an Australian native bee that is very important for the production of at least 30% of crops in Australia, by assisting with pollination.

BIOFILE

The Irish potato famine

In the 1800s the Irish imported a variety of potato from South America to feed a growing population in Ireland. The potatoes were grown asexually through vegetative propagation, so all the potato plants were genetically identical to one another. When the potato crops were infected by the plant pathogen *Phytophthora infestans* in the 1840s, the entire crop was destroyed because the lack of genetic diversity meant every potato was susceptible to the disease.

The Irish potato famine is a reminder of the importance of maintaining biodiversity in crops. The famine was responsible for the death of over 1 million people between 1845 and 1851. Another 1 million fled the country.

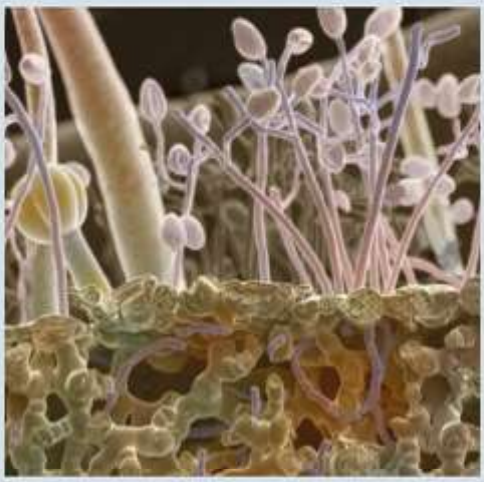


FIGURE 6.2.7 SEM of *Phytophthora infestans*.

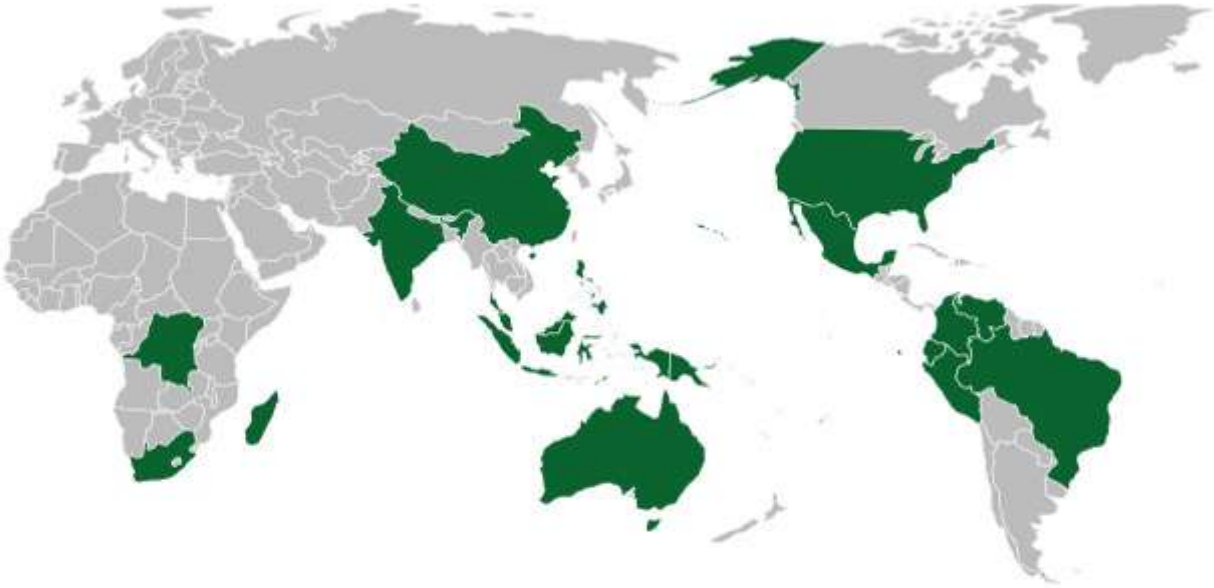


FIGURE 6.2.8 Earth's 25 terrestrial biodiversity hotspots (in green). Biodiversity hotspots cover a small fraction of the Earth but are home to a large number of species.

Reasons for conserving habitats

Some species have to be saved from the brink of extinction by growing them in special nurseries or breeding them in captivity, but saving species is best done by saving habitats and ensuring that populations are stable or increasing. Rainforests, woodlands, heathlands, grasslands, wetlands and coral reefs are among the most endangered habitats on Earth.

One obvious reason for saving areas of habitats is that it ensures the protection of a diversity of organisms. There are many species in a pond, or in the litter of a eucalypt forest, that we rarely see. Many insects, spiders, crustaceans, plants, protists, fungi and bacteria are undescribed and unnamed. They are all part of the food web and they are all important in maintaining the balance of the ecosystem.

Conserving certain types of habitats is especially important because they support many more species than others. Areas that have large numbers of species, especially **endemics** (species that are only found in one area of the world), are often referred to as 'hotspots' (Figure 6.2.8). Concentrating conservation efforts in these areas can help to maintain global biodiversity.

Another reason for the conservation of habitat is the interrelationships of organisms. For example, the broad-leaf ballart (*Exocarpos latifolius*) found in Northern Australia, is the food plant for the larval stages of a butterfly known as the fiery jewel (*Hypochrysops ignitus*), and it is also a parasitic tree that cannot survive without its host species (Figure 6.2.9). In the same way, endangered orchid species require their insect pollinators. Adult insects do the job of pollinating orchid flowers, but their larvae feed elsewhere. The plants that the larvae eat also have to be saved.

The population of the Tasmanian devil (Figure 6.2.10) has a low genetic diversity, possibly because the entire population on Tasmania originated relatively recently from a small group of animals. The rapid spread of Devil Facial Tumour Disease, and a lack of immunity among the devil population, is having a devastating impact on the species because of this low genetic diversity.

FIGURE 6.2.10 Tasmanian devils (*Sarcophilus harrisii*) may be at risk of extinction because of a lack of genetic diversity caused by inbreeding.

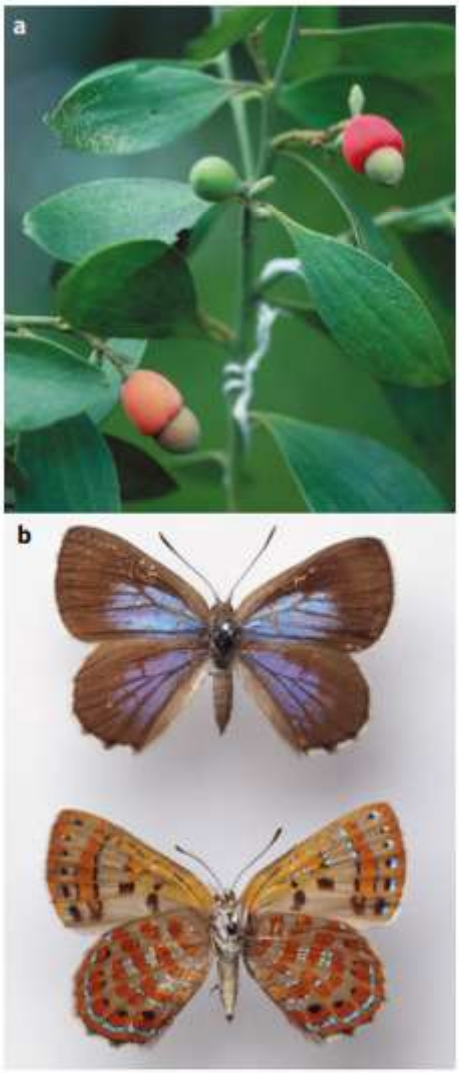


FIGURE 6.2.9 The broad-leaf ballart (*Exocarpos latifolius*) (a) is the food plant for the larval stages of the fiery jewel (*Hypochrysops ignitus*) (b).

STRATEGIES FOR MANAGING EARTH'S BIODIVERSITY

The world's biodiversity is under threat from many dangers. Humans have caused most of these. As the human population soars to more than 7 billion, the pressure on the natural ecosystems of the world is constantly increasing.

Conservation of species

There is no global consensus as to what constitutes an important species. However, species may be chosen for conservation if they fall into one of the following categories:

- species that are under threat of extinction
- species of ecological importance
- species that have economic value to humans
- species of cultural or social importance.

There are two main species-based conservation approaches:

- *in situ*, where the species is kept in its natural environment. This involves:
  - preserving the habitat through private purchase or government action
  - eliminating alien species from the area
  - managing protected areas to sustain native flora and fauna
  - restoring degraded ecosystems.
- *ex situ*, where the animal is bred in captivity, such as zoological gardens. This involves:
  - legally protecting the endangered species
  - managing the habitat
  - propagating the endangered species in captivity
  - reintroducing the species to the managed habitat.

Many conservationists prefer the in-situ approach because it means the species can interact with its environment, increasing its chance of survival. An ex-situ approach is needed if the population size is critical or there is too much damage to the habitat.

Establishing protected areas

Habitat loss is considered to be the primary cause of biodiversity loss around the world. To counter this, governments establish protected areas. Effective management of protected areas is essential to deal with human settlement, illegal harvesting or poaching, unsustainable tourism and impacts of alien species.

BIOFILE

Restoring regent honeyeater habitat

The regent honeyeater (*Anthochaera phrygia*) was once found throughout temperate woodlands and forests in south-eastern Australia. Today there are only a few fragmented populations in New South Wales and Victoria. The loss of woodland is the major cause of the decline, and continues to be a threat to the species. As part of conservation efforts, natural habitats of the regent honeyeater are being restored. For example, the regent honeyeater's native woodland habitat in the agricultural district of the Lurg Hills near Benalla in Victoria was restored by the community through revegetation.

FIGURE 6.2.11 Efforts are being made to protect the habitat of the regent honeyeater (*Anthochaera phrygia*) to ensure that it continues to survive in the wild.

BIOFILE

Numbat breeding program

The numbat (*Myrmecobius fasciatus*) was once found in southern and central Australia. But because of habitat destruction and the introduction of predators such as foxes and cats, the numbat is now found only in the Dryandra Woodland and Perup Nature Reserve in south-west Western Australia. The current population is about 1000.

As part of *ex situ* conservation, a breeding program has been established at Perth Zoo. In addition, numbats are also being reintroduced into managed predator-free sanctuaries such as Scotia Sanctuary in New South Wales.

FIGURE 6.2.12 The numbat (*Myrmecobius fasciatus*) population is rapidly declining. Populations of the numbat are stable only in managed predator-free habitats.

Protected areas may contribute to poverty in some countries where rural people are excluded from resources that have traditionally supported their way of life. The San bushmen from Namibia and Botswana (Figure 6.2.13) are an example of a people who have had to relinquish their way of life to make way for wildlife corridors, such as the Central Kalahari Game Reserve. The people are allowed limited access to protected areas but are no longer allowed to hunt or live off the land as they once used to. To support their families and supplement income, they show visitors aspects of their traditional life in their 'living museum'.

FIGURE 6.2.13 The Ju/Hoansi-San people of Namibia have been banned from their traditional way of life.

Prevention and control of invasive species

Some species can cause enormous damage by invading ecosystems where they do not normally occur. Species that become troublesome and occur where they are not wanted are known as **pest organisms.** Australia knows only too well the effect that pest organisms can have on our biodiversity. The cane toad, European rabbit, cat, red fox, lantana, prickly pear, water hyacinth and European carp have done extensive damage to the ecosystems they have invaded. These species out-compete or kill native species, or damage ecosystems so that native species cannot survive.

There are two strategies to counter pest organisms: prevention and control. The Australian Quarantine Inspection Service (AQIS) is responsible for preventing potential pest organisms entering Australia. Australia has extremely strict quarantine laws for this purpose.

If a pest species does become established, control measures need to be taken. These measures will depend on the type of organism. Pest plants can be controlled with herbicides, and insect pests can be controlled with insecticides. But the cost of herbicides and insecticides is usually high, and there is a risk of poison moving through food chains and affecting native species or humans. **Biological control**, which involves using a natural predator or parasite to control or eliminate pest species, is a more desirable method.

Plants

Herbicides are commonly used to kill pest plants, but some herbicides can have an adverse effect on native species, and some can be hazardous to humans. Removing the invasive species and replacing it with native vegetation is another strategy that is commonly used. Biological control has been successful, such as the use of the moth *Cactoblastis cactorum* to control the population of prickly pear, *Opuntia stricta* (Figure 6.2.14).

FIGURE 6.2.14 The prickly pear (*Opuntia stricta*) invaded farmland in Australia very quickly after its introduction. It out-competed native vegetation and became a pest for farmers. Biological control with the moth *Cactoblastis cactorum* destroyed almost all the prickly pears, and today they are rarely seen.

Animals

Control methods for animals include fencing, trapping, baiting, shooting and biological control. Biological control has also been used to control or eradicate feral species such as the European rabbit. In the 1950s the release of the **myxoma** virus killed 90% of rabbits as the virus swept through the temperate zone. Another virus, rabbit haemorrhagic disease virus (commonly known as rabbit calicivirus), also had success when it was released. However, rabbits that were naturally more resistant to these viruses survived and bred, and their resistance was passed on to their descendants. As a result rabbits today are largely resistant to the viruses.

Reducing pollution to protect species

Pollution created by humans can poison all forms of life on land and in water, and it is contributing to climate change. Transport, industry, construction, mining, power generation, volcanoes and bushfires all contribute polluting substances to the environment. These substances can directly cause death or disease in organisms, or alter the chemistry of the environment so that it is unfit for some organisms (Figure 6.2.15).

FIGURE 6.2.15 A sargassum fish (*Histrio histrio*) tangled in a discarded plastic rope.

BIOFILE

The mountain pygmy-possum and climate change

The tiny mountain pygmy-possum (*Burramys parvus*) could become a victim of climate change. It needs a snow depth over winter of at least one metre to provide enough insulation to keep it warm during hibernation. Snow compaction and the removal of boulders and vegetation cover, the development of ski fields, villages, car parks and roads have fragmented the pygmy-possum's habitat. Warmer temperatures could reduce the winter snow cover, exposing the animals to colder temperatures and making it even harder for them to survive the winter. A recovery plan for this species includes:

- establishing wildlife corridors to link populations that are separated
- revegetating damaged habitats
- minimising the environmental impact from skiers
- monitoring populations regularly
- eradicating introduced predators, including foxes and cats.

FIGURE 6.2.16 The mountain pigmy-possum (*Burramys parvus*).

Abiotic refers to the physical (non-living) parts of the environment such as water, soil and climate. Biotic refers to the biological parts of the environment, such as plants, animals and fungi.

By reducing pollution we can protect vulnerable species. While industry has a major role to play in reducing pollution, you can try to minimise your impact by:

- walking or cycling instead of travelling by car
- using a car that uses less fuel
- turning off electrical appliances when they are not being used
- choosing energy-efficient appliances
- using environmentally friendly cleaning products, which reduces the amount of phosphates and nitrates put into waterways
- reducing the amount of rubbish you generate by recycling and composting, and repairing rather than replacing goods
- limiting use of chemical fertilisers, pesticides, herbicides, and using environmentally friendly alternatives.

Combating climate change

Climate change is threatening many species that cannot evolve fast enough to cope with the increase in temperature. Extreme weather events may also pose a threat. Climate change will affect the abundance and distribution of organisms and will affect the crops we grow. If we can halt the increase in carbon dioxide levels, we may be able to prevent the devastating effects of climate change on species, habitats and ecosystems. International agreements such as the Kyoto Protocol aim to reduce the emissions of carbon dioxide world-wide, but not all countries are signatories to such agreements.

Regulation to counter overexploitation

Biodiversity is exploited mainly for food (meat, vegetables, fruits) and construction materials (wood, thatching) but also for industrial products, the pet trade, fashion and medicines. Most species can tolerate some exploitation without affecting the overall survival of its populations. However, overexploitation can push species towards extinction, upset the normal relationships between species in an ecosystem, and harm other species. For example, hunting a particular bird for food could reduce its numbers to an unsustainable level, reduce the food available to predators or cause predators to switch to another prey, and affect the survival of plants that depend on the bird for pollination or seed dispersal.

Overexploitation occurs because there is a benefit to the person who is exploiting the species, even though there might be an overall cost to other people and to the environment.

Overexploitation can often be managed by making strict laws and enforcing them, but this is often difficult to do in practice. For example, poachers in southern Africa will risk their lives to kill a rhinoceros for its valuable horn. The horn is sold as an ornament or more commonly ground up for use in traditional Chinese medicines, even though there is a lack of scientific evidence for any therapeutic value in rhino horn keratin. It is illegal to trade rhinoceros horns, however they fetch a very high price on the black market. Sometimes rangers at private game reserves remove rhinoceros horns as a deterrent to poaching. Even so, rhinoceroses are still killed by poachers for the remaining horn stub or as an act of vengeance.

According to the Australian Government, the main threats to biodiversity in Australian ecosystems include:

- loss, fragmentation and degradation of habitat
- the spread of invasive species
- unsustainable use of natural resources
- climate change
- inappropriate fire regimes
- changes to the aquatic environment and water flows.

BIOFILE

Grow your own rhinoceros horn

Rhinoceros horn is valuable mainly because of its use in traditional medicines. But it is made from the same keratin protein that forms human fingernails. Some scientists have suggested that people who pay large amounts of money for illegal powdered rhinoceros horn should save their money and just chew their own fingernails!

FIGURE 6.2.17 This black rhinoceros (*Diceros bicornis*) has had its horns removed by rangers at a private game reserve to deter poaching.

EXTENSION

Designing reserves

Throughout the world, governments put aside land for the preservation of animals, plants and ecosystems. Some reserves in the world are very large, covering thousands of square kilometres, such as the swamps of the Florida Everglades. But important reserves can also be quite small. For example, narrow reserves along roadsides and railway lines are important for many small animals and plants. Even home gardens can be important sources of food and nectar for birds. In Australia, Kakadu National Park, the Wet Tropics of Queensland, Lord Howe Island and the Great Barrier Reef are all listed as World Heritage Areas, which recognises their global importance (Figure 6.2.18).

Reserves that are small or fragmented may be unsuitable for animals that need large territories to search for food, build nests or find mates (Figure 6.2.19). Populations can become fragmented into small groups with a low genetic diversity. Small reserves are also more vulnerable to destruction. For example, a small group of trees can be damaged more severely by wind storms than a more extensive forest, where the trees buffer one another. Events such as fires and floods could also destroy a small reserve or make it uninhabitable for many species, and the animals might not be able to reach other suitable habitat.

If animals cannot find all the resources they need in a small fragment of habitat, especially food, they must try to reach other suitable habitat. This increases their chances of being killed by a predator, or run over by cars (Figure 6.2.20). Some small animals such as butterflies and birds are especially vulnerable to habitat fragmentation because they will not fly across clearings, even the width of a road.

Organisms in small reserves are more likely to be exposed to edge effects because of the relatively large length of the edges compared to the area of the reserve. Edge effects include an increase in sunlight and temperature, exposure to wind, lower humidity, and greater chance of invasion by pest plants and animals. The abiotic environment is quite different from the cool, dark, moist forest floor within the rainforest. Many organisms are not adapted to survive in the drier edge microhabitat (Figure 6.2.20).

FIGURE 6.2.18 The World Heritage listed Great Barrier Reef is the world's largest coral reef. It covers 348 000 square kilometres: larger than the United Kingdom, Netherlands and Switzerland combined.

FIGURE 6.2.19 Chobe National Park is a protected area of 21 000 square kilometres in Botswana and is home to about 50 000 elephants. Damage caused by the elephants is extensive in some areas and culls have been considered but are too controversial.

FIGURE 6.2.20 The environmental conditions at the edge of a reserve can be very different from those in the middle.

BIOLOGY IN ACTION

The Millennium Seed Bank Partnership

The Millennium Seed Bank Partnership aims to collect seeds from a quarter of the world's plants by 2020. The purpose of the seed bank is to save plants, especially plants that are most at risk from climate change and human activities, and plants most useful in the future (such as crop plants or plants with potential medicinal value). One potential use of the seed bank includes the ability to use the seeds for revegetation if a natural disaster destroys the native vegetation.

The partnership is coordinated by the Royal Botanic Gardens in London, and involves organisations in 80 countries, including the Royal Botanic Gardens in Melbourne. The seeds are stored in a vault in Sussex, England (Figure 6.2.21). There is also a seed bank in Svalbard, owned by the Norwegian government, where crop seeds are stored.

More than 150 million seeds in 300000 samples are now stored in the vault. The seeds are stored at –18 °C in specially sealed compartments. If properly maintained, the seeds will remain viable for at least 1000 years.

FIGURE 6.2.21 (a) The Svalbard Global Seed Vault is an insurance against loss of crop diversity. (b) Example of seeds kept as part of The Millennium Seed Bank Partnership.

FIGURE 6.2.22 A logging coupe in mixed eucalypt forest on the Paluma Range in northern Queensland. Several eucalypt species are logged in small patches, but habitat and seed trees are left untouched to enable the forest to regenerate and tree-dwelling animals to return.

SUSTAINABLE USE OF RESOURCES

Some ecosystems can be managed by humans in a sustainable way, without the habitat being destroyed. Sustainable use means that resources should be consumed no faster than they can be replaced naturally. For example, instead of cutting down all the trees in a forest for wood production, selected individuals of particular tree species can be harvested and sold as high-quality timber. Tree species will naturally regenerate in the gaps created, so the forest is sustained (Figure 6.2.22).

Much of our wood products now come from sustainable plantations of softwoods and hardwoods. In the future it is possible that all our requirements for timber and wood products will come from plantations, allowing native forests to return to their natural state.

Many other products that are useful to humans can be obtained sustainably from ecosystems. These include fish from carefully managed fisheries, wild fruits such as Davidsons plums, lemon myrtle and mountain pepper for use in foods, and honey from Victorian box–ironbark forests and Tasmanian rainforests.

BIOPROSPECTING FOR NEW FOODS AND DRUGS

Bioprospecting is the search for new plant and animal substances that have medicinal or other uses. This is not an entirely new thing to do. The indigenous people have been bioprospecting for a very long time. For example, Muyan is the name used by the Wurundjeri people in Victoria for the silver wattle tree (*Acacia dealbata*) (Figure 6.2.23).

Silver wattle timber is used for axe handles, and the bark is made into string for baskets and bags. Sap extracted from cuts in the wattle tree trunk can be mixed with ashes from a wood fire to make glue, or mixed with nectar from flowers to make a sweet drink. The wattle's seed pods can be cooked and eaten, or pounded to make flour. Currently there is research from all over the world into finding, developing and testing of chemicals produced by a range of plants. The National Cancer Institute in the United States alone has tested 35 000 species of plants for anti-cancer properties. Testing is also being done for properties to fight other diseases such as cardiovascular disease, arthritis and AIDS. Bioprospecting relies on biodiversity conservation to ensure that all plant species can be investigated for potentially useful substances.

Well-managed bioprospecting can be advantageous because it can generate income for developing countries and can provide motivation for conservation and management. But if it is managed poorly it could result in environmental, social and economic problems. Problems can also occur if private organisations or individuals exploit knowledge of the bioresources which they do not have ownership of without sharing the profits with the indigenous people. This is known as 'biopiracy'.

It is estimated that over 200 companies are screening plant and animal substances for drugs. About 20% of modern pharmaceutical drugs come from the Amazon rainforest (Figure 6.2.24). Interestingly, 90% of the drugs come from the southern hemisphere, but 90% of the people who use them live in the northern hemisphere. In 2010, which was the International Year of Biodiversity, the 10th Conference of Parties to the Convention on Biological Diversity adopted the Nagoya Protocol, which relates to access to bioresources and sharing of benefits. It specifically addresses the issue of bioprospecting and the rights of indigenous people to access forest resources, intellectual property and adequate compensation. The Protocol has been signed by 92 countries, 53 of which have ratified it so far. It came into force in 2014.

Most of the world's food supply depends on about 150 plant species, but only 12 species provide 75% of the world's food. More than half of the world's food energy comes from a limited number of varieties of three 'mega-crops': rice, wheat and maize. Sorghum, millet, potatoes, sweet potatoes, soybean and sugar provide another 25%. The world's poor depend on plants for as much as 90% of their needs (food, fuel, medicine, shelter, transport). Approximately 1.4 billion people, mostly resource-poor farmers, use and improve their own crop seeds to maintain and enhance the genetic diversity of crops. It is vital to ensure continued genetic diversity of these major crops to avoid vulnerability to diseases that could affect production worldwide. Plant and food research combines traditional breeding techniques with modern genetic techniques to develop better cultivars faster. Bioprospecting combined with genetic engineering could increase the diversity of food crops available.

BIOFILE

Conserving biodiversity in Australia

Australia's approach to conserving biodiversity includes:

- encouraging everyone to participate in biodiversity conservation
- increasing the participation of indigenous people in biodiversity conservation and education, as custodians of land and guardians of traditional ecological and cultural knowledge of Australia's natural environments
- enhancing partnerships and investments to ensure enough money is available for conservation projects to continue
- restoring and maintaining habitats and creating new reserves
- reducing threats to biodiversity
- monitoring, reporting on and evaluating biodiversity conservation projects.

FIGURE 6.2.23 The muyan or silver wattle, *Acacia dealbata*.

BIOFILE

Medicines from bark

Some important pharmaceuticals were originally derived from tree bark. An extract from the bark of the willow tree (aspirin), recognised for its effectiveness in managing fevers, pain and inflammation, has been in use for thousands of years. Quinine, an extract of the bark of the Peruvian cinchona tree, has been used to treat malaria since 1630. In the 1960s the bark of the Pacific yew tree (*Taxus berevifolia*) was found to yield one of the most important cancer-fighting drugs, taxol.

FIGURE 6.2.24 The Amazon Basin contains the largest collection of living plants and animal species in the world, many of them not yet known. Pharmaceutical companies are scouting the rainforest for possible new drugs and tapping into the wisdom of traditional indigenous healers. A vast selection of plants, barks, roots and leaves from the rainforest are available in markets throughout the rainforest.

BIOFILE

Sloth hair fungi fighting disease

The hair of three-toed sloths (*Bradypus variegatus*) that live in the rainforests of Costa Rica looks green because it has algae growing in it, which provides camouflage. Scientists at the Smithsonian Tropical Research Institute wondered what other organisms lived in sloth hair and whether they might have useful protective properties. They isolated 84 unique fungi from the hair, then tested 70 strains for bioactivity against malaria, the Chagas disease parasite, 15 pathogenic bacteria, and in a type of breast cancer cell.

A strain is considered to be highly bioactive if it inhibits the growth of 50% or more of the pathogen or cancer cell. The researchers, led by microbiologist Sarah Higginbotham, found that two of the fungi were effective against *Plasmodium falciparum* (the parasite that causes malaria), 15 were highly active against the breast cancer cell and 8 were active against *Trypanosoma cruzi* (the parasite that causes Chagas disease). This research may help to develop new drugs to fight these diseases in the future.

FIGURE 6.2.25 The three-toed sloth (*Bradypus variegatus*) hosts an entire ecosystem in its hair. Arthropods, bacteria, fungi and algae all live together. The algae makes the hair appear green and provides camouflage in the rainforests of Costa Rica.

BIOLOGY IN ACTION

Bioprospecting for new pastures

Cullen (*Cullen australasicum*) is an Australian native legume (Figure 6.2.26). Studies by the Future Farm Industries Cooperative Research Centre (Figure 6.2.27) have shown that cullen could be a useful perennial pasture plant for the difficult climates and soils in Australia's wheat belt.

FIGURE 6.2.26 Cullen (*Cullen australasicum*).

Cullen is adapted to drought conditions and, when eaten and digested by herbivores, might have the potential to reduce methane emissions.

Through a combination of the best genetics and seed production management practices, crops of Cullen resulted in high commercial seed yields with over one metric ton per hectare to be harvested from Cullen windrows. Despite the success in harvest, further work is required before this species can be considered a viable alternative. This is because infection by anthracnose (*Colletotrichum trifolii*) and alfalfa mosaic virus caused considerable damage in some experimental plots.

The CRC's research investigated Cullen seeds and tissue to look for qualities such as high seed production and harvest ability.

Eventually *C. australasicum* may emerge as a viable drought tolerant alternative for graziers in semi-arid to medium rainfall environments. In grazing trials, sheep preferred lucerne but also ate cullen before the lucerne was depleted. The trials demonstrated that cullen has a reasonable level of grazing tolerance.

FIGURE 6.2.27 Dr Jason Emms standing in a seed crop of cullen (*Cullen australasicum*), which has good potential as a new pasture plant in Australia.

6.2 Review

SUMMARY

- Species should be conserved because they have ecological, practical and aesthetic value.
- Saving species is best done by saving habitats or entire ecosystems, because species must interact with other species and do not live in isolation.
- Strategies for conserving biodiversity include:
  - *in situ* conservation, where the species is maintained in its natural environment
  - *ex situ* conservation, where the species is grown or bred in captivity.
  - establishing protected areas
  - controlling existing pest species
  - preventing new pest species from entering the country
  - reducing pollution to protect species
  - combating climate change
  - preventing overexploitation by legal and practical means
- Ecosystems can be used by humans without destruction of habitat and loss of species. The use of ecosystems should be sustainable, meaning that resources should be used no faster than they can be replaced.
- Bioprospecting is the search for new plant and animal substances that could have medicinal or other uses.

KEY QUESTIONS

1 Outline why maintaining biodiversity is important.

2 List the types of values possessed by a species that warrant its conservation, and give one example of each.

3 Describe the two main conservation strategies outlined in this chapter (*in situ* and *ex situ*).

4 Explain the ways in which an invasive species can have significant impact on the survival of a native species.

5 Outline some methods for controlling invasive species.

6 What does 'biological control' mean?

7 Define bioprospecting.

8 Our native plant and animal species are a priceless resource.

a Explain the argument that species should be saved because they have ecological value.

b Name an Australian species that is endangered, and explain why it should be saved using the three reasons listed in the text as a guide.

c For the Australian species that you have named in part b, outline the strategies currently used to conserve the species.

Chapter review

06

KEY TERMS

Archaea
Bacteria
binomial system
biodiversity
biological classification
biological control
biological species
bioprospecting
biosphere
class
domain
ecosystem
endemic
Eukarya
family
Fungi
genus
hierarchy
hyphae
kingdom
Linnaeus
Linnaean system
Monera
order
pest organism
phylogeny
phylum
Protista
species
subspecies
taxon
taxonomy
virion

KEY QUESTIONS

1 Outline the value of classifying organisms.

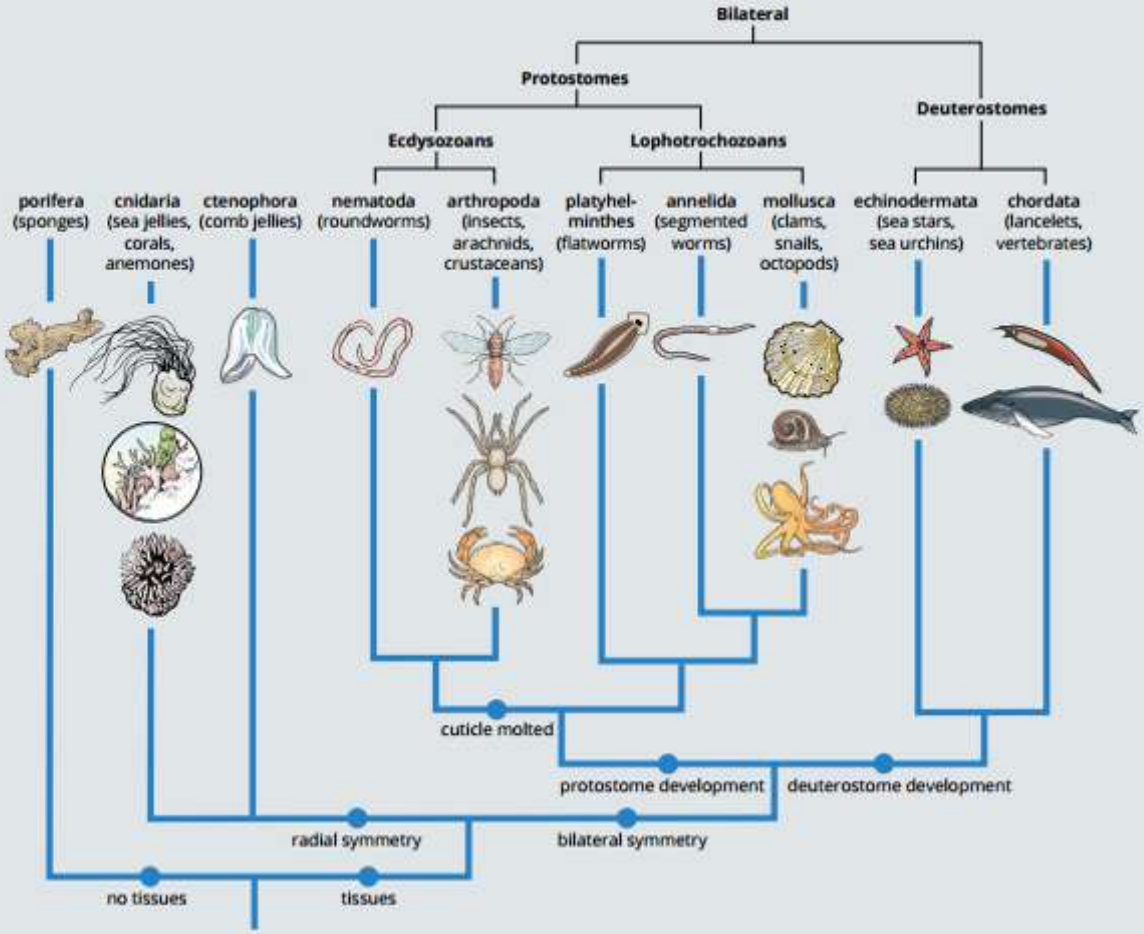
2 In the binomial system, which two taxa (groups) are used to identify a type of organism?

3 What are *Avicularia metallica* and *Poecilotheria metallica*?

A different subspecies of one species
B different species in the same genus
C the same species with two names
D different species in different genera

4 Fill in the blanks with the most suitable term:
Organisms classified at the level of _____ are most alike. Organisms in different _____ are most different. Species in different families are more _____ related to each other than species in the same genus.

5 The figure below shows a phylogenetic tree of some major animal phyla.



Question 5 continued

a Which animals are most closely related?

A sponges and corals

B roundworms and segmented worms

C molluscs and flatworms

D echinoderms and crustaceans

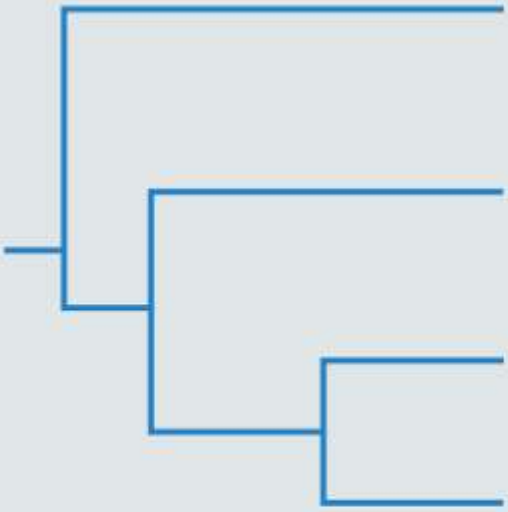
b Name one morphological characteristic that would enable a biologist to separate the following pairs into separate categories:

i a comb jelly and a platyhelminth

ii a comb jelly and a sponge

6 The following table compares the group names for red fox, arctic fox, dog and cat. Label the phylogenetic tree below, correctly indicating the relationships between these four animals.

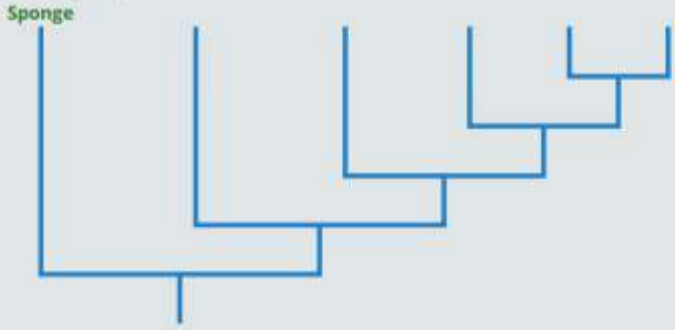
Group	Red fox	Arctic fox	Dog	Cat
Kingdom	*Animalia*	*Animalia*	*Animalia*	*Animalia*
Phylum	*Chordata*	*Chordata*	*Chordata*	*Chordata*
Class	*Mammalia*	*Mammalia*	*Mammalia*	*Mammalia*
Order	*Carnivora*	*Carnivora*	*Carnivora*	*Carnivora*
Family	*Canidae*	*Canidae*	*Canidae*	*Felidae*
Genus	*Vulpes*	*Vulpes*	*Canis*	*Felis*
Species	*Vulpes vulpes*	*Vulpes lagopus*	*Canis lupus*	*Felis catus*



7 The following table is a character matrix that lists six animals and four morphological characteristics. A tick (✔) indicates that the animal has this characteristic while a cross (✘) indicates that the characteristic is absent. (Hint: Organisms with more similar characteristics will be more closely related on the phylogenetic tree.)

Animal	**Spinal cord (vertebra)**	**Legs**	**Hair**	**Placenta present during pregnancy**
Blue-tongue lizard	✔	✔	✘	✘
Platypus	✔	✔	✔	✘
Red fox	✔	✔	✔	✔
Sponge	✘	✘	✘	✘
Funnel-web spider	✘	✔	✔	✘
Red kangaroo	✔	✔	✔	✔

Based on the features above, complete the phylogenetic tree below.



8 The world's human population is more than 7 billion. By 2100 the human population could be 12 billion. In order to sustain this number of people, more land will have to be used to grow crops that are consumed directly by humans, or fed to stock that are used to produce food for humans.

a What are the implications of human population growth and activities for the biodiversity of the planet?

b Outline two reasons why biodiversity is important.

9 Discuss the reasons for *ex situ* conservation of endangered species.

10 Discuss the reasons for *in situ* conservation of endangered species.

11 Outline one example of biological control of invasive species.

12 Discuss reasons for conserving the biodiversity of a rainforest ecosystem.

CHAPTER

07 Relationships in an ecosystem

By the end of this chapter you will have an understanding of the different types of relationships between species in an ecosystem and the ways in which species are interdependent. You will also learn about the factors that influence a population's size, density and distribution within an ecosystem.

Key knowledge

- the beneficial, harmful and benign relationships between species including amensalism, commensalism, mutualism, parasitism and predation
- interdependencies between species as represented by food webs, including the impact of changes to keystone species
- the distribution, density and size of a population of a particular species within an ecosystem and the impacts of factors including available resources, predation, competition, disease, chance environmental events, births, deaths and migration.

7.1 Interactions between species

FIGURE 7.1.1 Many flowering plants depend on their ability to attract insects and birds to pollinate flowers and disperse seeds. Rainbow lorikeets (*Trichoglossus haematodus*) feed on the nectar in eucalypt flowers, and at the same time transfer pollen from one flower to another.

FIGURE 7.1.2 The Queensland umbrella tree (*Schefflera actinophylla*) is an individual in an ecosystem.

FIGURE 7.1.3 A colony of spectacled fruit bats (*Pteropus conspicillatus*) is a population in the Daintree Rainforest.

Organisms do not live in isolation, but interact with their biotic and abiotic environment. In other words, they interact both with each other and with their physical surroundings (Figure 7.1.1). They interact with one another in many ways; they eat one another, and they also compete with one another for food, space, mates and nest sites.

This section explores the interactions between species, including mutualism, commensalism, parasitism, amensalism and predation.

INTERACTIONS IN THE ENVIRONMENT

Organisms affect, and are affected by, their physical surroundings. For example, earthworms live in soil, where they bury and consume dead plant material. This helps to recycle nutrients and make tunnels, which in turn helps to aerate the soil. Like all animals and plants, earthworms take in oxygen, water and nutrients and give out carbon dioxide and other wastes. Plants take in carbon dioxide and produce oxygen during photosynthesis. Without the first photosynthetic organisms that evolved billions of years ago, the Earth's atmosphere would have lacked oxygen and the biosphere would be very different today.

Human impacts on the environment

Humans also interact with other organisms and affect their surroundings. Sherbrooke Forest, in the Dandenong Ranges on the urban fringe of Melbourne, is a tall eucalypt forest that is home to lyrebirds, wombats and many other native animals. However, lyrebirds are becoming rarer. One reason is the direct effects of domestic pets, such as cats and dogs, that hunt and kill lyrebirds. Another reason is not so obvious: the area is criss-crossed by roads, and many wombats that graze on wire-grass are killed by cars. Without the controlling influence of wombats, the wire-grass grows into dense, tangled masses, so there are fewer open areas on the forest floor where lyrebirds can scratch for a meal of insects and worms. Also, male lyrebirds rake over the leaf litter, so that it decays quickly and releases nutrients back into the soil. Fewer lyrebirds means that nutrients are not recycled as quickly for the use of trees and shrubs.

Human impacts on environments can be reduced by studying ecosystems and understanding how they function. This knowledge can then be applied to restore areas that have been damaged in the past.

Organising the environment

Environments can be studied at different levels. These biological levels of organisation follow a highly structured hierarchy of living things:

- Individual: single organisms such as plants, animals or fungi, or unicellular organisms. A single Queensland umbrella tree could be studied on its own (Figure 7.1.2). This tree usually has many flowers which produce large amounts of nectar.
- Population: a group of organisms of the same species, living together in a defined geographic area. The spectacled fruit bat lives in colonies that roost in particular areas and interact with each other (Figure 7.1.3). The fruit bats in a colony could be described as a population.

- Community: an ecological grouping of different kinds of organisms that live together in a particular place at a particular time and interact with one another. Many species rely on the Queensland umbrella tree for the large amount of nectar it produces, including the spectacled fruit bat, various species of bird and the Bennett's tree kangaroo shown in Figure 7.1.4. The species living in and feeding in an area of a population of umbrella trees could be considered a community.
- Ecosystem: a system formed by organisms interacting with one another and their physical environment. The Queensland umbrella tree, spectacled fruit bat and Bennett's tree kangaroo can all be found in the Daintree rainforest in Queensland, Australia. The Daintree rainforest is regarded as the most complex ecosystem in Australia. It is a distinct area with a huge number of species that interact and thrive together (Figure 7.1.5).
- Biome: a group of communities that have similar structures and habitats, extending over a large area; for example, a grassland biome or coral reef biome. The Daintree rainforest is a part of the tropical rainforest biome. The tropical rainforest biome is close to the equator and experiences high temperatures and rainfall (Figure 7.1.6).

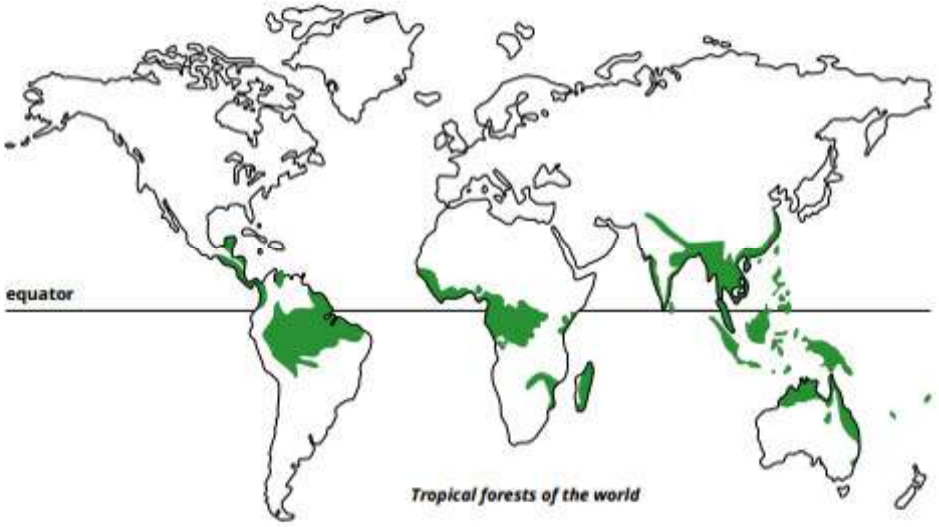


FIGURE 7.1.6 The tropical rainforest biome (shown in green) is found close to the equator.

- Biosphere: all the ecosystems on Earth. The biosphere covers all the regions of Earth that are inhabited by living things (Figure 7.1.7). It can be thought of as the largest ecosystem on Earth.

Habitat

In order to study an organism, you first have to know where to find it. The type of place where an organism lives is its **habitat**. It is the 'address' where you would go to find the organism.

The habitat of rock orchids, as the names suggests, is rock outcrops in forests. The habitat of a water lily is lakes and ponds. The bush rat lives in forests, while the swamp rat lives mainly in grasslands and heathland close to water. The European house sparrow, introduced into Australia, makes its home in towns and cities. Different habitats will support different species (see Figure 7.1.8, page 304).

FIGURE 7.1.4 Bennett's tree kangaroo (*Dendrolagus bennettianus*) lives in the canopy of rainforest trees. It is part of a community in the Daintree rainforest, Queensland.

FIGURE 7.1.5 The Daintree rainforest is part of a World Heritage Area. It is an ecosystem and includes a large number of species.

FIGURE 7.1.7 The biosphere is the global ecosystem. It consists of smaller interlinked ecosystems.

FIGURE 7.1.9 Flying-foxes inhabit forests in eastern Australia.

FIGURE 7.1.10 The trunk of the tree fern (*Dicksonia antarctica*) is a microhabitat for many species.

FIGURE 7.1.11 The trunk of a silver wattle (*Acacia dealbata*) is not the same microhabitat as the trunk of a tree-fern.

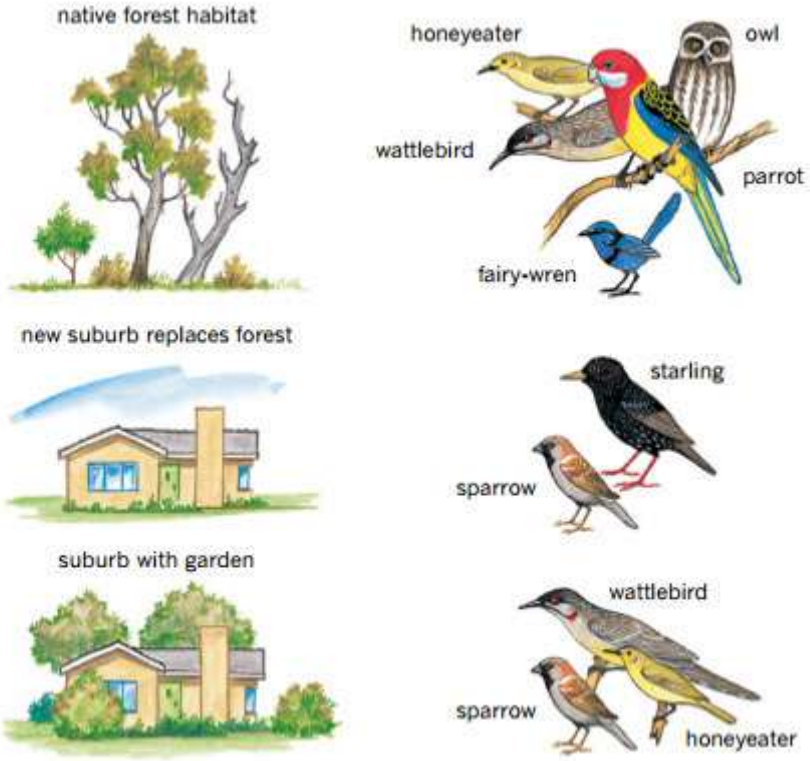


FIGURE 7.1.8 The bird community in a new suburb consists of sparrows and few native species. Gardens that include native plants provide a habitat for a greater variety of birds.

Some organisms live in only one type of habitat. In Victoria a species of snow daisy is found only in the mountains of the Snowy Range and nearby Mount Buller. The Sydney rock oyster, although found at many locations along the eastern coast of Australia, lives along the shore in a narrow band between high and low tide.

Other organisms live in a greater range of habitats. Australian flying-foxes (which are fruit-eating bats) inhabit forests, paperbark swamps and mangroves from Queensland to Victoria (Figure 7.1.9). Some organisms move from one habitat to another according to seasonal changes. For example, pelicans move inland from their coastal habitat to take advantage of wetlands that form during times of rain and flood.

Microhabitat

Within a habitat there are smaller areas known as microhabitats. A microhabitat could be a burrow, a tree canopy or even inside other organisms.

In a microhabitat an organism experiences a slightly different environment compared to the overall habitat, such as a lower temperature, more moisture, less sunlight or more humidity. This variation in environmental conditions can be essential for the organism to survive.

The moist trunk of the tree-fern (*Dicksonia antarctica*) in a wet forest is the microhabitat of many mosses, liverworts, filmy ferns, fungi, spiders and insects. The trunk of the tree-fern is shaded by its umbrella of large fern leaves and is soft and able to absorb and hold much water (Figure 7.1.10). The tree-fern trunk is a different microhabitat from the trunk of trees such as silver wattles (*Acacia dealbata*) in the same forest habitat (Figure 7.1.11).

Ecological niche

An organism's ecological **niche** is its role in its environment. This includes how the organism uses its resources and interacts with other species and its environment.

The competitive exclusion principle is an ecological principle which states that two species cannot have the same niche in an ecosystem. This means that two species cannot use the same resource in the same space at the same time.

However, it is common for different species to use different parts of a resource at the same time. For example, brown creepers (*Certhia americana*) feed on insects on the trunk of a tree, while nuthatches (*Sitta* species) feed on insects among the branches at the top of a tree (Figure 7.1.12).

FIGURE 7.1.12 (a) Nuthatches (*Sitta* species) feed on insects in the canopy of trees, while (b) brown creepers (*Certhia americana*) feed on insects on the trunk.

Communities

Organisms of a particular species, such as the superb lyrebird, live together in populations. Different kinds of populations (lyrebirds, tree ferns, insects, and so on) live together in communities. A **community** is an ecological grouping of different species that live together in a particular place at a particular time and interact with one another. For example, the insects, spiders, mosses, fungi and bacteria on a dead tree trunk make up a community of organisms that live and interact with one another. Spiders feed on insects, insects feed on one another as well as the fungi, and the mosses catch and hold rain water that all of the organisms require, and provide shelter for spiders and insects. The fungi and bacteria recycle the nutrients in the community by breaking down dead spiders, insects and mosses.

Ecosystems

An **ecosystem** is a system formed by a community of living organisms interacting with one another in a particular place at a particular time, together with their physical surroundings. To be defined as an ecosystem, a system must be self-sustaining; this means that it can be maintained into the future largely without inputs from outside the system.

Ecosystems can be almost any size. An ecosystem can be as small as a dead tree trunk, or it can be large like the Victorian Mallee (Figure 7.1.14). The Victorian Mallee covered 4.2 million hectares (about one-sixth of Victoria) at the time of European settlement. Today the Victorian Mallee covers approximately 3.9 million hectares.

Ecosystems also vary in complexity. A tropical forest is the most complex land ecosystem and contains the greatest number of species. A desert ecosystem is one of the simplest. Cities and towns are urban ecosystems.

FIGURE 7.1.14 The Mallee ecosystem is characterised by multi-stemmed mallee eucalypts such as the white mallee (*Eucalyptus dumosa*).

BIO FILE

The habitat and niche of small crabs

Small crabs survive in rock pools (their habitat) because they can shelter under seaweed or between rocks (microhabitats) and easily pick up food with their pincers (Figure 7.1.13). They feed on organic litter, a particular resource of rock pools (their niche). One example of the competitive exclusion principle is illustrated here where it is common place for only one species of crab to occupy this niche rock pool habitat.

FIGURE 7.1.13 This small hermit crab's niche is feeding on organic litter in a rock pool.

The largest and most complex ecosystem of all is the **biosphere**, which is the sum of all ecosystems on Earth. The biosphere includes all those parts of Earth that are accessible to living organisms, including oceans, rivers, lakes (**hydrosphere**), soil and rocks (**lithosphere**) and air (**atmosphere**). The biosphere occupies a thin layer of atmosphere, hydrosphere, and a thin layer of lithosphere (Figure 7.1.15).

Just as there are ecosystems within the biosphere, there are ecosystems within ecosystems. For example, rock pools along the seashore are part of larger marine ecosystems, but they can also be studied as small ecosystems (Figure 7.1.16).

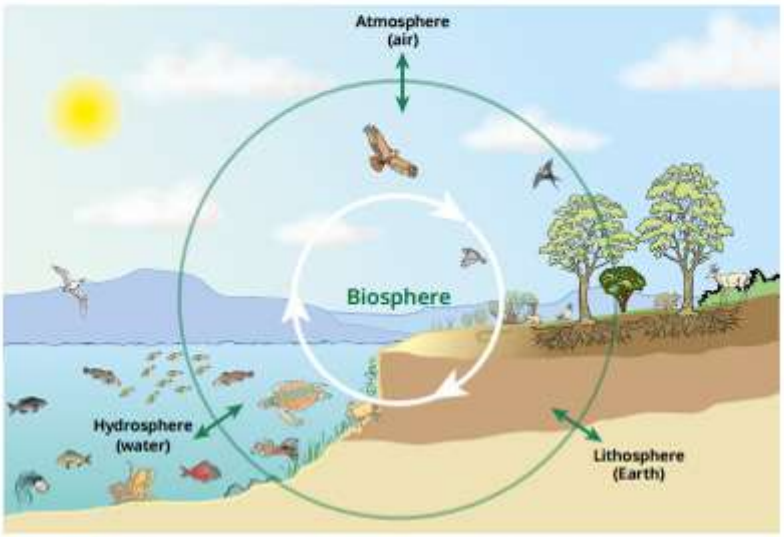


FIGURE 7.1.15 The biosphere is the portion of the Earth inhabited by living things. It occupies parts of the atmosphere, hydrosphere and lithosphere.

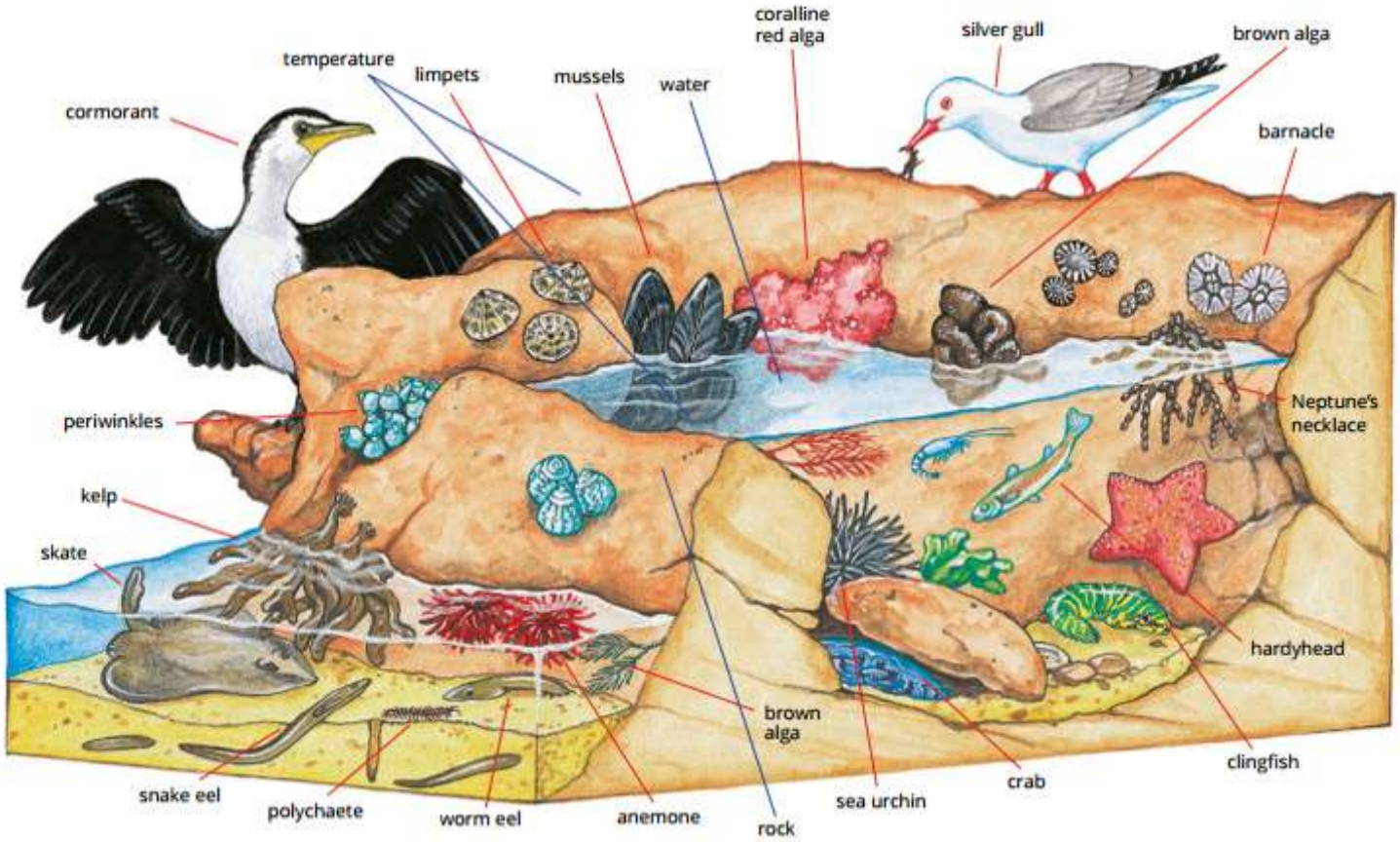


FIGURE 7.1.16 Rock pool ecosystems provide a habitat for a great number of different organisms whose survival depends on tides. An incoming tide brings cool, clean water, food and organisms. When the tide goes out it leaves behind a pool that is calm and can warm up in the sun.

BIO FILE

Biosphere 2

The Biosphere 2 research facility in the USA is a science research facility covering 160 000 square metres (Figure 7.1.17). It was designed to be a self-contained ecological system, with different types of biomes closed off from the outside world. Scientists have used Biosphere 2 to study the interaction between humans and nature, the impact of global warming, and even space colonisation.

FIGURE 7.1.17 The Biosphere 2 research facility in Arizona, USA.

COMPETITION BETWEEN SPECIES

The presence of other organisms may limit the distribution of some species through interspecific **competition**. Interspecific competition is a struggle between organisms of different species for the same supply of food, water, space, nest sites, or any other environmental resource that is in limited supply.

Because they use similar resources, green plants mainly compete with other green plants, herbivores with other herbivores, and predators with other predators. Competition can lead to one species being forced out of a habitat by its competitor. The loser usually continues to survive in adjacent parts of the habitat.

For example, populations of two species of protists, *Paramecium aurelia* and *Paramecium caudatum*, will grow rapidly in separate but identical cultures, and then both populations will level off, as shown in Figure 7.1.18. However, if these species are grown together, the population of *P. caudatum* grows initially, but then its population decreases to extinction. In other words, *P. aurelia* outcompetes *P. caudatum*. *P. aurelia* continues to reproduce to reach a similar population density as in the first experiment in which the two species were separated.

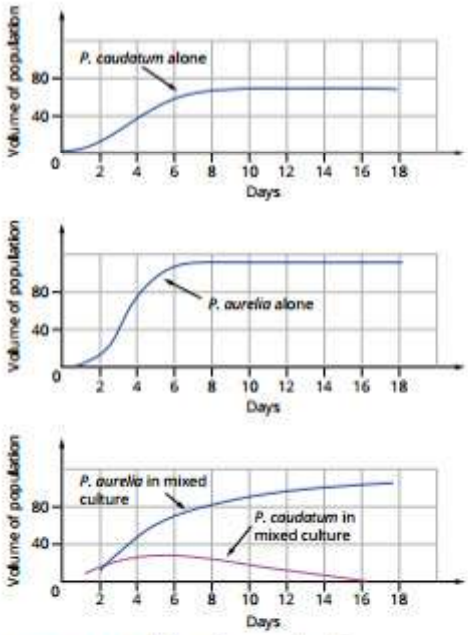


FIGURE 7.1.18 When two species of *Paramecium* are cultured together, the population growth of both species is slowed until eventually one species outcompetes the other.

INTERACTIONS BETWEEN SPECIES

Interactions between species are usually classified according to how the interaction affects the survival and reproduction of the species involved. They can be classified as:

- beneficial interactions (which benefit both species involved)
  - mutualism
  - obligate mutualism
  - facultative mutualism
- benign interactions (where one species is not affected by the interaction)
  - commensalism
- harmful interactions (where one species is harmed by the interaction)
  - parasitism
  - amensalism
  - predation.

Interspecific interactions can also be classified as feeding and non-feeding interactions. For example, mutualism is a non-feeding interaction, and predation is a feeding interaction.

BIO FILE

Symbiosis in the sea

Cleaner fish and cleaner shrimps have a symbiotic relationship with their hosts. They eat dead skin and parasites on the surface of larger marine animals. This photograph shows a suckerfish attached to the shell of a sea turtle. The suckerfish eats food scraps from the feeding activity of the turtle, as well as parasites on the turtle's shell.

FIGURE 7.1.19 A suckerfish attached to the shell of a sea turtle in the Red Sea.

Symbiosis

Organisms in ecosystems interact in a number of ways. Sometimes two quite different organisms live and function together in a close association, to the benefit of at least one of them. Different species living together in a close partnership is called **symbiosis**. Each species is called a symbiont. Two different types of symbiosis are mutualism and parasitism.

Symbiosis is a relationship in which two quite different organisms live and function together in close association, to the benefit of at least one of them. Mutualism, commensalism and parasitism are all examples of symbiotic relationships.

BENEFICIAL INTERACTIONS

Mutualism

Mutualism is a partnership between two different kinds of organism where both of them benefit. Some of the most common partners in mutualism are unicellular algae. The bright colours of corals, the green of some hydra and the brilliant blues of the mantles of giant clams are produced by algae living in the animal's tissues (Figure 7.1.20). The algae photosynthesise and produce sugar and oxygen, which are used by the animal partner for its own benefit. In turn, the animal produces carbon dioxide during respiration, which the algae need for photosynthesis. The algae also benefit by having safe shelter within the partner.

Mutualism sometimes involves adaptations that help the relationship. For example, most flowering plants have adaptations such as nectar or fruit that attract animals, which can pollinate the flowers or disperse the seeds (Figure 7.1.21).

FIGURE 7.1.20 Giant clams and unicellular algae have a mutualistic relationship.

Pollination is the transfer of pollen from an anther (in the male part of a flower) to a stigma (in the female part of a flower). Animals that transfer pollen are called pollinators, and can be considered to be in a mutual relationship with the plant.

FIGURE 7.1.21 The fruits of the desert quandong or Australian native peach (*Santalum acuminatum*) are eaten by emus. The emu can digest the soft part of the fruit, but not the seed, which it passes out in its droppings. The droppings act like fertiliser and help the seed germinate and grow. The emu and quandong have a mutualistic relationship—the emus benefit from eating the fruit, and the quandong benefits by having its seeds dispersed.

BIO FILE

Pollination adaptations

Many flowering plants have the anthers and stigmas on different flowers, so pollen has to be transported from one flower to another. For plants such as grasses this happens by wind dispersal, but many plants rely on animals to do this for them. The wide variety of colours and scents in flowers is often due to the plant needing to attract a particular pollinator. Because insects are more sensitive to blue and yellow wavelengths of light, flowers with insect pollinators usually show these colours. Insects also have a well-developed sense of smell, so insect-pollinated flowers usually emit a pungent scent. However, these are not necessarily pleasant. The carrion flower, a desert angiosperm, attracts flies by emitting the smell of rotting meat.

Birds such as hummingbirds are also efficient pollinators, and are attracted by red and yellow flowers. Flowers pollinated by fruit-eating bats emit scents similar to that of ripe fruits. These plants' petals are usually dark.

Depending on how the species interact, pollination can be either obligate or facultative mutualism. The pollinator usually gets something out of the relationship as well; for example, hummingbirds feed on the nectar of the flowers they visit.

FIGURE 7.1.22 The fly acts as pollinator for carrion flower (*Stapelia gigantia*). The fly is attracted to the flower by the red and yellow petals and the smell of rotting meat.

BIOLOGY IN ACTION

Bacteria and coral bleaching

Corals live in a symbiotic relationship with unicellular algae called zooxanthellae. The photosynthetic algae provide food for the coral polyps and the polyps produce a hard skeleton of calcium carbonate, which is a home for both organisms (Figure 7.1.23a). Corals are bleached (become pale) and eventually die when they lose their zooxanthellae (Figure 7.1.23b). This can occur when sea temperatures rise, causing the coral polyps to become stressed and to expel their algal partner. Increased coral bleaching has been connected with rising sea temperatures associated with climate change.

It has been suggested that the increased bleaching of corals may be caused by a bacterial infection that occurs when the seawater temperature rises. In 2004 Eugene Rosenberg found a new species of bacterium, *Vibrio shiloi*, that is always associated with bleached and dying coral (*Oculina patagonia*) in the Mediterranean Sea. This bacterium is closely related to *Vibrio cholerae*, the bacterium that cause cholera.

Experiments found that coral did not bleach in water at 29 °C, but did if *Vibrio shiloi* was present. No bleaching occurred even when the bacterium was present if the water temperature was only 16 °C. Rosenberg's research team found a temperature-dependent protein produced by the bacterium that enables it to stick to the coral. Once the bacterium has stuck to the coral, it multiplies and penetrates the polyp. Inside the polyp it synthesises a toxin that inhibits photosynthesis, killing the zooxanthellae. The temperature-dependent protein explains why the bacterium can only enter and grow in the coral polyp in the warm months of the year, causing coral bleaching at that time.

This is a remarkable example of the interactions between species (coral polyps, zooxanthellae and bacteria) and their dependence on a particular characteristic of the physical environment (water temperature).

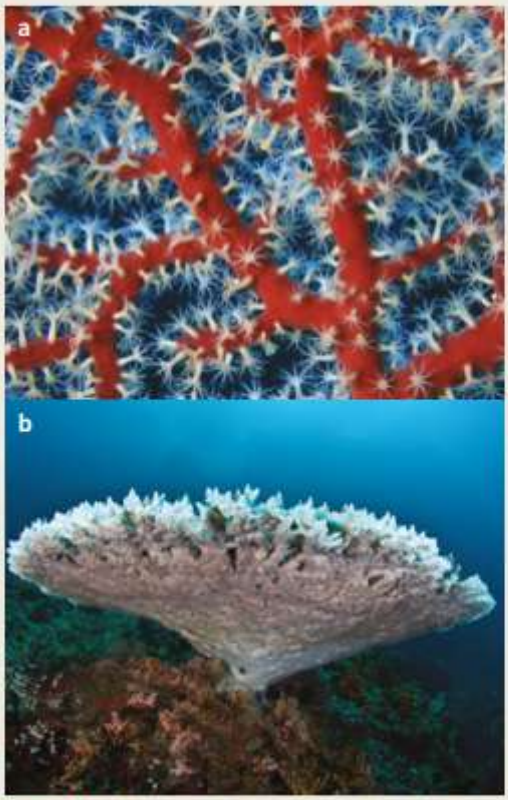


FIGURE 7.1.23 (a) Coral polyps have a mutualistic relationship with unicellular algae (zooxanthellae). (b) Coral bleaching.

EXTENSION

Obligate and facultative mutualism

Obligate mutualism

There are two types of mutualism: obligate mutualism and facultative mutualism. Obligate mutualism is when both species are completely dependent on each other for survival and reproduction. One cannot survive without the other. Many pollination relationships are examples obligate mutualism. Yucca plants (Figure 7.1.24) rely exclusively on yucca moths to move pollen from one plant to another, and in turn the moths depend on the flowers for a safe place to hatch their eggs.

Some species must cooperate to obtain all the nutrients they need. For example, many plants and soil-inhabiting fungi live in a close relationship called a mycorrhiza (Figure 7.1.25) where the thread-like hyphae of the fungi are very close to the outer layer of the root. Through these, the organisms transfer water, minerals, sugars and amino acids to each other. Because of the low level of nutrients such as phosphorus in many Australian soils, mycorrhizae are important in the growth of native plants.

FIGURE 7.1.24 A Yucca plant in Texas, USA. Yucca plants have an obligate mutualism relationship with yucca moths.

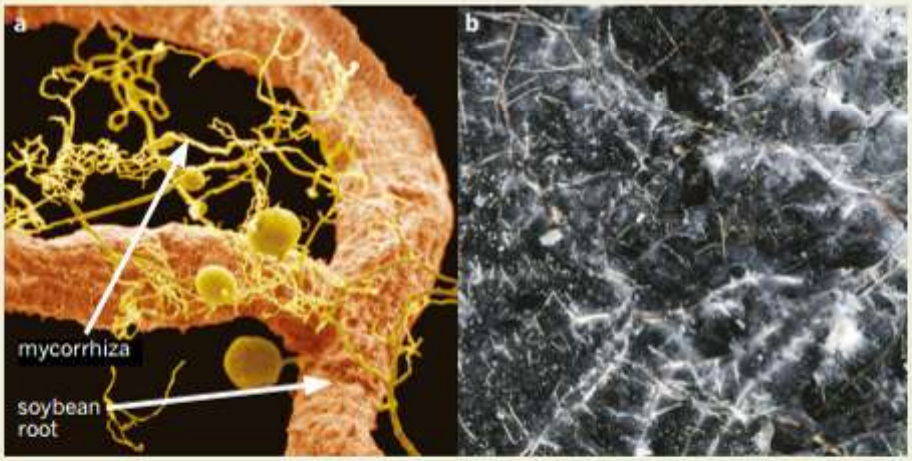


FIGURE 7.1.25 (a) An SEM of a mychorrhizal fungus (yellow-coloured fibres) on a soybean root (orange-coloured). (b) Mycorrhizal (symbiotic) fungi growing in association with the roots of a small-leaved lime tree, *Tilia cordata*. Symbiotic fungi are found growing on the roots of most trees; many will not grow properly unless the appropriate fungus is present. Mycorrhizal roots take up nutrients more efficiently than uninfected roots, while the fungi obtain carbohydrates and possibly B-group vitamins from the tree. The type of symbiosis seen here is known as endotrophic mycorrhiza; the fungal hyphae (white, fluffy structures) form a mantle around the tree roots and also penetrate into the soil.

BIO FILE

Lichens

Lichens look like they are one organism, but they are in fact two organisms in an obligate mutualistic relationship. They consist of an alga and a fungus that live and work together. The alga photosynthesises to produce food, which the fungus can share. The fungus shelters the alga and absorbs mineral nutrients and water. Lichens can break down and extract minerals from solid rock.

This close symbiotic relationship enables lichens to colonise areas that are hostile to other organisms. They can grow on tree trunks, on bare rocks, in the cold of Antarctica and in the heat of the desert—places where the algae and fungi would not survive on their own.

FIGURE 7.1.26 A lichen is an obligate mutual relationship between an alga and a fungus. The orange pigment that colours the lichen is produced by the fungus.

Facultative mutualism

Facultative mutualism is when both species benefit from interacting but do not rely on each other for their survival. This is sometimes called 'proto-cooperation'.

Some species are able to rid themselves of harmful parasites through facultative mutualism. For example, tick-birds and oxpeckers (Figure 7.1.27) stand on cattle or other large animals and feed on the parasites in the hair and on their skin of their host. The birds benefit from easy access to their food source.

Pollination can be facultative mutualism because a plant may rely on several species for pollination, and the pollinators may visit many plants for their needs. Bees are the most numerous insect pollinators (Figure 7.1.28). They usually visit a number of plant species to collect nectar and pollen, which are used as food for adults and larvae. As bees move from flower to flower they transfer pollen, enabling the plants to reproduce.

In a similar way, animals sometimes help plants by inadvertently carrying their seeds and dispersing them in new areas. This is an advantage to the plant because it reduces competition between the existing and new plants as they grow. Animal dispersal also propagates plants to new areas, promoting survival of plant species which the animals may rely on for food. In Queensland rainforests, the southern cassowary (Figure 7.1.29) is essential for spreading the seeds of some plants. It feeds on the fruits and transports the plant seeds elsewhere. The seeds are then excreted intact, and the bird's dropping acts as a ready-made fertiliser.

Vertebrate herbivores depend on microorganisms in their gut to digest cellulose. Cellulose is a large component of plant matter and is the main food source of these animals. Ruminants such as kangaroos, rabbits and cows rely on obligate mutualism with microorganisms in their digestive tract to break down the cellulose—a process called rumination. Bacteria and protozoans in the ruminant's digestive tract produce the enzymes necessary to break down cellulose to substances that the animal can use. The microorganisms benefit by being sheltered and constantly supplied with food. You will have explored the digestive systems of some herbivores in Section 4.4. Herbivorous insects such as termites and cockroaches also make use of protozoans in their gut to digest wood (Figure 7.1.30).

FIGURE 7.1.27 A yellow-billed oxpecker (*Buphagus africanus*) cleans ticks from a giraffe (*Giraffa camelopardus*).

FIGURE 7.1.28 The honeybee (*Apis mellifera*) is a common insect pollinator that has a facultative mutualism with many plants.

FIGURE 7.1.29 The southern cassowary (*Casuarius casuarius*) disperses the seeds of many plants that bear fruit by ingesting the seeds and depositing them elsewhere.

FIGURE 7.1.30 Protozoans in the gut of a termite help digest the cellulose in the termite's diet.

BIO FILE

Mutualism and the honeyguide bird

The 1974 film *Animals Are Beautiful People* popularised the idea that the African greater honeyguide bird (*Indicator indicator*) leads the honey badger (*Mellivora capensis*) to wild bee hives. But scientists who have studied the behaviour of these animals suggest that this is extremely unlikely.

However, there is a proven relationship between honeyguide birds and humans, which has probably evolved over thousands of years. The bird gives a distinctive call that indicates it knows the location of a bee hive. Humans have learned to recognise this call, and follow the bird when it flies off. When the bird reaches the hive it perches low in a tree, then waits for the humans to break open the hive. The humans get the honey, and the bird gets to feed on the beeswax and bee larvae left behind.

FIGURE 7.1.32 The belief that honeyguide birds lead honey badgers to bee hives is probably false. However, honeyguides do guide humans to bee hives.

BIO FILE

Commensalism or mutualism?

The relationship between clownfish and sea anemones is often said to be commensalism. The clownfish gains protection in the stinging tentacles and the sea anemone appears not to benefit. However, as the clownfish feeds, small bits of food come in contact with the tentacles on which the sea anemone may feed. So there is a slight positive benefit to the sea anemone, making this a case of mutualism rather than commensalism.

FIGURE 7.1.31 Three clownfish sheltering within sea anemones. The relationship is really mutualism rather than commensalism.

BENIGN INTERACTIONS

Benign interactions are interactions in which no species is harmed.

Commensalism

Commensalism is an interaction between species in which only one species benefits but the other species is not harmed. Animals such as birds or possums nesting in a tree hollow is an example of commensalism. In this case the bird or possum benefits and the tree is not harmed (Figure 7.1.33).

FIGURE 7.1.33 Many owl species nest in tree hollows where it is relatively safe during the day. This is an example of commensalism, because the owl benefits and the tree is not harmed.

Trees are also often host to epiphytes: smaller plants such as orchids, ferns, mosses, liverworts and lichens that live on the trunk or in the crown of the tree (Figure 7.1.34). The epiphyte receives sunlight and rainwater. This relationship is usually benign for the tree because it is neither helped nor harmed (unless it becomes overloaded with the weight of the epiphytes on its branches).

FIGURE 7.1.34 Epiphytes form a commensal relationship with the tree they grow on.

HARMFUL INTERACTIONS

Harmful interactions are those in which only one species benefits, and the other species is harmed as a result of the interaction.

Parasitism

In parasitism, one species (the parasite) benefits and the other species (the **host**) is harmed. Ectoparasites such as ticks and mistletoes live on or outside the host (Figure 7.1.35). Endoparasites such as parasitic fungi and wood-borers live inside the host (Figure 7.1.36). A **parasite** obtains its food from the host but does not necessarily kill it. The type of harm the parasite causes the host varies, but may include the following effects:

- shortened lifespan
- impaired functions such as digestion, photosynthesis or reproduction
- less ability to withstand stresses such as drought or cold
- greater vulnerability to predators.

FIGURE 7.1.35 Mistletoes are ectoparasites; they grow on other plant species and take nutrients and water from them.

FIGURE 7.1.36 This stick insect has been invaded, and is being killed, by a parasitic fungus. The fruiting bodies of the fungus are erupting from the insect's body and will release spores that will help the parasite to spread.

Many parasites have more than one host during their life cycle. A host that transfers a parasite to another host is called a vector. For example, the malarial mosquito is a vector for the *Plasmodium* parasite. It transfers the parasite when it bites a person to obtain blood. An infected person is also a vector for *Plasmodium* because they transfer the parasite to the mosquito when it bites them.

All organisms have parasites. For example, every species of plant and animal that has been studied has been found to have at least one parasitic species living in it. Tapeworms are a common parasite in animals (Figure 7.1.37). They are ingested and then attach to the small intestine, where they absorb nutrients and can grow quite large. Although they can cause illness, loss of appetite and anaemia, they sometimes produce no symptoms at all.

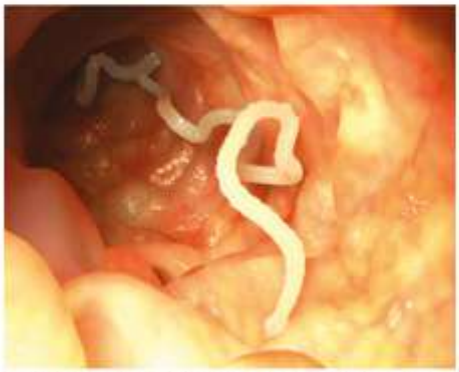


FIGURE 7.1.37 Tapeworms are endoparasites that infect animals, including humans.

BIO FILE

Viruses are obligate parasites

All forms of life—even bacteria—are susceptible to viruses. A virus is characterised by its ability to infect a living organism; it invades a living cell and uses the cell's own structures and metabolism to replicate. Viruses cannot grow or reproduce outside of a living host cell. This makes them obligate parasites, because they rely completely on their host for their survival.

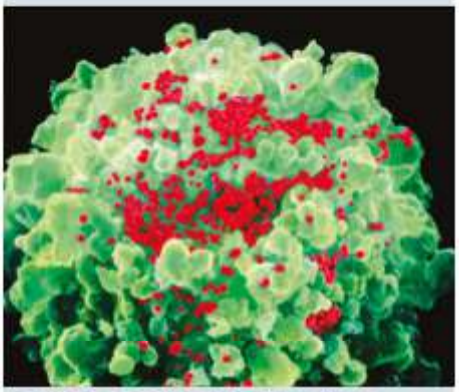


FIGURE 7.1.38 This living T-lymphocyte blood cell (green) is infected with human immunodeficiency virus (HIV) (red). Here the virus is a parasite, using the blood cell in order to reproduce.

Amensalism

Amensalism refers to an association between species in which one is inhibited or killed and the other species is unaffected.

A simple model of amensalism is the way in which animals can inadvertently damage vegetation around them but are unaffected by the relationship. For example, animals such as sheep and cattle often trample grass. The grass may be damaged or killed, but the animals receive no benefit from having done so (Figure 7.1.39a). Similarly, some waterbirds such as cormorants kill vegetation in places where they roost or nest (Figure 7.1.39b). This is because their droppings have a high nitrogen, phosphate and potassium content, which plants cannot tolerate.

FIGURE 7.1.39 (a) Larger animals such as sheep and cattle trample and damage grass, but are unaffected by the relationship. (b) Cormorant droppings can kill vegetation, but this does not benefit the birds.

Predation

Predation occurs when one animal species (the **predator**) kills and feeds on another animal (the **prey**). Predators are carnivores. Some predators hunt for their prey (Figure 7.1.40a), but others catch their prey in traps (Figure 7.1.40b). In both cases the predator benefits by eating and killing the prey, which is obviously harmed.

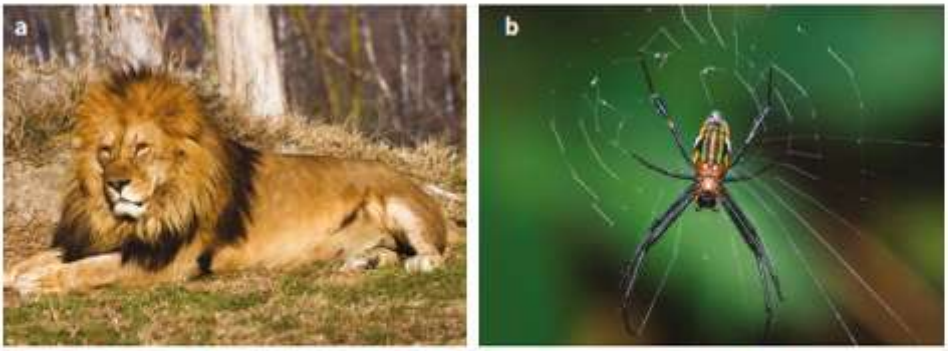


FIGURE 7.1.40 (a) Lions, as well as tigers and other cats, are predators that hunt for their prey. (b) Spiders are predators that create webs to trap passing insects, which they can then eat.

EXTENSION

Complex relationships: ants, plants and aphids

Many ants have developed a variety of symbiotic relationships with other invertebrates and plants. One of the most common is the herding or farming of sap-feeding insects such as aphids, scale bugs and mealy bugs.

The relationship between ants and aphids has been well studied. Home gardeners and horticulturalists are well aware of the damage done by aphids when they pierce the phloem vessels in plant stems and suck the sugar-rich fluids from the host plant. Because these liquids are low in nitrogen, aphids must consume large quantities of them to gain adequate nutrition. The aphids then need to excrete large quantities of waste, called honeydew, which has a high sugar content.

Some ants that consume this honeydew protect and cultivate the aphids to ensure the continued supply of the food (Figure 7.1.41). By stroking an aphid, an ant can induce it to release a honeydew droplet, a process known as 'milking'. The ants also care for aphid eggs, move the aphids to the best sap areas on the plant and prevent predators like ladybirds from eating the aphids.

This may seem like mutualism, benefiting both species. However, the ants control the relationship and may bite the wings off an aphid to prevent it from escaping. In addition, ants carry a chemical on their feet to mark trails and their territory; this same chemical is used by ants to tranquillise the aphids they are farming and prevent them from dispersing.

Aphids themselves have an obligate mutualism with specialist bacteria that live in certain cells in the aphid. The bacteria, which are passed down from aphid parent to offspring, provide essential amino acids that are lacking in plant sap. Aphids are also parasitic on their plants, disrupting the supply of sugary sap carried in the phloem.

While the ants do not damage the plants directly, they protect aphids and other sap-sucking insects that do. Because honeydew is sugar-rich it encourages the growth of sooty mould, a black fungus that is destructive to plants.

FIGURE 7.1.41 An ant tends a group of aphids so they will produce honeydew for the ant to eat.

BIO FILE

Allelopathy

Allelopathy is when an organism produces and secretes chemicals that affect the growth, reproduction or survival of other organisms. The organism producing the chemical can benefit or be unaffected.

Penicillium species are fungi that secrete penicillin, a compound that kills certain bacteria. This would benefit the *Penicillium* by reduced competition for nutrients and space from other microbes. The *Penicillium* may possibly benefit too by reducing populations of bacteria that make toxins that harm the fungus. This is an example of amensalism. Penicillin was first developed as a useful antibiotic for combating bacterial infections in the 1940s.

FIGURE 7.1.42 *Penicillium* species are fungi that secrete penicillin. A common species is blue mould, *Penicillium roquefortei*, which grows on old bread and is used to make blue cheeses.

7.1 Review

SUMMARY

- An ecosystem is a largely self-sustaining system formed by a community of living organisms that interact with one another, and includes their physical surroundings.
- Interactions between different species are known as interspecific interactions.
- Mutualism is a partnership between two species, in which both benefit. If the species depend on each other for survival, it is called obligate mutualism. If they help each other but are not dependent on each other, it is called facultative mutualism.
- Commensalism is a benign interaction in which one species benefits and the other species is unaffected by the interaction.
- Harmful interactions are those in which one organism is harmed. Parasitism, amensalism and predation are examples of harmful interactions.
- In parasitism, one species (the parasite) benefits, living in or on the other species (the host), which is harmed.
- Amensalism is an interaction in which one species is inhibited or killed and the other is unaffected.
- Predation is an interaction in which one animal species (a predator) feeds on another animal species (its prey). The predator benefits and the prey is harmed.

KEY QUESTIONS

1 What is an ecosystem? Give two examples of an ecosystem.

2 Compare and contrast the two types of mutualism. Use that information to identify the type of mutualism that exists between a plant being pollinated by an insect, when the plant has other potential pollinators.

3 The spotted jelly, *Mastigias papua*, needs to incorporate free-living algae called zooxanthellae, because it obtains its energy mainly from the carbon fixed by the algae. The spotted jelly is also able to obtain energy by feeding on phytoplankton, tiny invertebrates and microbes. What type of interspecific relationship do the spotted jelly and algae have?
   A predatory
   B commensalism
   C obligate mutualism
   D facultative mutualism

4 The pilot fish, *Naucrates ductor*, eats ectoparasites that live on the skin of white-tipped sharks, *Carcharhinus longimanus*. What type of interspecific relationship do the pilot fish and sharks have?
   A predatory
   B commensalism
   C obligate mutualism
   D facultative mutualism

5 Explain how parasitism differs from mutualism. Give examples of specific organisms.

6 The flame robin builds its nest on a tree branch. What type or types of relationships could this be? Why?

7 *Penicillium* species produce penicillin. Explain how this is an example of both allelopathy and amensalism.

8 State whether each of the following interactions is parasitism, mutualism or predation.
   a lice living in human hair and feeding on human blood
   b orangutan feeding on durian fruits
   c a sea eagle catching and eating a fish
   d a lizard eating an earthworm
   e clownfish feeding among sea anemones
   f vampire bats feeding on the blood of live birds or mammals
   g bees feeding on a flower and taking pollen to other flowers
   h a crown-of-thorns sea star feeding on coral polyps
   i *Plasmodium* protozoans living in humans and causing malaria

9 On a seashore rock platform, a marine biologist notices bare patches in an area covered by sea lettuce (a seaweed). She covers some of these patches in fine mesh that allows light to penetrate and sea water to flow over it. The sea lettuce grows again where the mesh has been placed, but not in the other bare patches. How do you explain this? What relationship is occurring?

7.2 Food webs and species interdependencies

In the previous section you learnt that organisms live together in ecosystems. In an ecosystem the organisms interact and depend upon one another for survival. They influence one another by being part of each other's environment. Organisms can be harmful or beneficial to one another.

One important way that species interact in an ecosystem is through feeding relationships. For example, a leaf-eating insect is part of the environment of a grevillea shrub. The insect has a source of food and benefits from the interaction, but the shrub is harmed because its photosynthetic leaf area is reduced. On the other hand, a honeyeater (Figure 7.2.1), which is another part of the environment of the shrub, is not harmful but useful to the tree. As the bird gathers nectar from the grevillea flowers it transfers pollen from shrub to shrub. The interaction benefits both organisms. The bird pollinates the grevillea and gathers its reward as food.

Species form a web of feeding interdependencies within an ecosystem. Any change to one species within an ecosystem will affect other species in the same food web. This can make some species vulnerable to change in the ecosystem. An example of this is shown in Figure 7.2.2. In this section you will learn more about food webs and what happens in ecosystems when changes to species occur.

FIGURE 7.2.1 When the scarlet honeyeater (*Myzomela sanguinolenta*) gathers nectar from grevillea flowers, it transfers pollen from one flower to another.

FIGURE 7.2.2 The giant panda (*Ailuropoda melanoleuca*) is a native of China and is a specialist feeder on bamboo. It needs to eat about 10 kilograms of various types and growth stages of plants a day. Such a specialist diet has made the panda very vulnerable to habitat destruction.

FIGURE 7.2.3 Sea otters (*Enhydra lutris*) have a feeding relationship with sea urchins which is important for ecosystem balance.

FEEDING INTERDEPENDENCIES IN ECOSYSTEMS

All organisms in an ecosystem require energy to survive. Some organisms are able to create their own food, but most consume a specific type of food from a particular environment. Some organisms feed on plants, some feed on insects or other animals, and others feed on dead and decaying material. Almost all organisms are consumed by at least one other organism.

Species in an ecosystem are interdependent; that is, they rely on each other. If one species is removed from an ecosystem, any species that interacted with it closely is affected. For example, sea otters along the coasts of the northern and eastern North Pacific Ocean feed on sea urchins and keep the sea urchin numbers in balance. If sea otters were suddenly removed from the ecosystem, sea urchin numbers would increase, and the kelp that the urchins feed on would be overgrazed (Figure 7.2.3).

The removal of a species may have a positive effect or a negative effect on other species in the ecosystem. Likewise, a species being added to an ecosystem can also have far-reaching effects. Examining the feeding relationships between organisms in an ecosystem can help in understanding why some species are affected by such changes.

Living in a eucalypt

A eucalypt tree is home to a variety of organisms. Each part of the tree acts in effect as a microhabitat. Some organisms live and feed among the leaves and branches in the crown of the tree. Some organisms live in the bark or on the trunk. Other organisms live at the base of the tree and among the accumulated litter of dead leaves and fallen bark. Seed-harvesting ants take seeds that fall to the ground. Some organisms live out of sight among the tree's roots. Animals come and go from the tree. Some are active only during the day, and others are active only at night.

The canopy provides food for many animals. The leaves of some eucalypts are food for koalas (Figure 7.2.4, page 318). Insect larvae also eat the leaves. The ring-tailed possum feeds on leaves and flowers. Small species of gliding possum eat nectar and pollen at night, and honeyeaters eat nectar during the day. Parrots such as rosellas crush the woody eucalypt fruits to eat the seeds inside.

FIGURE 7.2.4 Manna gum (*Eucalyptus viminalis*), swamp gum (*Eucalyptus ovata*) and river red gum (*Eucalyptus camaldulensis*) are the home of the koala, which eats the leaves.

i A food chain is a series of organisms linked by their feeding relationships.

i Producers are autotrophs and the first link in a food chain. All other organisms are consumers.

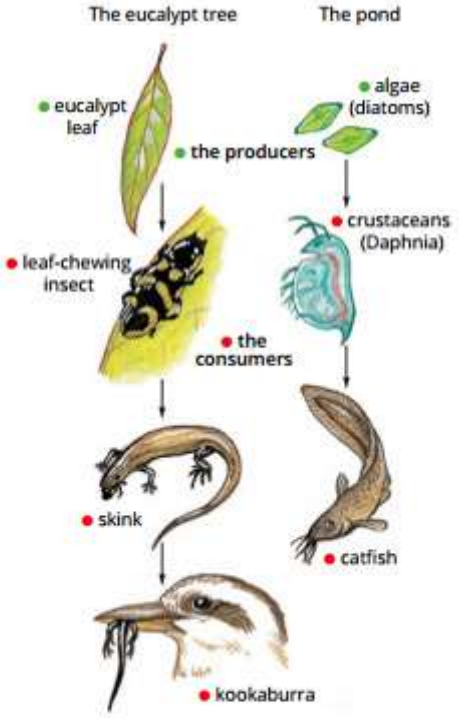


FIGURE 7.2.5 Two simple food chains: one in a eucalypt tree and one in a pond. The direction of the arrows indicate which organism eats which.

Spots on eucalypt leaves are evidence of fungi that break down leaf tissue for food. Tumour-like growths on the trunk are evidence of other fungi growing in the wood. Lichens and plants such as mosses, ferns and orchids use the trunk of the tree for support.

The smaller animals that eat the leaves and flowers are hunted by larger animals. The yellow-bellied glider mainly eats insects. Leadbeater's possum, which inhabits only mountain ash trees, catches tree crickets hiding in the bark. Spiders weave webs to catch their prey. Skinks feed on insects, and are themselves food for the sharp-eyed kookaburra.

Food chains

A **food chain** links organisms according to their feeding relationships. The two main groups of organisms in a food chain are producers and consumers. Energy captured by producers is first ingested by a consumer, which is in turn consumed by another consumer, and so on. In this way the energy in organic matter is transferred between organisms.

In a food chain diagram (Figure 7.2.5) the arrows show the flow of energy and matter through the chain. In a eucalypt tree, kookaburras feed on skinks that feed on insects that feed on the eucalypt leaves. This is an example of a food chain with four links (four kinds of organisms). In a pond the links are between catfish that feed on crustaceans that feed on algae.

Food chain participants

Producers

Plants and algae in a pond, and a eucalypt tree in a forest, play an important role as the first link in the food chain. They manufacture their own food by photosynthesis, so they are **autotrophs**. In food chains and food webs, autotrophs are called producers.

Producers are always the first link in a food chain. They produce organic compounds from simple inorganic compounds. There are two types of autotrophic producers.

Most producers, including plants and algae, are **photosynthetic** autotrophs (Figure 7.2.6). They use photosynthesis to make their own food. Some specialist autotrophs are **chemosynthetic**. This means they obtain their energy for producing organic compounds directly from inorganic molecules such as hydrogen sulfide and methane.

FIGURE 7.2.6 Plants are photosynthetic autotrophs. They are often the first link in a food chain.

Consumers

All organisms that are not producers are **consumers**. They are **heterotrophs** that obtain their energy by consuming other organisms. There are six types of consumers:

- herbivores
- carnivores
- parasites
- scavengers
- detritivores
- decomposers.

Consumers are further classified as primary, secondary, tertiary or quaternary depending on where they fit into a food chain. In the eucalypt tree, insects that eat the leaves are primary or first order consumers; skinks that eat the insects are secondary or second order consumers; and the kookaburra that eats the skink is a tertiary or third order consumer. If there is no other carnivore to consume it, the kookaburra is the top carnivore.

Consumers can be classified according to the type of organisms they feed on and the ways in which they feed on them. The different classifications are shown in Table 7.2.1, with examples of each type.

Predator–prey food chains

Many food chains are predator–prey food chains. A simple example from a pond is the catfish that feeds on crustaceans (*Daphnia*) that feed on algae (diatoms). The food chain linking the kookaburra, skink, insect and eucalypt tree (see Figure 7.2.5) is also an example of a predator–prey food chain.

Predators usually eat prey smaller than themselves; big fish eat little fish. A hawk preys upon animals the size of a mouse or small rabbit. Predator–prey food chains usually proceed from small organisms to large organisms.

Parasite–host food chains

Parasite-host food chains look a little different from predator-prey food chains. Parasite-host food chains have a large organism (the host) as a source of food for a smaller organism (the parasite). Figure 7.2.8 shows some parasite-host food chains involving the catfish in the pond.

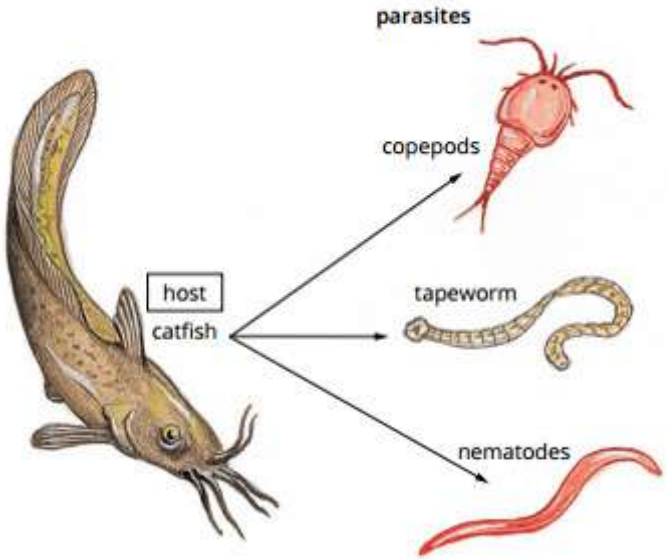


FIGURE 7.2.8 Parasite–host food chains in the pond. The food chains go from the larger host, the catfish (*Tandanus tandanus*), to smaller organisms, the parasites.

BIO FILE

Extreme bacteria

Chemosynthesis is at the heart of deep-sea communities. It sustains life in absolute darkness, where sunlight cannot penetrate. Around **hydrothermal vents** deep in the ocean, bacteria oxidise hydrogen sulfide to get energy for the synthesis of organic compounds. Heterotrophs such as giant tubeworms (*Riftia pachyptila*) feed from these bacteria. The producers in these unique ecosystems are bacteria rather than plants.

FIGURE 7.2.7 Giant tubeworms growing in a hydrothermal vent deep in the Pacific Ocean. They obtain their nutrients by feeding on chemosynthetic bacteria.

Name	Description	Examples	
herbivores	**Herbivores** feed on plants and other producers.	• catfish • swan • psyllid insect • koala • honeyeater • blue whale • giraffe (pictured)	
carnivores	**Carnivores** (eaters of flesh) consume other consumers. Carnivores that catch live prey are called predators.	• quoll • meerkat (pictured) • dingo • eagle • panther	
	Carnivores that feed directly on herbivores are secondary consumers (also known as first-order carnivores).	• dragonfly nymph • skink • frog (pictured) • sea star	
	Carnivores that feed on secondary consumers are tertiary consumers (also known as second-order carnivores).	• tuna • snake • penguin (pictured) • goanna	
	Carnivores that are the last link in the food chain are quaternary consumers (also known as third-order consumers and top consumers or top predators).	• crocodile • kookaburra • great white shark (pictured) • anaconda	
parasites	Parasites live and feed on the surface of or from inside other organisms (known as the host), causing them harm. At different stages of development, from larva to adult, the parasite may feed on a different host species.	• heartworm • tick (pictured) • malarial mosquito • liver fluke	
scavengers	**Scavengers** consume other dead animals.	• vulture • Tasmanian devil • planarian (flatworm) • hyena (pictured)	
detritivores	**Detritivores** feed on non-living organic material including fruits, remains of dead plants and animals, and also waste that accumulate as detritus. Detritivores are important because they physically break down organic material into smaller pieces.	• millipede • earthworm (pictured) • hermit crab • dung beetle	
decomposers	**Decomposers** break down (decompose) and then consume non-living organic material. They secrete enzymes over the non-living organic material, breaking it down into inorganic compounds (such as carbon dioxide, nitrogen and phosphate). Some of these inorganic compounds are absorbed by the decomposer—organisms that feed in this way are called saprotrophs. Some compounds escape into the environment—including the pond water, soil and air. Here, the inorganic compounds are then available to producers as nutrients, and the food cycle is closed. This makes decomposers the last link in food chains.	• bacterium • fungus (pictured)	

TABLE 7.2.1 Types of consumers

The life cycle of many parasites is complex. At different stages of development, from larva to adult, each feeds on a separate host species. Thus one species of parasite may be linked to a number of food chains. In Figure 7.2.9 the tapeworm *Ligula intestinalis* feeds on three hosts. An egg of the tapeworm hatches in the water. A copepod (first host) eats the larva. The larva grows in the intestinal cavity of the copepod after penetrating the intestinal wall. The copepod is eaten by a fish (second host) such as a bream, and continues to develop and grow in the intestine of the fish. An aquatic bird (third host), such as a grebe, then eats the fish. The adult tapeworm develops within two days of being eaten because of the higher temperature in the bird's intestine. Before they die in the bird, the adult worms produce eggs which pass out into the water, and the cycle continues.

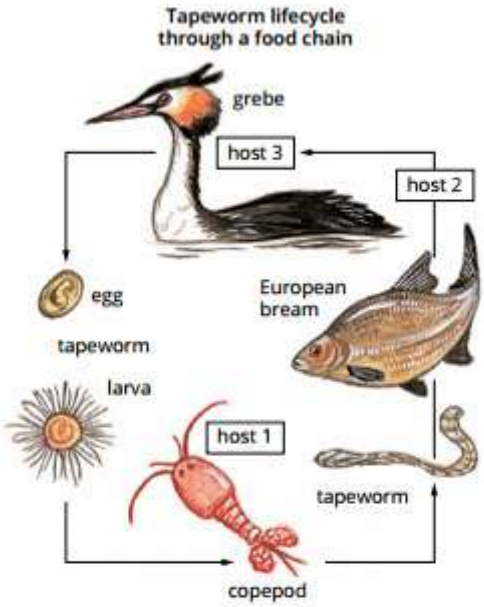


FIGURE 7.2.9 The lifecycle of a tapeworm through an aquatic food chain.

Detritivore and decomposer food chains

In temperate forests only about 10% of the plant material is eaten directly each year by herbivores. Much of the plant material falls as leaf litter. Dead leaves, dead branches, fallen tree trunks, dead roots in the soil, and the remains of dead animals are a major source of food for detritivores such as snails, worms, termites, springtails, millipedes and mites, and decomposers such as fungi and bacteria. Detritivore and decomposer food chains are most abundant in forests (Figure 7.2.10). They are also important in aquatic ecosystems where **detritus** builds up on the bottom of a pond, lake or bay (Figure 7.2.11).

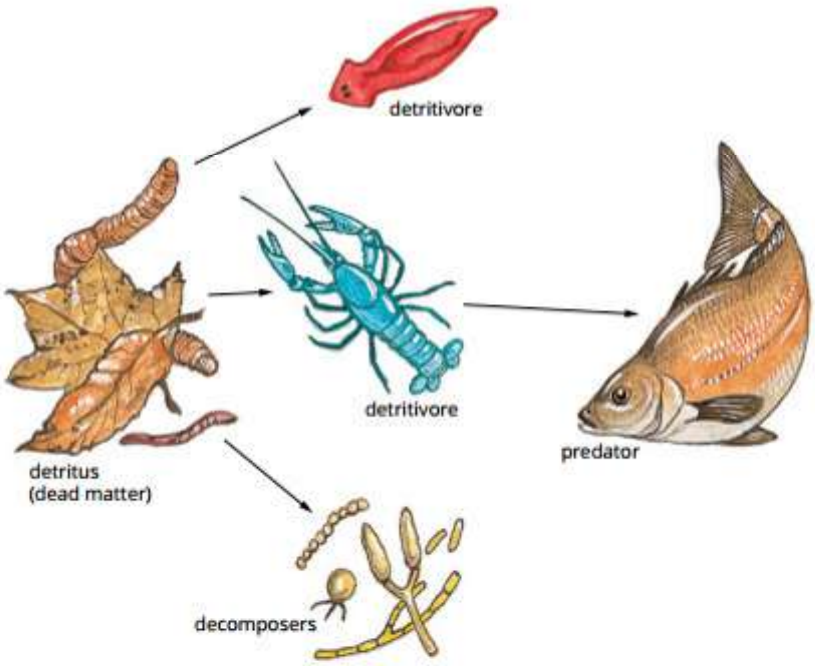


FIGURE 7.2.11 Detritivore and decomposer food chains in the pond both start with dead matter.

As a detritivore eats dead leaves, it also eats decomposers (bacteria and fungi) that are on and in the dead leaves. The detritivore also has symbiotic gut bacteria (microflora), distinct from the habitat microflora, which enables it to digest cellulose and other plant matter.

Detritivores and decomposers are organisms that consume dead organisms. Detritivores break down litter to small particles, which decomposers then break down.

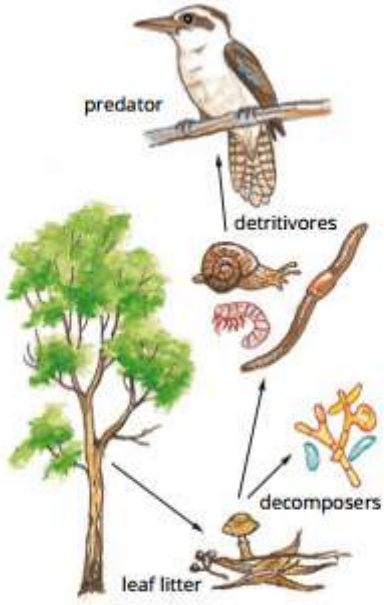


FIGURE 7.2.10 Detritivore and decomposer food chains are very important in terrestrial ecosystems, where plant litter accumulates on a forest floor.

BIO FILE

Dung for dinner

A lot of land in Australia is devoted to sheep and cattle agriculture. This has led to excessive amounts of sheep and cattle dung in arid and semi-arid environments. The dung dries out before it can be broken down, and fungi and bacteria might only be active during wetter periods. As a result the dung accumulates on the ground surface and is a breeding ground for bush flies and other types of flies.

Dung beetles are detritivores that bury faeces to conserve the moisture content before they eat them. Native dung beetles have evolved to consume the smaller faeces of native animals, but they are ineffective in burying and consuming large dung pads in grazing lands. Over 50 species of dung beetles, such as the elephant dung beetle, have been introduced into Australia from other countries in an attempt to reduce the accumulation of cattle dung and reduce the fly population.

FIGURE 7.2.13 Dung beetles bury fresh dung underground, where it will remain moist for consumption by the beetles later or will become part of a decomposer food chain. Bacteria and fungi will break down this organic matter, some of which they will use for themselves and some of which will be recycled into the environment.

Detritivores are important because they physically break down litter into small particles. Parts of the dead leaves that a detritivore chews pass out of the animal as faecal pellets. These smaller particles are then easier for decomposers to consume. Some detritivore animals also eat faecal pellets (either their own or those of other species). Fly and beetle maggots are two examples of animals that consume faeces and dead organisms.

The decomposers, bacteria and fungi, are the last link in this chain of eating, re-eating and breaking down detritus. The digestive enzymes that decomposers secrete break down the organic matter into soluble organic molecules such as sugars and amino acids, and eventually into inorganic nutrients such as carbon dioxide and phosphate. Some of these products are absorbed by decomposers and some remain into water, soil or the air.

Decomposers

Decomposers are the final link in the cycle of matter in ecosystems. They are able to use the materials left by all the other organisms in a food chain. All organisms eventually die, leaving carcasses. They also discard matter such as dead skin, undigested food, leaves and dead branches while they are alive. In the examples shown in Figure 7.2.12, the cabbage sheds its leaves after blooming, and all animals regularly deposit faeces.

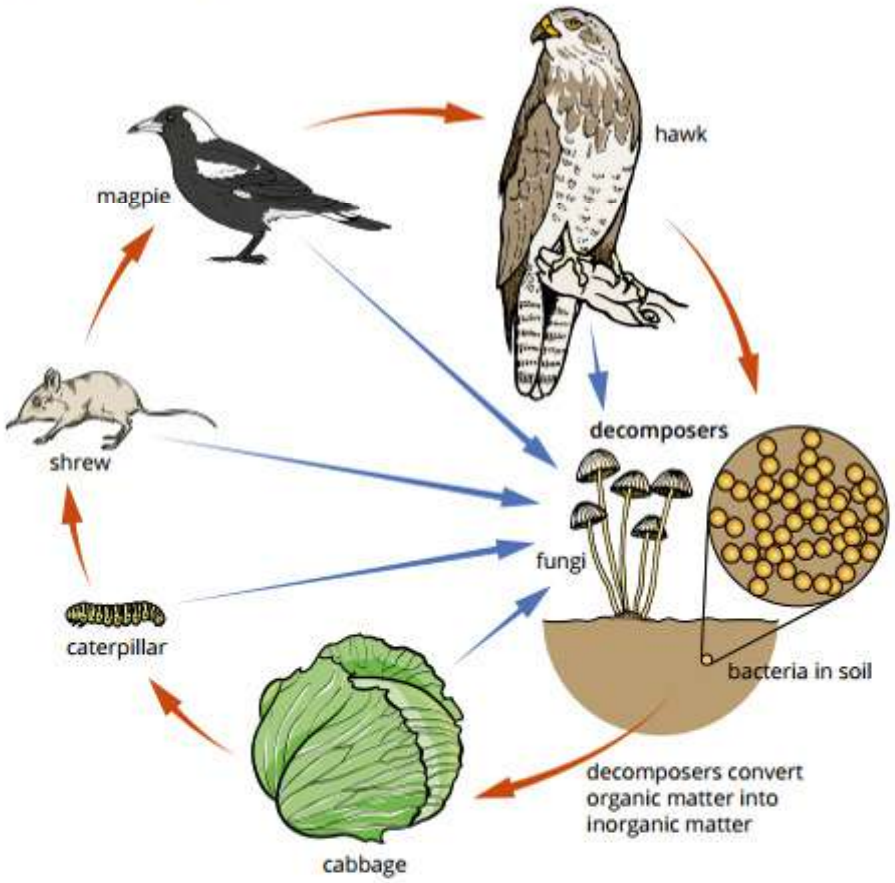


FIGURE 7.2.12 Decomposers complete the cycle of inorganic matter.

Decomposers can use these materials and transform them into simple inorganic compounds such as carbon dioxide, water, hydrogen sulfide and ammonia. These compounds can then be used by autotrophs. In this way, decomposers complete the cycle of matter. The inorganic matter taken up by autotrophs goes through producers and consumers and decomposers and back to inorganic matter.

FOOD WEBS

Most organisms are part of more than one food chain because they eat or are eaten by more than one type of organism. Because these food chains are linked, they form a complex system of feeding interactions called a **food web** (Figure 7.2.14).

A series of interacting food chains link up to form a food web.

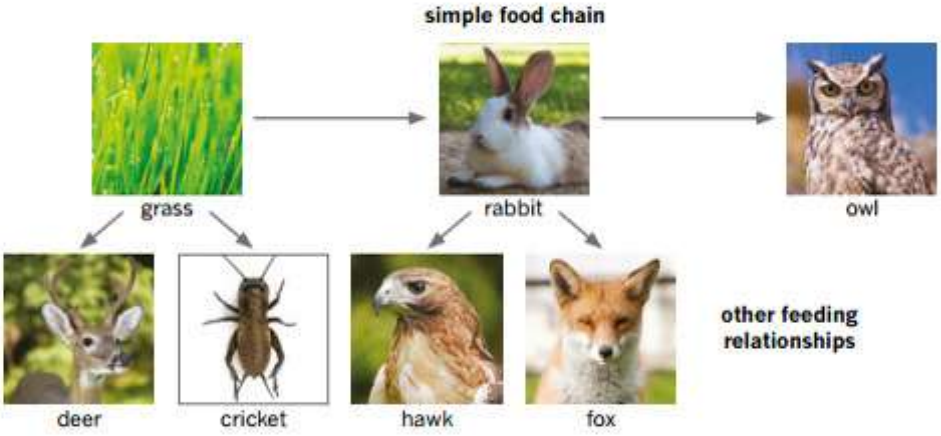


FIGURE 7.2.14 A simple food chain is a small part of the entire feeding relationships in an ecosystem. In this diagram you can see that a food chain can be turned into a food web by linking feeding relationships.

Simple food chains in which the organisms have only one food source are rare in nature. A plant is usually eaten by several herbivore species. Herbivores that feed on just one plant species are rare. Predators, even those that are specialised for catching and feeding on one type of animal, can adapt to a different kind of prey if the animals that they normally hunt are in short supply. An example of a predator that has done this is shown in Figure 7.2.15. As the diets of species become broader, the food web becomes more complex.

The complexity of the food web gives an ecosystem its stability. In a simple food chain, the removal of one species (i.e. one link) is likely to have a disastrous effect on other organisms. The loss of one species from a complex web has less effect, because alternative food sources are usually available. The food web involving the giant panda is an example of a vulnerable simple food chain.

FIGURE 7.2.15 The wedge-tailed eagle is a predator that can prey on a variety of animals. Before Europeans arrived in Australia, the eagle's diet was probably only reptiles and small mammals. Today its diet is mainly introduced rabbits and hares, although it continues to eat native animals.

TROPHIC LEVELS

Each feeding level in a food chain or web is called a **trophic level**. All the producers in a typical food chain or web make up the first trophic level. Herbivores (primary consumers) are at the second trophic level because they feed on the producers from the first level. Secondary consumers, which feed on herbivores, are at the third trophic level, and so on. You can see these roles labelled in the food chain in Figure 7.2.16.

Food chains are usually short, often with only three or four links (trophic levels). Insect and detritivore-dominated food webs may have up to six levels. For example:

plant litter (detritus) → springtail → mite → ant → skink → cat

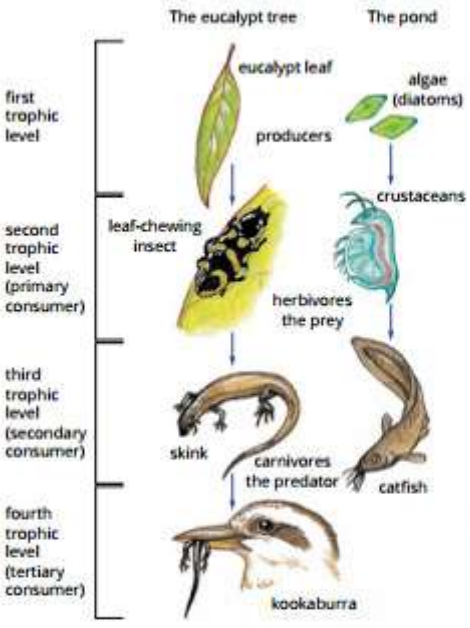


FIGURE 7.2.16 The trophic levels in food chains.

EXTENSION

Ecological detectives: analysing diets in food webs

How do ecologists find out what an animal eats, so they can work out a food web?

Direct observation

Field ecologists often watch animals feeding and note what they eat. A checklist of plants in the area can be used to work out the different species eaten by herbivores.

Scats and pellets

Heads, legs and wings of insects, bone, teeth, skin, eggshells, feathers, seeds and indigestible plant parts (Figure 7.2.17a and 7.2.17b) can be identified in the faeces and pellets of many animals. Studying faeces of large herbivores, and birds and mammals that eat insects, is especially successful. Faeces, also called scats, can be found on the ground and in nests and burrows (Figure 7.2.17c). Their shape and colour can often be used to tell what animal it came from. Regurgitated pellets that contain indigestible bones and feathers of owl prey can be used in the same way.

Inspection of roosting sites can reveal what a bird has eaten. For example, owls do not digest bones and fur, but regurgitate them as pellets, which can be found beneath nests.

Stomach contents

Inspecting stomach contents is a direct method of determining diet. Stomachs of birds can be pumped or flushed with saline solution, and the stomachs of dead animals such as trawled fish and road kills can be dissected to reveal the contents. Food may be found whole or in parts. Hard parts such as bone, fish scales, fur and seeds are often characteristic of species.

Exclusion experiments

Ecologists can determine what species of plants herbivores prefer to eat by exclusion experiments. A plot of vegetation is fenced to exclude the herbivore. The species of plants that grow in the plot are compared with the grazed area outside the fence. The differences between the grazed and ungrazed areas indicate which plant species have been grazed by the herbivore.

DNA analysis

In some cases, DNA analysis can be used to identify fragments of organisms in stomach contents, faeces or pellets. However, this analysis is time-consuming and expensive at present.

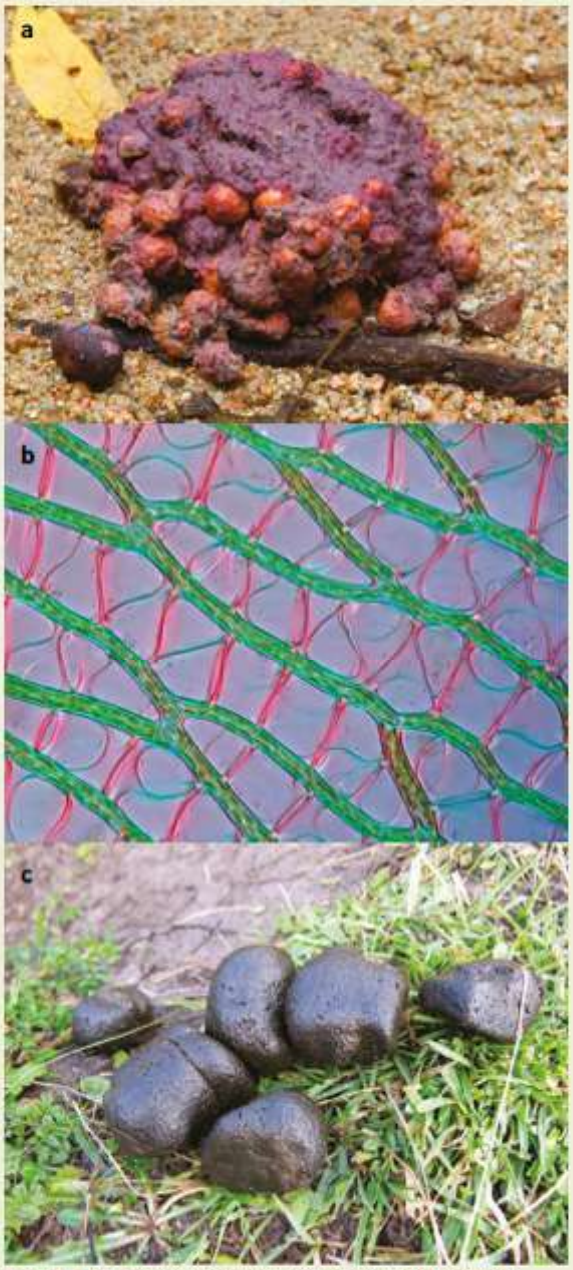


FIGURE 7.2.17 (a) Cassowaries eat up to 150 species of rainforest fruits. They eat the fruit whole, and their large piles of droppings contain undigested seeds that can be identified. (b) The cells of sphagnum mosses are so different from any other plants that they can be recognised among undigested food even if there are only a few cells. The size and shape of scats from animals such as koalas, wombats (c) and kangaroos can be used to work out the animal they came from.

An organism may function at more than one trophic level in a food web. In the example of the pond food web in Figure 7.2.18, the catfish feeds on small crustaceans and insects, as well as snails and small fish. The catfish is a secondary consumer at the third trophic level because it eats *Daphnia*, and a tertiary consumer at the fourth trophic level because it eats waterstriders that eat *Daphnia*.

Food chains are short, usually with three or four links (trophic levels). Insect and detritivore-dominated food webs are often exceptions, including up to six levels.

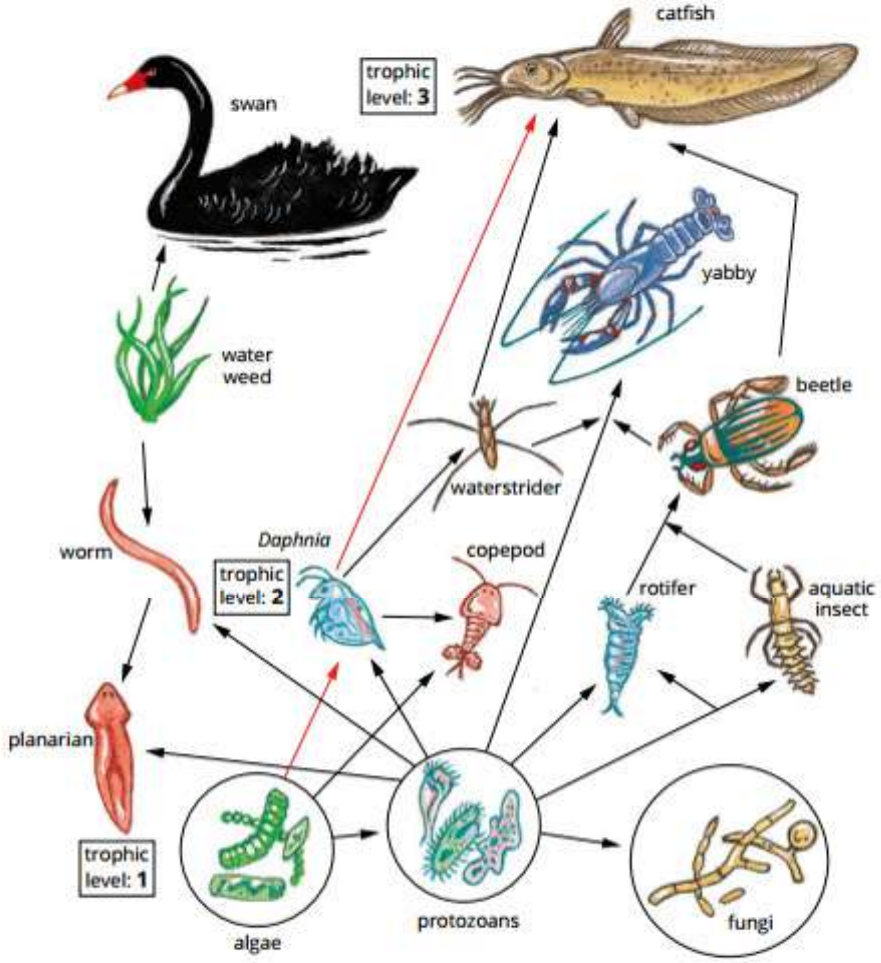


FIGURE 7.2.18 The food web for a freshwater pond. A food web diagram represents feeding relationships in an ecosystem. The chain of red arrows illustrates three different trophic levels.

CHANGES TO A SPECIES WITHIN AN ECOSYSTEM

Species are interconnected within food webs in ecosystems. So unsurprisingly, when a change occurs to one species, other species and sometimes even the entire food web are affected.

The complexity of a food web is what gives an ecosystem its stability. In a simple food web, the loss of one species would have a disastrous effect on the other organisms. In a complex food web, the loss of one species has less effect, since alternative food sources are often available.

Changes to a keystone species

Some species in an ecosystem can be identified as keystone species. A **keystone species** is a species that plays a critical role in maintaining the structure of their ecosystem (Figure 7.2.19). When a keystone species is removed from an ecosystem, the ecosystem becomes much less stable and its structure changes.

FIGURE 7.2.19 A keystone is the central stone that supports the arch structure in a stone archway. A keystone species is so named because it maintains the structure of its ecosystem in a similar way.

FIGURE 7.2.20 A cluster of sea stars (*Pisaster ochraceus*)—the predator species first termed a keystone species.

The first keystone species

The term keystone species was first applied during a study of food webs in rock pools. The carnivorous sea star *Pisaster ochraceus* (Figure 7.2.20) was identified as the top predator in the rock pools. As an experiment, all the *Pisaster* sea star were removed from one rock pool (with a second rock pool nearby left undisturbed, as a control). In the test rock pool, the remaining species competed with each other to occupy the extra space and to use the additional resources made available. Two types of barnacles and a mussel species began to dominate. They consumed so much of the limpets' food source (algae) that the limpet population decreased. Within a year, the number of limpet species decreased from 15 to 8. In the control rock pool, there was no change in species number or distribution. As these significant changes resulted from the removal of the sea star, *Pisaster ochraceus* was called a keystone species.

This experiment showed the huge effect that removing a keystone species from an ecosystem can have. Many other species of organisms have since been identified as keystone species. Naturally, such species are frequently targeted for conservation efforts.

FIGURE 7.2.21 The great white shark (*Carcharodon carcharias*) is an important predator and a keystone species in marine ecosystems.

The numbers of the great white shark (*Carcharodon carcharias*) have been declining (Figure 7.2.21), mostly because they are caught in fishing nets or are hunted. This has had far-reaching effects on marine ecosystems. The great white is a predator at the top of the food chain, keeping populations of the fish, seal and sea lion species they consume in check, as well as the animals that those species consume. The great white shark is a keystone species that helps maintain the stability of marine food chains.

Another well-known keystone species is the northern quoll (*Dasyurus hallucatus*), also known as the native cat (Figure 7.2.22). This species has become endangered for many reasons, including bushfires and feeding on poisonous cane toads. The quoll feeds on a large variety of foods, including fruit, insects, birds, mammals and reptiles. Through feeding, the quoll helps control the numbers of its prey species, and with the quoll's decline, the delicate balance of those populations is being disrupted.

FIGURE 7.2.22 The northern quoll (*Dasyurus hallucatus*) is an endangered species of carnivorous marsupial found in Queensland, the Northern Territory and Western Australia.

Keystone species and habitat

Some species are keystone species because they affect the habitats of an ecosystem. For example, elephants preserve the grasslands of African savannas by eating any young trees that grow (Figure 7.2.23). Without the elephants, the savannas would be invaded by trees and shrubs and eventually become forests or shrublands, and the many smaller grazing herbivores such as wildebeests and zebras would starve.

FIGURE 7.2.23 Elephants are a keystone species in African savannas because they maintain the grassland ecosystem.

Keystone species and human impacts

Human activities can have a detrimental effect on ecosystems, particularly where these activities affect a keystone species. One example is the culling of grey wolves from Yellowstone National Park in the United States (Figure 7.2.24). The wolves were originally seen as a pest, but their eradication led to a rapid increase in the elk population, and therefore massive overgrazing and the loss of aspen and willow plants. This led to a loss of habitat and food for many smaller species such as beavers and songbirds, as well as stream bank erosion and water sedimentation. In 1995, grey wolves were reintroduced and the ecosystem is slowly recovering.

FIGURE 7.2.24 Grey wolves are a keystone species in the Yellowstone National Park because they keep the elk population in check.

7.2 Review

SUMMARY

- Different species are interconnected in their ecosystem through feeding relationships. These relationships form linear food chains and broader food webs.
- Food chain diagrams are linear diagrams that show the flow of energy and matter through each trophic level, starting with a producer.
- Producers are autotrophic organisms; they can produce their own organic matter. They are the first trophic level in a food chain or web. There are two types of producers:
  - photosynthetic producers, which use photosynthesis to produce their own food
  - chemosynthetic producers, which use chemosynthesis to produce their own food.
- All other organisms are consumers (heterotrophs), which consume other organisms to obtain organic matter.
- Consumers can be divided into six groups: herbivores, carnivores and parasites (which all consume living organisms for food), and scavengers, detritivores and decomposers (which all consume dead organic matter).
- There are different types of food chains, called predator–prey, parasite–host, detritivore and decomposer food chains, depending on the relationships between organisms.
- Decomposers, including bacteria and fungi, are the last link in food chains because they break down food to inorganic compounds, which can then be taken up by producers.
- Food chains link together into food webs and this complexity of relationships provides an ecosystem with stability.
- A predator species that is part of more than one food chain in a food web is less likely to be affected by the loss of one source of food.
- Each level in a food chain or web is called a trophic level. A species may function at more than one trophic level in a food chain or web.
- If there is a change to one species, or if a new species is introduced, other species, and sometimes the entire food web, are affected because species are interconnected in their ecosystem through food webs.
- Keystone species are those that are critical to the stability of an entire ecosystem. If they are removed, the entire food web is affected.

KEY QUESTIONS

1 What kind of organism is always the first link in a food chain? Why?

2 What is the best description for the role of each organism in the following food chain?

3 Select the list that contains only decomposers and detritivores.

A algae, bacteria, termites, echidnas
B vultures, ticks, earthworms, fungi
C millipedes, earthworms, bacteria, fungi
D snails, maggots, dung beetles, crows

4 Explain with an example how a species might be at more than one trophic level in a food web.

5 Make up a table that lists the six different types of consumers and what they eat, and include two examples of each type of consumer. The first has been done for you.

Type of consumer	What it eats	Examples
herbivore	plant matter such as leaves, seeds and fruits	koala, mouse

6 **a** What is the difference between a food chain and a food web?

b What is the advantage of a complex food web over a simple one?

7 A keystone species is critical to the stability of a whole ecosystem. Give one example of a species like this and explain what makes it a keystone species.

7.3 Population dynamics

In theory, populations should continually increase in size as a species produces more individuals. However, this is rarely the case in an ecosystem. Instead, population size and density are determined by a variety of factors that influence rates of birth, survival, reproduction, emigration, immigration and death. Population sizes also vary considerably between species (Figure 7.3.1).

In this section you will explore the factors that affect the distribution, density and size of the population within an ecosystem.

FIGURE 7.3.1 King penguin colonies can consist of hundreds of thousands of penguins.

POPULATION DISTRIBUTION

Geographic distribution or range is all the places where a particular species can be found. For example, emus are found only in Australia, and kiwis are found only in New Zealand. The rock orchid *Dendrobium kingianum* is restricted to parts of eastern Australia (see Figure 7.3.2).

Geographic distributions may change over time. For example, humans have aided the spread of weeds and animal pests. Humans have also reduced the distribution range of species by clearing forests and interfering with other natural ecosystems.

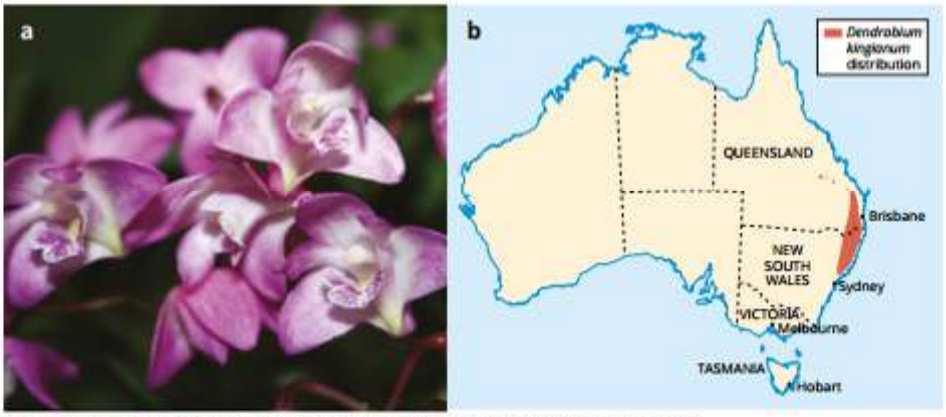


FIGURE 7.3.2 (a) *Dendrobium kingianum* and (b) its geographic distribution.

FIGURE 7.3.3 Blades of grass would be difficult to count for a population density measurement.

STUDYING POPULATION DENSITIES AND DISTRIBUTION

The density of a population is the number of individuals per unit of area or volume. For example, this might be the number of rabbits in a given area or the number of fish in a particular volume of water.

If it is difficult to count individuals, the size of a population can be measured in biomass. For example, counting blades of grass is a tedious process, so a grass population is often measured in kilograms per unit area (Figure 7.3.3). A small area of grass can be cut and weighed, and then this value can be used to calculate the total **biomass** of the population.

Biomass is an amount of organic matter. It is usually expressed as mass per unit, such as kg/m².

The area used to measure density might sometimes be represented by a less conventional unit. For example, the population density of plant lice can be expressed as the number of individuals on one leaf (Figure 7.3.4).

FIGURE 7.3.4 The density of plant lice can be measured by counting the number of lice per leaf.

There are three basic patterns of distribution (see Figure 7.3.5): random, uniform and clumped (or clustered).

FIGURE 7.3.5 The three patterns of population distribution: random, uniform and clumped.

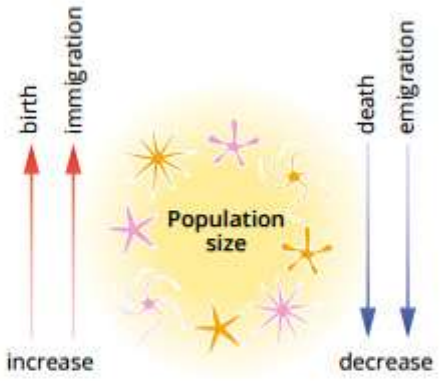


FIGURE 7.3.6 The size of a population depends on birth rate, death rate and migration.

POPULATION GROWTH

A **population** is a group of organisms of the same species living in a defined geographic area. The size of a population is affected by four processes:

- **natality** (births or germination)
- **mortality** (deaths)
- **immigration** (organisms moving in from outside the population)
- **emigration** (organisms moving out of the population).

Birth and immigration bring new population members and thus increase the population size. Death and emigration decrease the population size. Immigration and emigration are collectively known as **migration**. These four processes determine the rate of change in a population over time (Figure 7.3.6).

Exponential population growth

Theoretical exponential growth

Ecologists use mathematical formulae to model the theoretical growth of a population over time. The graph in Figure 7.3.7 shows a theoretical growth curve for a population in an ideal environment.

The graph assumes that the number of immigrants equals the number emigrants over time. Change in this population is therefore a function of births and deaths only. This type of growth is known as **exponential growth**. The J-shaped curve of the graph is characteristic of exponential population growth.

As long as the birth rate is higher than the death rate, a population will grow. If the birth rate remains consistently higher, then the population may grow exponentially.

Year	0	1	2	10
Size of population	100	200	400	102 400

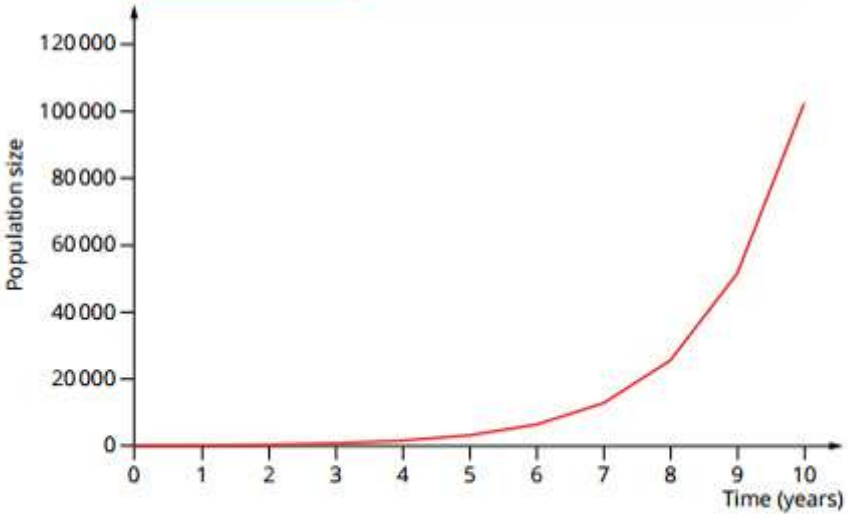


FIGURE 7.3.7 The size of a population over time (years), showing exponential population growth.

FIGURE 7.3.8 Salvinia fern (*Salvinia molesta*) is one of the world's most troublesome aquatic weeds.

Exponential growth in real populations

Species that tend to experience exponential population growth are those that have a short generation time and give rise to large numbers of offspring. Examples of these are bacteria, many weed species and some types of insects. In most instances exponential population growth occurs only for relatively short periods of time.

Exponential growth is normal for some plants and animals when environmental conditions are favourable and resources are abundant (plentiful). Because these conditions generally last only a short time, exponential growth is usually short-lived. But if favourable conditions continue then a '**population explosion**' may occur.

Salvinia fern is a free-floating aquatic weed that often has population explosions (Figure 7.3.8). It can survive for up to 20 months in dry conditions, but under favourable environmental conditions, such as high nutrient levels, it can double its population every two to five days. If these conditions continue, salvinia will form a dense mat on top of a waterway, preventing other aquatic plant life from receiving sunlight. Due to its growth rate and damage to aquatic habitats, this introduced species is a declared prohibited weed throughout Australia.

Some species may experience exponential growth during particular periods of their lifecycle. Organisms that reproduce during a particular period of the year often have massive increases in their population during this time, and decreases in population throughout the rest of the year. An example of this is sea turtles. Sea turtles come ashore once a year and bury large numbers of eggs in the sand. When these hatch, the turtle population is very large, however very few baby turtles make it safely to the water or survive predation in the ocean. Other species reproduce even less frequently. Periodical cicadas live underground for up to 17 years before emerging to reproduce, when the females lays hundreds of eggs in 3 or 4 weeks. The population growth at this time is tremendous, but only occurs for a short time (Figure 7.3.9).

FIGURE 7.3.9 The periodical cicadas (genus *Magicicada*) live most of their long life underground feeding on the roots of deciduous trees in North America.

BIOLOGY IN ACTION

Crown-of-thorns sea star population explosion

The crown-of-thorns sea star (*Acanthaster planci*) is a large echinoderm that lives on coral reefs of the Indian and Pacific Oceans, close to the coasts of eastern Africa, Japan, Hawaii and tropical Australia (Figure 7.3.10). Adults have up to 23 arms, all of which are covered on the top with poisonous spines. Adult crown-of-thorns eat anemones and the soft-bodied polyps of corals, leaving behind only the skeleton of the coral.

The crown-of-thorns has probably been on the Great Barrier Reef for as long as the reef has been in existence, keeping other fast-growing corals under control. However, population explosions occasionally occur, and they are caused by several factors.

The abiotic environment: The rapid rise in population has probably been triggered by heavy rains and cyclones, which result in increased nutrient levels being washed from the land into the sea. This in turn leads to an increase in phytoplankton, which is the food of crown-of-thorns larvae. With an abundant food source, more larvae survive into adulthood.

Reproduction: The crown-of-thorns can reproduce at a great rate when conditions are favourable. A female produces over one million eggs in a spawning season, so even a small increase in the survival of offspring will result in a much larger adult population.

Predator control: The sea star has some natural predators, such as large molluscs (tritons), but it is protected by its large size, poisonous spines and nocturnal behavior. Fishing may also have reduced the number of predators.

Dispersal: The crown-of-thorns can swim and spread for the first 3–4 weeks of its life before settling at the bottom of the sea.

Population explosions of the crown-of-thorns sea star reduce the coral population (Figure 7.3.11). Previously the coral has recovered over time. However, there is concern that coral will be destroyed faster than it can regrow. Research by the Australian Institute of Marine Science shows that the coral population has declined by approximately 50% in the past 30 years. The crown-of-thorns sea star is one of the major causes of this decline, along with cyclones and ocean warming.

FIGURE 7.3.10 The crown-of-thorns sea star (*Acanthaster planci*).

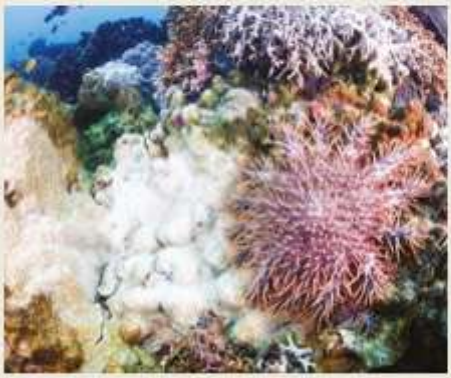


FIGURE 7.3.11 When numbers of crown-of-thorns sea star increase, coral is killed, leaving only bleached coral skeletons.

BIO FILE

An explosion of algae

An algal bloom is a population explosion of aquatic phytoplankton (algae or cyanobacteria), causing water to change colour and become toxic. A common culprit in lakes and ponds is the cyanobacterium *Anabaena*.

FIGURE 7.3.12 The algal bloom outbreak in this pond is very evident in the dense green colour of the water.

FACTORS THAT AFFECT POPULATION SIZE AND DENSITY

All populations have the potential for exponential growth, but a number of factors can affect population size and density and prevent initial or continued exponential population growth. The size of a population is affected by many factors interacting in complex ways. However, the effects of one factor can often amplify (increase) the effects of others factors.

Factors that influence population size are either **density-independent factors** or **density-dependent factors**.

DENSITY-INDEPENDENT FACTORS

Density-independent factors affect a population's size regardless of the size or density of the population. They include:

- the conditions in which the species can survive; that is, its daily and seasonal **tolerance range** for various **abiotic factors**
- major changes or disturbances to the environment, such as bushfires, droughts or floods.

Tolerance range of a species to abiotic factors

Every species has a particular range of conditions in which it can survive. For each abiotic factor there is an ideal range that is favourable for the growth, development and survival of the species. Abiotic factors that can affect population size include:

- temperature
- sunlight
- soil or water pH
- salinity
- humidity
- wind strength
- water availability
- pressure (e.g. water depth).

Outside its ideal range for a particular factor, an organism will experience stress. Development may be delayed, and survival and reproduction rates and lifespan may be decreased. At a certain point outside the ideal range, the organism will die. For example, a particular species may be able to survive between temperatures of 10–40 °C, but its ideal temperature for maximum survival and reproduction may be 25–30 °C. At temperatures below 10 °C or above 40 °C, death is likely. When graphed, an organism's tolerance to an abiotic factor is often a bell-shaped curve, as shown in Figure 7.3.13.

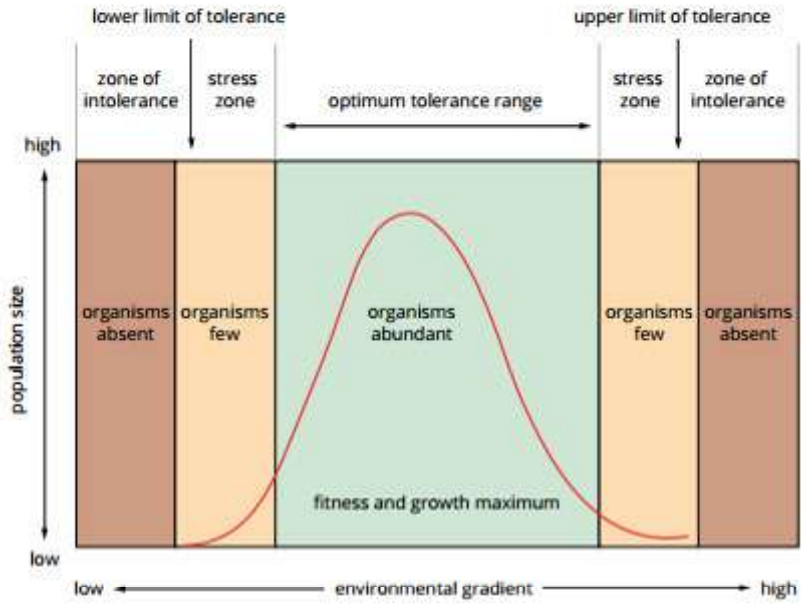


FIGURE 7.3.13 An organism's tolerance to an abiotic factor, for example temperature, is often a bell shaped curve (indicated here with a red line). As the environmental gradient increases and decreases, fewer individuals are seen.

Major changes to an environment

Other types of density-independent factors affecting population size are those related to sudden or major changes to an environment. These can occur in a number of different ways, including:

- natural disasters, such as flood, bushfire (Figure 7.3.14a), drought, volcanic eruption, tsunami, earthquake and cyclone
- human-made changes, such as construction or pollution.

Natural disasters and human-made changes can have wide-ranging effects on plant and animal species. The destruction of habitat (Figure 7.3.14b) can displace many organisms, and some major changes to the environment can kill organisms (Figure 7.3.14c).

FIGURE 7.3.14 (a) Bushfires affect many animal and plant populations. (b) Clearing rainforests for oil palm plantations in Malaysia destroys habitat for many species, including elephants, tigers and orangutans. (c) Pollution of waterways reduces oxygen levels and causes the death of fish and other marine organisms.

DENSITY-DEPENDENT FACTORS

Density-dependent factors influence the rate of births and deaths in a population. The effects of these factors increase as the population increases. Density-dependent factors include:

- competition for resources, such as food, water, shelter and mates
- predation
- crowding
- parasitism
- infectious disease.

Competition

All organisms have a set of biological requirements for their survival and reproduction. All organisms need resources such as nutrients and water to sustain themselves, shelter for protection, and mates for reproduction. If two organisms require the same resource and there is a limited access to this resource, there will be competition. Competition can be intraspecific (between individuals of the same species) or interspecific (between different species).

Limiting factor

The **limiting factor** of a population's size, density or growth is the scarcest of the resources needed by a population. For example, food, water, shelter, nutrients and light are essential for a population's growth. If all of these resources except water are available in large quantities, water is the limiting factor and organisms will have to compete for it (Figure 7.3.15).

FIGURE 7.3.15 During a drought, water becomes the limiting factor for population growth.

BIOLOGY IN ACTION

Competition and barnacle distribution

On rocky shores different species of barnacles grow in different vertical zones (Figure 7.3.16A). For example, in Scotland, *Balanus* barnacles live on rocks below the average high tide mark. These barnacles are covered by water for some part of each day. *Chthamalus* barnacles live on the rocks in the splash zone, above the high tide mark and the *Balanus* barnacles.

There are two possible explanations for this zonation. These two species may be restricted in their distribution by their inability to survive in each other's zone (microhabitat) (Figure 7.3.16B). Alternatively, competition between the two barnacles may be limiting their distributions (Figure 7.3.16C).

To determine the cause of the zonation of the barnacles, researcher J.H. Connell designed an experiment. He first removed *Chthamalus* barnacles from rocks in the splash zone. He found that *Balanus* still would not move into the zone and live there. He concluded that this barnacle cannot tolerate the exposed conditions of the splash zone.

When Connell removed *Balanus* from underwater rocks, however, he found that *Chthamalus* did move down and survive below the water line. Thus competition is limiting the distribution of *Chthamalus*, restricting it to the harsher splash zone. Young *Balanus* barnacles grow more rapidly than young *Chthamalus* in the lower zone and vigorously grows over and crushes its competitor.

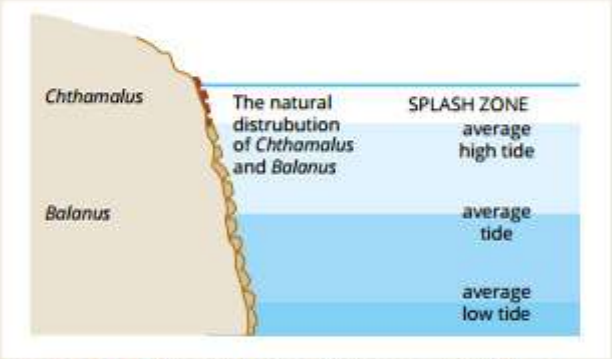


FIGURE 7.3.16A The distribution of *Balanus* and *Chthalamus* barnacles on rocks on a Scottish shore is controlled by characteristics of the organisms and competition.

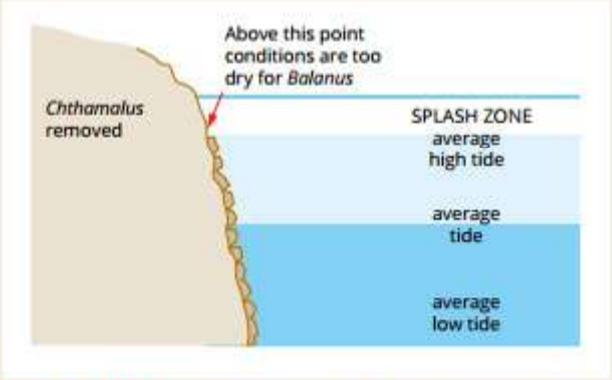


FIGURE 7.3.16B *Balanus* is restricted to deeper water because it is intolerant of the exposed conditions of the splash zone.

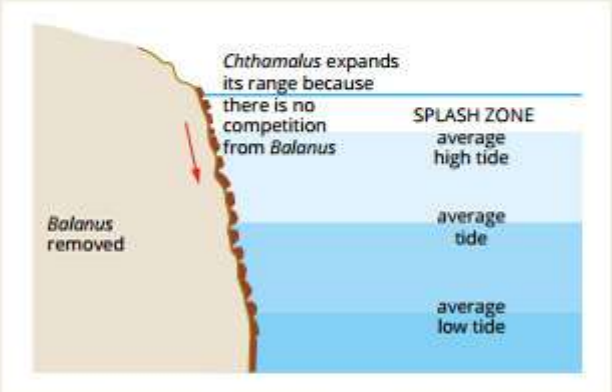


FIGURE 7.3.16C *Chthalamus* is restricted to the splash zone because it is outcompeted at lower depths by the stronger growing *Balanus*.

Interspecific and intraspecific competition

Competition can be interspecific or intraspecific. **Interspecific competition** occurs when different species compete for the same resource. For example, different species might need tree hollows for nesting and shelter. If trees with hollows are blown over or cut down, hollows might become the limiting factor for these species and they will have to compete for available sites (see Figure 7.3.17). If one species is much more abundant or much stronger than the other, then the population of the weaker species will decline.

Intraspecific competition occurs when individuals of the same species compete for a resource. For example, if the food resource of a species suddenly becomes scarce, individuals of the species will have to compete for the remaining food (Figure 7.3.18).

Competition can result in reduced growth, inability to reproduce, and death or emigration. Either type of competition is more likely to occur when population densities are high and there is greater demand for resources. However, intraspecific competition is far more likely to occur than interspecific competition, because all individuals in a population have the same basic requirements for survival. Different species generally have different basic requirements for survival, although some of their needs might overlap.

Both kinds of competition select for stronger individuals or species. In intraspecific competition only the strongest individuals will be able to acquire the resources needed to survive, as in Figure 7.3.18. In interspecific competition, if one species is much more abundant or much stronger than the other then the population of the weaker species may decline. An example of this is shown in Figure 7.3.19.

FIGURE 7.3.17 The pink cockatoo (*Cacatua leadbeateri*), also called the Major Mitchell cockatoo, needs tree hollows for nest sites and shelter. Other species in the ecosystem, such as parrots, owls, bees and possums, also compete for tree hollows.

Predation

Another way in which a species can affect the population of another species is through a feeding relationship, such as predation. If the density of the prey species increases, predators will have more access to this source of food and their population will increase. This will then reduce the population of the prey species because more predators are eating them. As the number of prey falls, intraspecific competition in the predator population will reduce its population size.

Predator and prey relationships constantly fluctuate in this way. For example, the Canadian lynx (*Lynx canadensis*) preys almost exclusively on the snowshoe hare (*Lepus americanus*) (Figure 7.3.20). The population of hares varies according to factors such as climate, disease, and availability of food. An increase in the hare population leads to an increase in the lynx population. When there are more predators, the hare population may decline because more are killed by lynxes. This in turn may cause the lynx population to decline again. The graph in Figure 7.3.21 on page 336 shows this repeating cycle.

FIGURE 7.3.18 Capuchin monkeys live in a hierarchical group. These monkeys are territorial and the strongest individuals obtain much larger quantities of food than the rest and thus have a higher fitness. The weakest individuals die.

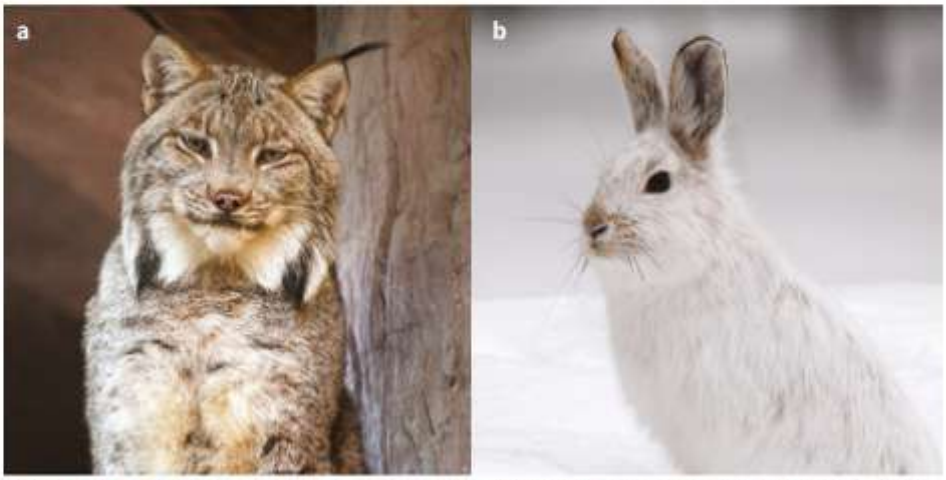


FIGURE 7.3.20 The (a) Canadian lynx (*Lynx canadensis*) and (b) snowshoe hare (*Lepus americanus*) form a predator–prey relationship.

FIGURE 7.3.19 When white clover and strawberry clover are planted together in the same field, the strawberry clover (shown here) with its longer leaf stalks grows taller, towering above the shorter white clover. Strawberry clover competes better for space and shades out the other species, eventually excluding it.

FIGURE 7.3.22 As population density increases, more aphid individuals develop wings.

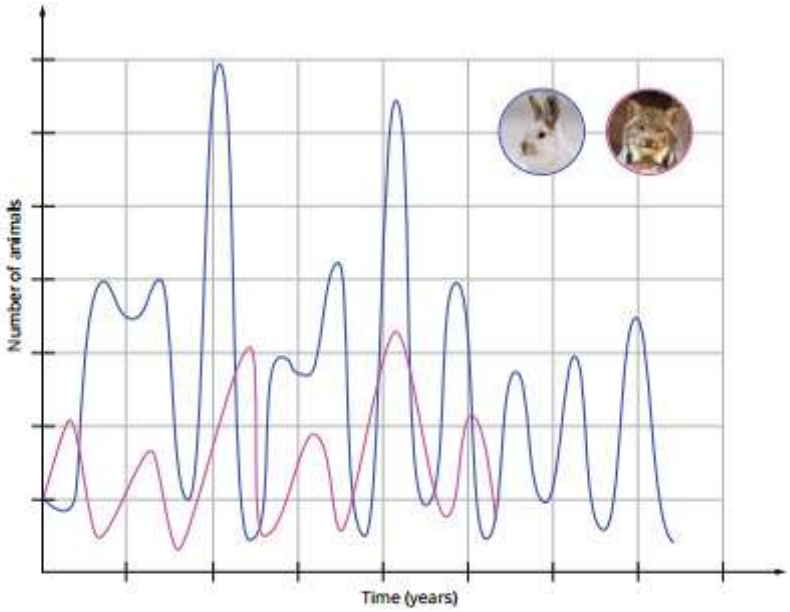


FIGURE 7.3.21 As the number of prey (snowshoe hares, indicated by the blue line) increase, so do the number of predators (Canadian lynxes, indicated by the pink line). Over time the prey population decreases as a result of predation, which leads to a decrease in the predator population.

BIO FILE

Studying parasite populations and host populations

The effects of parasites on populations are difficult to study. One of the difficulties is that populations without parasites rarely occur, which means there is no control group with which scientists can compare the parasitised population.

Another difficulty is that for practical reasons most studies focus on only one parasite. However, some parasites have little or no effect on their host population on their own, but do have a significant effect when other parasites are also present. For example, the fluke worm *Schistosoma mansoni* depresses the host's immune system to prevent the host from reacting to its presence, but this is not an observable effect. However, this allows other parasites to invade the host, and their effects may be observable.

FIGURE 7.3.23 Darkfield light micrograph of a *Schistosoma mansoni* fluke worm. Fluke worms depress their host's immune response to ensure their own survival.

Crowding

Crowding affects populations of different species in different ways. For example, when the density of aphids is low few aphids develop wings, because they do not need to move far to obtain the resources they need. However, as the population density increases, more aphids develop wings (Figure 7.3.22). Winged aphids can only produce about half the usual number of offspring, but they can disperse to areas with more resources and form new populations.

Some animals become stressed when their density is high and may produce fewer offspring, or their immune systems become affected and they will be more prone to disease infection. The density at which negative effects occur is different for each species.

Parasitism

Parasitism occurs when an organism lives in or on its host for an extended period of time or for its entire life cycle. When a population density increases, individual organisms have more contact with each other. They are also more likely to be weakened; for example, as a result of limited supply of a resource such as food. By these means, parasites are more easily able to invade and spread in a host species of increased density. Most parasites do not usually kill their host, but they may:

- reduce the host's ability to reproduce
- reduce the host's lifespan
- make the host more prone to disease
- reduce the host's ability to compete
- change the host's behaviour
- reduce the host's lifespan.

Infectious disease

Diseases may spread faster within a denser population, assuming that conditions are favourable for infection. Disease-causing fungi, bacteria and viruses that can kill individuals may then affect the size of the host population. However, organisms in natural environments may be infected with a disease but still be able to survive and reproduce.

A critical factor for any pathogen (disease-causing agent) is the method by which it spreads to other individuals (Figure 7.3.24). The rate at which a pathogen spreads depends on various factors, including environmental conditions such as wind, water flow and temperature. The genetic diversity of the host population can also affect the spread of a pathogen, because a more genetically diverse host population is more likely to have resistant individuals.

FIGURE 7.3.24 Some species of *Anopheles* mosquitoes carry a parasite called *Plasmodium*, which causes malaria in humans and other animals. Most human deaths resulting from malaria occur in Africa, because the species of mosquito there has a long lifespan and a tendency to bite humans rather than other animals.

CARRYING CAPACITY

In the absence of a limiting factor, the population growth of a species will be continuously exponential. However, in the real world, population growth is affected by density-dependent factors such as competition for resources.

When a species' population reaches **equilibrium** and becomes relatively constant, with the number of births and deaths in the population cancelling each other out, the species has reached the maximum population size that the ecosystem can sustain indefinitely. This is called the ecosystem's carrying capacity for that species.

i Equilibrium is a balance between opposing factors that keeps a parameter (such as population size) stable. For population size, these include the balance of births and deaths, immigration and emigration.

The S-shaped graph in Figure 7.3.25 shows the initial exponential growth of a population, which then flattens out as it begins to be affected by density-dependent factors. The population growth rate may decline until birth and death balance each other and the population is limited to the **carrying capacity** of the environment. This pattern of growth is known as **logistic growth**.

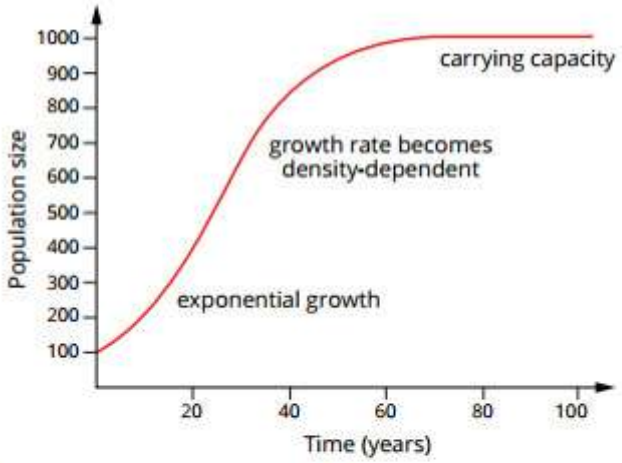


FIGURE 7.3.25 As a population increases, density-dependent factors may become important.

Consider the following example. A new volcanic island emerged in the middle of an ocean and became populated with plants and insects. A few birds of one species happened to be carried to the island by strong winds. They raised young and fed on the seeds, insects and fruit available. As they were the only bird species, they had no competition for space or food and no natural enemies, so the population grew rapidly. Eventually there was no space left for new nests. Seeds, fruit and insects became scarcer, and then rats arrived on the island by ship and began eating bird eggs. The bird population then levelled out (Figure 7.3.26).

FIGURE 7.3.26 Birds that cannot find a nesting site or sufficient food to raise their young cannot reproduce, which affects population growth. Predation also limits the growth of a prey population.

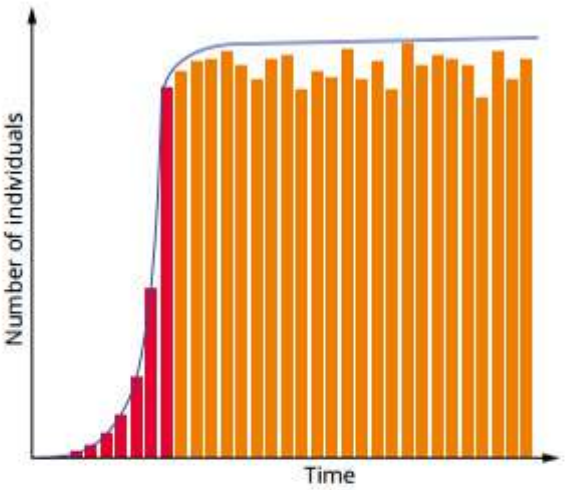


FIGURE 7.3.27 Initially the bird population grew increasingly quickly. When the population size reached the point where nesting areas and food were scarce, the population stabilised. The arrival of rats began a predator–prey relationship that caused the population to fluctuate.

The graph in Figure 7.3.27 shows the changes in the size of the bird species population over time. This pattern of growth is observed in every population in a natural environment.

The dynamic nature of carrying capacity

The carrying capacity of an environment is dynamic; that is, it varies over time. Factors that can affect carrying capacity include:

- weather and climate changes
- major changes to an environment
- fluctuation in populations of food species or competitors.

The factors that can affect carrying capacity can be abiotic or biotic (Table 7.3.1). Water availability is an example of an abiotic factor that can affect carrying capacity. For example, during a drought water availability might become the limiting factor for a population of kangaroos, and the number of individuals that the environment can support will be reduced.

Abiotic	• soil • water • space • shelter
Biotic	• fluctuation of prey species • fluctuation of predator species • fluctuation of species which compete for resources

TABLE 7.3.1 Abiotic and biotic factors affecting carrying capacity.

BIO FILE

Population crash

The reindeer population of St Matthew Island in the Bering Sea is an example of a population that collapsed after exponential growth. During World War 2 the US Coast Guard introduced 29 reindeer to the island. The intention was to farm the reindeer for food, but this did not eventuate and the island was abandoned at the end of the war.

By 1957 the herd size had reached over 1000, thriving on the abundant lichens on the island. In 1963, 6000 reindeer were counted. However, the animals were by then showing signs of stress such as poor coat condition, and many were underweight. The lichen had almost disappeared, and the reindeer were feeding on less nutritious plants such as sedges. When observers returned in 1966, the island was scattered with reindeer skeletons. The herd numbered just 42, with no fertile males and no calves. The reindeer had exceeded the carrying capacity, and the decline of the population had been rapid. By the 1980s there were no reindeer left on the island.

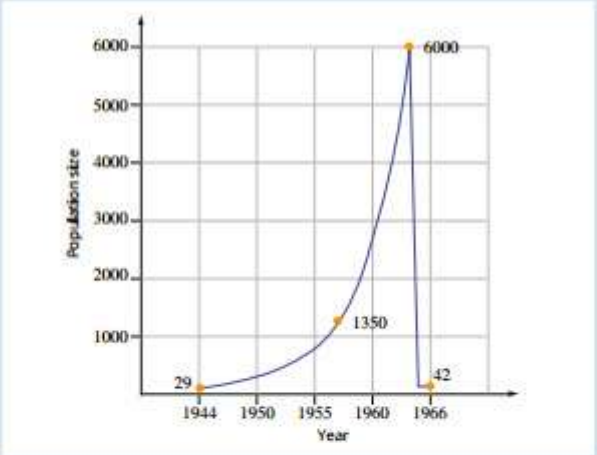


FIGURE 7.3.28 The initial population of reindeer on St Matthew Island after World War 2 grew from 29 individuals to 6000 in 19 years. The population crashed after the carrying capacity was exceeded and the reindeer's food resource was exhausted. Eventually the reindeer disappeared from the island.

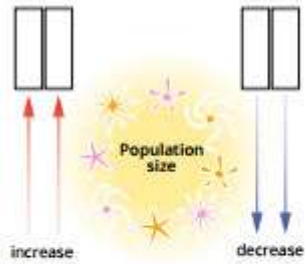
7.3 Review

SUMMARY

- A population is a group of organisms of the same species living in a defined geographic area.
- Population size is affected by four processes:
  - natality
  - mortality
  - immigration
  - emigration.
- Exponential growth is the rapid increase in the size of a population, shown as a J-shaped curve on a graph.
- Geographic distribution is all the places where a particular species can be found.
- Ecological niche is the role of an organism in its environment, including the ways the organism:
  - uses its resources
  - interacts with other species
  - interacts with its environment.
- The competitive exclusion principle states that two species occupying the same niche cannot coexist, leading to elimination through death or displacement of one of the species.
- The density of a population is the number of individuals per unit of area or volume.
- Density-dependent factors that influence population size and density include:
  - the tolerance range of a species to abiotic factors
  - major changes to an environment or chance disturbances.
- Density-independent factors that influence population size and density include:
  - competition for resources
  - predation
  - crowding
  - parasitism
  - infectious disease.
- The limiting factor of a population's size, density or growth is defined as the scarcest of the necessary resources needed by a population to grow.
- Carrying capacity is the maximum population size of a species that its environment can sustain indefinitely. Carrying capacity is not fixed.
- Logistic growth is the pattern of growth that begins with exponential growth, and then flattens as density-dependent factors take effect, levelling out to carrying capacity. It is shown as an S-shaped curve on a graph.

KEY QUESTIONS

1 Label the blanks in this diagram with the four processes that affect population size for every species.



2 **a** Describe an exponential growth pattern.
b In what kinds of organisms and under what conditions could this kind of population growth occur?
c Name two reasons why the crown-of-thorns sea star undergoes population explosions.

3 Compare the concepts of distribution and abundance of a species.

4 Below is a list of factors that influence ecosystems. State whether each one is a biotic or abiotic factor.

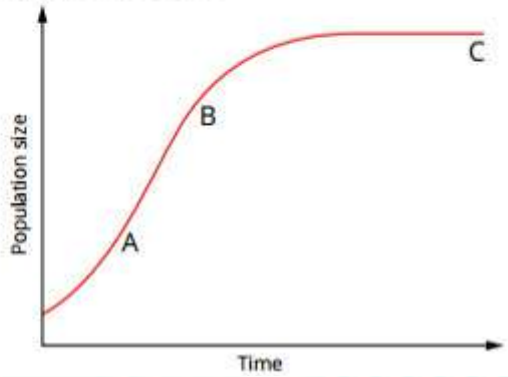
A water
B algae
C ph
D soil
E trees
F animals
G salinity
H hawk

5 Use a specific example to explain how one abiotic factor can affect population growth.

6 Which answer lists only density-independent factors?
A predation; water depth; availability of sunlight
B competition for food; loss of habitat; drought
C competition for water; bushfire; over-crowding
D temperature; pH of soil or water; salinity levels

7 **a** Compare interspecific and intraspecific competition and give an example of each.
b Name three limiting factors that affect population growth.

8 Name the parts of the following logistic growth graph at points A, B and C.



Chapter review

07

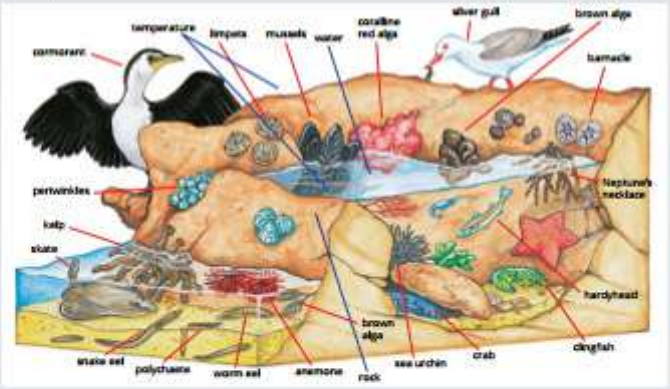
KEY TERMS

abiotic factor
amensalism
atmosphere
autotroph
biomass
biosphere
carnivore
carrying capacity
chemosynthetic
commensalism
community
competition
consumer
decomposer
density-dependent factor
density-independent factor
detritivore
detritus
ecosystem
emigration
equilibrium
exponential growth
facultative mutualism
food chain
food web
habitat
herbivore
heterotroph
host
hydrosphere
hydrothermal vent
hyphae
immigration
interspecific
intraspecific
keystone species
limiting factor
lithosphere
logistic growth
migration
mortality
mutualism
mycorrhiza
natality
niche
obligate mutualism
parasite
parasitism
photosynthetic
pollination
population
population explosion
predation
predator
prey
producer
protozoan
ruminant
scavenger
symbiosis
tolerance range
trophic level

KEY QUESTIONS

1 **a** What is the biosphere, and why can it be regarded as an ecosystem?
b The birds in a backyard aviary include galahs, corellas and sulphur-crested cockatoos. Is the aviary an ecosystem? Explain your answer.

2 The illustration below shows the organisms in a rock pool environment.



a List the ways that the sea anemone might depend on the physical surroundings of the rock pool.
b Explain why the rock pool can also be considered to be part of a larger marine ecosystem.

3 **a** What is a ruminant? Give one example of a ruminant species.
b Rumination is a form of mutualism. Explain how both organisms involved in rumination benefit.

4 Apart from mutualism, what is another form of interspecific interaction in which an organism lives inside another organism? Give an example.

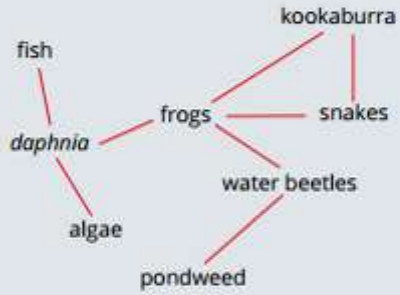
5 Most interactions are categorised by the effect they have on each of the two species involved. Below is a list of interactions between organisms found in the chapter. For each interaction, state the type of interaction and whether there is no effect, a harmful effect or a beneficial effect on each organism. (The first one has been done for you.)
a European bream and tapeworm in its gut — parasitism, European bream (harmful effect), tapeworm (beneficial effect)
b desert quandong and an emu feeding on its fruit
c owl nesting in a tree hollow
d zooxanthellae and coral polyps
e cattle trampling on grass
f stick insect and a fungus growing inside it
g lion feeding on an antelope

6 Describe an example of a benign relationship involving a tree and another species.

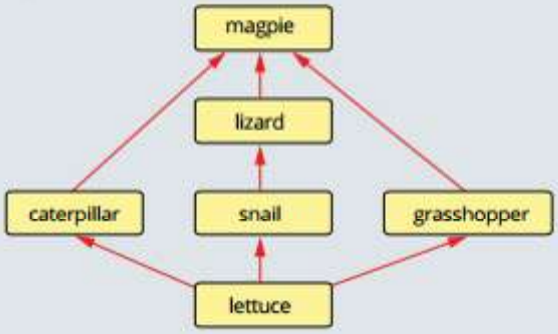
7 **a** An epiphyte growing on a tree is an example of which kind of interaction? Explain your answer.
b If the tree becomes so laden with epiphytes that the branches could break, is this still the same kind of interaction? Explain your answer.

8 **a** Define the term 'food chain'.
b Arrange the following organisms in order from producer to highest-order consumer.
seabird, alga, small fish, Inuit, zooplankton
c Explain how decomposers complete the cycle of matter in a food chain.

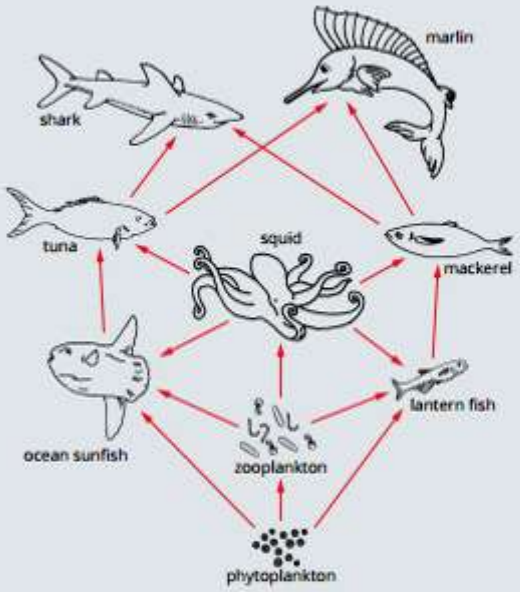
9 **a** What do the arrows in a food web represent?
b Draw in the arrowheads to complete this food web.



10 For the food web depicted below, describe the short-term and long-term effects of the magpie leaving the ecosystem.



11 Examine the following food web and then answer the questions that follow.



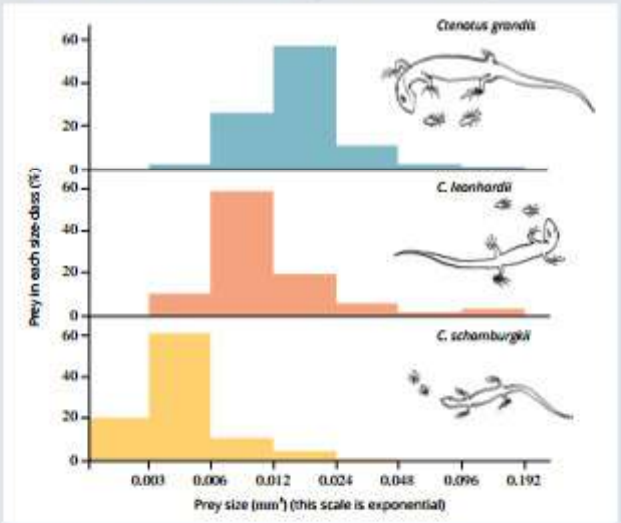
a What is the highest number trophic level in this food web?
b What roles do the phytoplankton, zooplankton and tuna play in this food web and why?

12 What is a microhabitat? Give two examples, and describe the kinds of organisms that might live in each.

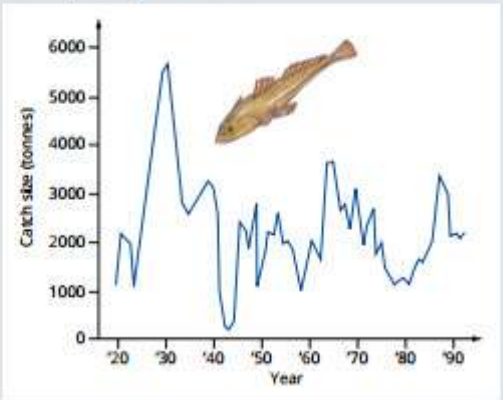
13 What type of measurement would you use to describe the density of species in each of these situations? Explain your answer in each case.
a sheep in a paddock
b grass in a field
c leaves on a plant

14 A species of fish on a coral reef undergoes a rapid decline in population growth after the arrival of another species of fish that uses the same sources for food. What kind of competition is this? Why would the population growth of the first fish decline?

15 The following graph gives information about three lizards and the termites that are their prey. Using the information in the graphs, explain how the three lizard species are able to exist together in an ecosystem.



16 Consider the following graph, which shows the annual catch of tiger flathead from 1920 to 1992. During which period was the tiger flathead population most stable? Explain your answer.



17 Discuss the reasons for *ex situ* conservation of endangered species.

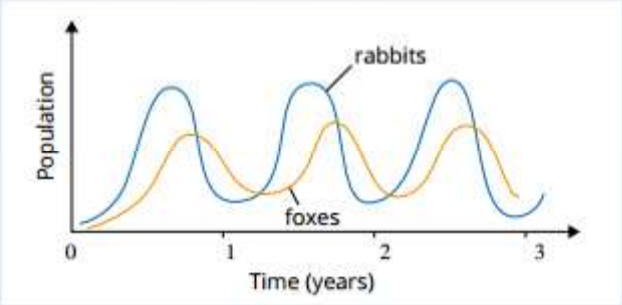
18 Discuss the reasons for *in situ* conservation of endangered species.

19 Outline one example of biological control of invasive species.

20 Discuss reasons for conserving the biodiversity of a rainforest ecosystem.

21 Which of the following situations describes a population that is increasing in size?
(B = birth, D = death, I = immigration, E = emigration)
A (B + D) > (I + E)
B (B + E) > (D + I)
C (D + E) < (B + I)
D (B + E) < (D + I)

22 Consider the following graph, which shows changes in the rabbit and fox populations on an isolated area of open farmland in western Victoria.



a What factors might have caused the initial growth in the rabbit population?
b Why does the growth in fox numbers follow that of rabbits?
c What factors could cause the decline in the rabbit population?
d How is it that rabbit numbers are able to build up again in the following year?
e What would happen to the fox population if the rabbit population suddenly crashed, for instance from the effects of calicivirus? Show this by extending the graph.

23 Consider a simple ecosystem consisting of a single food chain, in which a crop plant is eaten by an insect (such as a grasshopper), which is eaten by a bird (such as a kestrel).
a What might happen to the number of grasshoppers if the kestrels were killed?
b What subsequent effect might there be on the crop?
c If the ecosystem were more complex, with more food chains cross-linked in a food web, would the effect of shooting one species of bird be the same as it is in the simple ecosystem? Explain your answer.

24 Consider the following information. Cacti and sagebrush absorb sunlight for photosynthesis. Ants and rats both feed on cacti and sagebrush. Tarantulas feed on ants. Rats are a common food source for hawks, snakes and coyotes. Hawks and coyotes also feed on snakes. Coyotes will occasionally eat sagebrush.
a Construct a food web using the information given.
b Write down the longest food chain for this food web.
c State the trophic level for cacti and coyotes.
d State the type of consumer for ants and snakes.
e Suggest which organism is the keystone species. Give an explanation for your answer.
f A parasite that feeds on ants was introduced into the food web.
i State whether the introduction of the parasite is a biotic or abiotic factor
ii Outline the effects of the parasite on the food web.

REVIEW QUESTIONS

How do living systems sustain life?

Multiple choice questions

1 Four adaptations of the Australian red kangaroo are:

- **i** a dense network of blood vessels close to the skin in the forelimbs
- **ii** licking the forelimbs in hot weather
- **iii** a powerful tail that acts as a counterbalance when hopping
- **iv** the blood vessels in the forelimbs widen (dilate) in hot weather.

Which one of the following groups correctly classifies these four adaptations?

A i = physiological, ii = behavioural, iii = structural, iv = physiological
B i = structural, ii = behavioural, iii = structural, iv = physiological
C i = structural, ii = behavioural, iii = structural, iv = behavioural
D i = physiological, ii = behavioural, iii = physiological, iv = structural

2 A person is swimming in water that has a temperature of 20 °C. Which of the following correctly describes what happens to regulate that person's body temperature?

	Blood circulation to the skin	Sweat glands	Skeletal muscle
A	increased blood flow	increased secretion	decreased shivering
B	decreased blood flow	decreased secretion	increased shivering
C	decreased blood flow	increased secretion	increased shivering
D	increased blood flow	decreased secretion	increased shivering

3 The binomial name for the lesser bilby is *Macrotis leucura*. Which species shares the most physical characteristics with the lesser bilby?

A *Idiurus macrotis*
B *Macrotis lagotis*
C *Nyctinomops macrotis*
D *Oenanthe leucura*

4 In the classification of living things, a family consists of a group of:

A classes
B genera
C orders
D phyla

5 Which of the following statements regarding parasitism is false?

A All organisms have parasites.
B Many mould species are parasites.
C Parasitism is not a limiting factor for the host organism.
D Parasites live on or in their host.

6 Many lichens grow on the bark of trees. The relationship between the lichens and the trees is:

A parasite–host
B symbiosis
C mutualism
D commensalism

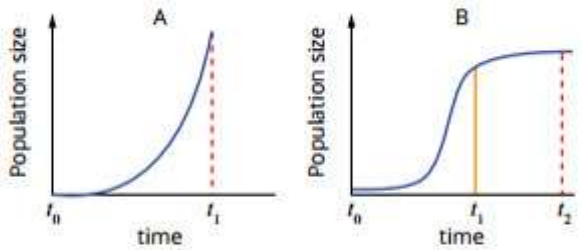
7 Herbivorous insects such as termites make use of protozoans in their gut to digest wood. Which of the following best describes this feeding relationship?

A herbivore food chain: wood → termite → protozoan
B parasite food chain: wood → termite → protozoan
C detritivore food web: wood → termite + symbiont
D decomposer food chain: wood → protozoan → termite

8 Which one of the following best defines the term 'food web'?

A the variety of food that a top carnivore eats
B a combination of different heterotrophs
C a long food chain with at least four trophic levels
D a diagram that shows all the feeding interactions in an ecosystem

9 The following two graphs show the population growth of species A and species B. Which of the following statements is correct?



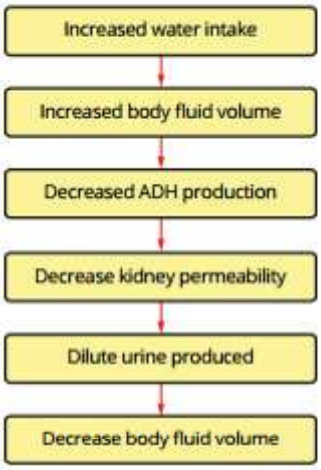
A Species A shows an exponential population growth between times t = 0 and t = 1, but species B does not.
B Species B has reached the carrying capacity of the ecosystem by time t = 2.
C No deaths occurred in species A or B between times t = 0 and t = 2.
D The graph for species B is typical of an insect population such as a locust plague.

10 Which one of the following is a density-dependent factor?

A rainfall
B fire
C temperature
D food supply

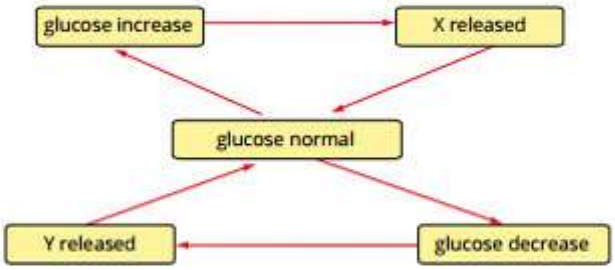
Short answer questions

11 The following diagram outlines the stimulus–response pathway for ADH in a mammal.



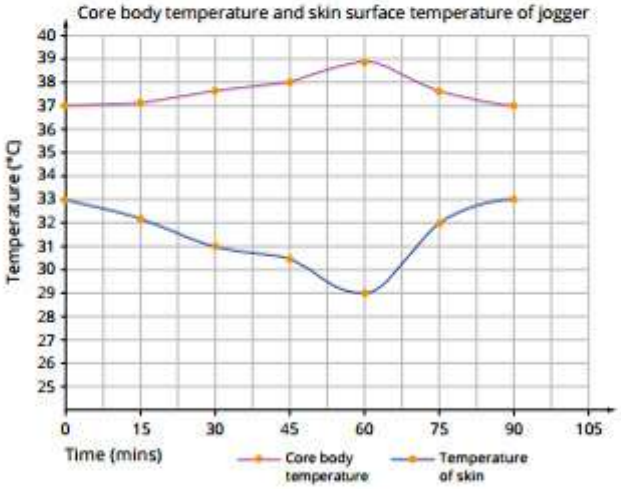
a Define the term 'homeostasis'.
b What is the stimulus that causes the release of ADH?
c Is the feedback mechanism of ADH production considered negative or positive? Explain why.
d Alcohol inhibits ADH production. Explain why alcohol consumption can cause dehydration.

12 The following diagram shows how the body regulates the glucose concentration in blood.



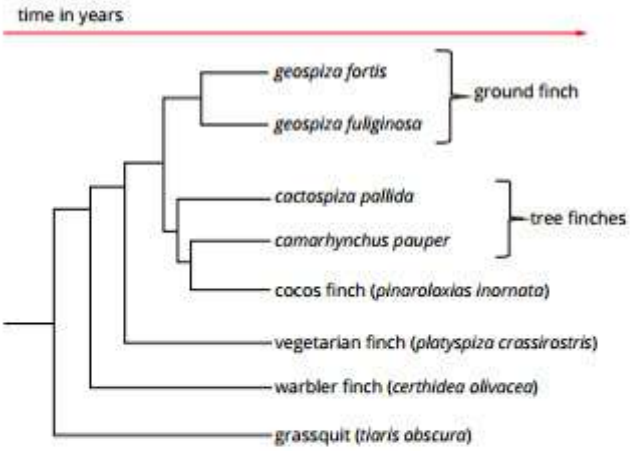
a Identify X and Y.
b Explain how the body regulates the glucose concentration in blood.
c Draw a circle on the diagram to show which process is stopped when a person suffers from type 1 diabetes.

13 The diagram shows the changes in the core body temperature and skin surface temperature of a jogger. He jogged from $t = 0$ to $t = 60$ minutes. From $t = 60$ to $t = 90$ minutes, the jogger stopped and sat on a chair.



a Describe the changes in core body temperature and temperature of the skin from 0 to 60 minutes.
b Explain the patterns described in part a.
c Suggest why the temperature of the jogger's skin started to rise after 60 minutes.

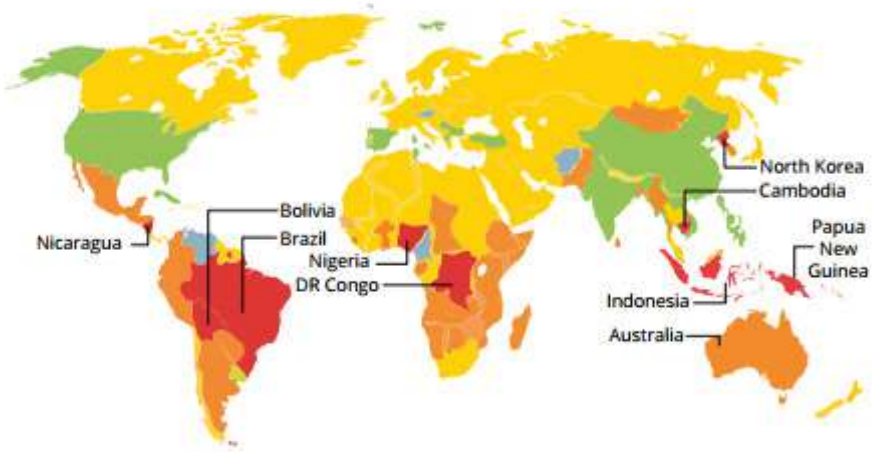
14 The following diagram shows a phylogenetic tree of Darwin's finches using mitochondrial DNA.



a The finches *Geospiza fortis* and *Geospiza fuliginosa* belong to the same genus. What is considered to be a characteristic of the members of a genus?
b Explain why scientists do not use common names such as 'tree finches' when they are communicating with other scientists.
c In terms of morphology (physical structure and appearance), which finch is least similar to the other finches?
d Explain the differences between the phylogenetic classification system and the Linnaean classification system.

15 Map 1 below shows the deforestation index for various parts of the world. This index is a measure of the risk of deforestation. Map 2 shows the biodiversity hotspots (highlighted in green) around the world. These are areas where biodiversity is unusually high.

Map 1



Legend
extreme risk
high risk
medium risk
low risk
no data

Rank	Country	Rating
1	Nigeria	extreme
2	Indonesia	extreme
3	North Korea	extreme
4	Bolivia	extreme
5	P.N.G.	extreme

Rank	Country	Rating
6	DR Congo	extreme
7	Nicaragua	extreme
8	Brazil	extreme
9	Cambodia	extreme
10	Australia	high

Map 2

a Define the term 'biodiversity'.

b In which areas is biodiversity at the greatest risk from deforestation?

c Explain why it is essential to protect biodiversity hotspots.

d Most of the areas at extreme risk of deforestation are along the equator, where most of the tropical rainforests are found. Discuss the economic reasons for the conservation of tropical rainforest biodiversity as a form of *in-situ* conservation.

e Pest organisms have had a big impact on Australian biodiversity.

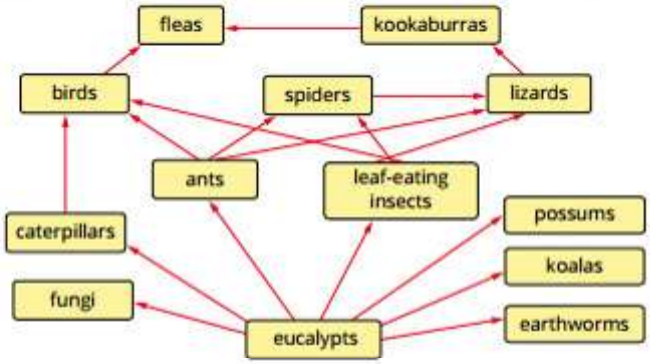
i Define the term 'pest organism'.

ii Discuss how one pest organism has affected Australian biodiversity, including the measures that have been used to solve the problem.

16 Australia is one of the world's most biodiverse nations. More than 80% of Australia's two million species of plants and animals are not found anywhere else in the world, making Australia a potentially rich area for bioprospecting and for developing models based on biomimicry.

- **a** Distinguish between bioprospecting and biomimicry.
- **b** Give an example of biomimicry.
- **c** Suggest how conservation of species for bioprospecting can provide avenues for innovation in biomimicry.

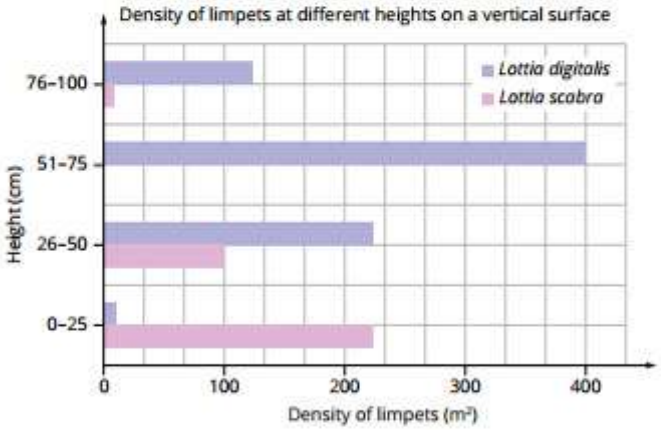
17 Study the following food web of a eucalypt forest.



- **a** What is the original source of energy for organisms in the food web?
- **b** Name the producers in this food web.
- **c** For this food web, describe a:
  - **i** predator–prey relationship
  - **ii** parasite–host relationship
- **d** Kookaburras are carnivores. Explain how they depend on producers.
- **e** 'Food webs are more stable than food chains.' Explain why this is so, using an example from the food web shown.

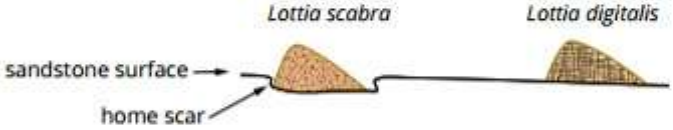
18 Limpets in the genus *Lottia* are aquatic molluscs that feed on the green algae that grow on rocks on seashores. Black oystercatchers (*Haematopus bachmani*) are birds that feed on limpets.

A study was conducted in the Monterey Bay area in the US state of California to determine the density of two species of limpets (*Lottia digitalis* and *L. scabra*) on a vertical surface of sandstone. The results of the study are shown in the following graph.



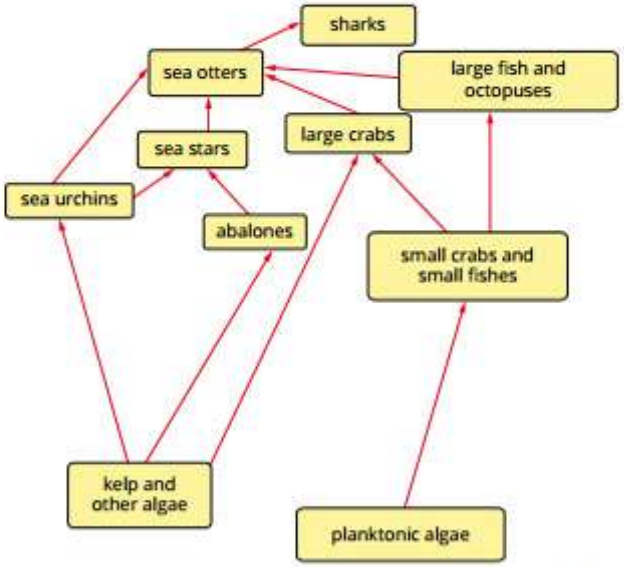
- **a** Construct a food web to show the feeding relationship between the two species of limpets, the black oystercatchers and the green algae.
- **b** Which species tend to dominate the upper areas of the vertical surface?
- **c** Black oystercatchers are unable to climb vertical surfaces, so when they feed they tend to stay at the bottom of the vertical surface. The typical height of black oystercatchers is approximately 35 cm. Suggest which species of limpet is the preferred prey of black oystercatchers. Give an explanation for your answer.

The following diagram shows a cross-sectional view of how each species of limpet adheres to sandstone. *Lottia scabra* secretes a substance that dissolves sandstone. By scraping the softened rock with its radula (a rough tongue-like structure), the limpet creates a 'home scar' in the rock surface.



- **i** State the type of adaptation displayed by *Lottia scabra*.
- **ii** Suggest how the presence of a home scar would be an advantage for this limpet.

19 The following diagram shows a kelp forest food web.



a Identify the primary producers in this food web.

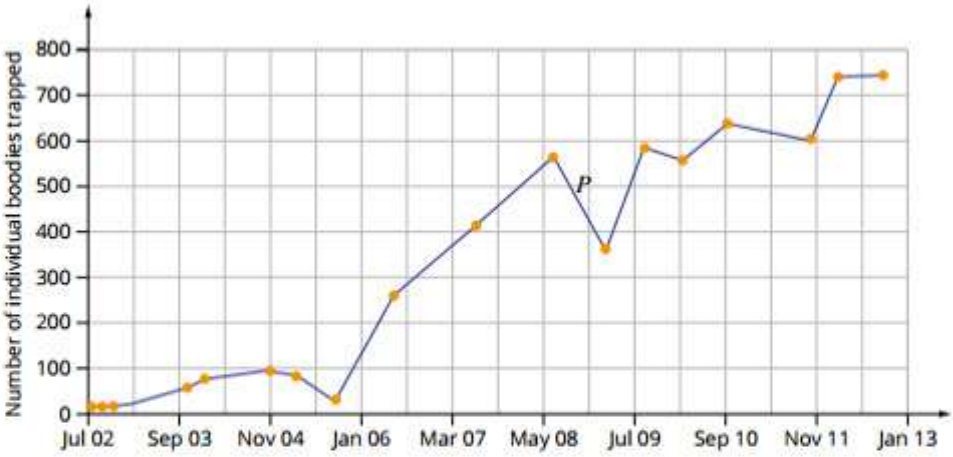
b Write down one food chain that involves four trophic levels.

The sea otter is a keystone species in the kelp forest.

c Define the term 'keystone species'.

d Explain what would happen if sea otters were removed from the kelp forest.

20 Boodies (*Bettongia lesueur*) were reintroduced into a feral-free animal sanctuary called Faure Island. The boodie population has been monitored using a trap-and-release method. The graph below shows the changes in the population from July 2002 to January 2013.



a Explain why there is a slow increase in population on the island from July 2002 to November 2004.

b Suggest an explanation for the fall in the boodie population at point P.

c Do you think that the population has reached carrying capacity? Explain your answer.

d Compare the benefits of the reintroduction of boodies to Faure Island to the captive breeding programs of the boodie in zoos.

21 Students wanted to investigate the distribution patterns of periwinkles and brown algae at various distances from the high tide mark along an intertidal rocky shore. First they made a transect line, starting from the high tide mark (a). The students placed a quadrat (0.5 m × 0.5 m) at the 0 m mark on their transect, then every 5 metres along the transect. They counted the number of periwinkles in the quadrat and also determined the percentage of the quadrat covered by brown algae (b).

The results of the survey are shown in the following table.

Distance from high tide mark (m)	Number of periwinkles in quadrat	Percentage cover of brown algae in quadrat (%)
0	147	0
5	162	4
10	20	13
15	0	7
20	1	9
25	10	50
30	1	8
35	0	0
40	0	0
45	0	0
50	0	0

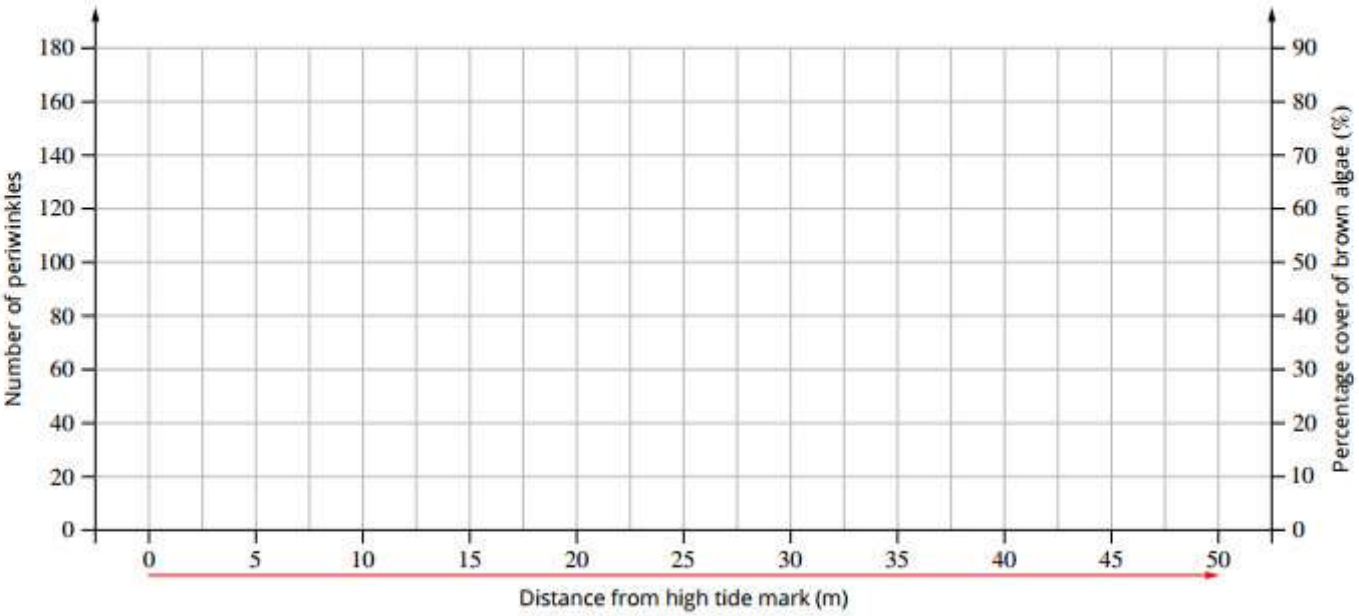
a b

a Plot the results of the survey on the graph below.

b The students did some research on brown algae. They discovered that some brown algae contain phlorotannins, which act as a chemical defence against grazing by organisms such as periwinkles. The students hypothesised that the change in the density of periwinkles along the transect from high tide mark to the 50 m mark is due to the inability of periwinkles to graze on brown algae. Evaluate the students' hypothesis.

c Suggest how the reliability of the results could be improved.

Distribution of periwinkle and percentage cover of brown algae at different distance from high tide mark



UNIT 2 How is continuity of life maintained?

AREA OF STUDY 1

How does reproduction maintain the continuity of life?

Outcome 1: After completing this unit you should be able to compare the advantages and disadvantages of asexual and sexual reproduction, explain how changes within the cell cycle may have an impact on cellular or tissue system function, and identify the role of stem cells in cell growth and cell differentiation and in medical therapies.

AREA OF STUDY 2

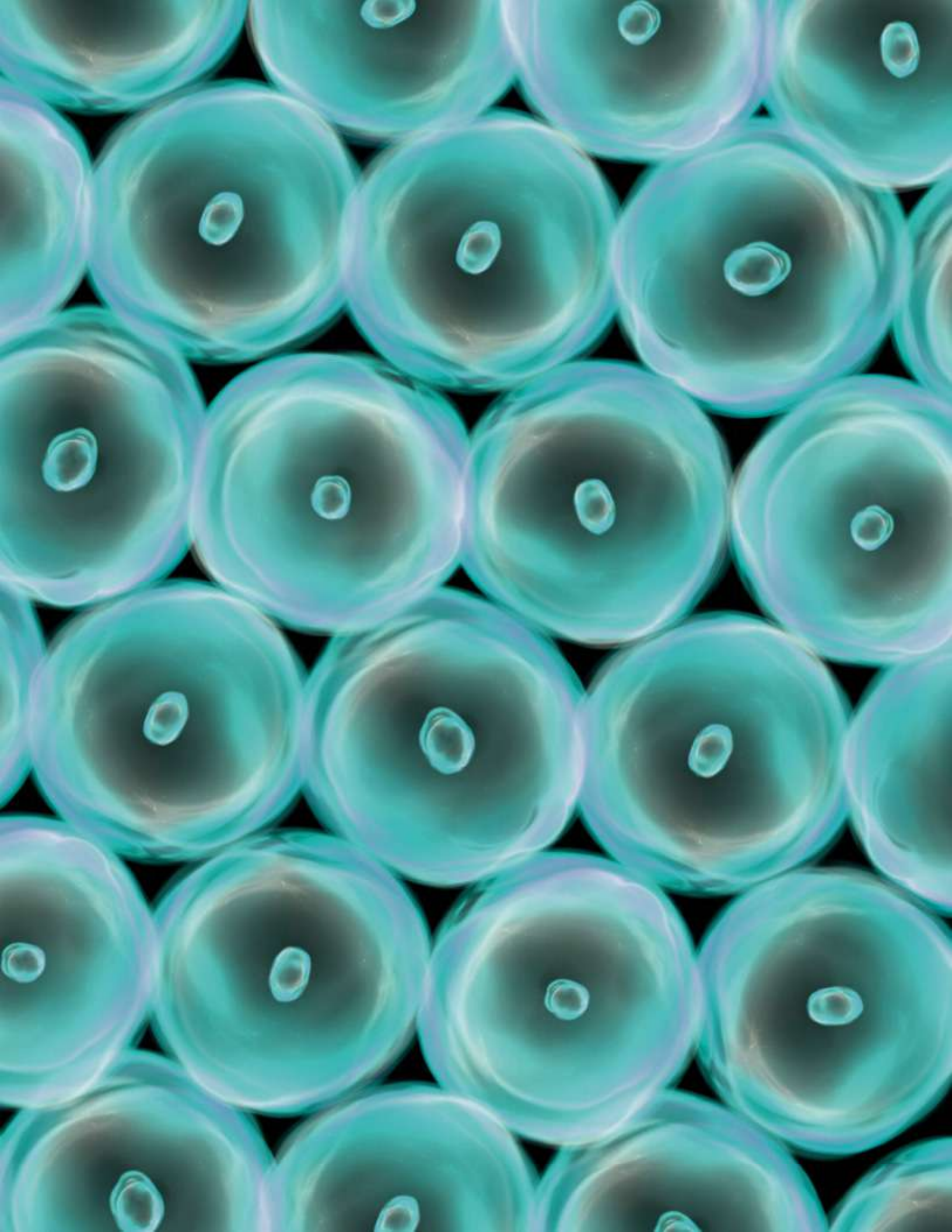
How is inheritance explained?

Outcome 2: After completing this unit you should be able to apply an understanding of genetics to describe patterns of inheritance, analyse pedigree charts, predict outcomes of genetic crosses, and identify the implications of the uses of genetic screening and decision-making related to inheritance.

AREA OF STUDY 3

Investigation of an issue

Outcome 3: After completing this unit you should be able to investigate and communicate a substantiated response to a question related to an issue in genetics and/or reproductive science. To achieve this outcome you will draw on key knowledge outlined in Area of Study 3 and the related key science skills in Chapter 1.



CHAPTER

08 Cell replication

Cells need to replicate (make copies of themselves) in order to maintain the continuity of life. This is the case for both unicellular and multicellular organisms. In this chapter you will investigate how eukaryotic and prokaryotic cells replicate, and the purposes of replication. You will also examine the mechanisms that control replication, and what happens if these mechanisms fail.

You will learn about the significance of stem cells in the development and maintenance of an individual organism, and discover how stem cells are being used to develop medical therapies. Ahead of learning about DNA synthesis, you may wish to have more background knowledge on the basics of DNA. This information can be found in Section 10.1.

Key knowledge

- the derivation of all cells from pre-existing cells through to the completion of the cell cycle
- the rapid procession of prokaryotic cells through their cell cycle by binary fission
- the key events in the phases (G1, S, G2, M and C) of the eukaryotic cell cycle, including the characteristics of the sub-phases of mitosis (prophase, metaphase, anaphase and telophase) and cytokinesis in plant and animal cells
- the types and function of stem cells in human development, including the distinction between embryonic and adult stem cells and their potential use in the development of medical therapies
- the consequences of stem cell differentiation in human prenatal development including the development of germ layers, the types of tissues formed from germ layers and the distinction between embryo and foetus
- the disruption of the regulation of the cell cycle through genetic predisposition or the action of mutagens, which gives rise to uncontrolled cell division including cancer and abnormal embryonic development

8.1 Cell replication

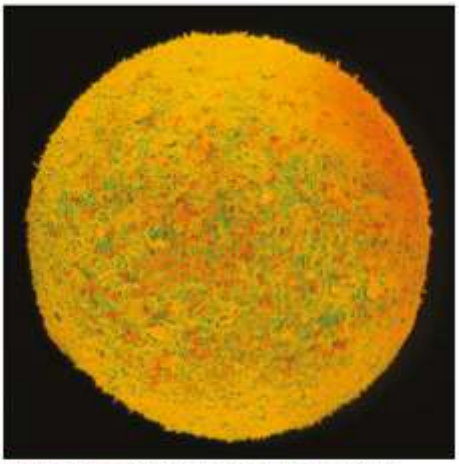


FIGURE 8.1.1 Coloured SEM of a fertilised human egg (zygote). This one cell must replicate to become a foetus.

Once, you were a single cell—a fertilised egg known as a zygote (Figure 8.1.1). Now, your body is made up of about 37 trillion cells. In order to start creating the millions of cells that make you, that first single cell had to replicate itself. As the cells in your body wear out and die or are damaged, more cells are replicated to replace them. Replication results in genetically identical cells.

The cell theory, which you studied in Chapter 1, states that all cells arise from pre-existing cells. In order for this to occur, cells must be able to replicate. This process is essential to the life of all organisms. In this section, you will learn about the reasons for cell replication and the methods of replication for eukaryotes and prokaryotes.

PURPOSES OF CELL REPLICATION

Cell replication is a form of cell division in which a parent cell divides to produce two genetically identical daughter cells. It is essential that the genetic information is passed on accurately, because the activities of cells are controlled by the genetic information in the nucleus (in eukaryotes) or nucleoid (in prokaryotes).

In eukaryotes (protists, fungi, plants and animals), cells replicate by **mitosis**. Mitosis is part of the eukaryotic cell cycle, which is described more fully in Section 8.2.

Cells replicate for a number of reasons. For a multicellular organism, cells replicate for:

- restoring the nucleus-to-cytoplasm ratio
- growth and development
- maintenance and repair.

Unicellular organisms do not need to replicate for these purposes because they remain a single cell throughout their entire life cycle. Instead, cell replication in unicellular organisms (whether prokaryotes or eukaryotes) is a simple form of reproduction and creates a new, genetically identical individual.

Replication is not the only way that new cells are made. However, it is the only way that a cell can be made that is genetically identical to its parent cell.

The cell cycle is the series of stages that a cell passes through, from its formation by cell division through its growth and function until it divides again.

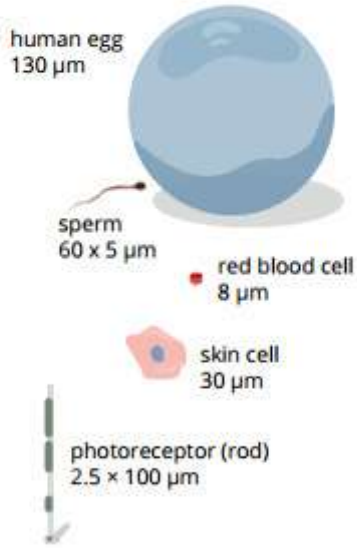


FIGURE 8.1.2 The human egg cell is many times larger than other human cells.

Restoring the nucleus-to-cytoplasm ratio

Most cells in multicellular organisms are microscopic. The largest cells are egg cells (Figure 8.1.2). Some egg cells, such as bird and reptile eggs, are many millions of times larger than the body cells of the animals into which they will grow.

In most cells of a multicellular organism the nucleus is able to control the cytoplasm very efficiently. Egg cells, however, have a very low nucleus-to-cytoplasm ratio. In other words, there is too much cytoplasm for one nucleus to control.

After an egg is fertilised, the cell divides repeatedly by mitosis (mitotic division) to produce many smaller cells during this first stage of development. These early rounds of mitotic division serve to restore the nucleus-to-cytoplasm ratio, so that each nucleus is located in a normal-sized cell in which the nucleus can effectively control the cytoplasm. The overall size of the organism does not change much during this stage.

You can see the cell division from 2 to 32 cells in the development of an embryo in Figure 8.1.3. You will notice that the overall size of the embryo does not increase as the number of cells increases.

Growth and development

Multicellular organisms grow in size by increasing the number of their cells through repeated cell replications. The new cells then grow in size, increasing the size of the organism. As the new individual continues to develop, new cells become specialised for different purposes. Muscle cells in animals and phloem cells in plants are examples of specialised cells (Figure 8.1.4). More replications follow and the specialised cells become organised into tissues, which form the body of the organism.

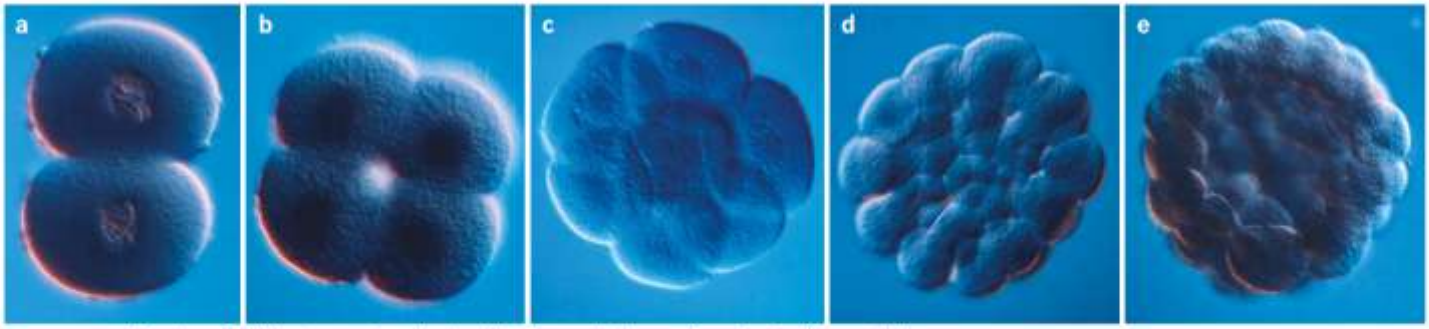


FIGURE 8.1.3 A series of light micrographs showing the change in the nucleus-to-cytoplasm ratio in the first five divisions of a zygote by mitotic cell division. The first division (a) results in 2 cells; the second (b) results in 4 cells; the third (c) results in 8 cells; the fourth (d) results in 16 cells, and the fifth (e) results in 32 cells.

Development in multicellular organisms involves a balance between cell replication and cell death. As development continues to the adult form, some cells are destined to die through 'programmed cell death', which is known as apoptosis. Other cells, such as nerve cells and red blood cells, may become highly specialised and no longer undergo replication.

FIGURE 8.1.4 As this soya bean plant grows, cells replicate and specialise (for example, into root or leaf cells). As growth and development occurs, some cells will also undergo apoptosis.

Apoptosis, also called programmed cell death, is a series of changes in a cell that results in the death of the cell. The changes are driven by biochemical changes.

A cell **organelle** is an organised structure with a specialised function, such as a nucleus, endoplasmic reticulum or chloroplast.

BIOFILE

Permanent cells: the vertebrate lens

In some tissues there is no cell replication. Sufficient numbers of specialised cells are produced during development to last the entire life of the organism. These permanent cells include the cells of the eye lens in vertebrates (Figure 8.1.5). Although permanent cells cannot be replaced, they can be repaired by the replacement of various organelles, a process that continues throughout the life of the cell.

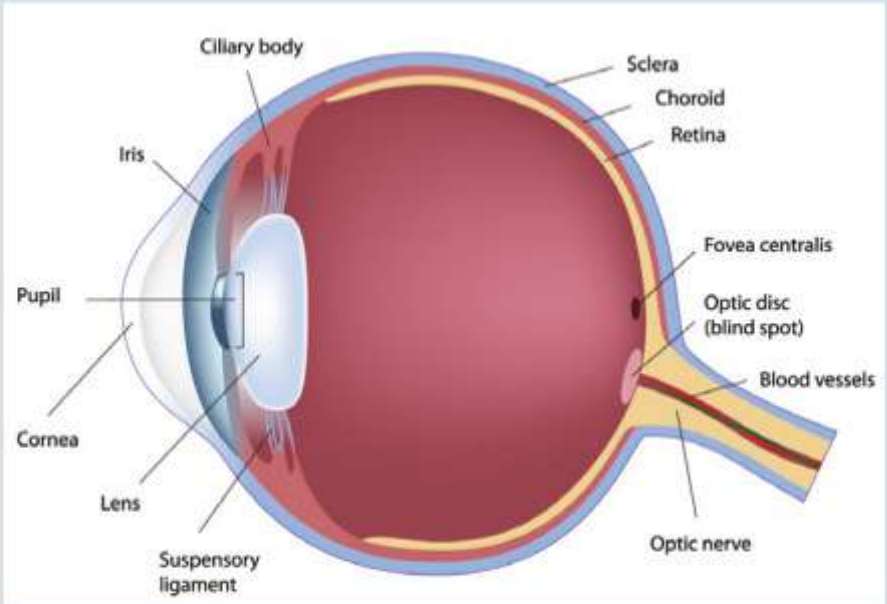


FIGURE 8.1.5 The highly specialised cells that make up the lens of a vertebrate eye must be transparent so that light can pass through the lens without being distorted. Once the lens has formed, individual cells cannot be replaced.

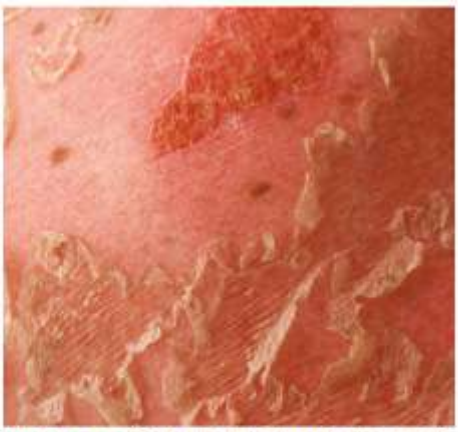


FIGURE 8.1.6 Sunburn kills skin cells. Layers of dead cells then peel off, while healthy skin cells underneath replicate to replace them.

Tissue maintenance and repair

Cells in the tissues of multicellular organisms, such as the skin cells covering the body's surface, become damaged or die as a result of normal functioning, and also as a result of injury, such as sunburn in the case of skin cells (Figure 8.1.6). In either case, maintaining and repairing tissues requires the production of new cells to replace those that die. These new cells are produced by cell replication.

The extent to which different organisms can carry out repair varies dramatically. Given the right conditions, many plants can grow from a fragment of a stem or leaf, and most mosses and liverworts can regrow from just a few cells. In most animals, stem cells (cells that retain some embryonic characteristics and can turn into specialised cells) are involved in the growth, repair, replacement and regeneration of tissues. For example, stem cells in bone marrow give rise to the different blood cells and replenish them as needed by the body (Figure 8.1.7).

A sea star can produce an entire new individual from a single arm by cell replication and subsequent specialisation (Figure 8.1.8). Humans can repair many tissues, but they cannot grow new limbs. A nematode, once hatched, cannot produce any new cells at all.

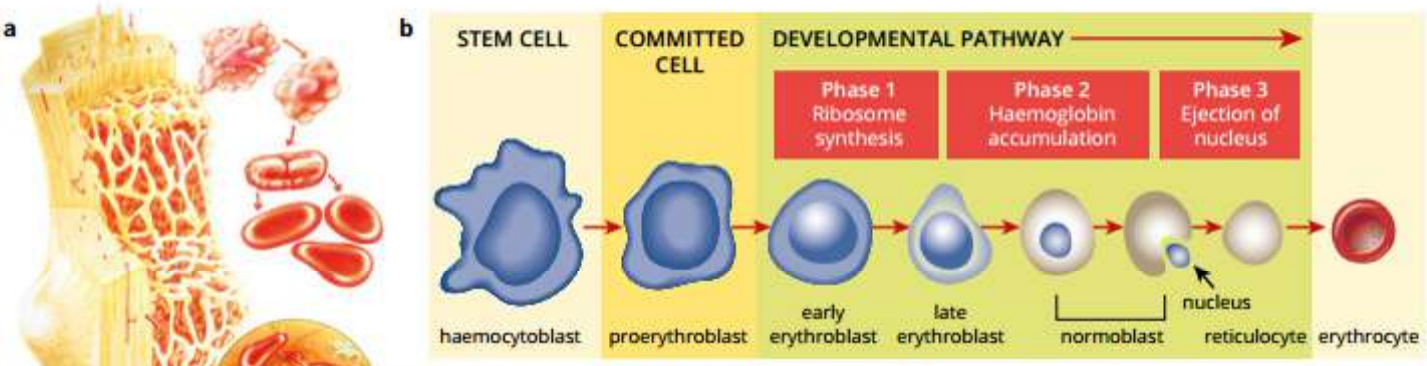


FIGURE 8.1.7 (a) A cross-section of bone marrow (highlighted in red) inside the bone, illustrating the formation of red blood cells from stem cells in the marrow. (b) The development of haemocytoblasts (stem cells from the bone marrow) into red blood cells. Note the nucleus exclusion during the later stages to create the red blood cell.

FIGURE 8.1.8 This sea star is regenerating from a single arm. The large arm (upper right) was severed from the body of a mature sea star. If the original sea star survived the injury, it will have grown a new arm. This arm, meanwhile, is developing into a new sea star, with four new arms growing.

BIOFILE

Nematodes

Growth in the size of an organism usually involves increasing the number of cells, but nematode are unusual. Cell division ceases when a nematode hatches from its tiny egg. Nematodes (Figure 8.1.9) hatch as miniature adults, and all subsequent growth is the result of the increasing size of cells present at hatching. Because there is a fixed number of mitotic divisions before hatching, all individuals of a species have exactly the same number of cells. This uniformity in number of cells makes the nematode, *Caenorhabditis elegans*, a good model organism for studies in cell biology.

FIGURE 8.1.9 SEM of nematode worm *Caenorhabditis elegans*.

CELLS DIVIDE EXPONENTIALLY

As cells replicate, their numbers increase exponentially: 2 cells give rise to 4, 4 cells give rise to eight, 8 cells give rise to 16, and so on (Figure 8.1.10). The total number of cells doubles at every replication, because two cells are produced from each cell replication. This can be explained by the formula, $C = 2^n$ where C is the number of cells and n is the number of cell divisions that have occurred.

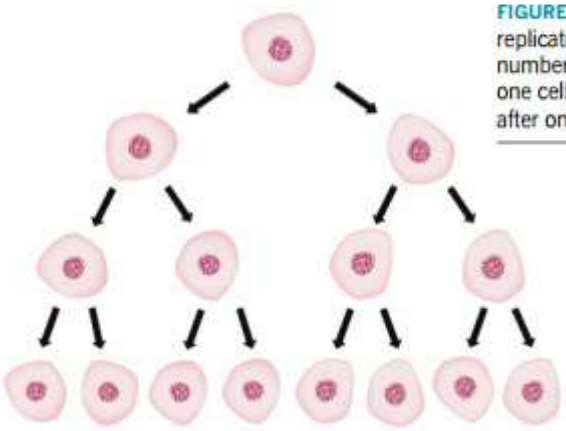


FIGURE 8.1.10 When cells replicate, they increase their numbers exponentially. This one cell becomes eight cells after only three divisions.

Replication and reproduction in multicellular organisms are different processes. Replication produces two genetically identical cells from one parent cell. Reproduction produces a new organism from one or two parent organisms.

Exponential growth by cell replication:
$C = 2^n$
where
C = number of cells
n = number of cell divisions that have occurred

CELL REPLICATION IN EUKARYOTES

In eukaryotes (protists, fungi, plants and animals), cells replicate by mitosis followed by **cytokinesis**.

Mitosis is the division of the nucleus into two daughter nuclei. At the end of mitosis the cytoplasm also divides, separating the two nuclei and other organelles into two complete daughter cells. This separation of the cytoplasm is known as cytokinesis. Mitosis and cytokinesis are part of the cell cycle, which is covered in more detail in Section 8.2.

Another form of cell division in eukaryote cells is **meiosis**. Meiosis is not a form of cell replication because the daughter cells are different from each other and also from the parent cell. Meiosis is an important cell division that is required for sexual reproduction; it produces four daughter cells that are genetically unique.

BIOFILE

The chessboard problem

According to one legend, when chess was introduced to the shah of Persia he was so impressed with the game that he wanted to reward the inventor. The shah told the inventor that he could ask for whatever he wanted. The inventor asked for wheat. He told the shah to put one grain of wheat on the corner of the chessboard, put twice as many grains on the next square, then twice as many again on the square, and so on until the last square. The shah agreed, although he was thought that the inventor's reward would be too small.

However, the shah soon discovered that he did not have enough wheat in his kingdom to fulfil the request. Although the number of grains appeared to be small in the beginning, they increased exponentially, so that there would be an enormous number of grains on the last square of the chessboard. The same thing would happen to the number of daughter cells that arise from cell replication if it continued without interruption.

FIGURE 8.1.11 A chessboard has 64 squares. If you put one grain of wheat on one square and doubled the number of grains for each square, you would need 2^{64} grains of wheat—an extremely large number—to cover the board.

CELL REPLICATION IN PROKARYOTES

Prokaryotes such as bacteria and cyanobacteria are simple single-celled organisms (Figure 8.1.12). Prokaryotes have no nucleus or membrane-bound organelles; instead they only have a single continuous DNA chromosome attached to the plasma membrane at a point called the **origin**. Eukaryotes, on the other hand, have a lot more organelles and also more chromosomes. Due to the lack of organelles and smaller amount of DNA, cell replication in prokaryotes occurs more quickly than in eukaryotes.

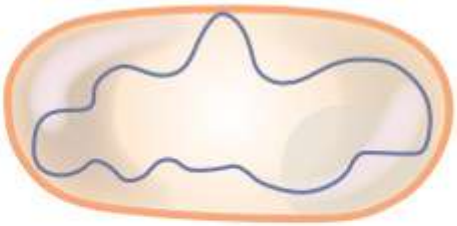


FIGURE 8.1.12 Prokaryotes are simple cells with a single continuous (or circular) DNA chromosome (shown in blue).

Cell replication in prokaryotes is called **binary fission**. Binary fission is a relatively rapid form of reproduction and produces a new organism from the parent. Like mitotic division, binary fission is an exponential process because (in ideal conditions) the population doubles after every cycle of division.

Some bacteria can undergo binary fission every 20 minutes. In other words, the number of cells can double every 20 minutes. This means that in six hours up to 18 cycles of binary fission could occur, and in this time one bacterium could have produced 218 (262 144) individuals.

One consequence of this method of reproduction is that (except for mutations) all organisms in a colony of bacteria (Figure 8.1.13) are clones; that is, they are genetically identical. This means, for example, that a drug designed to kill a bacterium of a specific type will kill all or almost all members of a bacterial colony with which it comes into contact.

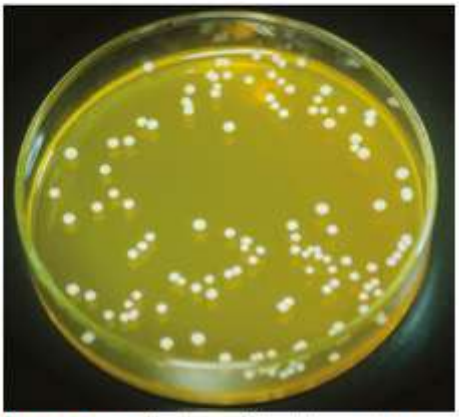


FIGURE 8.1.13 A colony of bacteria growing on an agar plate. Each bacterium in a colony is genetically identical.

Binary fission

Binary fission then proceeds by a sequence of steps, as shown in Figure 8.1.14.

1 Before a prokaryote cell undergoes binary fission, it has just one DNA molecule.

2–3 The DNA molecule (which in bacteria is in a circular chromosome) is duplicated within the nucleoid, resulting in two identical DNA molecules.

3–4 The cell grows until it has almost doubled in size.

5 The two DNA molecules are pulled to separate poles as the cell increases in size.

6 A new cell wall and membrane form between the separating chromosomes, dividing the cell into two relatively equal halves. These halves eventually separate, forming two daughter cells from the single parent cell.

Figure 8.1.15 shows binary fission in a bacterium. At this stage the new cell wall and membrane are beginning to form.

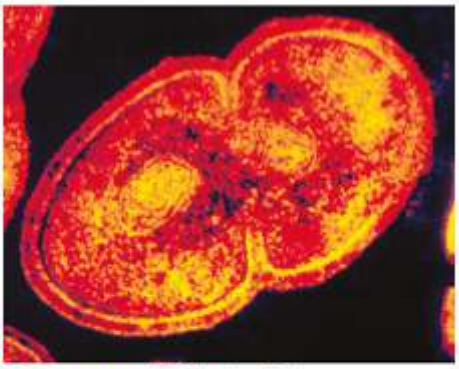


FIGURE 8.1.15 A TEM of an *Enterococcus faecalis* bacterium undergoing binary fission. The regions containing the nucleic material are visible as round, yellow structures within the two daughter cells. The formation of new cell walls can also be seen as yellow indentations in the sides of the cell.

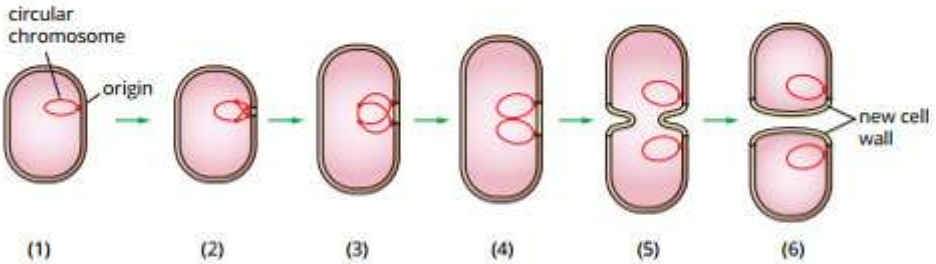


FIGURE 8.1.14 Division of a prokaryotic cell. Replication of the chromosome begins at a point called the origin, after which new cell wall and membrane is laid down to form new cell walls that divide the cell in two.

8.1 Review

SUMMARY

- Eukaryotic cells replicate by mitotic cell division.
- For multicellular organisms, the purposes of cell replication are to restore the nucleus-to-cytoplasm ratio, growth, development, maintenance and repair.
- Some cells, such as fertilised eggs, can replicate many times while keeping the same amount of cytoplasm. Therefore, replication can restore the nucleus-to-cytoplasm ratio in cases where there is too much cytoplasm for the nucleus to control.
- As cells multiply through replication, they can also enlarge and specialise, allowing the organism to grow and develop.
- As cells die or are damaged, cells produced through replication can replace those cells, allowing an organism to maintain and repair itself.
- As cells replicate, their numbers increase exponentially with the formula $C = 2^n$, where C is the total number of cells and n is the number of cycles of replication that have occurred.
- Mitotic cell division occurs in two fairly distinct stages: mitosis (a division of the nucleus) followed by cytokinesis (the division of the cytoplasm).
- For unicellular organisms, the purpose of cell replication is reproduction.
- Prokaryotic cells replicate by binary fission.
- Binary fission is an efficient process wherein the DNA molecule replicates, the cell grows larger and then splits into two daughter cells.

KEY QUESTIONS

1 Which of the following is **not** a purpose of cell replication by mitosis in multicellular organisms?
- **A** growth
- **B** repair
- **C** reproduction
- **D** restoring the nucleus-to-cytoplasm ratio

2 Which of the following statements is true?
- **A** Cytokinesis is also called binary fission.
- **B** Cytokinesis involves the division of the nucleus.
- **C** Cytokinesis occurs during meiosis.
- **D** Cytokinesis occurs after mitosis.

3 **a** Outline the purposes of cell replication.
b Give an example of a specific tissue or cell type in both plants and animals that illustrates each point in (a).

4 Classify the examples of cell replication into the correct purposes.
- toddler's height increasing by 2 cm
- cut healing
- bacteria cell dividing
- embryonic cell dividing
- seed germinating
- unicellular Protista organism dividing

Purpose	Example
reproduction	
repair and maintenance	
growth and development	
restoring nucleus-to-cytoplasm ratio	

5 State the two types of cell division and the number of daughter cells produced at the end of each type of cell division.

6 Describe the key events in binary fission in bacteria.

7 If a bacterial organism undergoes binary fission in ideal conditions every 30 minutes, calculate how many organisms there would be after four hours.

8.2 The cell cycle

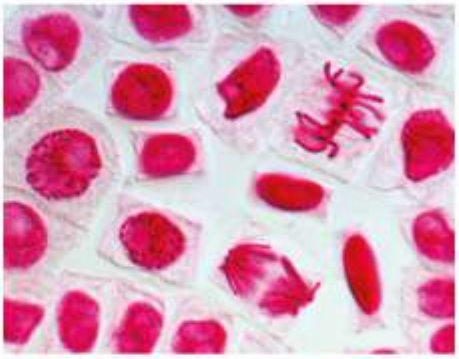


FIGURE 8.2.1 Light micrograph of hyacinth root cells undergoing mitosis. Mitosis is one of the phases of the cell cycle.

Individual organisms have a life cycle. A life cycle is simply the phases through which an organism passes during its life, including reproduction. A butterfly's life cycle, for example, moves from egg, to caterpillar, to chrysalis, to butterfly. The cycle of life begins again when the adult butterfly lays an egg.

Just as individual organisms have a life cycle, so do cells. The phases in the life of a cell are known collectively as the cell cycle. The cell cycle begins with a single cell that grows and then divides into two daughter cells through replication. Figure 8.2.1 shows plant cells in different phases of the cell cycle.

In this section you will learn about the cell cycle and its sequential phases.

THE EUKARYOTIC CELL CYCLE

In eukaryote cells the cell cycle has three main phases:

- interphase
- mitosis
- cytokinesis.

These phases always occur in this order, beginning with interphase. During interphase the cell doubles its mass and duplicates its entire components. During mitosis the nucleus divides, and during cytokinesis the cytoplasm divides.

The dividing of the cytoplasm during cytokinesis marks the creation of the two new cells. So the cell cycle is the period between one cytokinesis and the next. In actively growing cells, mitosis and cytokinesis occupy only a small part of the cell cycle, and interphase occupies a large portion, as you can see in Figure 8.2.2.

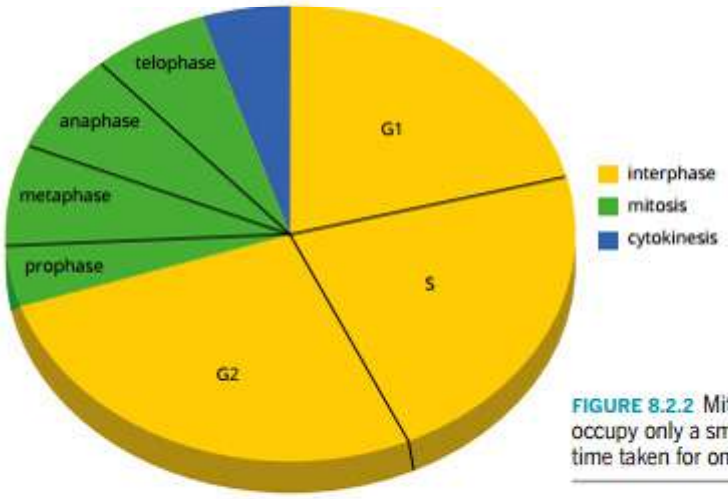


FIGURE 8.2.2 Mitosis and cytokinesis occupy only a small proportion of the time taken for one cell cycle.

Interphase

The first stage of the cell cycle is interphase. It begins immediately after the end of cell division. During interphase, a cell that is about to divide grows larger, and copies its chromosomes in preparation for cell division. Interphase is divided into three main phases:

- G1 (pre-DNA synthesis)
- S (DNA synthesis)
- G2 (post-DNA synthesis).

During interphase there is sometimes a fourth phase called G0 (G zero), also known as the 'resting phase'.

The G0 resting phase is usually considered to be part of the interphase. However, it is sometimes treated as a separate stage in the life of a cell, outside the cell cycle.

During interphase the cell grows by producing proteins and organelles such as mitochondria and Golgi apparatuses. Chromosomes however, are only copied during the S phase. Thus a cell grows (G1), continues to grow as it duplicates its chromosomes (S), then grows more as it completes preparation for cell division (G2). As the cell grows, the normal functions of the cell occur alongside the activities described above, including the synthesis of the many components required for G1, S and G2. Interphase always lasts much longer than mitosis, which lasts for about two hours in a human cell (Figure 8.2.3). The length of time a cell spends in interphase varies. Slow-growing cells, such as liver cells, spend many weeks or even years in interphase. Bone marrow cells may pass through interphase in less than a day as they generate many new blood cells. In an early embryo there is little growth and the cells rush from one round of mitosis to the next (Figure 8.2.4).

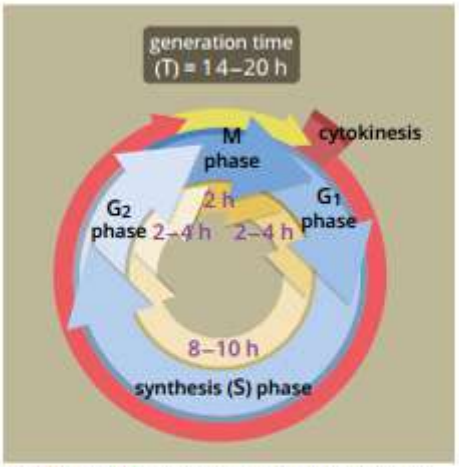


FIGURE 8.2.3 An example of the time phases (in hours) in a eukaryotic cell cycle. The S phase lasts about eight to ten hours. The G1 and G2 second growth phases last for about two to four hours. The cell cycle time, called the generation time (T), varies considerably, but in this example lasts 14 to 20 hours.

G1 phase

After division, a daughter cell is quite small. During G1 the cell gains energy and undergoes metabolic processes such as protein and membrane synthesis, and almost doubles in size. This growth includes various structures within the cytoplasm, including a large increase in the number of organelles. The progress of G1 is very variable, and if conditions are not right the cell is arrested in G1 or goes into G0. In any group of dividing cells, most will be in interphase. Most cells are seen in the G1 phase because it is the longest part of interphase.

G0 phase

At the start of G1, cells may enter the G0 or resting phase. During G0 they carry out the normal functions of the cell but do not change their internal structure or size. In most of these cells G0 is temporary and ends when the cell re-enters the G1 phase. However, some specialised cells such as nerve cells and red bloods remain permanently in the G0 phase and therefore usually do not replicate (Figure 8.2.5). For example, in skin cells, the surface keratinised cells are highly specialised and terminally differentiated. Skin replacement is from precursors in lower layers that still replicate and are not yet terminally differentiated.

FIGURE 8.2.4 Early in the development of an embryo, such as this chicken embryo, cells replicate rapidly but little growth occurs.

To differentiate, cells almost all leave the cell cycle, and don't go back. G0 is the pathway to differentiation. Of course, other cells do rest, then come back out of G0 phase and then return to the G1 phase.

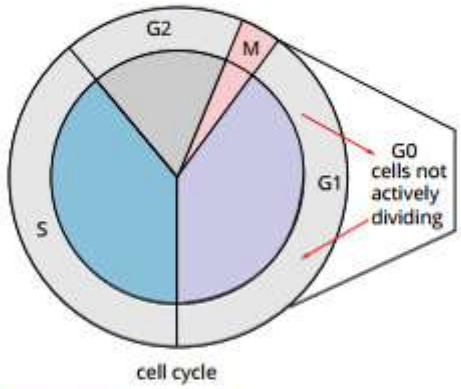


FIGURE 8.2.5 The cycle of a cell that has temporarily entered the G0 phase and then returned to the G1 phase. Not all cells enter the G0 phase. Of the cells that do enter this phase, some enter it permanently and others temporarily.

BIOFILE

Cell cycle 'gaps'

In 1879, German physician and professor of anatomy Walther Flemming was the first to observe the behaviour of the chromosomes during cell division. He achieved this by using a stain he had developed that highlighted the nucleus of the cell during cell division. Because of the limited power of the microscopes available at the time, all the activity of the cell during interphase was not evident. For this reason the phases of interphase were incorrectly named Gap 1 (G1) and Gap 2 (G2). We know now that interphase is a period of growth and activity in the cell cycle.

FIGURE 8.2.6 Walther Flemming (1843–1905), a pioneer in research on cell division.

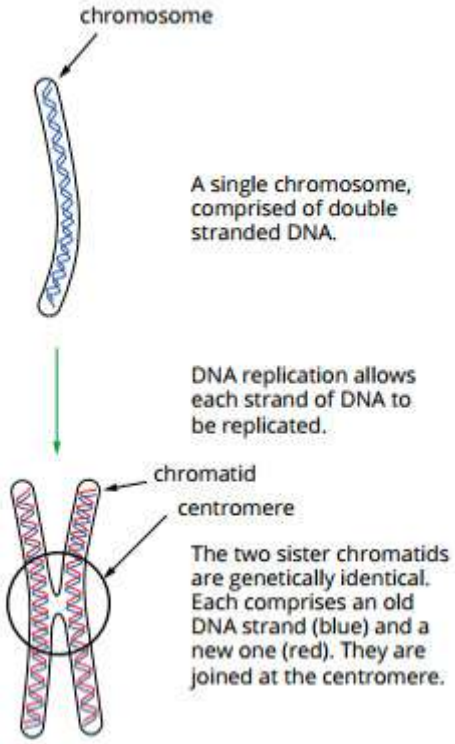


FIGURE 8.2.7 When a single chromosome replicates during the S phase (DNA synthesis), it forms two sister chromatids, joined at the centromere. This new structure is also known as a chromosome.

S phase

The 'S' in S phase stands for synthesis. During this phase, chromosomes are replicated in the nucleus. Figure 8.2.7 shows how each chromosome, which in eukaryotes are linear, makes an exact copy of itself in preparation for mitosis. Each strand of the replicated chromosomes is known as a **chromatid**. Chromatids are held together at the centromere. At the end of this phase the amount of DNA in the cell doubles, but the number of chromosomes (ploidy) of the cell remains the same.

G2 phase

During G2 the cell undergoes a secondary stage of growth, metabolism and energy acquisition. It prepares for mitosis by synthesising the materials such as proteins needed for division.

Mitosis

Mitosis is the division of the nucleus. It is a continuous process but has four sub-phases:

- prophase
- metaphase
- anaphase
- telophase.

Each sub-phase can be distinguished by the appearance and the position of the chromosomes in the cell. During interphase in the cell cycle, the chromosomes are duplicated. However, they are not visible under a microscope because they have not condensed. Figure 8.2.8 shows the movement of the chromosomes during mitosis, which is explained further on the following pages.

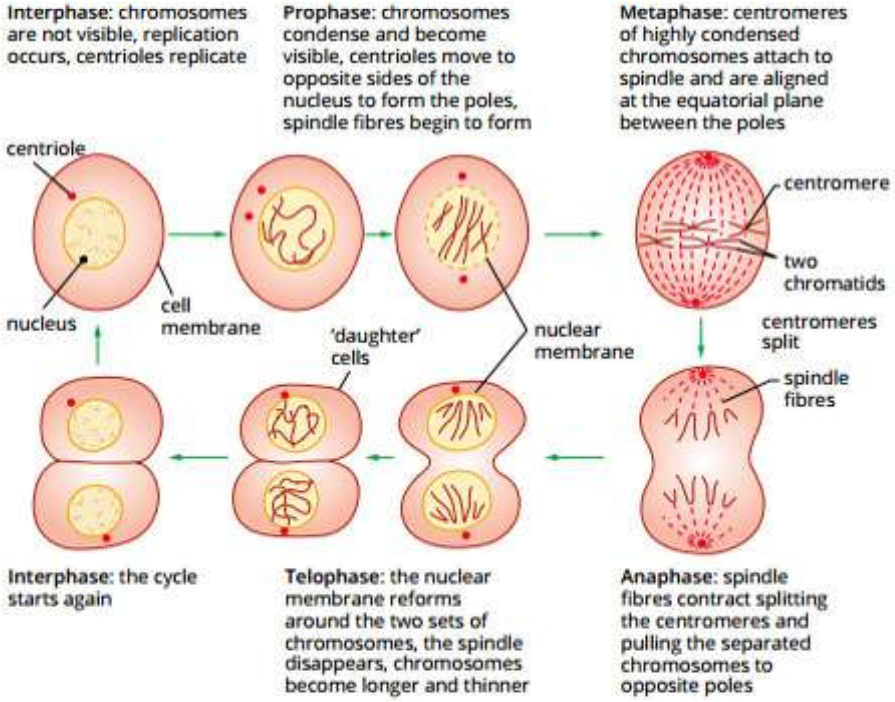


FIGURE 8.2.8 Major stages in the cell cycle, including mitosis.

Prophase

Early in prophase, chromosomes begin to condense (shorten and thicken) and become increasingly visible under the microscope. As they condense further, each chromosome can be seen as two chromatids held together at the **centromere**. At the same time the **centrioles**, which were replicated during interphase, move to opposite ends of the cell to form the poles.

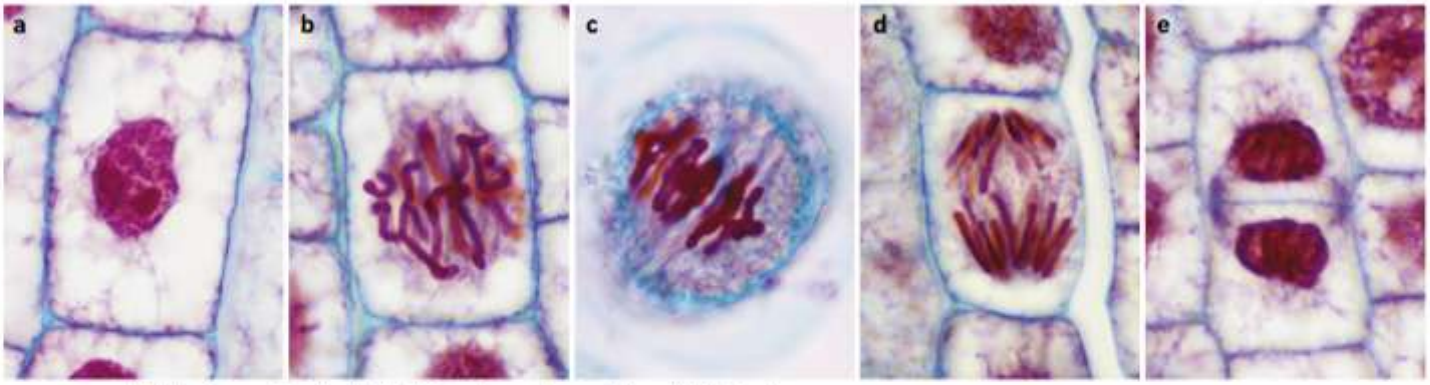


FIGURE 8.2.9 Light micrographs of mitotic division in a garlic root tip cell: (a) interphase, (b) prophase, (c) metaphase, (d) anaphase and (e) telophase.

Later in prophase the nuclear membrane breaks down. The centrioles begin to form a network of fibres, called the **spindle**, which extends between the two poles of the cell. The centromere of each individual chromosome attaches to spindle fibres extending from each of the poles. Plant cells do not usually have centrioles; they use a different mechanism to produce the mitotic spindle.

Metaphase

During metaphase the centromeres continue to be drawn by the spindle fibres so that the chromosomes are aligned in the middle of the cell. Chromosomes are most easily observed at this stage because they are highly condensed.

Anaphase

In anaphase the spindle fibres contract, pulling the centromere in two directions. The centromere splits, separating the two chromatids. Contraction of the spindle fibres continues and the separated chromatids are pulled to opposite poles. Thus, daughter cells receive the same genetic information—one copy of every chromosome that was in the original nucleus at interphase.

Telophase

The final stage of mitosis is called telophase. It is rather like prophase in reverse. A nuclear membrane forms around the chromosomes at each pole. The spindle is dismantled and disappears. The chromosomes become longer and thinner, and therefore less visible under the microscope. When mitosis is complete, each daughter nucleus moves into G1 of interphase.

At the end of mitosis the cell contains one copy of every chromosome that was present in the parental cell. Before a cell can divide again, the chromosomes must again replicate into two identical 'sister' chromatids. This replication of the DNA occurs during interphase.

You can see the stages of interphase through to telophase in the light micrographs in Figure 8.2.9.

Cytokinesis

During cytokinesis the cytoplasm divides and the new nuclei separate (Figure 8.2.10). Cytokinesis in animal cells occurs in a different way to cytokinesis in plant and fungi cells.

In animal cells the plasma membrane moves inwards, pinching the two daughter cells apart. Plant and fungi cells lay down a new plasma membrane and cell wall between the two daughter nuclei to separate the daughter cells. Components of the new cell wall, called the cell plate, are initially deposited in the centre of the cell (Figure 8.2.11). The growth of the cell plate extends outwards until the two daughter cells are completely separated.

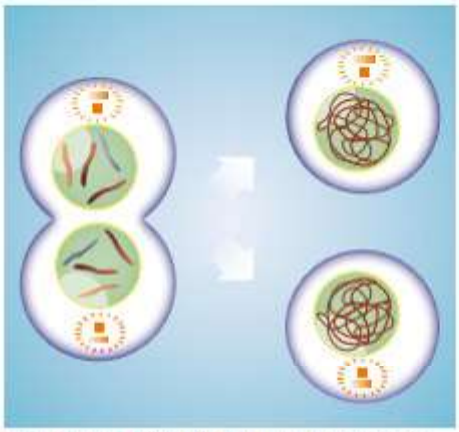


FIGURE 8.2.10 Cytokinesis is as important as mitosis in eukaryotic cell replication because it results in the generation of two daughter cells. In order to form two cells, the cytoplasm of the parent cell must be divided into two by the cell membrane.

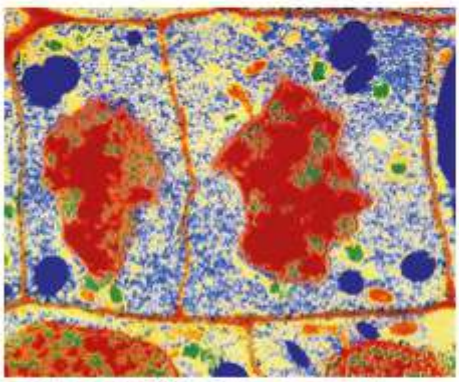


FIGURE 8.2.11 TEM of a late stage of cell division in a plant cell. The image has been coloured to show the organelles. The daughter nuclei (red and green bodies) are reforming into membrane bound organelles. Between the two forming nuclei is the developing cell wall.

In some cells mitosis is not followed by cytokinesis, resulting in a large cell containing many nuclei. This type of cell is called a coenocyte. Examples of coenocytes include the endosperm of plant seeds, filamentous fungi and plasmodial slime moulds.

In contrast, a syncytium is a multinuclear cell formed from fusion of many separate cells, rather than a lack of cytokinesis. Skeletal muscle is an example of fusion of myocytes, which arose through normal mitosis.

DIFFERENCES BETWEEN BINARY FISSION AND MITOSIS

As mentioned in the previous section, prokaryotic cells are much simpler than eukaryotic cells. As a result, the cell replication of prokaryotic cells (binary fission) is much simpler and quicker than that of eukaryote cells (mitosis). Table 8.2.1 highlights some of the differences between binary fission and mitosis.

Feature	Binary fission	Mitosis
Cell type	prokaryotic	eukaryotic
Rate and complexity	• relatively faster • relatively simpler	• relatively slower • relatively more complex
Structural changes	• no nuclear membrane to break down and reform • no spindle fibres form	• nuclear membrane must break down and reform • spindle fibres form, then attach to and separate chromosomes

TABLE 8.2.1 Differences between binary fission and mitosis.

DNA SYNTHESIS

The DNA molecule is passed on from one cell to another when cells divide. In order to be able to transmit an exact copy of the DNA molecule without losing any instructions, cells must have a mechanism for accurately copying (replicating) and synthesising new DNA.

DNA is a double-stranded molecule. Each chromosome is one long strand of DNA. During chromosome replication, each strand of a parental DNA molecule acts as a template strand on which a new strand is synthesised. This involves the double-stranded DNA 'unzipping'. New nucleotides then pair up with the template, using the rules of complementary base pairing (A pairs with T, C pairs with G), to make new strands.

As each daughter DNA molecule consists of one old and one newly synthesised strand, DNA replication is described as semi-conservative replication. It is an extremely accurate process with three distinct phases (Figure 8.2.12).

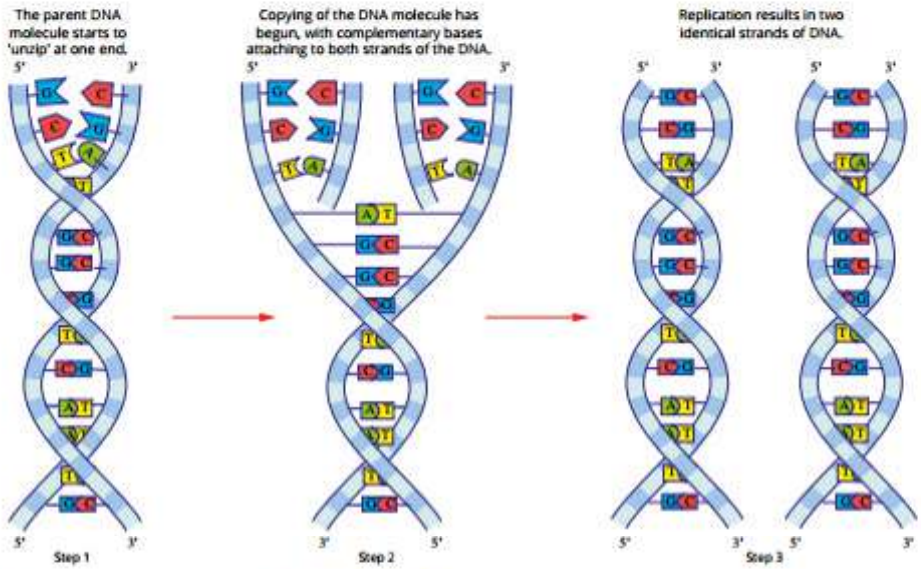


FIGURE 8.2.12 DNA replication involves three distinct phases.

8.2 Review

SUMMARY

- The cell cycle has three main stages: interphase, mitosis and cytokinesis.
- Cytokinesis marks the beginning of two new cells, and the cell cycle is the period between one cytokinesis and the next.
- Interphase involves three phases: G1 (pre-DNA synthesis), S (DNA synthesis) and G2 (post-DNA synthesis). Some cells move out of the cell cycle into an additional phase called G0 (resting phase).
- Cellular activities that usually occur during interphase include DNA synthesis (replication of chromosomes), synthesis and normal cell processes, specialisation, increase in size, and preparation for mitosis.
- Mitosis is a continuous process that is described in sub-phases: prophase, metaphase, anaphase and telophase.
- During mitosis, identical copies of each chromosome are passed from the parent cell to two daughter cells.
- Cytokinesis is the division of the molecules and organelles of the cytoplasm, and the separation of the new nuclei, to form two new daughter cells.
- Mitosis (eukaryotic cell division) is relatively slower and more complex than binary fission (prokaryotic cell division).
- Binary fission is a faster and simpler process of replication than mitosis.
- DNA replication involves synthesising new DNA by replicating parent strands of DNA strands. Daughter DNA molecules consist of one parent strand and one synthesised DNA strand.
- The characteristics of the sub-phases of mitosis are summarised in the following table.

Mitosis	Prophase	• Chromosomes condense and become visible. • Centrioles move to opposite sides of the nucleus and form poles. • Nuclear membrane breaks down. • Centrioles form spindle fibres between the two poles. • Centromere of each chromosome attaches to spindle fibres extending from each pole.
	Metaphase	• Chromosomes align at equatorial plane of cell. • Spindle fibres attach to centromeres of chromosomes.
	Anaphase	• Spindle fibres contract, splitting the centromeres and separating the sister chromatids. • The single-strand chromosomes are separated. • Chromosomes are pulled to opposite poles.
	Telophase	• Nuclear membrane reforms around the two sets of chromosomes. • Spindle fibres disappear. • Chromosomes become longer and thinner.

KEY QUESTIONS

1 Which organelle divides into two during mitosis?
- **A** nucleus
- **B** vacuole
- **C** mitochondrion
- **D** chloroplast

2 Which of the following statements is **not** correct?
- **A** Although it is divided into stages, mitosis is a continuous process.
- **B** Cytokinesis marks the beginning of two new cells.
- **C** DNA is replicated during interphase.
- **D** Mitosis is the longest phase of the cell cycle.

3 Distinguish between a chromatid and a chromosome. When are they visible?

4 What events occur during interphase of the cell cycle?

5 Does every cell go through the G0 phase? What is the result if a cell does not move out of this phase?

6 Use diagrams to show the events that occur at each phase of mitosis.

7 **a** Cell replication involves two processes. Name the two processes and describe them.
b Explain why it is necessary for the nuclear division to be exact, but not the division of the cytoplasm.

8 Explain how cell division in plants is different from cell division in animals.

9 How do cells ensure that the DNA is copied correctly to the daughter cells?

8.3 Controlling cell division

Cells replicate by dividing: a parent cell divides to create two new daughter cells. If all of the cells in your body replicated at the same rate as the first embryonic cells (2–3 times faster than adult cells), each day you would make up to 100 trillion cells—enough to make three bodies! This does not happen because the rate of cell replication is controlled, so that most cells are not replicating at any particular time. Some cells also take on specialist roles and do not replicate again. Cell division is a carefully controlled process.

In this section you will examine the factors that cause cells to divide (Figure 8.3.1) and the factors that prevent them from dividing. You will also learn how cell division in eukaryotic cells is controlled.

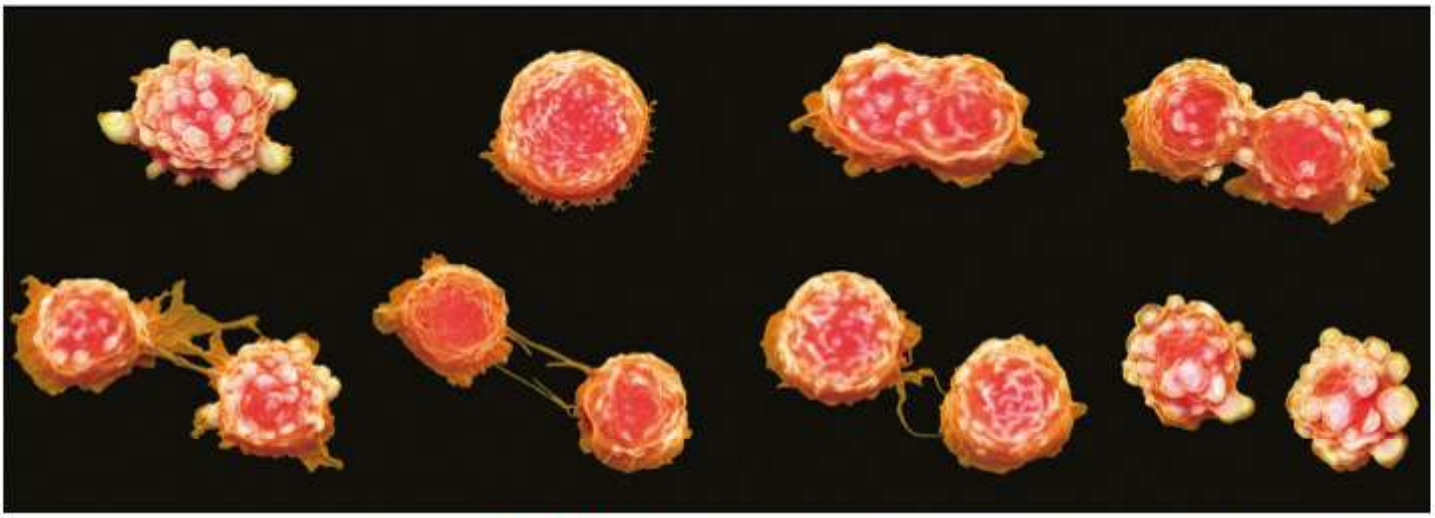


FIGURE 8.3.1 SEM of dividing bowel cancer cells. Cancerous cells ignore or override some of the factors that control cell division, often replicating a lot faster than the organism's own cells.

REGULATING THE CELL CYCLE

The eukaryotic cell cycle is a highly regulated process. This regulation is critical to the proper development and function of organisms. A decrease or increase in the rate of cell replication can have negative effects. For example, if replication of bone marrow cells slowed down, this would also slow down the production of red blood cells, which takes place in the bone marrow. This would in turn have serious consequences for the supply of oxygen to cells.

The cell cycle is regulated by internal and external factors.

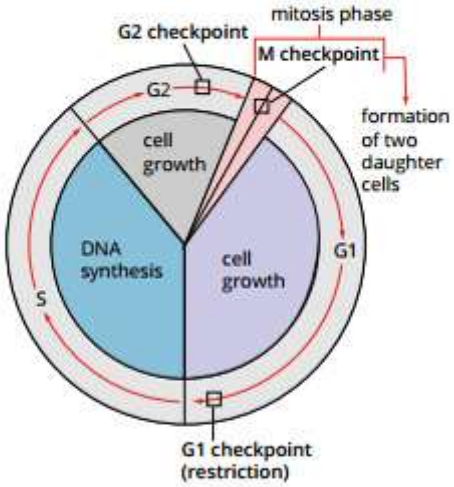


FIGURE 8.3.2 The cell cycle is controlled at three checkpoints: the G1 checkpoint, G2 checkpoint and M checkpoint.

Internal checkpoints in the cell cycle

The purpose of the cell cycle is to produce two genetically identical daughter cells. If a genetic abnormality such as a **mutation** occurs during the cycle, these need to be repaired or the cycle needs to stop.

An internal regulation system consisting of a group of regulatory proteins produced within the cell is responsible for determining whether the cell cycle continues or stops at each stage. It is known as the cell **cycle control system** (Figure 8.3.2). The regulatory proteins in this control system are active at three checkpoints in the cell cycle:

- G1
- G2
- metaphase (M).

G1 checkpoint

The G1 checkpoint occurs towards the end of G1 in interphase. This checkpoint, also known as the restriction point, checks three things:

- There are adequate resources for the cell to divide, such as enough nucleotides and energy supply to copy the DNA.
- The cell is large enough to divide.
- The DNA in the nucleus has not been damaged.

If a cell passes this checkpoint, it is committed to the cell division process.

G2 checkpoint

The G2 checkpoint occurs towards the end of G2 in interphase. As in the G1 checkpoint, the cell is checked for adequate resources, such as proteins required for mitosis, and cell size. However, the most important check is of the DNA and chromosomes, to ensure that they have all been replicated without mistakes or damage. A cell cannot enter the mitotic phase if all of these requirements are not met.

M checkpoint

The M checkpoint occurs towards the end of metaphase in mitosis. This checkpoint, also known as the spindle checkpoint, determines if all of the spindle fibres have correctly attached to the sister chromatids and that the chromosomes are correctly aligned at the midline (equator) of the cell. The cell will not proceed to anaphase unless all sister chromatids are correctly attached and aligned.

BIOFILE

Protein pairs

The internal regulation system of a cell consists of protein pairs that drive the cell cycle. A protein pair consists of a cyclin and a cyclin-dependent kinase (CDK) that pair up to drive cells through each stage of the cell cycle.

External cell cycle controls

Signals for cell division can also originate from outside of the cell. Signals from outside the cell include contact inhibition, where crowding and contact with neighbouring cells cause a cell to slow its passage through the cell cycle or to stop in interphase (stop dividing). Lack of contact inhibition is typical of cancer cells, which keep growing rampantly regardless of the level of crowding and contact.

Molecules called mitogens act as signals to promote cell division. Mitogens include molecules such as growth factors and hormones. This is important during development and in repair. When cells die in a tissue, neighbouring cells release mitogens that stimulate cell division for tissue repair. These are the types of factors that can bring cells resting in G0 back into the cell cycle. One example is the ability of liver cells to return to the cell cycle for tissue repair after liver damage. Tumours can also release factors that stimulate division in nearby capillary cells, directing the growth of their own personal blood supply (Figure 8.3.3).

In addition to these molecular signals that promote the cell cycle, environmental conditions must be optimal for the cell cycle to progress. These include temperature, pH and the amount of nutrients.

FIGURE 8.3.3 A tumour can release growth factors that encourage new blood vessels to grow into the tumour. This allows the tumour to grow larger and more quickly.

CELL REPAIR AND CELL DEATH

During both embryonic development and after birth, many cells are only temporarily useful. Once they have done their job they are removed. This also applies to cells that have been irreversibly damaged.

Cells cannot function properly if the genetic material is damaged. Damage to a cell's DNA can occur during DNA replication or it can be caused by environmental factors. Checkpoints throughout the cell cycle check for damage to the DNA. If the damage to the DNA cannot be repaired, the cell will undergo apoptosis (programmed cell death).

Repair

Cells have enzymes that can detect and repair damage to DNA. These enzymes run along strands of DNA like a zip, checking that the DNA is intact and has been replicated properly (Figure 8.3.4). If there is minor damage, such as DNA breakages, these will be corrected by enzymes before the cell continues its progress through the cell cycle.

An **enzyme** is a protein molecule produced by an organism that acts as a biological catalyst. Enzymes speed up rates of reactions that would otherwise have taken place much more slowly. They are essential for many complex chemical reactions in living organisms. Their action is specific: they catalyse only one type of reaction.

The base-excision repair (BER) enzyme, called uracil-DNA glycosylase, is responsible for triggering the first step in the removal and replacement of damaged DNA bases. Other enzymes, such as DNA ligase, stitch up the DNA 'backbone' (Figure 8.3.4). They act throughout the cell cycle to ensure that no mutations occur.

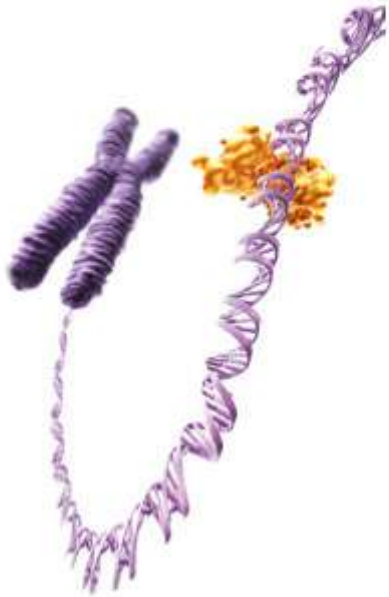


FIGURE 8.3.4 The enzyme, DNA ligase (shown in yellow), joining together a broken strand of DNA. Millions of DNA breaks occur during the normal course of a cell's life. Without molecules that can connect the pieces, cells can malfunction, die or become cancerous.

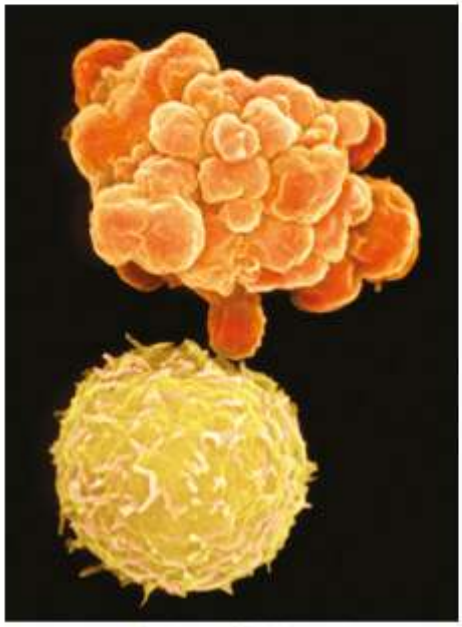


FIGURE 8.3.5 Coloured SEM of two human white blood cells. The top cell is undergoing programmed cell death, or apoptosis. Its cytoplasm is forming clusters. The cell will later break into vesicles, which will then be engulfed by phagocytes.

Apoptosis

Apoptosis, also called programmed cell death, is a highly regulated form of cell death that is vital for the normal functioning of every organism. If damage to the DNA of a cell is too great, enzymes will be activated that will cause the cell to die (Figure 8.3.5).

Several specific alterations take place in apoptosis that result in cell shrinkage and separation from adjoining cells. The cells surface membrane buds to form what are known as apoptotic bodies. These contain the remnants of the cytoplasm, organelles, and **chromatin** fragments. Phagocytic cells (cells specialised to engulf and break down cellular debris) remove the apoptotic bodies. In this way, apoptosis has a role in maintaining the genetic integrity of cells, or in other words in ensuring that only cells with intact DNA proceed through the cell cycle.

Apoptosis is also a necessary part of normal development. An example is the programmed breakdown and death of the cells forming the initial webbing in the developing limbs of humans and some other vertebrates, which breaks down to allow the fingers and toes individual movement. If the normal process of apoptosis does not occur or is incomplete, webbing remains between the fingers or toes. This condition is called syndactyly (Figure 8.3.6). Apoptosis occurs in many other tissues, too. In the developing brain, many more nerve cells are produced than will survive in the adult. Those nerve cells that do not make a functional connection with other parts of the nervous system will die by apoptosis (Figure 8.3.7).

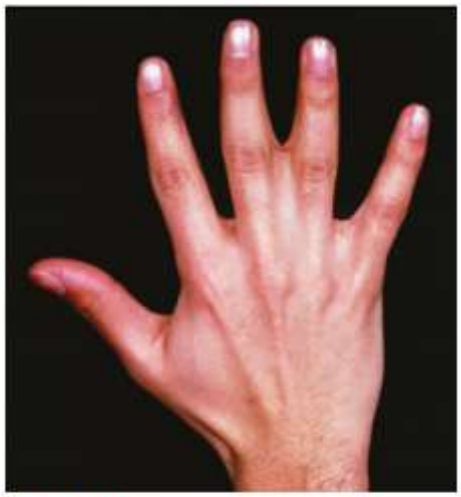


FIGURE 8.3.6 Syndactyly (excess webbing between the fingers or toes) can occur in humans if the apoptosis of the webbing between fingers or toes is incomplete during development.

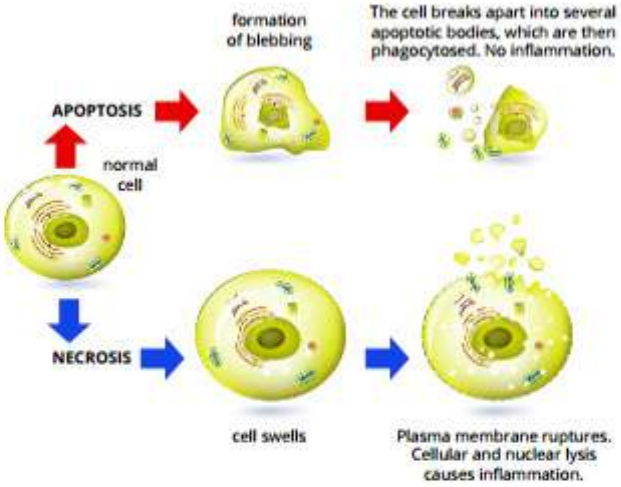


FIGURE 8.3.7 Illustration showing the difference in the structural changes of cells at cell death via apoptosis and necrosis. Apoptosis is triggered by normal, healthy processes in the body. Necrosis is cell death that is triggered by external factors or disease, such as trauma or infection.

Necrosis

Not all cells die by apoptosis. Some cells die by necrosis (accidental cell death). This can occur as a result of physical damage or a lack of oxygen. It often affects large, compact clusters of cells. In necrosis the cell membrane becomes damaged, allowing water and ions to enter the cell, causing it to swell. This results in a messy 'explosion' as illustrated in Figure 8.3.7. Cell contents are released in an uncontrolled manner, resulting in inflammation and damage to surrounding cells.

LIMITED MITOTIC DIVISIONS

Another internal cell cycle control is rather like an internal clock that counts the number of divisions that have occurred in a line of cells. In **tissue culture**, cells from most multicellular organisms, including mammals, do not normally live indefinitely but die after a certain number of divisions. If the cells are taken from an embryo or young animal, they undergo more divisions than if they are taken from an adult.

It is as though the cells can 'count' how many divisions they have made. It seems that they do this by losing a small amount of DNA from the tips of their chromosomes, known as **telomeres**, at each division (Figure 8.3.8). After about 50 or so divisions, the tips are lost and the cell either stops dividing or enters apoptosis.

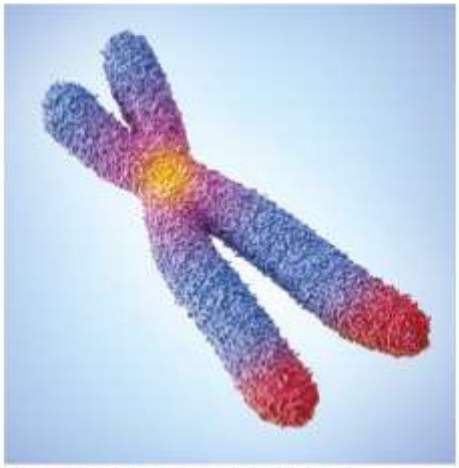


FIGURE 8.3.8 Illustration of a human chromosome. Chromosomes are composed of deoxyribonucleic acid (DNA). This chromosome consists of two chromatids (blue) joined at their centres by the centromere (yellow), which is involved in cell division. At the tip of each chromatid are the telomeres (red), which protect the ends of the chromosome from degrading. Telomeres get a bit shorter with each chromosome replication.

Tissue culture is a method of growing cells or tissues in an artificial medium containing essential nutrients, salts and growth factors. A population of cells grown continuously in culture is called a 'cell line'.

Mitotic divisions: exceptions

There are now many cell lines that can be isolated and grown in culture indefinitely, especially cells derived from tumours. 'HeLa' cells are a particular line of cultured cells that are used worldwide in experimental studies of cell functions. These cells were isolated from a human cervical carcinoma in 1952 and have been grown continuously ever since (Figure 8.3.9). They are named after the person from whom they were obtained, Henrietta Lacks.

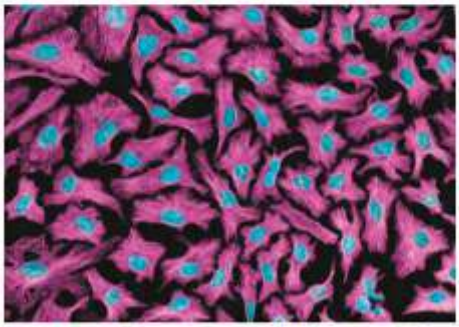


FIGURE 8.3.9 Fluorescence LM of a group of cultured HeLa cells, showing the cell nuclei (stained blue). HeLa cells are a continuously cultured cell line of human cancer cells that are widely used in biological and medical research.

UNCONTROLLED CELL DIVISION

Although the cell cycle is highly regulated, there are times when cells divide uncontrollably. If uncontrolled cell division occurs during embryo development, the embryo will be abnormal and, in most circumstances, will abort. If uncontrolled cell division occurs in a mature organism, a neoplasm may form.

A **neoplasm** is an abnormal growth of tissue that usually, but not always, forms a mass. Neoplasms are more commonly referred to as tumours, but not all are cancerous. There are three types of neoplasm:

- benign—these form localised masses but do not transform into cancer
- potentially malignant—these form localised masses that will eventually invade other tissues and transform into cancer
- malignant—these form masses that invade other tissues and transform into cancer (Figure 8.3.10, page 368).

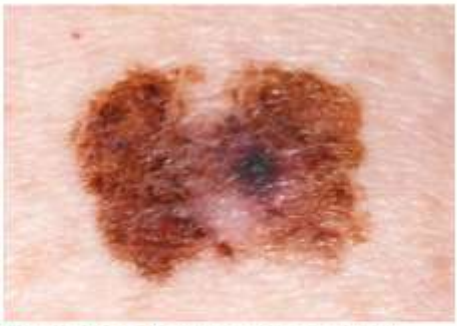


FIGURE 8.3.10 A melanoma is a malignant neoplasm that will continue to grow as a skin cancer unless removed.

Comparing benign and malignant neoplasms

Benign and malignant neoplasms can seem similar; the following table outlines the main differences between them.

Benign neoplasms	Malignant neoplasms
Cells divide uncontrollably, yet not as rapidly as those of a malignant neoplasm.	Cells divide uncontrollably.
The organism controls the growth of the neoplasm to a certain extent by encapsulation. Cells are contained and do not penetrate the blood and lymph vessels.	Growth of the neoplasm: uncontrolled cell growth breaks out of capsule. Neoplastic cells can spread to other tissues (i.e. they metastasise).
Because the neoplasm grows inside a capsule, it does not destroy the surrounding tissues.	The growing neoplasm destroys the surrounding tissues.

TABLE 8.3.1 Comparison of benign and malignant neoplasms.

BIOFILE

Cancer cells that never die

Cancer cells differ from normal cells in many ways:

- They divide at a faster rate than normal cells of the same type. Some divide very rapidly, others more slowly.
- They are not affected by the normal signals that control the cell cycle, such as contact inhibition.
- They look different and may become less specialised.
- They release factors that stimulate the development of their own blood supply.
- Their DNA mutates, making them different and sometimes resistant to earlier successful treatments.
- They can 'colonise' new parts of the body and continue to grow unchecked.
- They can continue dividing endlessly, whereas normal cells undergo a limited number of cell cycles.
- They avoid proceeding to death by apoptosis.

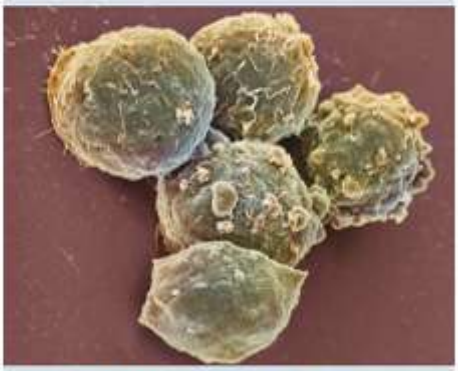


FIGURE 8.3.11 Cancerous white blood cells, shown here, look very different from normal white blood cells.

DISRUPTIONS TO THE CONTROL OF CELL DIVISION

While the cell cycle is highly regulated, the regulatory mechanisms can be disrupted by a number of factors. If this occurs, uncontrolled cell division may lead to neoplasms, which can eventually transform into cancer.

Genetic factors

Genes code for the enzymes that regulate cell division or regulate apoptosis. When mutations to these genes occur, regulation of cell division or apoptosis can cease.

Proto-oncogenes

Proto-oncogenes are a group of normal genes involved in the regulation of cell division. One of their functions is to stimulate cell growth. They are required for the normal growth and development of cells. However, mutations of these genes can change them into oncogenes, which induce uncontrolled cell division leading to the development of neoplasms.

One example is an important regulator of cellular proliferation called platelet derived growth factor (PDGF). Mutations of the PDGF gene are connected with the development of brain cancer. Mutations of the PDGF receptor gene are associated with thyroid cancer (Figure 8.3.12).

Oncogenes are cancer-causing genes. Oncology is the medical field that studies and treats cancer.

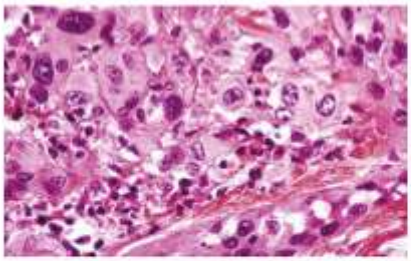


FIGURE 8.3.12 Light micrograph of thyroid cancer tissue.

Tumour-suppressor genes

The group of genes that code for proteins involved in the slowing down of cell division, the repair of DNA or apoptosis are called **tumour-suppressor genes**. If these genes are damaged, cell division may go unchecked.

Inherited genes

Some people also have a genetic predisposition to certain forms of cancer. An individual inherits their genes from their parents, so they could receive an oncogene or mutated tumour-suppressor gene from one or both parents. This does not necessarily mean that all family members with that gene will develop the cancer. It appears that more than one mutation in a gene must occur before cancer develops.

However, individuals with that gene do have a higher chance of developing the cancer because they have one such mutation.

A family history of breast cancer, for example, is associated with mutations in the BRCA1 or BRCA2 genes, which are located on chromosome 17. A protein coded by these genes takes part in the repair of damaged DNA, but changes in its structure lead to uncontrolled growth. The growth occurs mainly in tissues whose functioning depends on oestrogens, for example, tissues in the mammary glands (Figure 8.3.13) and ovaries.

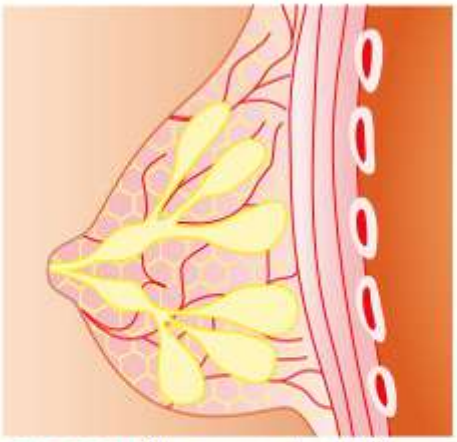


FIGURE 8.3.13 The mammary glands of the breast (highlighted in yellow) contain tissues that depend on oestrogens and are vulnerable to neoplasms caused by changes in the BRCA1 or BRCA2 genes.

Environmental factors

Environmental factors such as exposure to radiation or certain chemicals can damage DNA. Such agents that cause damage in DNA are called **mutagens**. If the damage occurs to proto-oncogenes or tumour-suppressor genes, the control of cell division can be disrupted.

There are three types of carcinogens (cancer-causing agents): chemical, physical and biological. Some examples are outlined in Table 8.3.2.

Carcinogen type	Examples	
Chemical	Tobacco contains mutagenic and carcinogenic compounds. Smokers are much more likely to develop malignant neoplasms of the respiratory system, pharynx, larynx and lungs than non-smokers.	
	Chemicals in air pollution. Factories can emit smoke containing chemicals that increase the risk of developing a neoplasm.	
Physical	The ionising radiation in X-rays can have dangerous effects on cells because it can cause cancerous mutations in cells.	
	Ultraviolet light is a mutagen. Overexposure to sunlight or tanning beds, and therefore ultraviolet radiation, increases the risk of skin cancer or melanoma.	
Biological	Some viruses such as HTLV-1 virus, which is responsible for certain types of leukaemia or blood neoplasms, that is, an oncogenic virus. HTLV-1 is a retrovirus, a type of virus that inserts its genetic information into the host cell's chromosomes. Such viruses either carry oncogenes themselves or enhance the host cell's proto-oncogenes.	

TABLE 8.3.2 The three types of carcinogens.

Loss of immunity

The immune system is usually able to detect and destroy abnormal cells, including those that are replicating in an uncontrolled manner. If an individual's immune system is weakened, cells that are dividing in an uncontrolled manner may not be detected and may continue to divide to form tumours.

8.3 Review

SUMMARY

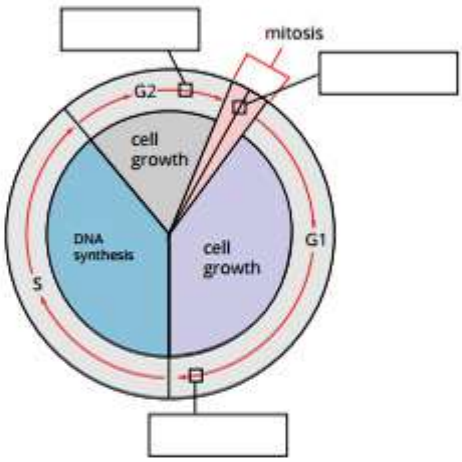
- The cell cycle is controlled by signals from inside and outside the cell.
- There are three internal checkpoints in the cell cycle: the G1 checkpoint, G2 checkpoint and metaphase (M) checkpoint.
- External cell cycle controls include:
  - contact inhibition
  - growth factors and hormones
  - environmental conditions such as temperature and pH.
- Apoptosis is programmed cell death during which cells respond to signals and die in a controlled way. Apoptosis is important during development.
- Necrosis involves a damaged cell bursting in an uncontrolled manner. It can cause inflammation and damage to surrounding cells.
- Cells usually have a limited number of mitotic divisions.
- Uncontrolled cell division can result in neoplasms. Neoplasms can be benign, potentially malignant or malignant.
- Uncontrolled cell division can be due to genetic factors, environmental factors, pathogens and loss of immunity.

KEY QUESTIONS

1 Which of the following is **not** checked during the G1 checkpoint of the cell cycle? Select the correct answer.

A DNA
B the attachment of the spindle fibres to the centromeres
C the amount of resources in the cell
D the size of the cell

2 Label the parts of the following diagram.



3 Classify each of the following as either internal or external controls of the cell cycle.

- temperature
- DNA quality
- telomere length
- contact inhibition
- size of cell

4 **a** Which section of the chromosome is important for attachment to spindle fibres and thus progression of cells through the M checkpoint?

b Which section of the chromosome do scientists believe has a function in controlling the number of mitotic divisions that a cell can undertake? Where is this section located?

5 When a tadpole develops into a frog, the cells in the tail die. What is the name given to this type of cell death?

6 **a** State the two types of cell death.

b How do the two types of cell death differ?

7 Give an example for each of the chemical, physical and biological factors that cause neoplasms.

8 Explain how proto-oncogenes and tumour-suppressor genes can cause cancer.

8.4 Stem cells

Stem cells are cells that are yet to be specialised (Figure 8.4.1). In other words, they have the potential to become different types of specialised cells. For this reason scientists believe that stem cells could replace damaged cells that the human body cannot repair on its own, such as nerve cells. However, stem-cell research is often associated with ethical concerns around the use of stem cells from embryos.

In this section you will learn more about the role and function of different types of stem cells, the potential use of stem cells in medical therapies and the ethical considerations surrounding stem cell research and use.

FIGURE 8.4.1 SEM of a clump of stem cells. The particular type of stem cells in this image are able to differentiate into any of the cell types in the human body.

EMBRYO DEVELOPMENT

All humans start life as a single cell, which is a fertilised egg called a zygote. When the zygote undergoes mitosis to become two cells it is no longer a zygote, but is now known as a **morula**. The morula continues to divide until it consists of 16 cells (after about three to four days) and then enters the uterus. The morula is a ball of unspecialised embryonic stem cells.

In the uterus, mitotic divisions continue, and the morula becomes a **blastocyst** (Figure 8.4.2) as cells begin to specialise. The blastocyst consists of a single layer of surface cells, which enable it to implant in the uterus and eventually develop into the placenta, and an inner cell mass that will later give rise to the embryo. After the blastocyst is implanted, gastrulation occurs over approximately five days, and the blastocyst becomes a **gastrula**, which has three different layers of cells. Eventually the gastrula becomes an **embryo**, and then a **foetus**. These development stages are shown in Figure 8.4.3.

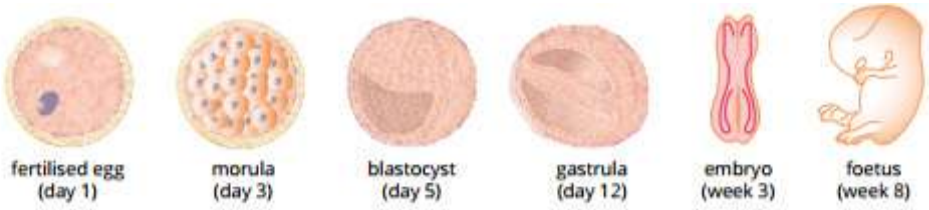


FIGURE 8.4.3 The development of a human zygote (fertilised egg) into a foetus.

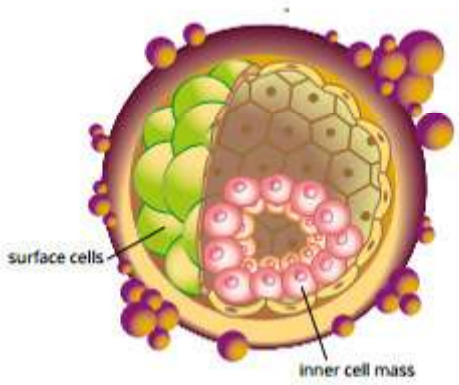


FIGURE 8.4.2 The blastocyst is characterised by an inner and outer cell mass.

The difference between each stage of embryo development (Figure 8.4.4) is determined by the characteristics of the developing individual. For example, at about the eighth week of embryo development, the embryo is recognisable as human, and is then known as a foetus. At this stage some of the internal and external organs and structures begin to form and function:

- The brain, spinal cord and heart, which began development in the fifth week, continue to grow, the heart beats in a regular rhythm and the lungs begin to form
- Tissues grow that will become the spine and other bones.
- Eyes and ears begin to form.

Limb buds develop in the fifth week from the ectoderm and mesoderm. Hands and feet begin to form and look like paddles, with webbing between the digits. Apoptosis eventually removes the cells of the webbing.

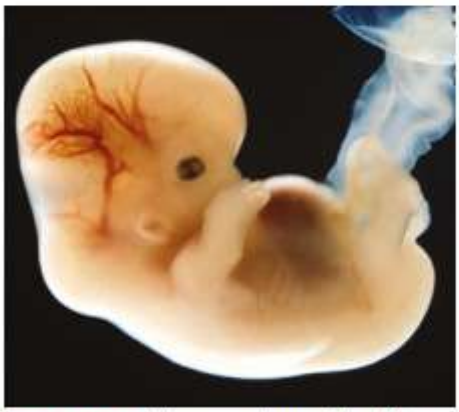


FIGURE 8.4.4 A human embryo at about the seventh week of development.

Embryonic germ layers and cell specialisation

After implantation in the uterus the blastocyst undergoes **gastrulation**, folding in on itself to form a gastrula with three primary layers of cells: ectoderm, mesoderm and endoderm. These primary layers are known as **germ layers** (Figure 8.4.5). The germ layers are also supported by two membranes:

- the yolk sac which surrounds the egg yolk. It has a well-developed vascular system that transports nutrients from the egg yolk to the developing embryo.
- the amnion, which surrounds the developing embryo, is filled with fluid. Its main role is as a shock absorber to protect the embryo against any impacts or movements.

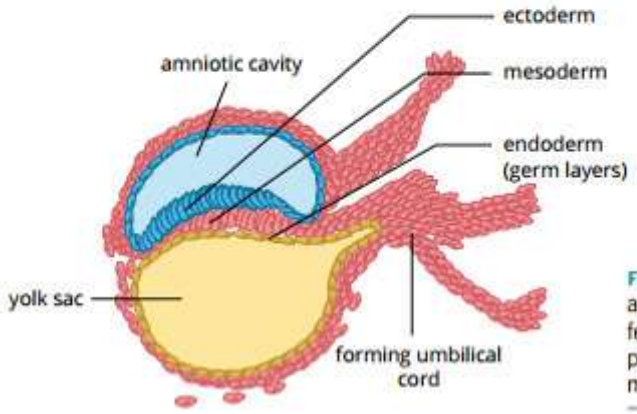


FIGURE 8.4.5 A gastrula approximately 16 days after fertilisation, showing the three primary germ layers: ectoderm, mesoderm and endoderm.

The three embryonic germ layers that form will eventually give rise to the different types of specialised cells that make up the tissues and organs in humans (Figure 8.4.6).

- The ectoderm (outermost layer of the embryo) forms epidermis, hair, peripheral nervous system, brain and spinal cord cells
- mesoderm (middle layer of the embryo) forms muscle, cartilage, kidney and gonad cells
- endoderm (innermost layer of the embryo) forms the lungs, bladder and lining of the digestive system, including the stomach, colon, liver and pancreas.

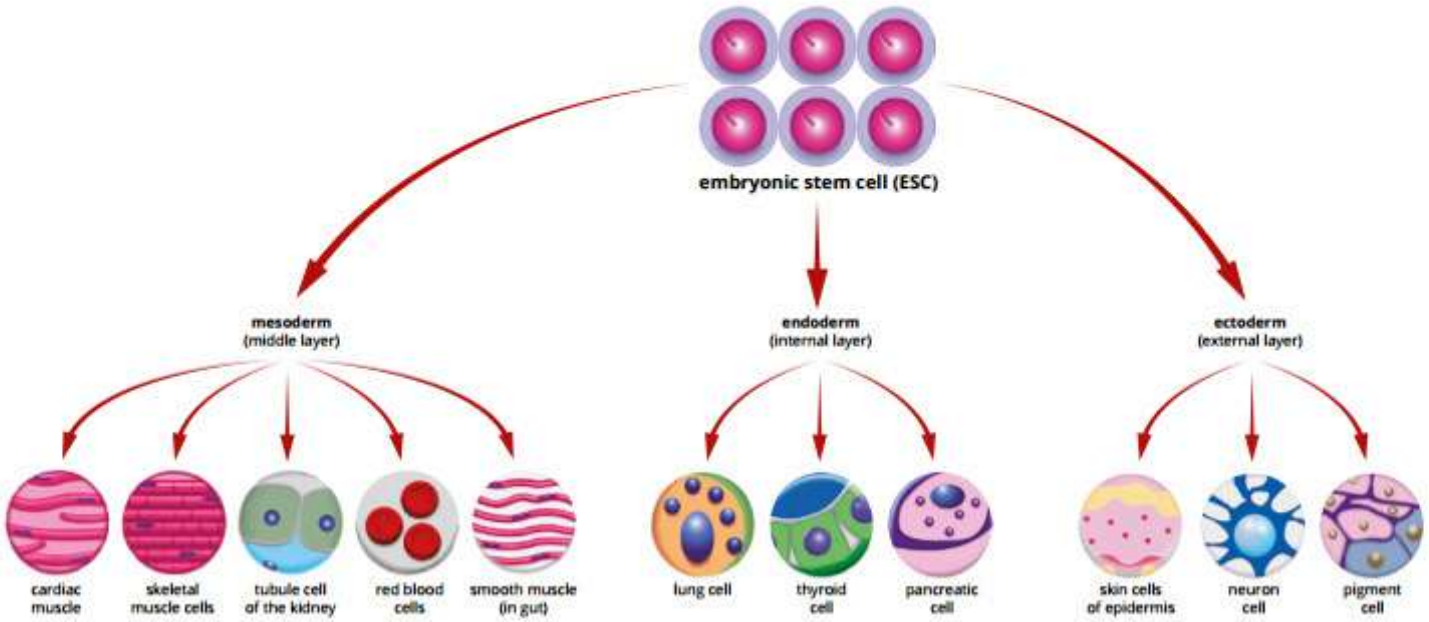


FIGURE 8.4.6 The three layers of embryonic germ cells in humans give rise to all the different types of specialised cells.

STEM CELLS

Stem cells are capable of self-renewal, that is replicating themselves as new stem cells, as well as differentiating into distinct cell types. Certain stem cells are able to divide indefinitely in order to replace cells. There are two types of stem cells that come from different sources and have different properties. It is important to note the distinction between the two.

Embryonic stem cells

Embryonic stem cells are the undifferentiated or relatively undifferentiated cells of embryos (from the zygote to blastocyst stage). They can be obtained from surplus three- to five-day-old embryos from IVF programs. Embryonic stem cells can become many types of cell and can replicate indefinitely.

Adult stem cells

Adult stem cells are present in small numbers in some adult tissues, such as hair follicles, bone marrow, the spinal cord and germ cells, and remain as stem cells throughout an individual's life. They can give rise only to a limited range of cells, such as bone marrow (haemopoietic) stem cells (Figure 8.4.7). The biological purpose of adult stem cells is repair and regeneration of damaged and aged tissue, such as skin and liver cells. Adult stem cells cannot replicate indefinitely.

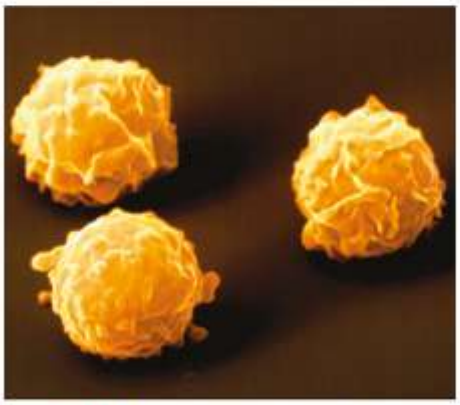


FIGURE 8.4.7 SEM of human bone marrow stem cells. These stem cells can give rise to different types of blood cells.

Potency

Scientists also characterise stem cells by cell potency. Cell potency is a cell's ability to differentiate into other cells types. The more cell types into which a cell can differentiate, the greater its potency. Stem cells are classified as totipotent, pluripotent, multipotent or unipotent, depending on what sort of cells they can become:

- **totipotent** stem cells, which are capable of giving rise to any cell type or even another embryo. A zygote and its divisions up to the 16-cell morula stage are the only stem cells that are totipotent;
- **pluripotent** stem cells, which can differentiate into any of the three germ layers: endoderm (e.g. lungs and gut lining), mesoderm (e.g. muscle, bone, blood) or ectoderm (e.g. skin and nervous system). These cells are present in the blastocysts. The primordial germ cells (PGCs) that give rise to gametes are also pluripotent;
- **multipotent** stem cells, which have the ability to give rise to multiple, but limited, cell types. Haematopoietic (blood forming) stem cells from red bone marrow are an example of this cell type, as they can give rise to lymphocytes, macrophages, platelets and other blood cells (Figure 8.4.8);
- **unipotent** stem cells, which can only differentiate into one cell type found in a specific tissue but can divide repeatedly. Skin epidermal stem cells are examples of unipotent cells that give rise only to new skin cells.

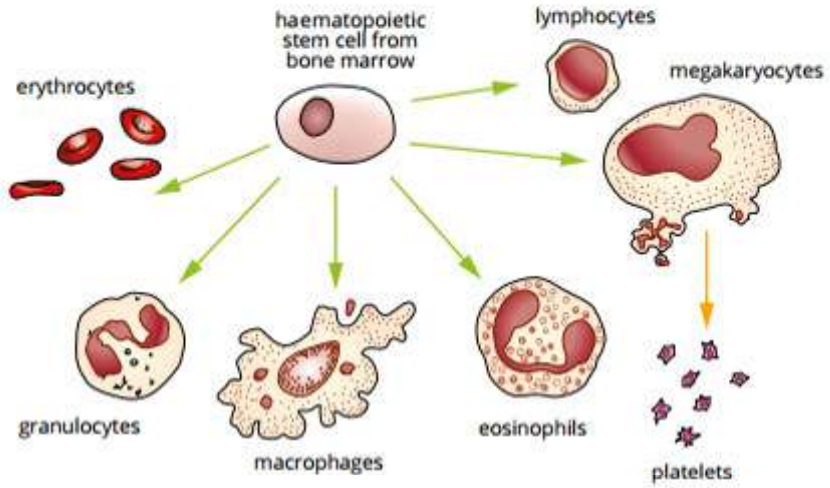


FIGURE 8.4.8 Haematopoietic cells (blood forming) stem cells are set apart very early in development. They are found in bone marrow and are responsible for the continued production of a number of distinct cell types.

Embryonic stem cells (ESC) are totipotent or pluripotent. Adult stem cells are multipotent or unipotent. The four potencies of stem cells and the life stages in which they are found are outlined in Figure 8.4.9.

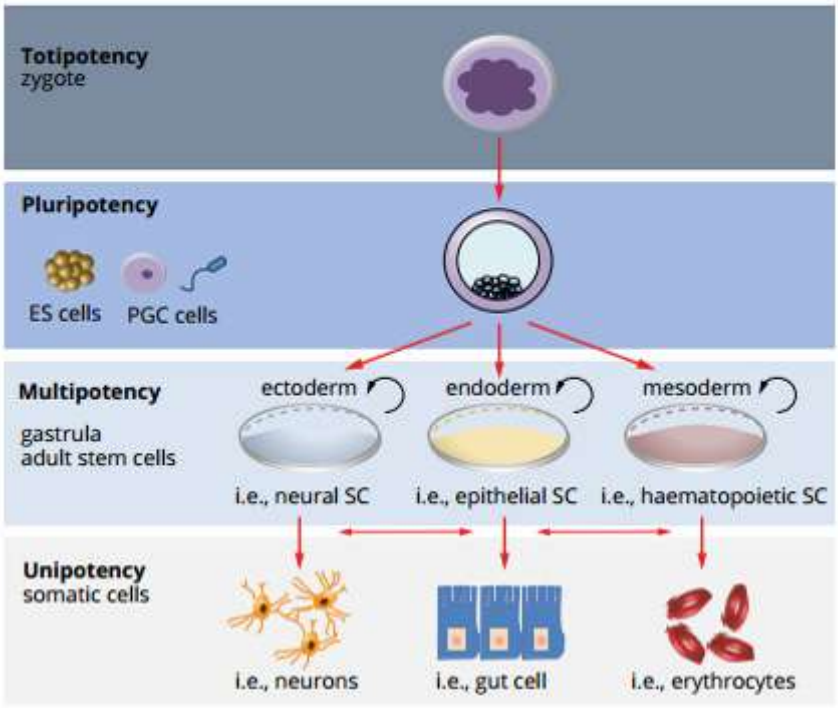


FIGURE 8.4.9 Cell potency is determined by how many cell types the stem cell can differentiate into. Totipotent cells have the greatest cell potency, followed by pluripotent cells, then multipotent cells.

BIOFILE

FIGURE 8.4.10 This marine planarian, or flatworm, has a population of stem cells that enables it to regenerate if severed.

Stem cells in other organisms

Stem cells are found in most adult organisms. Some organisms, such as free-living planarians (Figure 8.4.10) and sea stars, retain a population of stem cells throughout their life. These stem cells can develop into any cell type in the body, giving these organisms the remarkable ability to regenerate a body part that is completely lost through injury (Figure 8.4.11). While stem cells are found in many different organisms, we will focus on human stem cells in this section.

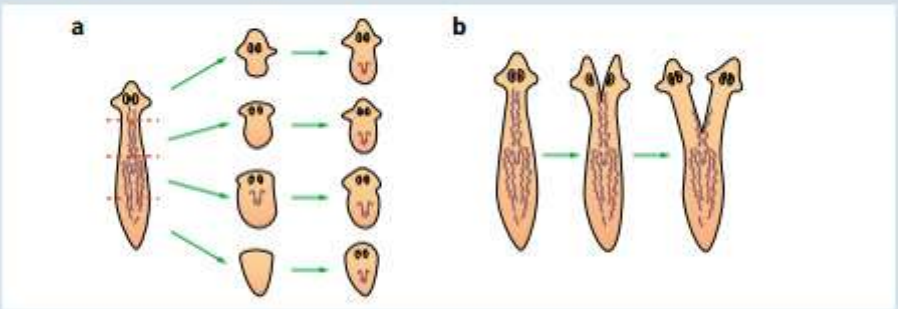


FIGURE 8.4.11 Planarians can regenerate completely after being cut in half. (a) A planarian that has been cut transversely. (b) A planarian that has been cut longitudinally. Anterior regions are able to regenerate a new head faster than more posterior regions.

STEM CELL THERAPIES

There is still much to learn about stem cells and the way that they normally work in maintenance and repair, such as how they find their way to damaged tissues and how they limit replication and avoid forming neoplasms. Stem cell research has the potential to revolutionise medicine. Stem cells are considered by many to be the basis of a potentially powerful new technology in medicine, called **stem cell therapy**.

The ability to control cell division and differentiation would mean the ability to generate healthy laboratory-cultured tissues and organs to replace damaged ones. Stem cell research has also shown that injecting stem cells directly into an individual can assist with repairing damage within the body. For example, stem cells have been injected into individuals with cardiovascular disease, which has led to some regeneration of heart tissue.

For stem cell therapy to work:

- stem cells must be able to replicate themselves in cultures within a laboratory
- stem cells must be able to differentiate into the particular cells required to treat the disease or disorder
- stem cells must not remain as self-renewing stem cells with the potential to grow out of control
- the immune system must not reject the stem cells or tissue created from stem cells. There is evidence that embryonic stem cells may be better tolerated by a person's immune system than foreign adult stem cells. However, the best tolerated cells will be adult stem cells from a person's own tissues.

Stem cells are already being used in a range of treatments, and research into the possible uses of stem cells is continuing. The most likely conditions to be effectively treated by stem cell therapy are those where a small and defined cell population is damaged, such as Parkinson's disease (in which a small group of cells in the brain dies), type 1 diabetes (beta cells in the pancreas are destroyed) and macular degeneration (retinal cells are destroyed). Examples of stem cell therapies under investigation are described below.

Bone marrow and blood stem cells

Bone marrow is the soft, fatty tissue found within bones. Bone marrow contains stem cells (called haematopoietic stem cells) that give rise to all of your blood cells. If the stem cells in a person's bone marrow are damaged or diseased, they may need a bone marrow or stem cell transplant to replace the damaged stem cells. For example:

- Chemotherapy and radiotherapy used in some cancer treatments can damage the stem cells in bone marrow.
- Leukaemia is a cancer that affects the blood cells; patients with leukaemia have diseased stem cells in their bone marrow.
- Some disorders, such as aplastic anaemia, can be caused by defective DNA or exposure to toxins that damage the blood stem cells.

Harvesting bone marrow or blood stem cells involves collecting the stem cells from a healthy patient. For bone marrow transplants, the bone marrow is taken from the pelvic region by inserting a large needle into the bone and withdrawing the marrow with a syringe (Figure 8.4.12). This procedure can be painful for the donor.

An easier and less painful procedure is to collect stem cells that are circulating in the blood. To collect these stem cells, a patient is connected to a machine and his or her blood is filtered to collect the stem cells, while the rest of the blood is returned to the patient (Figure 8.4.13).

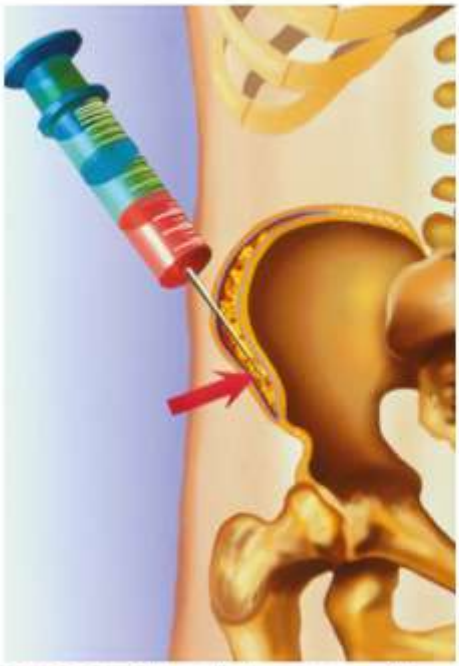


FIGURE 8.4.12 Harvesting bone marrow. The donor's bone marrow, which produces blood cells, is removed from the pelvis using a syringe. The collected marrow is then filtered and treated before it is infused into the recipient.

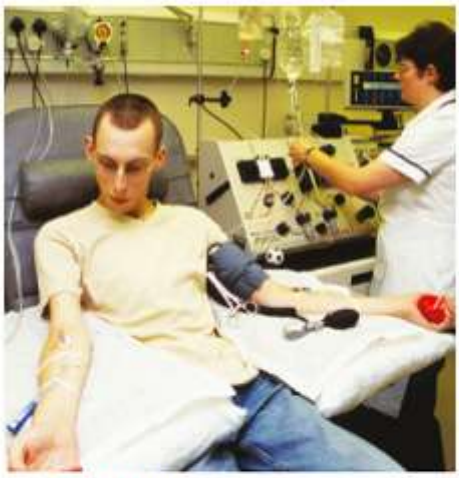


FIGURE 8.4.13 Harvesting stem cells from the blood of a patient. Blood is being taken from one arm, passed through the machine to retrieve the stem cells, and then returned to the other arm.

FIGURE 8.4.14 A donated human placenta being prepared for the harvesting of umbilical cord stem cells.

Cord blood

Blood stem cells can also be taken from **cord blood**, which is blood taken from the umbilical cord after the birth of a baby (Figure 8.4.14). This blood contains 'adult' stem cells for the blood and immune systems in the body. The stem cells in cord blood are younger and healthier than stem cells from adult bones. In addition, if the individual from whom the cord blood was taken required a transplant later in life, using their own blood stem cells would avoid the problem of immune rejection.

Cord blood stem cells have been used to treat type 1 diabetes, providing patients with new insulin-producing cells.

Intestinal stem cells

The lining of the intestines is a vital tissue in humans because it is the layer across which nutrients are absorbed into the body. The epithelial lining of the intestines has a remarkable ability to repair and renew itself because it contains adult stem cells (Figure 8.4.15). Scientists in the United States first harvested viable stem cells from the human intestine in 2013, and research into the possible uses of intestinal stem cells is continuing.

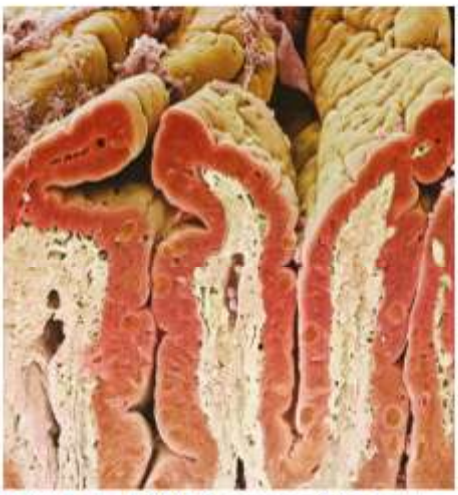


FIGURE 8.4.15 SEM of a section of the small intestine. The surface consists of deep folds, and the surface (epithelial) cells are shown in red. These cells are able to repair and renew very rapidly with the help of the adult stem cells present.

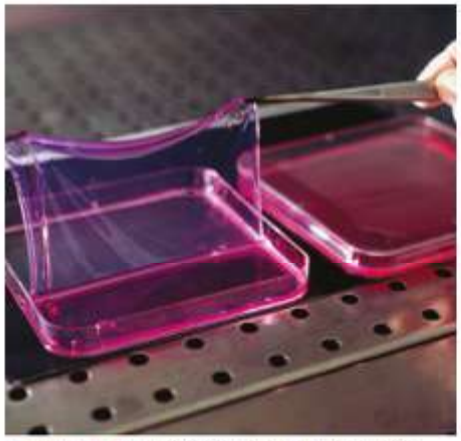


FIGURE 8.4.16 Artificially grown human skin being removed from a culture dish in order to make a skin graft. The cultures are made by transferring epithelial skin cells onto fibrin gel. The gel contains the nutrients needed by the cells to multiply and form skin. It takes only three weeks to grow a whole square metre of cultured skin.

BIOFILE

Rapidly replicating stem cells

Bone marrow is a notable example of a source of stem cells because, given the short lifespan and high requirement for red blood cells, haematopoietic (blood-forming) stem cells in bone marrow churn out about 3 to 5 million red blood cells every second. A teaspoon of bone marrow, cultured carefully, can yield about 300 million stem cells in two weeks. Skin and the lining of the intestines are also noted for their high levels of stem cell replacement.

FIGURE 8.4.17 Coloured SEM of the outer layer of human skin showing the overlapping skin cells. These cells are constantly shedding and being replaced with cells from the fast dividing layers of epidermal stem cells underneath.

Epidermal stem cells

The skin is a very important organ in our bodies because it regulates body temperature and acts as a barrier against pathogens. Like the intestines, it also has a remarkable ability to repair and renew itself after damage, using adult epidermal stem cells.

Skin stem cells are already being used to treat patients. Epidermal skin cells harvested from a person can be used to grow epidermis in a laboratory (Figure 8.4.16). These new layers of epidermis can then be grafted on to patients who have lost significant amounts of skin through, for example, third-degree burns.

Researchers are continuing to investigate the possible uses of epidermal stem cells to treat a range of disorders, including genetic disorders that affect the skin.

Embryonic stem cells

Embryonic stem cells are obtained from embryos in the earliest stages of development, when they are three to five days old. The embryos used in experiments are donated by people attending in vitro fertilisation (IVF) clinics. When a woman undergoes IVF, often more embryos are produced than are needed. Surplus embryos are stored in a freezer and discarded after five years if they are not used. Embryonic stem cells can be harvested from these surplus embryos. The cells in the embryo are cultured under conditions that enable them to divide rapidly (Figure 8.4.18).

Embryonic stem cells can be used to treat tissues and organs that have been damaged by disease or injury. The stem cells can make replacement cells for any type of tissue, including gut, skin, blood or nerve cells. However, scientists still have much to learn about how to stimulate stem cells to develop into a particular type of cell.

FIGURE 8.4.18 Stem cells are carefully cultured in conditions that enable them to divide rapidly.

Induced pluripotent stem cells

One area of interest in cell biology currently is the development of induced pluripotent stem cells (iPSCs). iPSCs are adult cells that have been genetically reprogrammed to an embryonic stem cell–like state. This forces the cell to express genes and factors which are characteristic of embryonic stem cells. Although iPSCs by definition are pluripotent stem cells, it is not known whether there are clinical differences in these two stem cell types.

Preliminary research shows that human iPSCs demonstrate important characteristics of pluripotent stem cells, including the expression of stem cell markers and capability of generating cells characteristic of all three germ layers.

This is a promising discovery and with further research scientists hope to use iPSCs in transplantation medicine.

BIOLOGY IN ACTION

Growing 'beating hearts'

In 2015, researchers from the University of California published the results of a study in which they used human pluripotent stem cells (iPSCs) to grow miniature 'beating hearts'. These were nothing like the four-chambered heart inside your chest, but the cells did form hollow, pulsating chambers rather than simple layers of cells. Previously, stem cells had been grown in wells that were about 2.5 centimetres in diameter, such as those shown in Figure 8.4.19, and under these conditions they only grew into flat sheets of cells.

To create the beating chambers, the researchers created tiny wells in the bottom of a petri dish only 200 to 600 μm wide—the thickness of a few strands of human hair. They then took iPSCs that had been genetically reprogrammed from human skin tissue and grew them in the tiny wells. The stem cells formed 'microchambers' because the mechanical pressure on the cells on the outside caused them to develop into cells that produced collagen, while the cells on the inside developed into heart muscle cells.

Once they had created the beating microchambers, the researchers added thalidomide, which is a drug known to cause heart defects and deformities in foetuses. They found that the drug made it difficult for the microchambers to contract, which resulted in them beating slower than ones that had not been exposed to thalidomide.

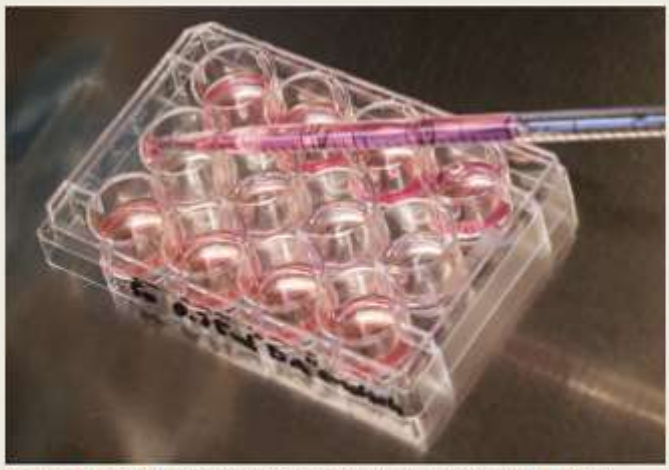


FIGURE 8.4.19 A standard 12-well culture dish containing human stem cells.

Stem cells will not be used to create replacement hearts for people in need of heart transplants any time soon, but thanks to this new research, using them to create beating heart microchambers that can then be used to test drugs for any side effects on heart chamber formation is now a reality.

ETHICAL CONSIDERATIONS OF STEM CELL THERAPY

The main ethical considerations of stem cell therapy involve the use of embryonic stem cells. This is because the first harvesting techniques for embryonic stem cells involved the destruction of embryos at the blastocyst stage. However, new harvesting techniques that do not damage the embryo are being developed (Figure 8.4.20).

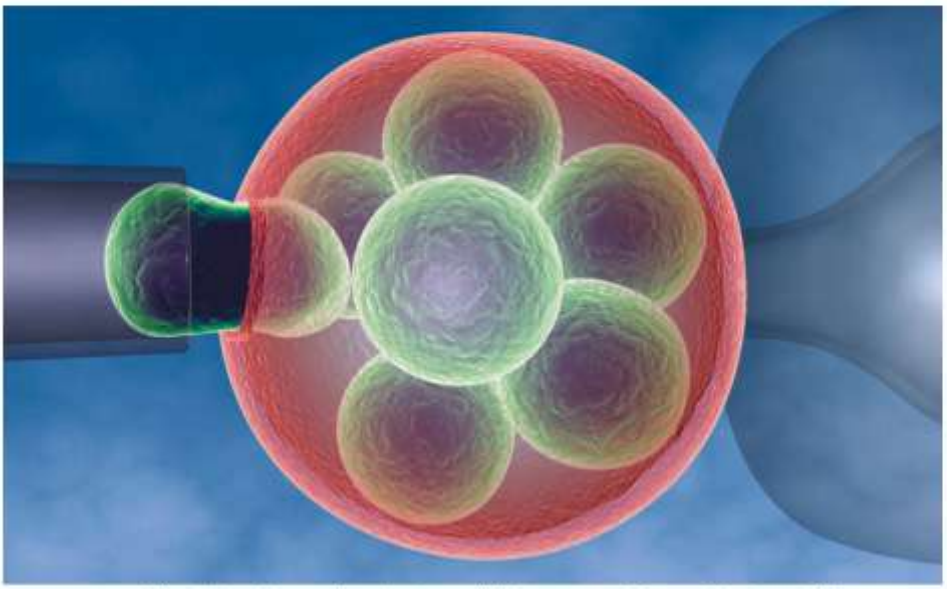


FIGURE 8.4.20 Illustration of an embryonic stem cell being removed from a blastocyst. This technique removes only one cell, so the blastocyst remains intact.

Adult stem cells are usually harvested from adults or from cord blood during a birth. In both cases, those who are donating the stem cells are able to give their consent and there are minimal adverse side effects.

Despite the ongoing ethical and moral debates about the use of embryonic stem cells, research into embryonic stem cell use is exciting as these stem cells can theoretically be made to differentiate into any human tissue type and thus treat many more diseases and disorders than adult stem cells can.

Table 8.4.1 outlines the advantages and disadvantages of use of embryonic and adult stem cells in stem cell therapy.

	Embryonic stem cells	Adult stem cells	Induced pluripotent stem cells
Advantages	• unlimited supply, e.g. left over from IVF • cell division can occur indefinitely • can grow into large quantities • can differentiate into any type of cell	• already programmed to make a particular cell type and thus can be used for a specific treatment, e.g. brain stem cells make new neurons	• use normal somatic cells (many cells available) • use cells from the person who needs replacement cells • no immune rejection
Disadvantages	• not yet technically possible to train stem cells to become every particular cell type • ethical objections • potential for uncontrolled growth (including teratoma formation)	• no indefinite growth • limit on cell types into which they can differentiate • difficult to obtain • small number of cells in only some tissues • potential for uncontrolled growth	• time and technology required to reprogram the cells • may be limited differentiation capability • not enough knowledge yet about how to differentiate into all cell types • objections to any genetic reprogramming of human cells • potential for uncontrolled growth

TABLE 8.4.1 Advantages and disadvantages of embryonic, adult and induced pluripotent stem cells.

8.4 Review

SUMMARY

- All humans start life as a single cell, a fertilised egg known as a zygote. As the zygote undergoes mitotic divisions, it becomes a morula, a blastocyst, a gastrula, an embryo and then a foetus.
- An embryo is considered a foetus eight weeks after fertilisation.
- From the blastocyst to the gastrula stage, the embryo undergoes gastrulation to form three germ layers:
  - ectoderm (outer layer)—forms cells of the epidermis, hair, peripheral nervous system, brain and spinal cord
  - mesoderm (middle layer)—forms cells of the muscles, cartilage, kidneys and gonads
  - endoderm (inner layer)—forms cells of the lungs, bladder and the lining of the digestive system, including the stomach, colon, liver and pancreas.
- There are two main types of stem cells: embryonic stem cells and adult stem cells.
- Embryonic stem cells can be thought of as 'all-purpose' cells that have the potential to develop into many different kinds of cells; stem cells are relatively undifferentiated cells.
- Stem cells can also be defined according to their potency, referring to the number of different types of cells they can give rise to.
- Stem cell therapy involves the use of stem cells to treat particular disease or disorders.
- There are ethical and moral considerations regarding the use of stem cell therapy. Most of these revolve around the use of embryonic stem cells.

KEY QUESTIONS

1 **a** What is the name given to embryonic cells that self-renew and remain undifferentiated when removed from the embryo?
b What advantages do these cells have for the body?

2 Name the three germ layers, from outermost to innermost.

3 **a** What are adult stem cells?
b What is their role?
c How do they differ from embryonic stem cells?

4 Classify the following cell types with their correct potency.
- zygote/morula cell
- embryonic stem cell
- adult stem cell

5 State the four types of stem cells. How do the different types of stem cells differ?

6 Planarians (flatworms) retain a population of totipotent stem cells throughout their life. How does this observation explain why a planarian, when cut in half, can regenerate the missing part?

7 Which one of the following conditions is necessary for successful stem cell therapy?
A The stem cells must be embryonic.
B The stem cells must be able to replicate themselves within a laboratory.
C The stem cells must be able to produce embryos.
D The stem cells must be able to repair themselves.

8 Skin stem cells replicate rapidly, so how could they be useful in stem cell therapies?

9 Outline the ethical and biological advantages and disadvantages concerning stem cell research.

Chapter review

08

KEY TERMS

apoptosis
binary fission
blastocyst
carcinogen
cell cycle
cell cycle control system
cell plate
centriole
centromere
chromatid
chromatin
cord blood
cytokinesis
embryo
enzyme
foetus
gastrula
gastrulation
germ layer
interphase
meiosis
mitogen
mitosis
morula
multipotent
mutagen
mutation
neoplasm
origin
pluripotent
proto-oncogene
spindle
stem cell therapy
telomere
tissue culture
totipotent
tumour-suppressor gene
unipotent

KEY QUESTIONS

1 Which process is **not** associated with cell division?
- **A** cytokinesis
- **B** DNA replication
- **C** pairing of homologous chromosomes
- **D** formation of two diploid daughter cells

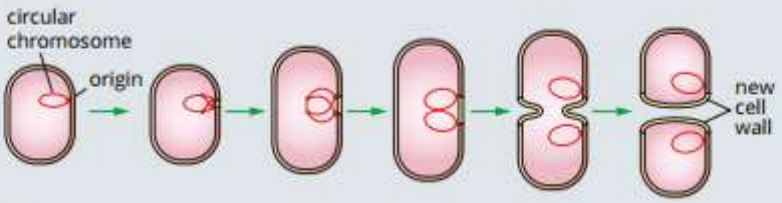
2 Which of the following statements shows a correct sequence of events for mitosis?
- **A** chromatids separate, chromosomes duplicate, cytokinesis occurs
- **B** cytokinesis occurs, chromosomes duplicate, chromosomes line up at the equator
- **C** chromosomes line up at the equator, chromatids separate, cytokinesis occurs
- **D** chromosomes duplicate, cytokinesis occurs, chromatids separate

3 Describe the importance of cell division to an organism.

4 Consider a defect in a multicellular organism resulting in the inability to complete mitosis correctly all the time. Outline some of the possible consequences for the organism.

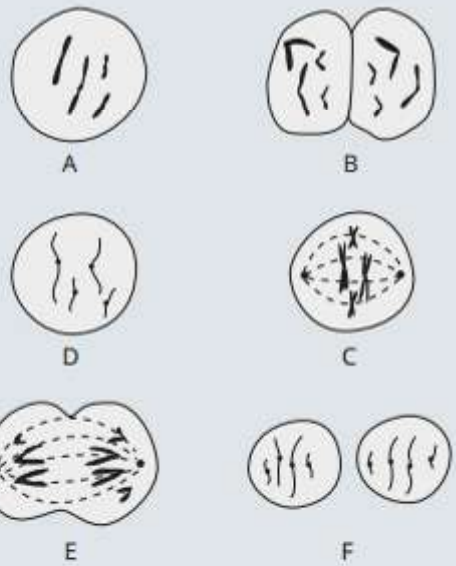
5 Different organisms vary in how much repair their cells can carry out. Describe how three different organisms vary in their ability to carry out replication and, therefore, repair.

6 Consider the following diagram.



- **a** What process does this diagram show?
- **b** Explain the steps involved in this process.
- **c** What is one advantage and one consequence of this process when it is used as a form of reproduction?

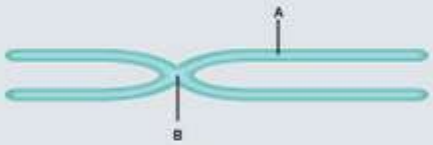
7 The diagram below represents the stages of mitosis, but they are not in the correct order. Determine the correct sequence and add labels for the name of each stage of mitosis.



8 Mitosis in unicellular eukaryotes has a different function to mitosis in multicellular organisms. Explain the purposes of mitosis in:

- **a** unicellular eukaryotes
- **b** multicellular eukaryotes.

9 Examine the following diagram of a chromosome.



- **a** Name structures A and B.
- **b** During what phase of mitosis does the chromosome first appear in this state? Explain what happens to cause this appearance.
- **c** Chromosomes do not always look like the one shown in the diagram. Describe the changes in the appearance of chromosomes during the different phases of the cell cycle.
- **d** Draw a typical representation of an animal cell in interphase.

10 Use a table to summarise the different phases of the cell cycle and what occurs during each phase.

11 Contrast cytokinesis in plant and animal cells.

12
- **a** Explain what is meant by apoptosis.
- **b** Why is programmed cell death important in embryo development?

13 Describe where mitosis would be occurring in a pregnant woman.

14 The cell cycle is regulated by the cell cycle control system, which ensures that no abnormalities occur.

- **a** Name the checkpoint at which the process would cease if the following occurred:
  - **i** Some of the spindle fibres have not attached to the sister chromatids.
  - **ii** The cell is too small to divide.
  - **iii** The DNA has not been correctly copied.
- **b** Name the phases of the cell cycle associated with the three checkpoints.

15 Explain the origin and behaviour of HeLa cells.

16 List three differences between malignant and benign neoplasms.

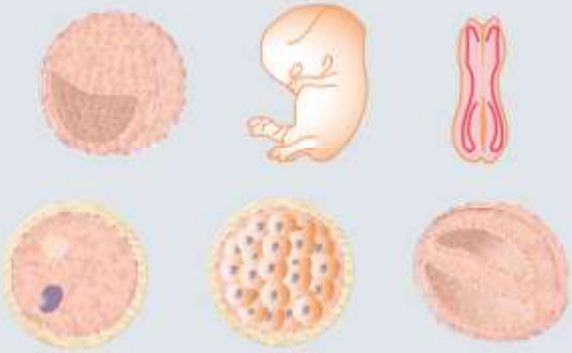
17 Some cancers are at least partially hereditary; the genetic predisposition can be passed down in a family line.

- **a** Give one example of a hereditary predisposition to cancer.
- **b** If one family member has a particular type of hereditary cancer, do all other relatives develop the cancer? Why/why not?
- **c** What other factors can influence the development of a neoplasm?

18 Suggest how the cell cycle may differ in stem cells and fully differentiated cells.

19 Name the developmental stages of an embryo shown below and number them to indicate the order in which they occur.

20 Name one type of stem cell therapy already in use and what it is used to treat.



21 It has been suggested that human embryos should be used as a source of stem cells to grow replacement tissues for their donors in case they develop diseases such as Parkinson's disease and Alzheimer's disease. Discuss some of the practical and ethical issues surrounding the development and use of embryos for this purpose.

CHAPTER

09 Asexual and sexual reproduction

Organisms need to reproduce in order for their species to survive. In this chapter you will learn how organisms can reproduce asexually and sexually, and the advantages and disadvantages of each method of reproduction.

You will also explore the production of gametes in sexual reproduction through the key events in meiosis, and the differences between asexual and sexual reproduction in terms of the genetic make-up of daughter cells.

Issues associated with cloning will also be investigated.

Key knowledge

Asexual reproduction

- the types of asexual reproduction including fission, budding, vegetative propagation and spore formation
- the biological advantages and disadvantages of asexual reproduction
- emerging issues associated with cloning, including applications in agriculture and horticulture

Sexual reproduction

- how an offspring from two parents has a unique genetic identity
- the key events in meiosis that result in the production of gametes from somatic cells including the significance of crossing over of chromatids between homologous chromosomes in Prophase I and the non-dividing of the centromere in Metaphase I
- the biological advantage of sexual reproduction, specifically the genetic diversity in offspring

9.1 Asexual reproduction

FIGURE 9.1.1 Pin moulds (*Mucor* species), like all fungi, reproduce asexually. This pin mould is growing on a tomato.

Individual organisms do not live forever. The continuity of life from generation to generation is the result of reproduction. Reproduction is one of the distinctive characteristics of living organisms. The simplest way that organisms can reproduce is asexually.

Asexual reproduction is the production of offspring from just one parent. Asexual reproduction occurs in bacteria and fungi (Figure 9.1.1) as well as in many plants and some animals.

In this section you will learn about the different forms of asexual reproduction, and the biological advantages and disadvantages of this type of reproduction. You will also explore cloning, its applications in agriculture and horticulture, and the issues associated with this technology.

GENETICALLY IDENTICAL OFFSPRING

Asexual reproduction produces new individuals or offspring by **mitosis**, in which each daughter cell receives a copy of every chromosome of the parent cell. The offspring are therefore **clones**—individuals that are genetically identical. Although offspring from asexual reproduction are genetically identical, they are not necessarily identical in appearance; environmental conditions also affect their growth and development.

FIGURE 9.1.2 Potato plants reproduce asexually through tubers.

The potato is an example of a plant that reproduces asexually. A shoot grows from the buds or 'eyes' on the tuber (the starch-rich part of the potato that you eat). When planted, a shoot grows into stems above and below the soil. Roots grow from the underground stem, which eventually produces new tubers. Each tuber can then grow into a new potato (Figure 9.1.2).

Asexual reproduction is an efficient way to reproduce when environmental conditions are ideal. Asexually reproducing organisms are therefore commonly found in relatively stable and uniform environments to which they are well suited. However, when environmental conditions are variable, asexually reproducing populations are at a disadvantage. Because these organisms are genetically the same, they will all respond to change in the same way. Lack of genetic diversity in a population means that there will be no unusual individuals that may be able to tolerate changed environmental conditions. As a group, they will either survive or die.

For example, the New Zealand mudsnail (*Potamopyrgus antipodarum*), shown in Figure 9.1.3, is able to reproduce either asexually or sexually. Experiments have shown that when a bacterial or viral disease is introduced into an asexually reproducing population of these snails, the entire population may be killed. But when the same disease is introduced into a sexually reproducing population of the snails, the number of snails initially drops but the population soon recovers. This is because some resistant individuals will survive to produce resistant offspring, which will then produce new resistant offspring, and so on.

FIGURE 9.1.3 A New Zealand mudsnail (*Potamopyrgus antipodarum*). This species is able to reproduce asexually or sexually, taking advantage of both modes of reproduction.

Clones are offspring that are genetically identical. Clones produced by asexual reproduction are also genetically identical to their parent.

WAYS OF REPRODUCING ASEXUALLY

Asexual reproduction is the most common method of reproduction for unicellular organisms. This is because there is no cell specialisation or differentiation in unicellular organisms, so there are no sex cells or reproductive organs. Many multicellular organisms also have the capacity to reproduce asexually. In multicellular organisms, the new individual arises from ordinary body cells, known as **somatic cells**. Asexual reproduction can be by:

- fission
- budding
- fragmentation
- spore formation
- vegetative reproduction
- parthenogenesis.

Asexual reproduction has short-term benefits, enabling rapid population expansion, but the lack of genetic variation in asexual populations limits their adaptability and evolutionary potential in the long term.

Fission

Fission is the most common form of asexual reproduction among unicellular organisms, such as bacteria and protozoans. Fission occurs when a single parent cell divides into two approximately equal parts, each of which develops into a new organism. As cell replication is a form of asexual reproduction for unicellular organisms, fission in unicellular organisms occurs either by binary fission (in prokaryotes) or mitosis (in eukaryotes).

Longitudinal fission occurs when the cell splits along its longest axis (Figure 9.1.4a). **Transverse fission** occurs when the cell splits across its shortest axis (Figure 9.1.4b). **Strobilation** is similar to transverse fission, but it occurs in multicellular organisms. A segment on the parent organism forms, and when it matures it detaches to become a new individual (Figure 9.1.4c).

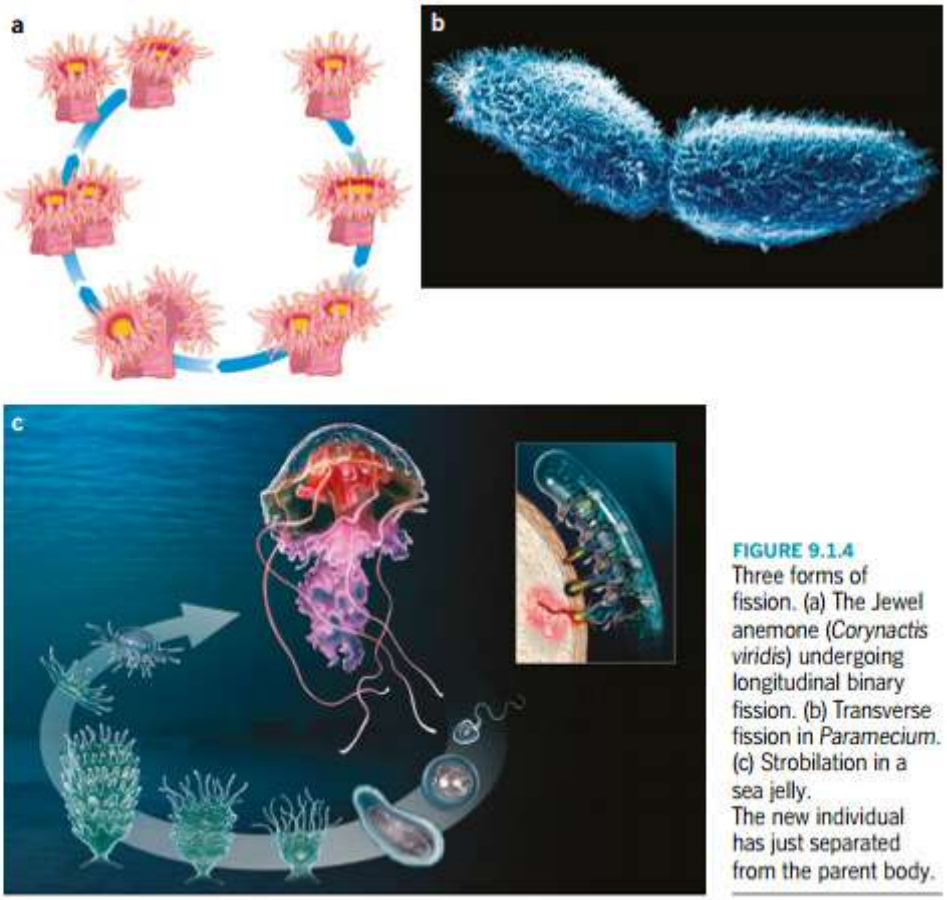


FIGURE 9.1.4 Three forms of fission. (a) The Jewel anemone (*Corynactis viridis*) undergoing longitudinal binary fission. (b) Transverse fission in *Paramecium*. (c) Strobilation in a sea jelly. The new individual has just separated from the parent body.

BIOFILE

The New Zealand mudsnail

The New Zealand mudsnail (*Potamopyrgus antipodarum*) was once only found in New Zealand. However, it probably 'hitchhikes' on ships and has now become established in many parts of the world, including Australia, North America and Europe.

The adaptability of mudsnails makes them a highly invasive species. Mudsnails can tolerate temperatures from 0 °C to 34 °C, depths of 4 to 45 metres and a wide range in salinity. The ability of mudsnails to reproduce asexually also gives them an advantage when colonising a new habitat. A single snail can start an infestation, and in some places their density may be over 5000 individuals per square metre.

FIGURE 9.1.5 Although *Potamopyrgus antipodarum* is only a few millimetres long, it can cause major environmental problems in river systems.

Budding

FIGURE 9.1.6 A hydra undergoing budding. The new individual is the bud on the left. When it detaches, it will be considered an individual organism.

Budding of unicellular organisms such as yeasts is similar to fission, except that the division of the cytoplasm is unequal. The new individual arises as an outgrowth, or bud, from the parent. Budding also occurs in small multicellular animals such as hydra (Figure 9.1.6).

Fragmentation

Fragmentation is similar to fission, but it happens in multicellular organisms. The body of the organism breaks into two or more parts, each of which regenerates the missing pieces to form a new, complete individual (Figure 9.1.7). Fragmentation is common in some flatworms, marine worms and echinoderms.

From a horticultural point of view, propagation from fragments of plants (by grafting, cuttings or tissue culture) is advantageous for maintaining varieties that are genetically identical. It guarantees that the features of an 'ideal' plant are preserved from generation to generation.

Spore formation

Spore formation is a form of asexual reproduction that occurs in some organisms such as fungi. Spore formation can be either asexual or sexual. **Spores** that are produced asexually are often called **mitospores** and are produced by mitosis. The spores are cells that are encased in a protective coating that enables them to survive in unfavourable environments.

Some fungi produce a cluster of spores inside a structure called a **sporangium** (plural sporangia), as you can see in Figure 9.1.8. The spores are released when the sporangium wall disintegrates and are dispersed by wind or water. When a spore lands in a suitable environment it germinates, forming a new fungus. Spore formation and dispersal can rapidly increase the population of a species.

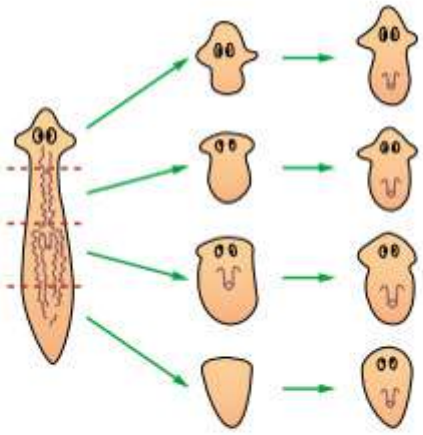


FIGURE 9.1.7 Fragmentation occurs when a part of the parent organism breaks off and grows into a new individual. Planarians (free-living flatworms) have a remarkable ability to regenerate in this way.

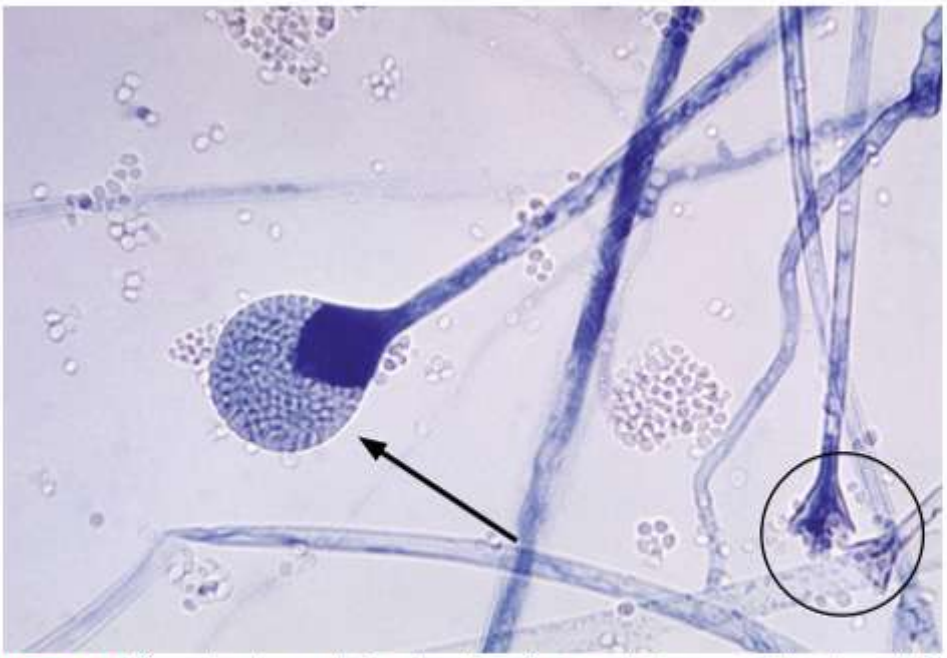


FIGURE 9.1.8 Sporangium (arrowed) of a mature *Mucor* fungus containing spores. When the wall of the sporangium disintegrates, the spores will be released. Broken sporangia can be seen in the lower right corner of the image (circled), along with released spores in the background.

The clouds of green powder that come off the surface of a mouldy lemon are a particular type of asexually reproduced spore of blue mould (*Penicillium expansum*). These spores, produced by budding, are called **conidia** (Figure 9.1.9). In *Penicillium expansum* these spores are formed in long chains.

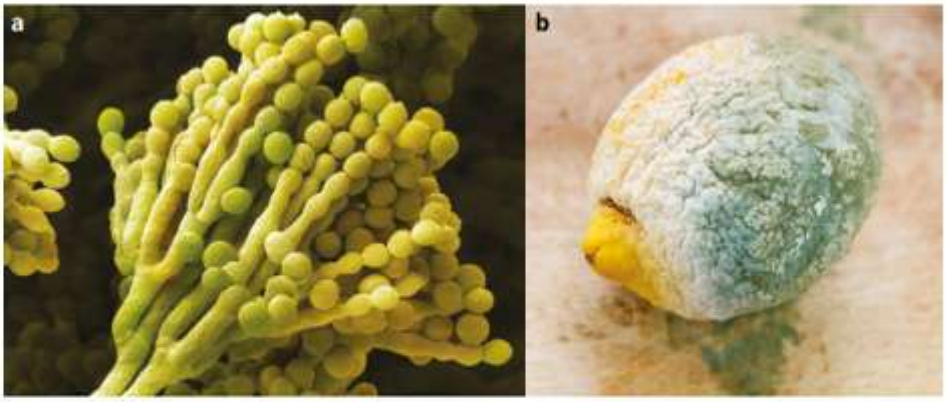


FIGURE 9.1.9 (a) Microphotograph of conidiophores of blue mould (*Penicillium expansum*), which produce spores called conidia by budding. (b) Blue mould on a rotting lemon. The spores are visible on the surface of the fruit; they are white at first but later turn blue.

Vegetative reproduction

Many plants, including flowering plants, can reproduce asexually by **vegetative propagation**. This does not involve the formation of seeds or spores, or fragmentation of stems or leaves. Instead it is the growth of specialised plant tissues that can grow into a new plant if it becomes separated from the parent plant. Naturally occurring vegetative reproduction may arise from many parts of the plant, such as the leaves and underground stems. Some types of vegetative reproduction in plants are described below.

Rhizomes are underground stems that branch and give rise to new shoots and roots. Well-known examples of plants with rhizomes are couch grass, irises and ginger (Figure 9.1.10a).

Stolons are like rhizomes, but they grow above ground. Examples include spider plants and strawberry plants (Figure 9.1.10b).

Tubers are swollen underground stems with buds ('eyes') that easily grow into new plants (Figure 9.1.10c).

Bulbs and **corms** produce lateral buds that also develop into new plants. Examples include daffodil and hyacinth bulbs (Figure 9.1.11a) and gladioli corms (Figure 9.1.11b).

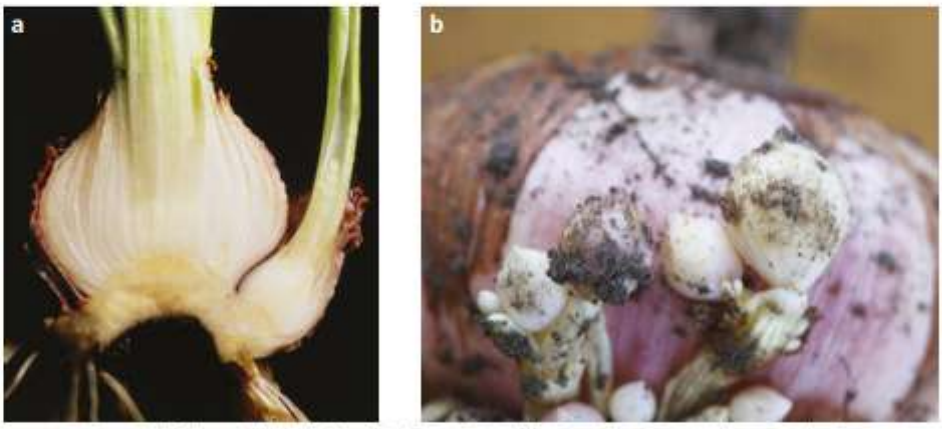


FIGURE 9.1.11 (a) A hyacinth bulb (*Hyacinthus orientalis*) undergoing vegetative reproduction. If the growing bulb on the right is removed from the parent bulb, it can grow into a new individual. (b) This sword lily (*Gladiolus* spawn) has produced multiple cormlets, which can be separated from the corm to form many new individual plants.

FIGURE 9.1.10 Some types of vegetative reproduction. (a) Rhizome formation in ginger (*Zingiber officinale*). (b) Stolon (runner) formation in the garden strawberry (*Fragaria* species). (c) Tuber formation in cassava (*Manihot esculentum*), an important vegetable in Africa and Asia.

Although plants are able to reproduce sexually by flowering and producing seeds, or forming spores, many can also reproduce asexually by vegetative reproduction. An advantage of vegetative reproduction is a rapid increase in the number of plants growing in a favourable area so that they **outcompete**, or displace, neighbouring species. In contrast, seeds produced by sexual reproduction may land in unfavourable conditions and fail to germinate. Potential disadvantages of vegetative reproduction are competition from sister and parent plants for resources, and lack of genetic variation to protect the population against disease or changing environmental conditions.

Parthenogenesis

The development of an egg in the absence of fertilisation is an unusual form of asexual reproduction known as **parthenogenesis**, a Greek term meaning 'virgin birth'. Because it involves the development of an egg, parthenogenesis can occur only in females. Parthenogenesis is a normal part of the life cycle of some lizards, birds, insects (bees, wasps and ants), rotifers and nematodes.

In some geckoes (Figure 9.1.12), eggs develop by parthenogenesis into females; no males are present in these populations. In these species there is an extra doubling of the chromosomes during egg development, resulting in a full clone of the mother. However, genetic recombination (see Section 9.2) can occur, increasing genetic variation.

FIGURE 9.1.12 Female Bynoe's geckoes (*Heteronotia binoei*) can reproduce by parthenogenesis.

ADVANTAGES AND DISADVANTAGES OF ASEXUAL REPRODUCTION

Given the abundance of organisms that reproduce by asexual means, there must be significant advantages to asexual reproductive strategies. At the same time, because asexual reproduction results in genetically identical offspring, there are some disadvantages. The key advantages and disadvantages of asexual reproduction are set out in the following table.

Advantages	Disadvantages
• Efficient form of reproduction. • The amount of time and energy to produce offspring is minimal. • Population sizes can increase rapidly in optimal environments. • There is no need to find a sexual partner. • Offspring are genetically identical to the parent cell, so they are well suited to a stable environment.	• Rapid population growth can lead to overcrowding and increased competition for resources. • There is a lack of genetic variation. • The lack of genetic diversity in a population can cause death of the entire population if conditions change (e.g. pathogen or temperature).

TABLE 9.1.1 Advantages and disadvantages of asexual reproduction.

CLONING

Cloning is the production of new individuals that contain the same genetic information as the parent organism. A clone is produced by asexual reproduction when a single parent cell divides to produce two new daughter cells. The daughter cells carry identical genetic information to the parent cell—they are clones.

Although **cloning** occurs naturally in some cells and organisms, the term cloning is also used to refer to artificial methods of producing genetically identical organisms. Artificial methods of cloning currently used in horticulture and agriculture include:

- cuttings and grafts
- tissue culture
- embryo splitting
- nuclear transfer.

> **In genetics the term 'cloning' can also refer to the production of identical copies of a gene.**

Cuttings and grafts

Cuttings and grafts are both forms of asexual propagation in plants. Growing plants from cuttings is one of the oldest and simplest forms of artificial cloning. To clone a plant in this way, a section of the plant (stem, root or leaf) is removed from the parent and planted in soil or water (Figure 9.1.13). Under the right conditions the cutting will develop new roots, stems and leaves, because cells in the cutting re-enter the cell cycle, replicate, and differentiate into new structures. As in all forms of asexual reproduction, new plants grown from cuttings are clones of the parent plant.

FIGURE 9.1.13 Plant cuttings are the simplest method of cloning in horticulture and agriculture.

Grafting is a more complex form of cloning. It involves transferring part of the stem of a plant on to the cut stem of another plant with well-developed roots (rootstock). Rootstock is selected for characteristics that the cultivar (the desired variety of plant) lacks. The cultivar from which the graft is taken is usually selected for fruiting, flowering or aesthetic qualities. Rootstock must be carefully chosen so that it does not overtake the desired grafted plant. For example, a citrus rootstock that grows vigorously may mean that the nutrients from the plant are used to grow roots rather than to produce fruit from the grafted plant.

Figure 9.1.14 shows how a cutting from the desired plant cultivar is spliced into the rootstock and firmly attached, joining the vascular tissue of the two plants. If the grafting successfully connects the vascular tissues of the plants, the cutting will begin to grow. The plant that develops is a clone of the plant from which the graft was taken.

FIGURE 9.1.14 Grafting a bing cherry (a cultivar of the wild cherry, *Prunus avium*).

There are many advantages to grafting, including an increase in yield, an increased tolerance to cold, disease resistance, early fruiting and production of new varieties of plants. Grafting enables much more efficient and rapid growth of desired plant varieties because they do not need to be grown from seeds. The qualities of the cultivar have been carefully selected over many generations and grafting ensures these qualities can be cloned for future propagation. Grafting is commonly used in horticulture to grow fruiting and ornamental trees.

Tissue culture

Tissue culture is a cloning technique used to grow large numbers of plants rapidly. It is used commercially to develop large crops with ideal characteristics, such as wheat with large grains. The technique is also being used in research and recovery programs for endangered plant species.

To clone plants using plant tissue culture, fragments or single cells from a parent plant are selected and grown in a culture medium. Plant fragments are treated with a sterilising solution to kill any fungi and bacteria that could contaminate the culture. The culture medium contains nutrients and hormones to encourage plant growth and differentiation. Figure 9.1.15 shows how the plant sample grows quickly, sprouting new shoots. The new shoots can be removed and placed on another culture medium to repeat the process. This process of cloning plants from stock plant material, using tissue culture methods, is called micropropagation.

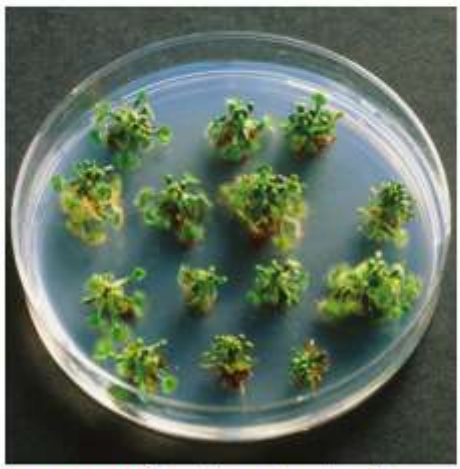


FIGURE 9.1.15 Round-leaved sundews (*Drosera rotundifolia*) growing from tissue cultures in a Petri dish. This carnivorous plant, endemic to North America, is endangered. Tissue culture allows large numbers of these plants to be produced rapidly for research and revegetation.

Plant tissue culturing can produce thousands of genetically identical plants very quickly, but it is very labour intensive and expensive. The following table outlines the main advantages and disadvantages.

Advantages	Disadvantages
• A large number of plants can be produced in a short time. • The technique provides the opportunity to control growth conditions and to synchronise the processes of growth and development, making it possible to obtain plants with preferred characteristics. • New genes can be introduced into the plants, which boost crop yield or confer resistance to pests and infections.	• All the plants that are produced have the same genetic material, so they are equally vulnerable to environmental factors, infections and pests. • A lack of new combinations of traits, which only result from meiotic division and genetic recombination (see Section 9.2). • The genetic diversity of the plants is reduced and some gene variants (alleles) can be irreversibly eliminated from the gene pool.

TABLE 9.1.2 Advantages and disadvantages of plant tissue cultures.

Embryo splitting

During the early stages of embryonic development, each cell is capable of developing into a complete organism. This is possible up until the 16-cell stage of development, because all the cells of the embryo are undifferentiated. At the 32-cell stage, cells begin to undergo cellular specialisation.

If an embryo splits during the early stages of embryonic development, identical twins, triplets or even quadruplets can result. When this happens, all of the offspring are genetically identical.

Embryo splitting can be used in livestock breeding programs to increase the number of offspring born in each breeding season. Rather than allowing livestock to breed naturally, farmers use **in vitro fertilisation** (IVF) techniques. By fertilising eggs in a Petri dish, scientists are able to split embryos in the early stages of embryonic development (up to the 16-cell stage) to create multiple genetically identical embryos, which are then implanted into surrogate mothers (Figure 9.1.16).

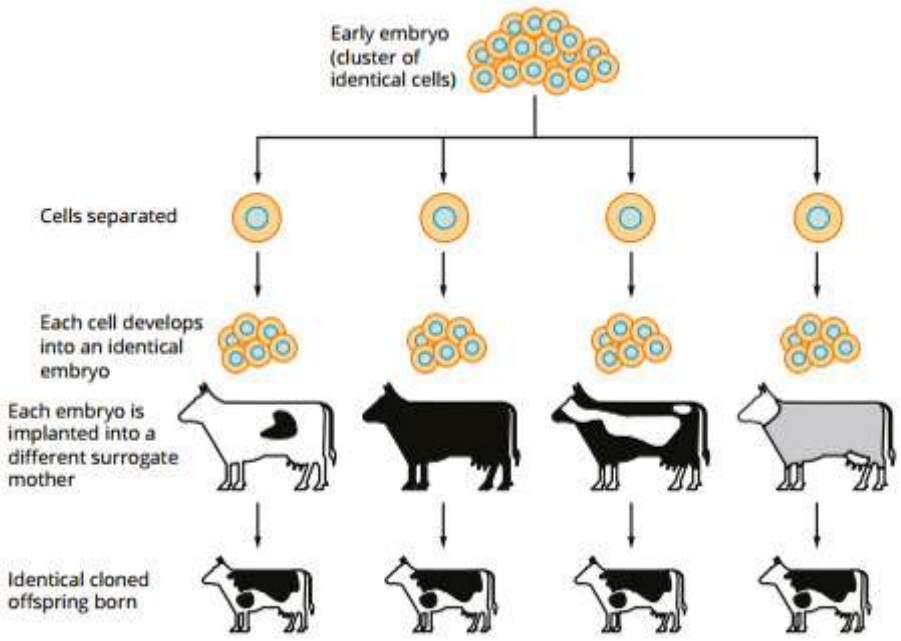


FIGURE 9.1.16 Cloning by embryo splitting is used in livestock breeding to increase the number of offspring produced each season.

Nuclear transfer

The most advanced cloning technique is used in agriculture and is known as nuclear transfer. This technique has been used in many organisms, including sheep, dogs, cats and horses. It involves removing the nucleus from an unfertilised egg and replacing it with a nucleus from an adult **somatic cell** (Figure 9.1.17). The egg is then transplanted back into a host mother, or surrogate, where it will develop into a new individual. The new individual is genetically identical to the donor of the somatic cell.

This technique is also known as somatic cell nuclear transfer, or SCNT. Dolly the sheep is perhaps the most famous example of this cloning technique.

FIGURE 9.1.17 LM of an egg from a cow (centre) held in place by a pipette (right) during nuclear transfer. The egg's genetic material has been removed and now an adult cell nucleus is being injected in its place with a needle (left).

Emerging issues with cloning

Cloning can have social, ethical and legal implications. Although humans have been cloning plants for hundreds of years, modern cloning technology is much more complex and extends to the animal kingdom including humans, and therefore has wider implications.

BIOLOGY IN ACTION

Dolly the sheep

In 1996 the 'most famous sheep in the world', Dolly, was born. Dolly was the first mammal to be cloned from the cells of an adult individual using somatic cell nuclear transfer, or SCNT (Figure 9.1.18). In SCNT the nucleus of an egg cell from one animal is removed, and the nucleus of a somatic cell from another animal is extracted. The nucleus is then inserted into the ovum, which then reprograms the nucleus. An electric shock applied to the ovum then causes the ovum to enter the G0 stage of meiosis and begin dividing. When the ovum reaches the embryonic stage it is transplanted into a host organism to continue development.

In Dolly's case a number of embryos were produced from a Finn Dorset ewe and a Scottish blackface ewe. The embryos were transplanted into 13 surrogate Scottish Blackface ewes. Eventually one ewe gave birth to a healthy Finn Dorset lamb—Dolly. The cloning of Dolly showed that an adult somatic cell (in Dolly's case, a mammary cell) could be used to produce a whole organism.

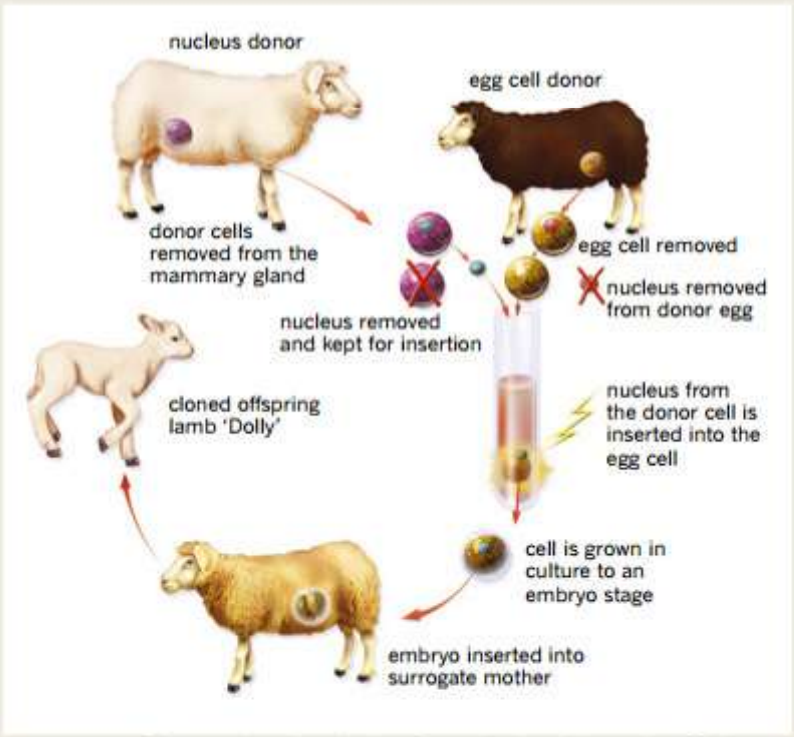


FIGURE 9.1.18 The somatic cell nuclear transfer method used to produce Dolly.

Although the normal life expectancy for sheep is approximately 12 years, Dolly was euthanised at the age of six and a half because she was suffering from an incurable lung disease and arthritis. It has been speculated that Dolly may have been born with a genetic age of six, the same age as the donor sheep, after research found that she had decreased telomere lengths. Telomeres are the ends of chromosomes linked to the ageing process.

During her lifetime Dolly gave birth to six healthy lambs. The cloning of other large mammals such as pigs and horses has since benefited from research about Dolly.

FIGURE 9.1.19 If all the world's wheat crops were genetically identical, they would be very susceptible to disease or changes in the environment.

FIGURE 9.1.20 Animal health and welfare is a concern in cloning programs.

FIGURE 9.1.21 A team led by Professor Ian Wilmut cloned Dolly the sheep, the first mammal successfully cloned using somatic cell nuclear transfer (SCNT). Dolly's lifespan was only around half that of a regular healthy sheep.

Susceptibility to disease

The main concern about widespread cloning, especially for crops and animals raised for meat, is the risk that populations with less genetic diversity are more susceptible to disease and changes in environmental conditions (Figure 9.1.19). This in turn would leave human populations vulnerable to a wide-scale loss of food resources. There may also be legal issues of cross-contamination between cloned and non-cloned populations.

High failure rate

The current cloning technology associated with SCNT is highly inefficient; the rate of production of offspring is about 0.1 to 3%. Failure may occur at the nuclear transfer stage, the embryonic cell division stage, the implantation stage, or at many stages throughout foetal development.

Adverse health effects

A growing area of concern in industrial farm production is the welfare of animals. Many cloned animals have experienced adverse health effects, such as impaired immune systems and organ malformations. Significant defects associated with cloning can lead to a wide range of medical problems throughout the animal's life. Any cloning techniques should ensure the health and welfare of the animals are not negatively affected (Figure 9.1.20).

Premature ageing

Associated with the welfare of cloned animals is the premature ageing that has been observed in cloned animals. As a cell ages, the telomeres on the chromosomes shorten. Using the genetic material from an adult organism for cloning purposes means that the newborn cloned organism is already genetically old at birth. Dolly the sheep (Figure 9.1.21) had a significantly shorter lifespan and also suffered age-related illnesses, such as arthritis. Her shorter lifespan is thought to be associated with the decreased telomere length of the donor sheep's chromosomes.

Cloned food products

Another concern regarding cloning is the use of these products as food and their labelling to indicate to consumers that the food has been produced via cloning. In 2006 the US Food and Drug Administration (FDA) approved the use of meat products from cloned animals for human consumption. Although the FDA states that cloned animal products are identical to those from animals bred conventionally and are safe for human consumption, there is some consumer concern around cloned products entering the food supply without sufficient tracking and labelling. Cloned animal products have not yet entered the food supply in Australia.

9.1 Review

SUMMARY

- Asexual reproduction involves a single parent producing a new individual from part of itself. It involves mitosis and produces offspring that are genetically identical to their parent.
- Asexual reproduction is suited to organisms living in relatively stable and uniform environments. It is a disadvantage in changing environmental conditions.
- Ways of asexual reproduction include fission, budding, fragmentation, spore formation, vegetative reproduction and parthenogenesis.
- Parthenogenesis is an unusual form of cloning in which an egg develops without fertilisation to form a new individual.
- Humans have been cloning organisms for hundreds of years, particularly in horticulture. Modern science has seen the development of much more advanced cloning techniques.
- Cloning techniques include cuttings and grafting, plant tissue culture, embryo splitting and nuclear transfer.
- There are many social, ethical and legal issues that must be considered in relation to cloning.

KEY QUESTIONS

1 Define 'asexual reproduction'.

2 What sort of nuclear division is involved in asexual reproduction?

3 What are the ideal environmental conditions for asexual reproduction?

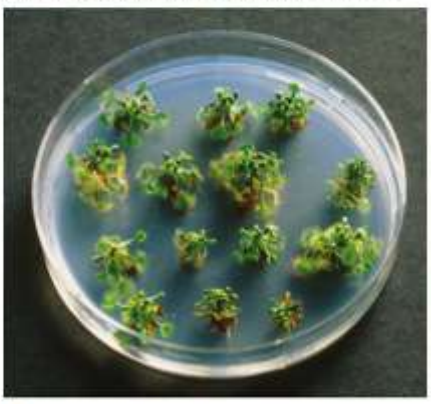
4 Match each type of asexual reproduction to its correct description.

budding	Separation of structures from a parent plant to form a new, independent plant, without the formation of seeds or spores.
fission	Form of asexual reproduction in which the new organism arises as an outgrowth or bud from the parent.
fragmentation	Development of an egg in the absence of fertilisation by sperm; a normal part of the life cycle of some insects and crustaceans.
spore formation	Form of asexual reproduction of unicellular organisms where the parent cell divides into two approximately equal parts.
parthenogenesis	Formation of structures that are resistant to adverse environmental conditions and can give rise to complete organisms when conditions become favourable.
vegetative reproduction	Form of asexual reproduction of multicellular organisms in which an organism breaks into two or more parts, each of which regenerates the missing pieces to form a complete new organism.

5 State three advantages and three disadvantages of asexual reproduction.

6 What must connect for a grafting on a plant to be successful?

7 What is tissue culture used for, and what are two advantages of using this technique?



8 Define 'embryo splitting' and explain why it is not possible to do this after the 32-cell stage of embryonic development.

9.2 Sexual reproduction

FIGURE 9.2.1 Blue ringtail damselflies (*Austrolestes annulosus*) form a mating 'wheel' when mating. The male (top) is holding the female's neck, while the female has moved her abdomen towards the male's genitalia to receive his sperm.

Sexual reproduction involves the union of male and female sex cells to form a unique individual (Figure 9.2.1). Most multicellular organisms, including humans, reproduce sexually, although some multicellular organisms can reproduce asexually as well, as discussed in Section 9.1. Some unicellular organisms are also capable of sexual reproduction.

In this section you will learn about how an offspring of two parents has a unique genetic identity and the biological advantages of sexual reproduction. You will also explore the key events in **meiosis** that result in the production of **gametes** from somatic cells.

In meiosis two successive cell divisions produce four daughter cells, each with half the number of chromosomes of the parent cell.

Identical (monozygotic) twins develop from one fertilised egg, so they have identical genes. But because of non-genetic factors that affect the way the embryos develop, identical twins are actually not exactly identical.

INTRODUCING VARIATION: SEXUAL REPRODUCTION

Multicellular organisms are composed of two main types of cells—somatic cells and **germ cells**. Somatic cells are all the cells in the body of an organism apart from the sex cells (gametes). Examples of somatic cells include skin cells, muscle cells and nerve cells. Germ cells are the cells that give rise to gametes, which are the specialised sex cells that combine in sexual reproduction.

Male gametes (sperm) and female gametes (eggs) are often different in appearance. The formation of gametes occurs by meiosis in specialised reproductive organs, called gonads. The sperm or eggs formed as a result of this cell division are **haploid**, which means the number of chromosomes in the gametes is halved. A normal eukaryotic organism is composed of **diploid** cells (represented as $2n$), or one set of chromosomes (n) from each parent.

Female gametes (eggs or ova) are large, immobile cells. They contain the food stores needed for the development of the embryo. The male gametes (spermatozoa or sperm) contain limited food reserves and usually have a tail (or flagellum) for motility, which enables them to move towards an egg.

After **fertilisation** the two haploid cells fuse to form a diploid zygote (Figure 9.2.2). The zygote then divides by mitosis to produce a large number of cells, which differentiate to form the tissues that make up the new organism. The organism continues to develop by mitotic divisions and becomes an adult. The reproductive cycle may then begin again.

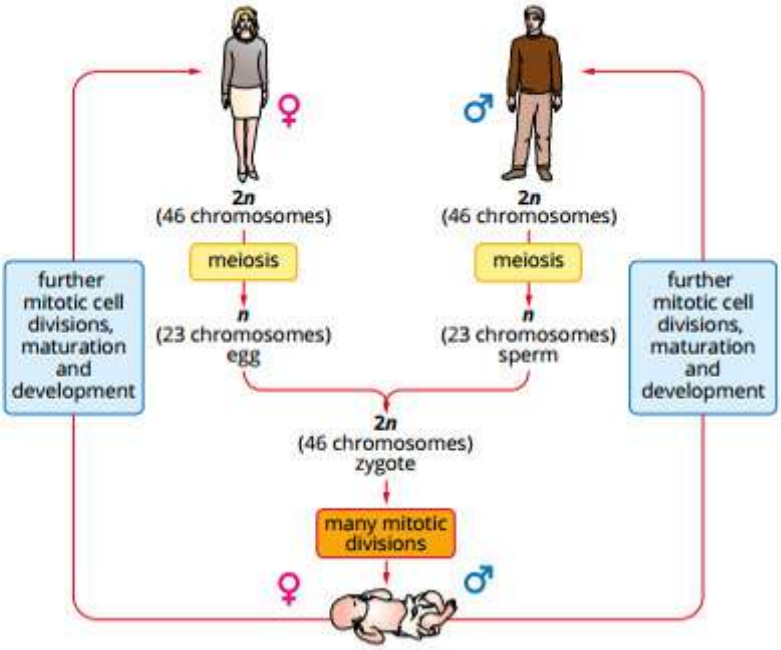


FIGURE 9.2.2 Meiotic cell divisions in females and males give rise to haploid (n) ova and sperm. When fertilisation occurs, an ova and sperm fuse to form diploid ($2n$) zygotes. The zygote develops into a new organism after many mitotic divisions and cellular differentiation.

MEIOSIS

The process of cell division that produces gametes is meiosis (see Chapter 8, page 355). Meiosis occurs only in eukaryotes and only in the gametes. The process of meiosis is essential to sexual reproduction and the creation of new genetic variation. Although similar to mitosis, the outcomes of meiosis are quite different. Table 9.2.1 and Figure 9.2.3 highlight the key differences between mitosis and meiosis.

	Mitosis	Meiosis
Genetic recombination	Mitosis does not involve recombination of alleles.	Meiosis rearranges alleles between chromosome pairs, creating unique genetic variation.
Number of cells	Mitosis produces two genetically identical daughter cells.	Meiosis produces four genetically unique daughter cells.
Number of chromosomes	The daughter cells produced from mitosis have the same number of chromosomes (diploid, $2n$) as the parent.	The daughter cells produced from meiosis have half the number of chromosomes (haploid, n) of the parent.

TABLE 9.2.1 Key differences between mitosis and meiosis.

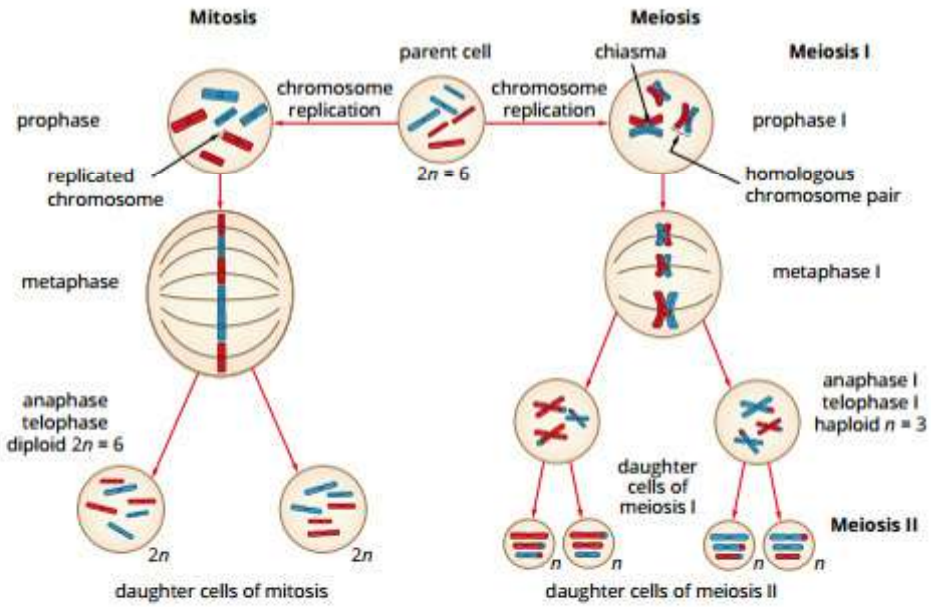


FIGURE 9.2.3 Mitosis and meiosis are both processes of cell division, but they are different in a number of important ways.

Meiosis produces haploid gametes

In order to maintain the chromosomal number of a species, the number of sets of chromosomes in somatic cells and gametes differs. In humans, for example, somatic cells have 46 chromosomes (23 pairs) whereas human gametes have 23 chromosomes. This means that when the haploid gametes combine during fertilisation, the resulting zygote will have a full complement of chromosomes (23 chromosomes from the sperm + 23 chromosomes from the ovum = 46 chromosomes in human somatic cells).

Somatic cells in most animals are diploid ($2n$) because they contain two sets of homologous (matching) chromosomes, one from each parent. (See Section 10.3 for more details.) The following description refers to diploid cells, which have matching pairs of chromosomes called **homologous chromosomes**.

Meiosis is called a **reduction division** because it reduces the number of chromosomes in gametes (daughter cells) to half (n) of that in somatic cells. Cells with n chromosomes are called haploid cells. Gametes receive only one copy of each pair of homologous chromosomes (23 chromosomes in human gametes). Compare this to mitosis, where each daughter cell receives a copy of every chromosome (they are genetically identical).

Humans have 22 pairs of homologous chromosomes and two sex-determining chromosomes, called X and Y chromosomes. In human females the sex-determining chromosomes are a homologous pair of X chromosomes (XX), but in males they are one X and one Y chromosome (XY). The presence of a Y chromosome determines male development. After meiosis in males, four haploid gametes (sperm) are formed from the original diploid parent cell. Each sperm cell contains 23 chromosomes (one of each homologous chromosome and either an X or Y chromosome). However, in females, only one haploid gamete results (the ovum) and the other three haploid cells degenerate (Figure 9.2.4). This occurs because of the uneven distribution of cytoplasm in cytokinesis, so that one daughter cell is very large and contains most of the cytoplasm. Each ovum also contains 23 chromosomes (one of each homologous chromosome and one X chromosome).

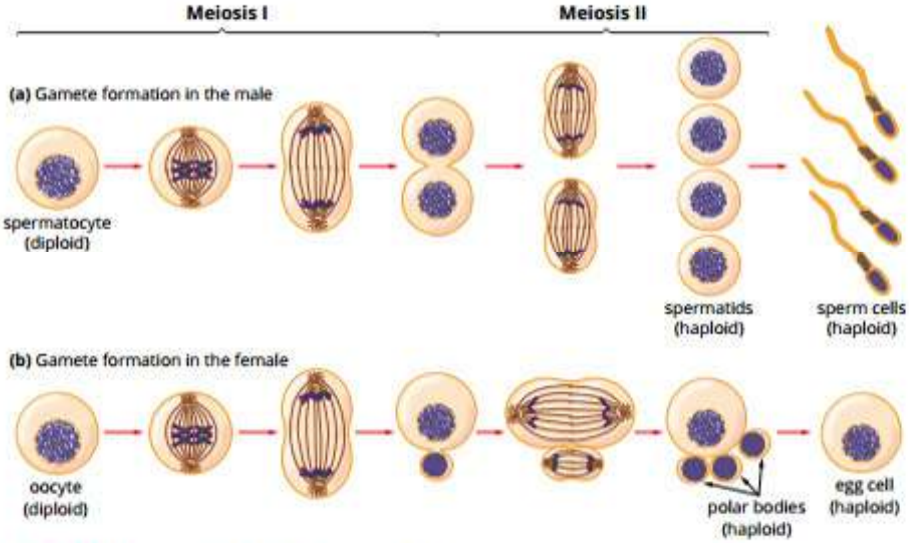


FIGURE 9.2.4 Haploid male (a) and female (b) gametes are produced by meiosis.

Meiotic cell division

Like mitosis, meiosis is a form of cell division that involves prophase, metaphase, anaphase, telophase and cytokinesis (see Figure 9.2.6, page 398). These occur in the following order.

1 prophase I—Chromosomes condense from fine threads. Each chromosome is composed of two chromatids, connected at the centromere. Crossing over of homologous chromosomes occurs in late prophase.
2 metaphase I—Members of a chromosome pair align, chromatids (two per chromosome pair) become apparent and the nuclear membrane breaks down.
3 anaphase I—The spindle draws members of each chromosome pair to opposite poles of the cell, and the cell membrane begins to pinch in.
4 telophase I and cytokinesis—The cytoplasm divides and nuclear membranes form. Two haploid daughter nuclei are created, but each chromosome is still in the replicated state.
5 prophase II—The nuclear envelope breaks down and the meiotic spindle is recreated.

6 metaphase II—Chromosomes at each end of the cell move to a central position. This begins the second division.

7 anaphase II—The centromeres split, separating the sister chromatids, and the single-strand chromosomes move to opposite poles of the cell.

8 telophase II and cytokinesis—The cytoplasm divides and nuclear membranes reform. Four haploid daughter cells are created.

Unlike mitosis, there are two sequential rounds of division in meiosis, called meiosis I and meiosis II.

During meiosis I, homologous chromosomes are separated, reducing the chromosome number by half (reduction division) and producing two haploid daughter cells.

Meiosis II is similar to mitosis in that sister chromatids are separated. This produces four haploid daughter cells.

The first division of meiosis: meiosis I

DNA replication occurs in interphase. During the first division of meiosis (meiosis I), each chromosome pairs up precisely along its length with its matching (homologous) chromosome. This pairing is called synapsis. (This is very different from mitosis, where homologous chromosomes are completely independent of one another.) Because each chromosome has already replicated, each chromosome consists of two copies, called sister chromatids. So a pair of homologous chromosomes has a total of four chromatids.

Crossing over and recombination

A key event now occurs. Chromatids of homologous chromosomes may exchange portions of their genetic information in a process called **crossing over**. Crossing over is a natural genetic process that occurs between homologous chromosomes and leads to the switching of genetic material between the chromosomes. DNA strands from the chromatids of two homologous chromosomes are cut at the equivalent point, a segment is exchanged, and the strands are reconnected (Figure 9.2.5).

The point where crossing over occurs is called a **chiasma** (plural chiasmata). It consists of a temporary molecular scaffold that disappears later. A long chromosome may have several chiasmata.

The significance of crossing over is that it produces chromosomes with new combinations of genetic information. This process is called recombination.

When crossing over is finished, the homologous chromosome pairs align along the midline of the cell; they do this randomly, meaning the maternal and paternal chromosomes do not line up on the same side of the midline. The homologues then separate (segregate) and move to opposite poles. These two steps result in the random assortment of maternal and paternal chromosomes and their alleles in the gametes. The centromeres do not split. It is the chromosomes of a pair that separate, not the chromatids. The spindle breaks down and the nuclear membrane may reform. At the end of this first division of meiosis, there are two daughter cells with the chromosome number halved—they contain only one set (n) of chromosomes. Each chromosome is still made up of two chromatids.

FIGURE 9.2.5 A light micrograph showing the formation of chiasmata between homologous chromosomes. Longer chromosomes have more chiasmata.

The probability of two genes on the same chromosome exchanging alleles is related to the distance between these genes. The greater the distance, the greater the probability that crossing over between the genes will occur.

The second division of meiosis: meiosis II

The second division of meiosis does not involve chromosome duplication:

- Chromosomes align on the spindle equator, the centromeres split and the chromatids separate.
- A chromatid from each chromosome moves to each pole.
- The final nuclei from the two divisions are each haploid (n). The cytoplasm divides by cytokinesis, and four daughter cells are formed from one original parent cell.

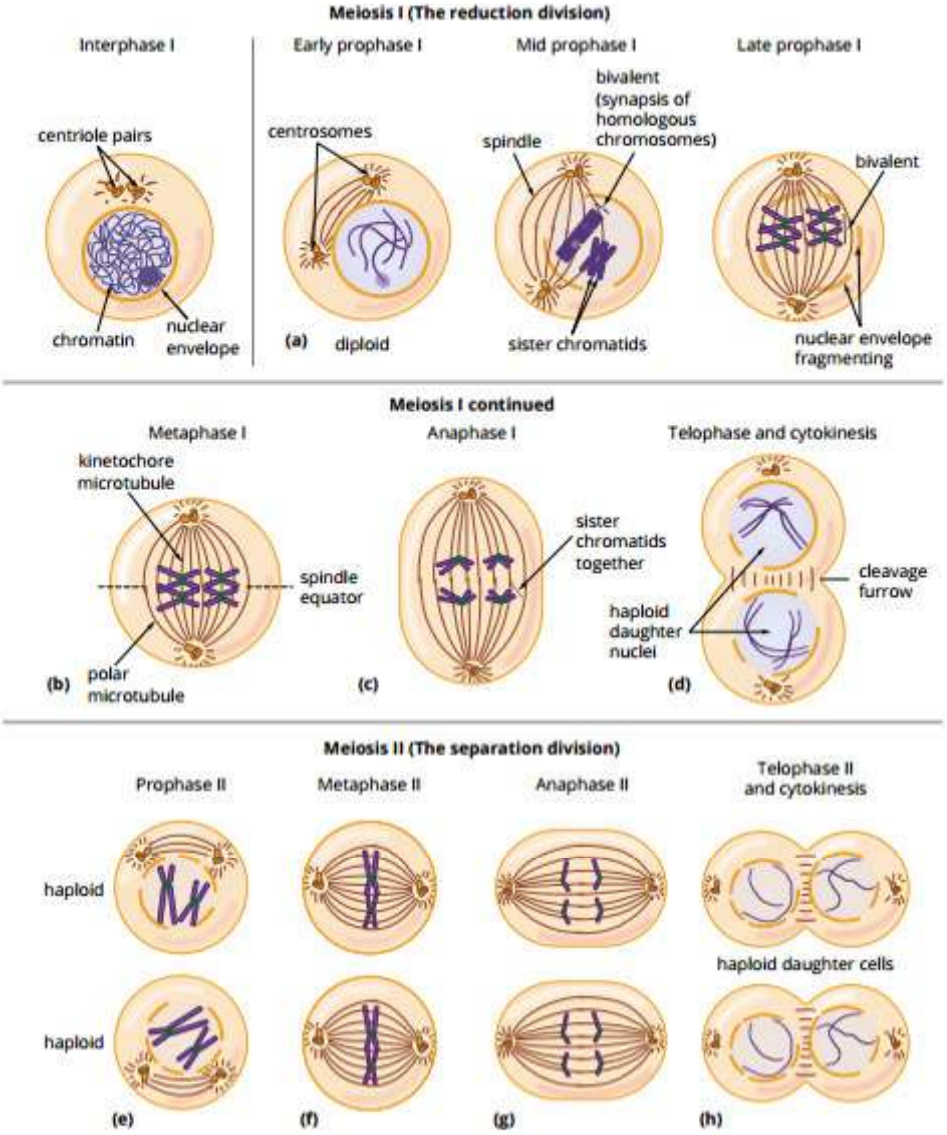


FIGURE 9.2.6 Stages of meiosis in an animal cell with a diploid number of chromosomes (2*n*). Reduction in the chromosome number (from diploid to haploid), crossing over and genetic recombination occur in the first meiotic division. By the end of the second division, four haploid nuclei have been produced from the one original parent cell.

SEXUAL REPRODUCTION AND GENETIC VARIATION

Each gamete has its own unique combination of alleles. There will be similarities in genetic content between parents and offspring, but the offspring are always genetically different from the parents (Figure 9.2.7). This genetic variation arises from two features of meiosis.

Gametes have only half the genetic information of their parent cell because they receive only a single set of chromosomes from the parent cell. Which particular chromosome in a homologous pair ends up in a particular gamete is a random event.

When chromosomes pair up during meiosis, crossing over produces chromosomes with new combinations of genetic information. Each gamete has a unique combination of alleles.

Meiosis ensures that a wide range of genetic combinations occurs during the formation of sperm and eggs. Variability is further increased when different genetic combinations are brought together at fertilisation. Therefore, populations of organisms that reproduce sexually have considerable genetic flexibility, which enables species to survive and reproduce in varied and changing environments.

FIGURE 9.2.7 The physical differences between family members are due to the unique combination of genes that are packaged into gametes during meiosis along with the recombination of this genetic material during fertilisation.

Every person is unique because of the genetic variation created during gamete formation (meiosis) and recombination that occurred at conception.

EXTENSION

Unicellular sexual reproduction

Some unicellular organisms have the ability to reproduce sexually as well as asexually. These include protists classified in the phylum Ciliophora, known as ciliates because of the presence of cilia along the body of the cells.

Many ciliates are voracious predators of bacteria and other protists, chasing them down and engulfing them. Ciliates have two types of nuclei: a micronucleus, which contains a normal diploid set of chromosomes, and one or more macronuclei, which contain many sets of chromosomes (polyploid).

Ciliates known as paramecia (genus *Paramecium*) usually reproduce asexually by mitosis of the micronucleus. The macronuclei simply pinch into two roughly equal pieces, and then fission occurs across the middle of the cell.

However, under stressful environmental conditions paramecia can also reproduce sexually, by a method known as conjugation. Two paramecia fuse to each other for a few hours (Figure 9.2.8). Their micronuclei undergo meiosis and the individuals exchange haploid versions of their micronuclei, by cell-to-cell contact. The micronuclei fuse to form a new diploid nucleus in each cell. In each new cell, the macronucleus then degenerates and is replaced by the recombinant DNA that resulted from the fusion of the two micronuclei (Figure 9.2.9).

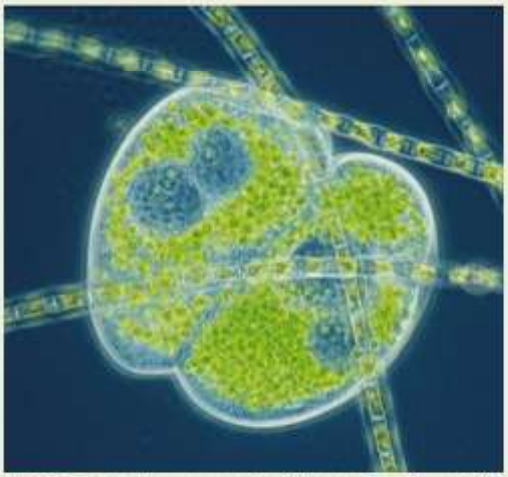
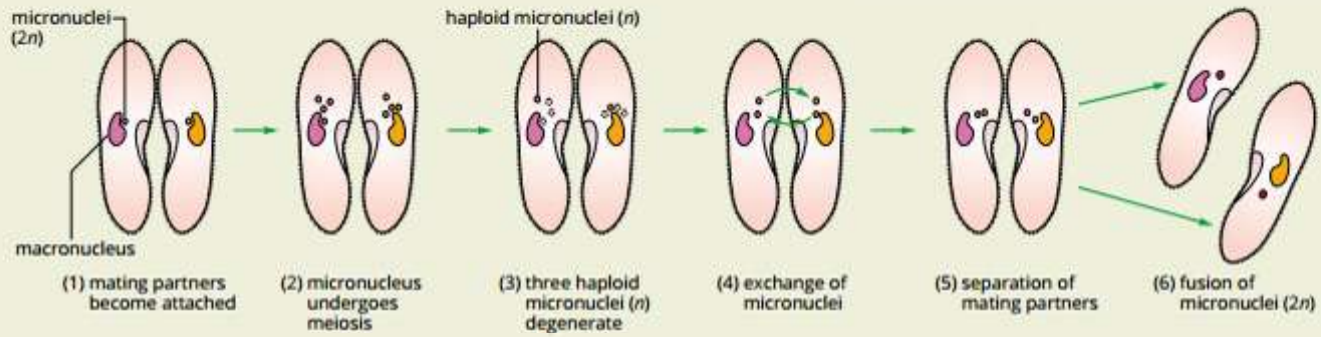


FIGURE 9.2.8 Two paramecia (*Paramecium bursaria*) undergoing conjugation. This is a form of sexual reproduction in which two individuals fuse and exchange genetic material.

FIGURE 9.2.9 The process of sexual reproduction (conjugation) in paramecia.



The **karyotype** of an organism is the number and structure of chromosomes in a cell. A normal human karyotype consists of 22 homologous pairs and two sex chromosomes, making a total of 46 chromosomes.

BIOFILE

Hermaphrodites

Sexual reproduction usually requires two parents for the production of offspring. However, this is not the case for all species. Many plants and some animals, such as tapeworms, snails, earthworms and some fish, have both male and female reproductive organs in the same individual—they are **hermaphrodites**. Some species are able to self-fertilise, while others require a partner. Even when hermaphrodites self-fertilise, the recombination of genes and random assortment of chromosomes that occurs during meiosis means that the offspring are always genetically unique.

FIGURE 9.2.10 Earthworms are hermaphrodites. They have both male and female reproductive systems in their bodies.

When meiosis goes wrong

Meiosis is usually an exact process, but sometimes errors occur. Missing, extra or malformed chromosomes can result from defective gametes, which may have serious consequences for offspring.

Non-disjunction

Sometimes during meiosis a chromosome does not separate. This is known as a non-disjunction. A non-disjunction can occur during meiosis I if members of a pair of homologous chromosomes do not move apart properly, or during meiosis II if sister chromatids fail to separate. As a result, one gamete receives two of the same type of chromosome and another gamete receives no copy. If either of the gametes unites with a normal gamete at fertilisation, the zygote will also have an abnormal number of a particular chromosome. This condition is known as **aneuploidy** and commonly results in abnormal development. An example is non-familial Down syndrome, which is the result of a karyotype with three copies of chromosome 21 and is often referred to as trisomy 21 (Figure 9.2.11).

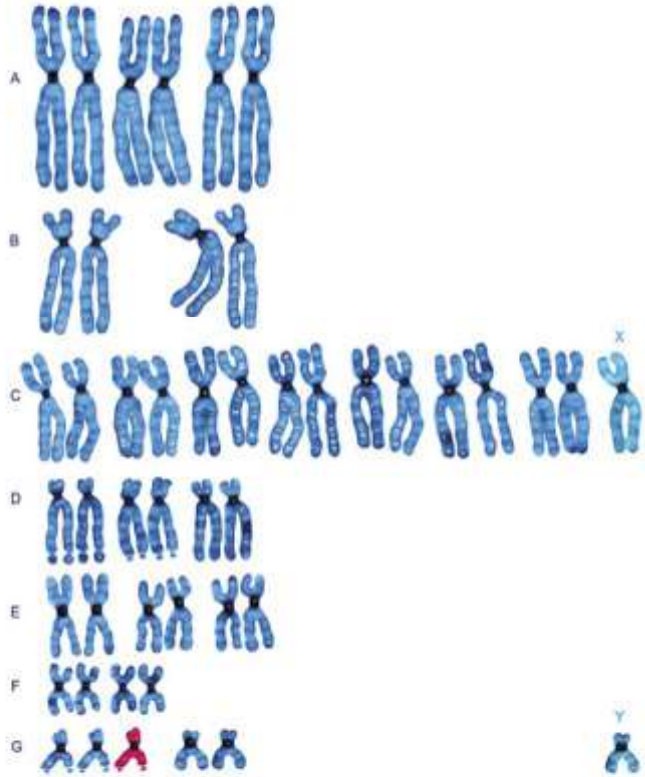


FIGURE 9.2.11 The karyotype of a male with Down syndrome. This condition is caused by trisomy 21, which is the presence of an additional copy of chromosome 21 (highlighted in red).

In people with non-familial Down syndrome, the extra copy of chromosome 21 usually results from an error in meiosis in one of the parents. Figure 9.2.12 illustrates the behaviour of chromosome 21 during meiosis (the segregation of the other chromosomes being normal). Chromosome 21 undergoes non-disjunction so that cell division produces gametes with either an extra or missing chromosome 21. If a gamete with $(n + 1)$ chromosomes unites with a normal gamete (n) the zygote will be trisomic $(2n + 1)$.

The additional chromosome 21 results in slower and more limited physical development, so people with non-familial Down syndrome tend to be shorter and have less muscle development than people without the syndrome. Intellectual development is also slowed, but this can be off-set to some extent by well-designed educational programs. The physical and intellectual expressions of Down syndrome also vary greatly; some individuals are more severely affected than others.

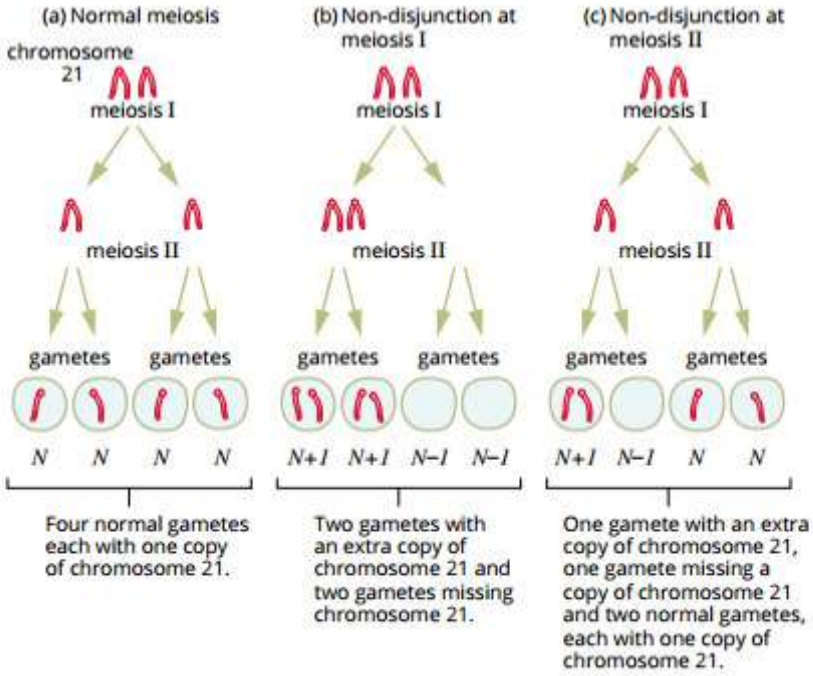


FIGURE 9.2.12 Gametes resulting from non-disjunction of chromosome 21 at the first or second division of meiosis in a parent who has a child with Down syndrome. Normal meiosis is shown for comparison. All other chromosomes segregate normally in each case.

The use of karyotypes to identify other chromosome abnormalities is covered in Section 10.3.

Changes in chromosome structure

Changes in chromosome structure can also occur during meiosis. Four types of changes can occur: deletions, duplications, translocations and inversions (Figure 9.2.13). A deletion occurs when a chromosome segment is lost, so that the chromosome lacks certain genes. The 'deleted' segment might become attached as an extra segment to a sister chromatid, producing a duplication. A chromosomal segment might also reattach to the original chromosome but in the reverse orientation, producing an inversion. A chromosomal segment might join a non-homologous chromosome, a rearrangement called a translocation.

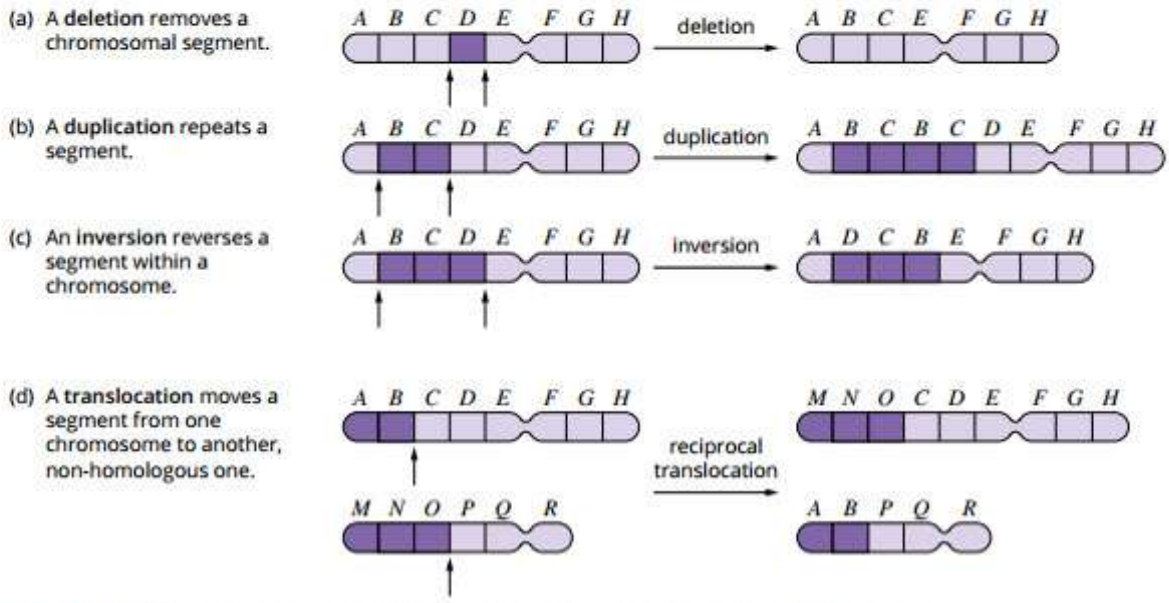


FIGURE 9.2.13 Changes in chromosome structure. Arrows show where the breakage in chromosome occurs. Dark purple shows the chromosomal parts affected by the rearrangements.

Deletions and duplications are more likely to occur in meiosis. During crossing over, non-sister chromatids sometimes exchange unequal-sized segments of DNA. A result of the exchange of unequal-sized segments of DNA is one chromosome with a deletion and one chromosome with a duplication.

Deletions result in the embryo having a number of essential genes missing and are usually lethal. Duplications, translocations and inversions can result in changes in physical characteristics because a gene's expression can be influenced by its location among neighbouring genes.

Polyploidy

Having more than two sets of chromosomes (for example $3n$, $4n$, $6n$) in a genome is called **polyploidy**. Polyploidy can come about through errors in meiosis; for example, gametes may end up being diploid rather than haploid. If a diploid sperm fertilises a haploid egg, the resulting zygote carries an extra set of chromosomes and is triploid ($3n$). If it fertilises a diploid egg, a zygote with four sets of chromosomes—a tetraploid ($4n$)—would result.

In humans, polyploid zygotes do not survive. However, polyploidy can also arise during mitosis and produce groups of somatic polyploid cells. Having a few cells with an abnormal chromosome number may not affect health. A liver, for example, may function normally but have patches of polyploid cells.

Polyploidy is more common in plants than animals because many plants can survive by asexual reproduction (Figure 9.2.14). For example, a triploid plant ($3n$) is typically sterile or has low fertility because of problems with chromosome pairing during meiosis and gamete formation. But it could survive by vegetative reproduction. Some banana varieties are triploid ($3n$); cultivated cotton and potatoes are examples of tetraploid ($4n$) organisms; bread wheats are hexaploid ($6n$); and strawberries are octoploid ($8n$). Polyploid animals include some insects, earthworms and tree frogs.

Polyploidy in some crop plants can result in larger and more vigorous plants. The artificial induction of polyploidy usually involves the use of the chemical colchicine, which prevents microtubule formation during cell division. As a result, the chromosomes do not pull apart like they normally do, resulting in the doubling of the number of chromosomes. Polyploids are now found in a large number of agricultural crops such as turnips, spinach, apples, radishes, grapes and watermelons. A drawback of inducing polyploidy in plants is that the seed crop produced by many polyploids have lower fertility rates than their diploid types.

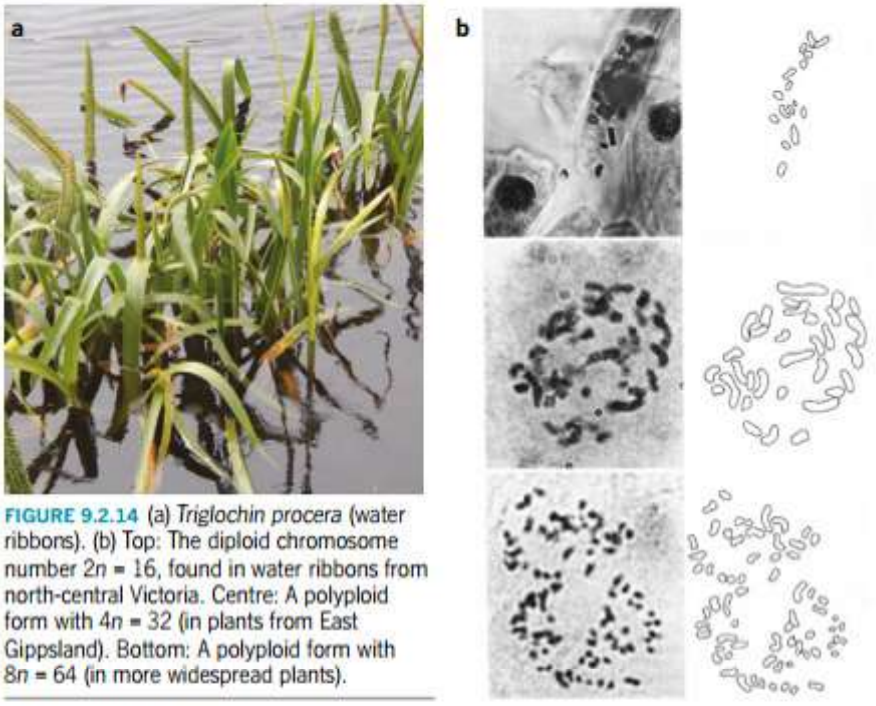


FIGURE 9.2.14 (a) *Triglochin procera* (water ribbons). (b) Top: The diploid chromosome number $2n = 16$, found in water ribbons from north-central Victoria. Centre: A polyploid form with $4n = 32$ (in plants from East Gippsland). Bottom: A polyploid form with $8n = 64$ (in more widespread plants).

EXTENSION

Reproductive systems in mammals and flowering plants

Animals and plants have an amazing diversity of reproductive strategies, often involving complex behavioural, physiological and structural adaptations for attracting mates, mating, and protecting and nurturing developing offspring.

As organisms moved from protective aquatic environments to exposed terrestrial environments, there was a need to shift from external fertilisation to internal fertilisation. This evolution of reproductive strategies is evident in animals today.

For example, many aquatic animals reproduce by external fertilisation, and amphibians return to aquatic environments to lay and externally fertilise eggs. Reptiles and birds reproduce by internal fertilisation but protect their developing offspring in hard-shelled eggs on land, and mammals use internal fertilisation and protect their developing offspring within the female's body.

Placental mammals

The internal reproductive structures of female mammals are essential for creating a protective, watery environment for fertilisation, and provide nourishment and protection for the developing embryo and foetus. The stages of reproduction and development in eutherian (placental) mammals include the formation of gametes, fertilisation and the development of the embryo and foetus.

The male reproductive system

The male reproductive system (Figure 9.2.15) consists of paired testes, which produce mature sperm continuously during mating periods; paired accessory glands that produce secretions that make up about 95 per cent of the volume of semen; and a paired system of ducts leading to the urethra. Luteinising hormone (LH) stimulates the secretion of the male steroid hormone testosterone by the testes.

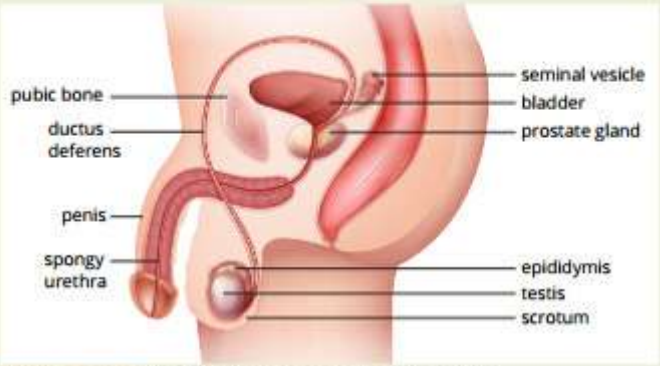


FIGURE 9.2.15 The human male reproductive system.

Mitotic divisions of precursor cells in the testes produce spermatocytes, each of which divides by meiosis to produce four sperm cells. During mating, contractions of the vas deferens move sperm towards the urethra. Secretions of the accessory glands are added, forming the seminal fluid, which has two main functions: it causes the sperm to become motile, and it provides a nutritious medium that is rich in ions, vitamins and sugar.

The female reproductive system

The human female reproductive system (Figure 9.2.16) consists of a uterus, ovaries, fallopian tubes, cervix and vagina. Before birth, meiosis begins in all oocytes (immature egg cells) but is arrested at an early stage (prophase 1). Oocyte development is first arrested at the early stage of prophase I. Once puberty is reached, pituitary hormones cause continuation and completion of meiosis I. Meiosis II begins, but is arrested in metaphase II. Meiosis II only completes after fertilisation. A female is therefore born with all her egg cells in her ovaries. After reaching maturity (puberty), ovarian cycles commence. Under the influence of follicle stimulating hormone (FSH), one or more of the oocytes will resume its meiotic division up to metaphase II and matures within a group of nutritive cells called a follicle. Only one egg forms from each oocyte during meiosis.

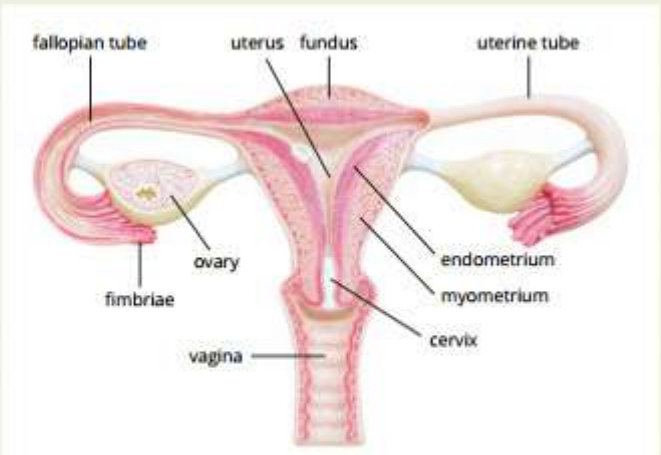


FIGURE 9.2.16 The human female reproductive system.

Developing follicles release oestrogen, which causes changes to the lining of the uterus (the endometrium) and also acts on the anterior pituitary gland. The uterine lining becomes thicker, softer and spongy, and richly supplied with blood vessels in readiness to receive a fertilised egg.

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Ovulation is triggered by a surge of luteinising hormone (LH) released from the anterior pituitary gland. The ovum (ripe egg) bursts out of the follicle and is drawn by fluid currents into the oviduct. (Eggs, unlike sperm, cannot move by themselves.) Contractions of the oviduct help to propel the egg towards the uterus.

Left behind in the ovary, the burst follicle, now without its egg, is called the corpus luteum. The corpus luteum, stimulated by LH, secretes large amounts of both oestrogen and progesterone. These hormones cause a further thickening of the lining of the uterus during the latter part of the cycle. These actions on the uterine lining are to prepare the uterus to receive an embryo, should fertilisation occur.

If it is not fertilised, the egg simply passes out of the reproductive tract. The corpus luteum slowly disintegrates and stops releasing its hormones. As a result, the thickened uterine lining breaks down and menstruation occurs.

Fertilisation and cleavage

Fertilisation is the fusion of two gametes to form a zygote. In mammals (and most terrestrial animals) it occurs internally following mating (copulation), and usually takes place in the upper part of the oviduct, which in humans is known as the fallopian tube (Figure 9.2.16). Fertilisation involves four sequential events:

- The sperm dissolves and penetrates any protective layer surrounding the egg to reach the plasma membrane.
- Molecules on the sperm surface bind to receptors (specialised proteins on plasma membrane) to ensure that a sperm of the same species fertilises the egg. Nucleus of the sperm enters the egg cell cytoplasm.
- Changes at the surface of the egg occur to prevent the entry of multiple sperm nuclei into the egg.
- Fusion of the egg and sperm nuclei. The result of fertilisation is a zygote.

The first stage of development of the new embryo is cleavage, which commences following activation of the egg by sperm penetration. Cleavage is a period of cell proliferation during which the zygote is divided into many hundreds of smaller cells by mitosis. Development continues as the tiny embryo passes down the oviduct.

Implantation and the placenta

When the embryo reaches the uterus it is known as a blastocyst. The blastocyst adheres to the lining of the uterus and becomes implanted there. The outer layer of embryonic cells sends out finger-like projections into the wall of the uterus, which together develop into the placenta.

The placenta has various shapes in different species of mammals, but its functions are the same. It is an exchange organ containing blood vessels of the embryo that are in close contact with maternal blood. The placenta is also an important source of hormones that maintain the pregnancy.

Embryonic and foetal development

During the embryonic period of development, the major organs of the body are formed from the three primary layers (see Section 8.4). In humans this is completed about eight weeks after the last menstrual period.

At the end of the embryonic stage, the developing organism has distinct features and is known as a foetus for the remainder of its development. Organs continue to develop for the rest of the gestation period, and cells and tissues become specialised to carry out their particular functions. The foetus is protected by the amniotic cavity, which is a fluid-filled environment in which it can move about (Figure 9.2.17).

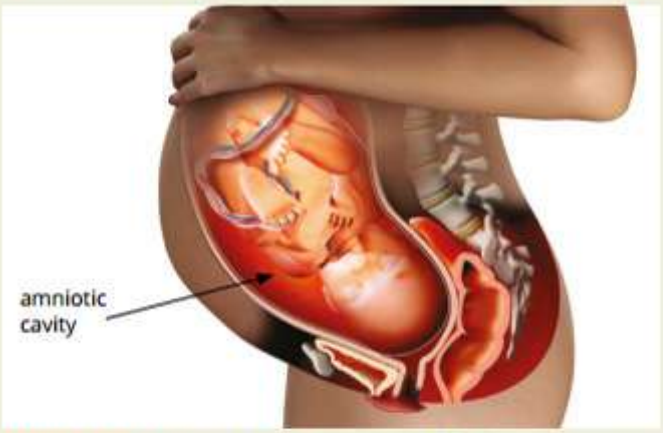


FIGURE 9.2.17 Anatomical view of a full-term (37–40 weeks) human pregnancy.

Flowering plants

Sexual reproduction in flowering plants involves meiosis, which produces haploid spores that undergo several mitotic divisions and develop into male or female gametophytes. The male gametophyte is the pollen grain, which contains sperm cells, and the female gametophyte is the embryo sac, which contains the egg.

Flowers are for reproduction

Figure 9.2.18 illustrates how the reproductive organs of flowering plants are contained in flowers. On the outside of a flower are sepals and petals. The sepals enclose and protect the other parts of the flower during the bud stage. Sepals are usually small and green, but in some species they are large and brightly coloured.

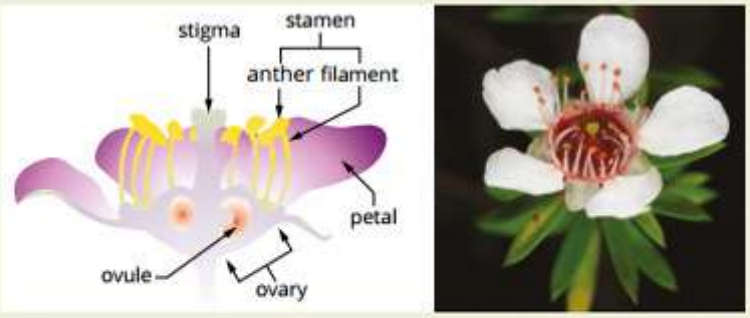


FIGURE 9.2.18 The reproductive organs of a tea-tree flower.

The petals are arranged in a circle or cylinder around the reproductive organs. Inside the ring of petals are the stamens, which are the male reproductive organs. Each stamen usually has a long stalk called the filament with a small yellow sac on the end, the anther.

In the centre of the flower is the female reproductive organ, called a pistil. Some species have more than one pistil in a flower. Each pistil consists of an ovary, which is a central swelling at the base, and a slender stalk called the style bearing the stigma, which is the receptive surface for pollen.

Most flowers contain both stamens and pistils and are therefore bisexual. In some species the male and female organs are in separate flowers on the same plant, and in other species they are on different plants.

Pollination and fertilisation

In most plants, pollination is carried out either by insects or by the wind. Less commonly, the agents of pollination are birds, bats, other animals or water.

Pollination occurs when a pollen grain lands on a receptive stigma and begins to grow (Figure 9.2.19a). One of the cells in the pollen grain produces a tube that penetrates the surface of the stigma. The pollen tube carries two sperm cells and grows down through the style inside specialised nutritive tissues, towards the ovary, until it reaches an ovule. Fertilisation takes place in the ovule when the egg fuses with one of the two sperm cells.

Although most flowers are bisexual, most of them are not capable of self-fertilisation, which would reduce the genetic variation in the offspring. Flowering plants have efficient mechanisms for preventing self-fertilisation. One mechanism includes the maturation of the stamens and carpels and the pistons at different times. A second mechanism to avoid self-pollination is that the plant also rejects its own pollen. Successful fertilisation can occur only following acceptance of the pollen grain by the stigma and of the pollen tube by the style. The plant will also not be fertilized by the pollen from other species.

In the ovule, fertilisation between one of the two cells and the egg cell gives rise to a diploid zygote, from which a new seedling arises. Other cells in the ovule combine with the second sperm cell and then divide rapidly to provide nutritious tissue called endosperm for the developing embryo (Figure 9.2.19b).

Seeds and fruit

After fertilisation the ovule develops into a seed protected by a tough outer seed coat. This process involves the ovule (in which the zygote develops) expanding, the endosperm forming, and the zygote undergoing a series of mitotic divisions to produce a multicellular embryo. The embryo develops seed leaves (cotyledons) and a root tip; epidermal and vascular tissues begin to form.

As the ovule develops into a seed, the ovary in which the ovule is contained becomes a mature fruit. Nutrition for seed development and fruit growth is obtained from the parent plant. Fruits are specialised structures that protect the seeds and may enhance seed dispersal.

Germination and development

The embryos in seeds lie dormant until appropriate conditions arise. Water, oxygen, warmth and usually light are major environmental factors that influence the start of germination of a seed.

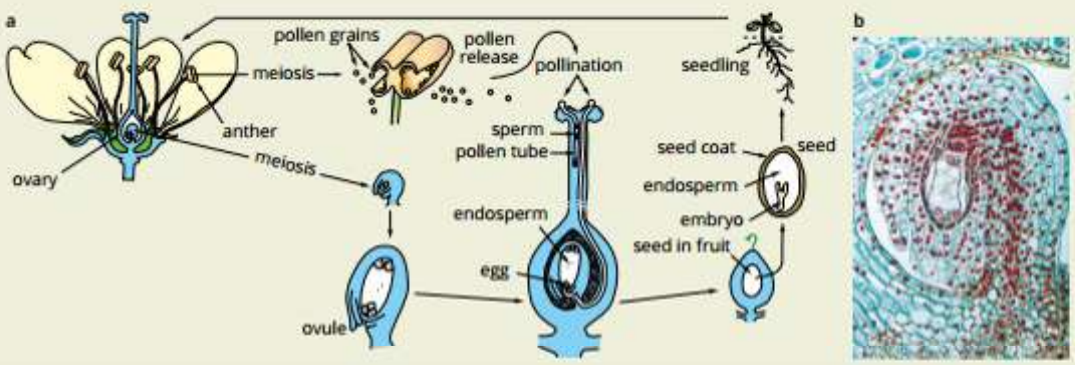


FIGURE 9.2.19 (a) Life cycle of a flowering plant showing fertilisation and seed formation. (b) Cross-section through an ovule.

ADVANTAGES AND DISADVANTAGES OF SEXUAL REPRODUCTION

The considerable benefit of sexual reproduction is evident in its widespread occurrence in almost all eukaryotic organisms. The most beneficial aspect of sexual reproduction is the genetic variation that is introduced through gamete production and genetic recombination.

FIGURE 9.2.20 Fighting between male springboks (*Antidorcas marsupialis*) may look dramatic, but often one of the competitors will back down before serious injury occurs.

Genetic diversity within a population enables a species to survive and reproduce in varied and changing environments. In the long term, increased genetic variation provides greater adaptability and evolutionary potential in changing conditions. The pool of genetic variation in a population also facilitates the selection of beneficial traits and elimination of unfavourable traits, according to the survival and reproductive success of individuals. This process ultimately benefits the population, as those individuals that are most successful will reproduce, increasing beneficial genetic variants in the population.

However, sexual reproduction usually involves changes in an organism's way of life, and these changes are not without cost. Finding and competing for a mate can be energetically costly and risky. Some reproductive behaviours, such as calling in frogs to attract the attention of potential mates, might also attract the attention of predators. In some animals, mating leads to considerable, and potentially harmful, competition between males (Figure 9.2.20).

Providing care and protection for offspring also uses the time and resources of parents and shortens their lifespan because of the excess expenditure of energy. For reproduction, some of the food resources of the parent must be used to produce gametes and to ensure that mature gametes are brought together at the right time of year. In other words, not all of the food the parent eats is used to maintain its own body systems.

The widespread occurrence of this reproductive strategy shows that the benefits to the species far outweigh any costs to the individuals (Table 9.2.2).

Advantages	Disadvantages
Long-term evolutionary potential	Slower reproductive rate—fewer offspring are produced over a longer timespan.
Unfavourable (deleterious) genetic variation is eliminated from the population more efficiently.	Recombination can break apart beneficial genomic combinations and introduce deleterious variation to populations.
Generates genetic variation and selects for beneficial genetic variation more efficiently.	Potential for spread of sexually transmitted diseases throughout population.
Populations are better able to adapt to and survive changing environmental conditions.	Energetically costly; that is, requires a lot of ongoing energy input from the parent.

TABLE 9.2.2 Advantages and disadvantages of sexual reproduction.

9.2 Review

SUMMARY

- Germ cells are cells that give rise to gametes.
- Gametes are the sex cells that combine in sexual reproduction.
- Sexual reproduction in multicellular organisms involves the fusion of gametes from two different individuals to form a zygote.
- The great advantage of sexual reproduction is that it produces variation between individuals of a population. However, there is often considerable cost to the parents.
- Sexual reproduction involves equal genetic contributions from male and female parents.
- Meiosis is a division of the nucleus that halves the normal number of chromosomes and produces different genetic combinations in the haploid gametes.
- Variation in gametes arises from the random assortment of chromosomes and exchange of alleles through recombination during meiosis.
- Chromosomal abnormalities, such as non-disjunction, sometimes occur during meiosis, and an extra or missing chromosome in a gamete can have severe effects in offspring.
- Down syndrome is the effect of having three copies of chromosome 21 (trisomy-21).
- If whole sets of chromosomes fail to separate, a gamete may end up with a number of sets of chromosomes, leading to polyploidy.
- Some unicellular organisms can undergo sexual reproduction, but no gametes are involved.
- The primary sex organs are ovaries, which produce eggs, and testes, which produce sperm. Secondary sex organs include other glands and organs involved in mating and reproduction.
- The sperm contributes a single set of chromosomes to the new individual and often determines its sex. The sperm cell contains 22 chromosomes and either an X or a Y chromosome.
- The egg provides a single set of chromosomes, nutrients for the growth of the embryo and regulatory factors that control early development.
- Flowers contain reproductive organs. The male parts are the stamens, composed of filaments and anthers. The anthers release pollen, which contains sperm cells. The female part is the pistil, composed of the stigma, style and ovary, which contain ovules with egg cells.
- Pollination involves a specific interaction between pollen grains and stigma, growth of a pollen tube down the style, and fertilisation between sperm and egg in the ovule.
- After fertilisation, the ovule becomes a seed containing the embryo and endosperm, surrounded by a tough outer coat.
- The ovary containing the ovule(s) becomes the fruit, which may be dry or fleshy, and which is often adapted for dispersal.

KEY QUESTIONS

1 What is the difference between a somatic cell and a gamete? Give an example of each.

2 In which phase of meiosis does crossing over occur?
- **A** prophase I
- **B** anaphase I
- **C** metaphase II
- **D** anaphase II

3 Which one of the following processes does **not** occur in meiosis?
- **A** cytokinesis
- **B** DNA replication
- **C** pairing of homologous chromosomes
- **D** formation of two diploid daughter cells

4 Outline how:
- **a** prophase I differs from prophase II
- **b** metaphase I differs from metaphase II
- **c** anaphase I differs from anaphase II
- **d** telophase I differs from telophase II

5 Explain how an error in meiosis can lead to Down syndrome.

6 **a** When a cell with chromosome number $n = 24$ undergoes mitosis, how many daughter cells are produced, and what is their chromosome number?
- **b** When a cell with chromosome number $n = 24$ undergoes meiosis, how many daughter cells are produced, and what is their chromosome number?

7 List three advantages and three disadvantages of sexual reproduction.

Chapter review

09

KEY TERMS

allele
anther
asexual reproduction
blastocyst
budding
bulb
centromere
chiasma
chromatid
cleavage
clone
cloning
conidia
corm
cotyledon
crossing over
diploid
endometrium
endosperm
fertilisation
filament
fission
foetus
fragmentation
gamete
gametophyte
gene
germ cell
germination
haploid
hermaphrodite
homologous chromosome
implantation
in vitro fertilisation
karyotype
longitudinal fission
meiosis
mitosis
mitospore
monosomy
oestrogen
parthenogenesis
pistil
pollination
polyploid
recombination
reduction division
rhizome
sepal
somatic cell
spermatocyte
sporangium
spore
stamen
stigma
stolon
strobilation
style
synapsis
totipotent
transverse fission
trisomy
tuber
vegetative reproduction

KEY QUESTIONS

1 Which of the following statements about chromosomes in mammalian gametes is correct?

- **A** They are all identical to those in the parent cell.
- **B** They are different to those in the parent cell but only because of mutation.
- **C** They are all identical to those in the parent cell because crossing-over and recombination between homologues does not create new combinations of alleles.
- **D** They are different to those in the parent cell partly because of the effects of independent assortment.

2 Why is meiosis a necessary process in living organisms?

- **A** It happens in the reproductive organs.
- **B** It is necessary for the growth of an organism.
- **C** It produces new cells to replace dead or dying cells.
- **D** It enables each parent to contribute genetic information to the offspring.

3 Why is asexual reproduction more likely to be successful in the short term rather than the long term?

4 Which type of reproduction is common in many invasive species? Discuss why this strategy makes organisms successful invaders of a new habitat and what impact this has on the native species in that environment.

5 A farmer grows a range of plants. The table below outlines the reproductive strategies of the plants.

Plant	Type of reproduction
tulip	asexual
poppy	sexual
lily	asexual
strawberry	asexual and sexual

If a virus infects all of the plants, which plants are most likely to survive?

- **A** poppy and strawberry
- **B** tulip and lily
- **C** tulip, lily and strawberry
- **D** poppy only

6 What type of reproduction and reproductive structures are responsible for the mouldy bread in your pantry?

7 What are four methods of cloning currently used in horticulture and agriculture? Discuss one of these methods, using an example of its application in horticulture or agriculture.

8 Arrange the following stages of plant tissue culture in the correct order, from first to last.
- New shoots are removed and placed on another culture medium.
- Plant hormones promote the rapid growth of shoots and roots.
- A sample of the ideal stock plant is removed.
- The sample is sterilised and placed on a culture medium.

9 What are four ethical issues associated with cloning?

10 Arrange the following stages of meiosis in the correct order, from first to last.
- metaphase II
- telophase II
- prophase I
- anaphase I
- metaphase I
- anaphase II

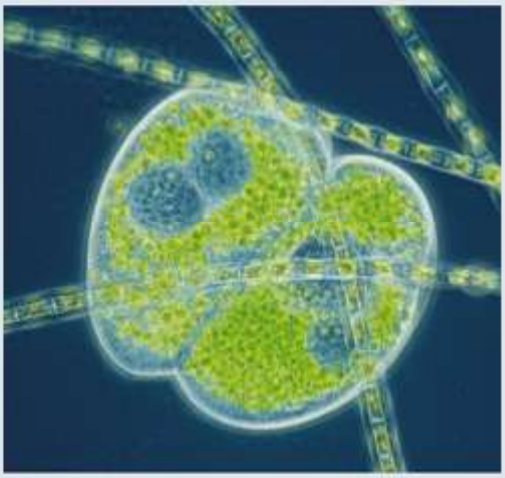
11 What is the significance of crossing over in meiosis?

12 How are monozygotic twins produced, and are they truly identical? Explain your answer.

13 Do hermaphrodites reproduce via asexual or sexual reproduction? Explain your answer.

14 The diploid number of chromosomes in horses is 64. How many chromosomes would you expect in a horse's:
a fertilised ovum?
b sperm cell?
c somatic cell?

15 *Paramecium* protists can reproduce sexually. Arrange the following events that occur during sexual reproduction in *Paramecium* in order, from first to last.
- three haploid micronuclei (n) degenerate
- separation of mating partners
- micronucleus undergoes meiosis
- mating partners become attached
- exchange of micronuclei
- fusion of micronuclei ($2n$)



REVIEW QUESTIONS

How is the continuity of life maintained?

Multiple choice questions

1 By which process do most bacteria divide?

A mitosis
B meiosis
C budding
D binary fission

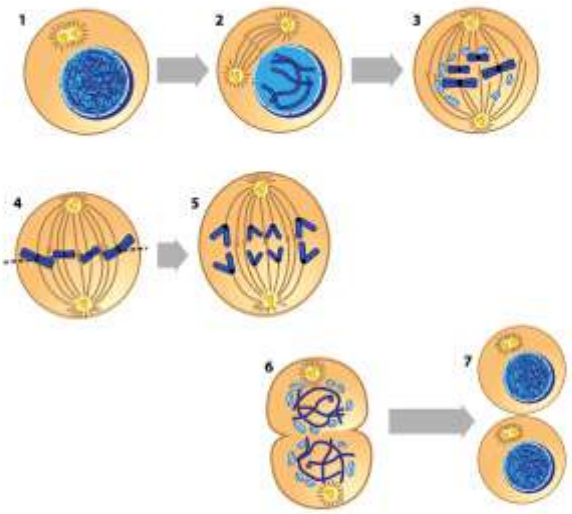
2 Which of the following is not true about binary fission and mitosis?

A Binary fission occurs more rapidly than mitosis.
B The nuclear membrane breaks down and reforms during mitosis, but not during binary fission.
C Spindle fibres are present during mitosis, but not during binary fission.
D Binary fission occurs in eukaryotes, and mitosis occurs in prokaryotes.

3 Which one of the following statements about the cells resulting from mitosis is correct?

A They are identical in shape, size and content to the original cell.
B They are each half the size of the original cell and have identical nuclear content.
C They are daughter and son cells.
D They are each one quarter of the size of the original cell.

4 The following figure represents the stages of mitosis, but they are not in the order in which they occur.



Which of the options below shows the correct order for mitosis?

A 1, 6, 7, 3, 4, 2, 5
B 2, 5, 1, 3, 7, 6, 4
C 5, 1, 6, 7, 3, 4, 2
D 5, 1, 7, 6, 3, 4, 2

5 A cell with a diploid number of 12 chromosomes undergoes mitosis. What will the product at the end of mitosis be?

A 2 cells each with 12 chromosomes
B 4 cells each with 6 chromosomes
C 2 cells each with 6 chromosomes
D 4 cells each with 12 chromosomes

6 Which of the following is not an example of asexual reproduction?

A reproduction via budding in baker's yeast
B formation of spores during sporogenesis without meiosis in red algae
C formation of plantlets on specialised leaves of kalanchoe
D fertilisation of orchids resulting in formation of a fruit

7 The use of embryonic stem cells has attracted a great deal of attention in the scientific world and in the media. Pluripotent stem cells are taken from embryos. They can be stimulated to become any type of cell in the body. This technology has given rise to many ethical questions because:

A differentiated stem cells have no practical use outside the laboratory
B stem cells must be taken from two-week-old embryos that have been removed from the uterus
C there is no source of embryonic stem cells other than from aborted foetuses
D stem cells are taken from excess embryos produced through the IVF process that would otherwise be discarded

8 Which of the following is a feature of cancer cells that makes them different from normal cells?

A Cancer cells are unable to synthesise DNA.
B Cancer cells are arrested at the S phase of the cell cycle.
C Cancer cells continue to divide even when they are tightly packed together.
D Cancer cells are always in the M phase of the cell cycle.

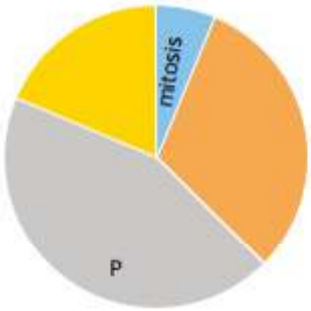
9 Which of the following factors can contribute to a person developing cancer?

- **i** genetic factors
- **ii** oncogenes
- **iii** exposure to a carcinogen
- **iv** infection by human papillomavirus

A i only
B i and iii only
C ii and iv only
D i, ii, iii and iv

Short answer questions

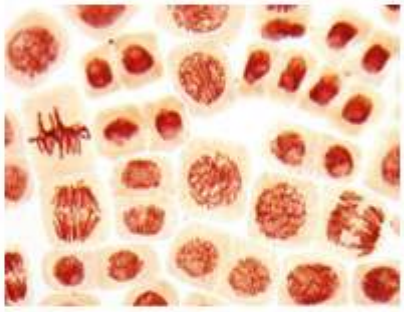
10 According to cell theory, all cells arise from pre-existing cells. This figure shows the cell cycle of a eukaryotic cell of a diploid organism.



a Explain what is meant by the term 'cell cycle'.
b Identify the phase of the cell cycle labelled P.
c Describe the process that is occurring during part P of the cell cycle.
d For some cells, there is a fourth phase in the cell cycle known as G0. Copy the cell cycle diagram shown, and mark on it where the G0 phase occurs.
e What are some of the reasons why cells enter into the G0 phase?
f There are checkpoints in the cell cycle to ensure that two genetically identical daughter cells are produced at the end of the cell cycle.

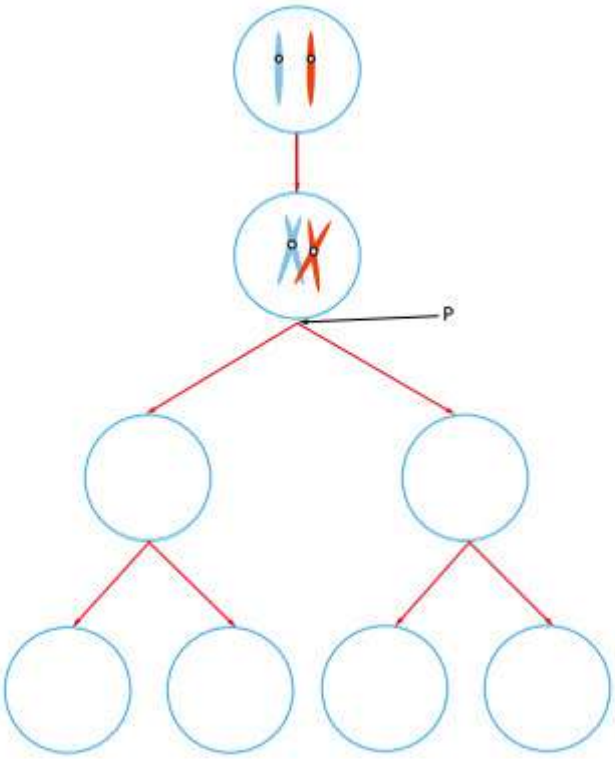
- **i** On your diagram, draw and label the three checkpoints in the cell cycle.
- **ii** Outline what happens during each of the three checkpoints.
- **iii** Cells can undergo cell death if damage to the cell is too great. State the two types of cell death and outline the conditions that will result in each type of cell death.

11 The following image shows a light micrograph of a group of cells undergoing mitosis.



a Circle and label one cell in each of the following stages: prophase, metaphase and anaphase.
b Describe the major events that occur during mitosis.
c Colchicine is a chemical substance that is used to prevent the formation of spindle fibres. What stage of mitosis will be prevented if dividing cells are treated with colchicine?
d Describe the differences during cytokinesis between plant and animal cells.

12 The following diagram shows a stage during meiosis. The circles represent the cell and the structures within represent a homologous pair of chromosomes.

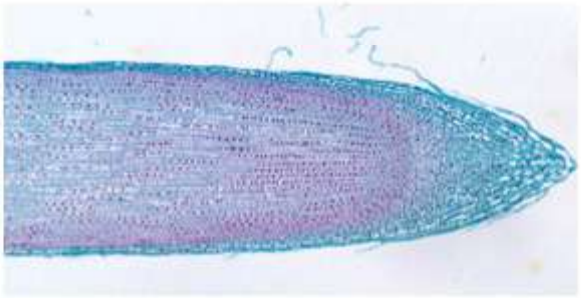


a Copy the diagram and then complete it by drawing the chromosomes in the cells.
b Explain what is happening at P.
c Explain how meiosis promotes variation in a species.

13 Lectin is a type of glycoprotein produced by plants, and can have toxic effects on animal cells. After considering whether plants would produce molecules that are toxic to plant cells, a group of students conducted an experiment to determine whether lectin has an effect on the rate of mitosis in onion root tips.

The roots of one onion bulb were immersed in distilled water for 48 hours, while the roots of another onion bulb were immersed in distilled water containing lectin for 48 hours. Three onion root tips from each onion were then harvested, stained and viewed under a microscope (see below). For each root tip, the number of cells in the field of view was counted. These cells were in interphase and undergoing mitosis in the apical meristem.

The results were recorded in tables, as shown below. Table 1 shows the number of cells in interphase and mitosis for onion tips immersed in distilled water only. Table 2 shows the number of cells in interphase and mitosis for onion tips immersed in distilled water containing lectin.



	Number of cells at:		
Onion root tip	**Interphase**	**Undergoing mitosis**	**Total**
1	47	34	81
2	36	29	65
3	37	30	67
Total	120	93	213

TABLE 1 Results for onion tips immersed in distilled water only.

	Number of cells at:		
Onion root tip	**Interphase**	**Undergoing mitosis**	**Total**
1	52	44	96
2	83	25	108
3	90	54	144
Total	225	123	348

TABLE 2 Results for onion tips immersed in distilled water containing lectin.

a Calculate the percentage of cells in interphase and undergoing mitosis for onion root tips treated with lectin and immersed in distilled water. Write down your answers in the following table.

Type of onion root tip	Percentage of cells (%)	
	Interphase	**Undergoing mitosis**
treated with lectin		
immersed in distilled water		

b Write a hypothesis for this experiment.

c Based on the results, what conclusion can you make about the effect of lectin on the rate of mitosis in onion root tip? Do the results support your hypothesis?

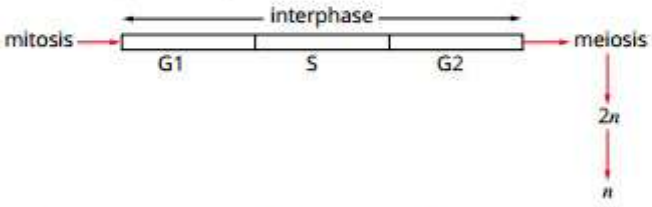
14 Bananas are classified in the genus *Musa*. Cultivated bananas are sterile and the fruit develops without seeds. However, cultivated bananas can be propagated by tissue culture. The resulting new plant is a clone of the parent plant. The overall banana production around the world has decreased recently because of banana freckle disease.

a Discuss the advantages and disadvantages of cloning crops such as bananas.

b How is the process of propagating plants by tissue culture different from cutting and grafting?

c What is the advantage of using tissue culture to grow plants?

15 Meiosis is a type of cell division that results in the production of gametes. Meiosis is divided into phases, but before meiosis can start a special phase called interphase is required. The following diagram is a summary of interphase and meiosis.



a The first cell division of meiosis is called the reduction division. Explain why.

b Which stage of meiosis is similar to mitosis? Explain your answer.

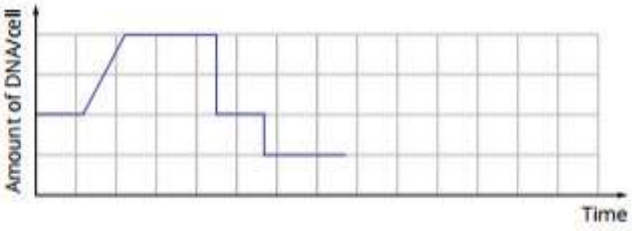
16 Sometimes two separate species can interbreed to create a hybrid species. For example, a zebra and a horse can interbreed to produce a zorse. Zebras have a diploid number of 46. Horses have a diploid number of 64.

- **a** Explain the term 'species'.
- **b** How many chromosomes would you find in the gamete of a zebra?
- **b** How many chromosomes would you find in the gamete of a horse?
- **c** What is the diploid number of a zorse?
- **d** Using your understanding of meiosis, explain why zorses are usually sterile.

17 Some species of aphids are capable of reproducing either asexually (via parthenogenesis) or sexually.

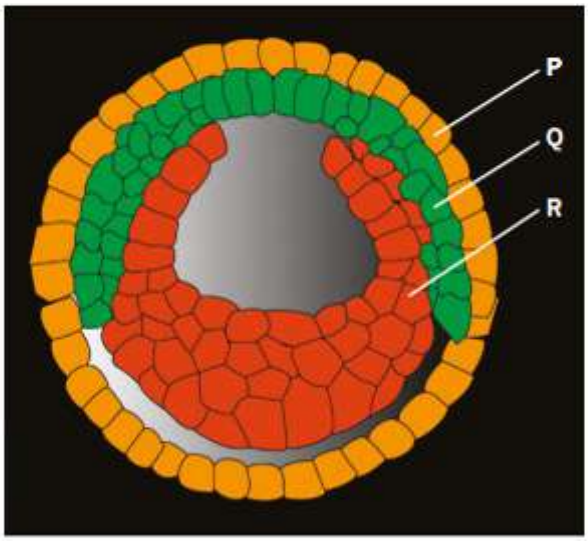
- **a** What might be the advantage or disadvantage of:
  - **i** asexual reproduction when the environment is favourable?
  - **ii** switching to sexual reproduction when the environment becomes unfavourable?
- **b** Examine the differences between parthenogenesis and fragmentation.

18 The following graph represents the changes in the amount of DNA in a cell as it goes through meiosis.

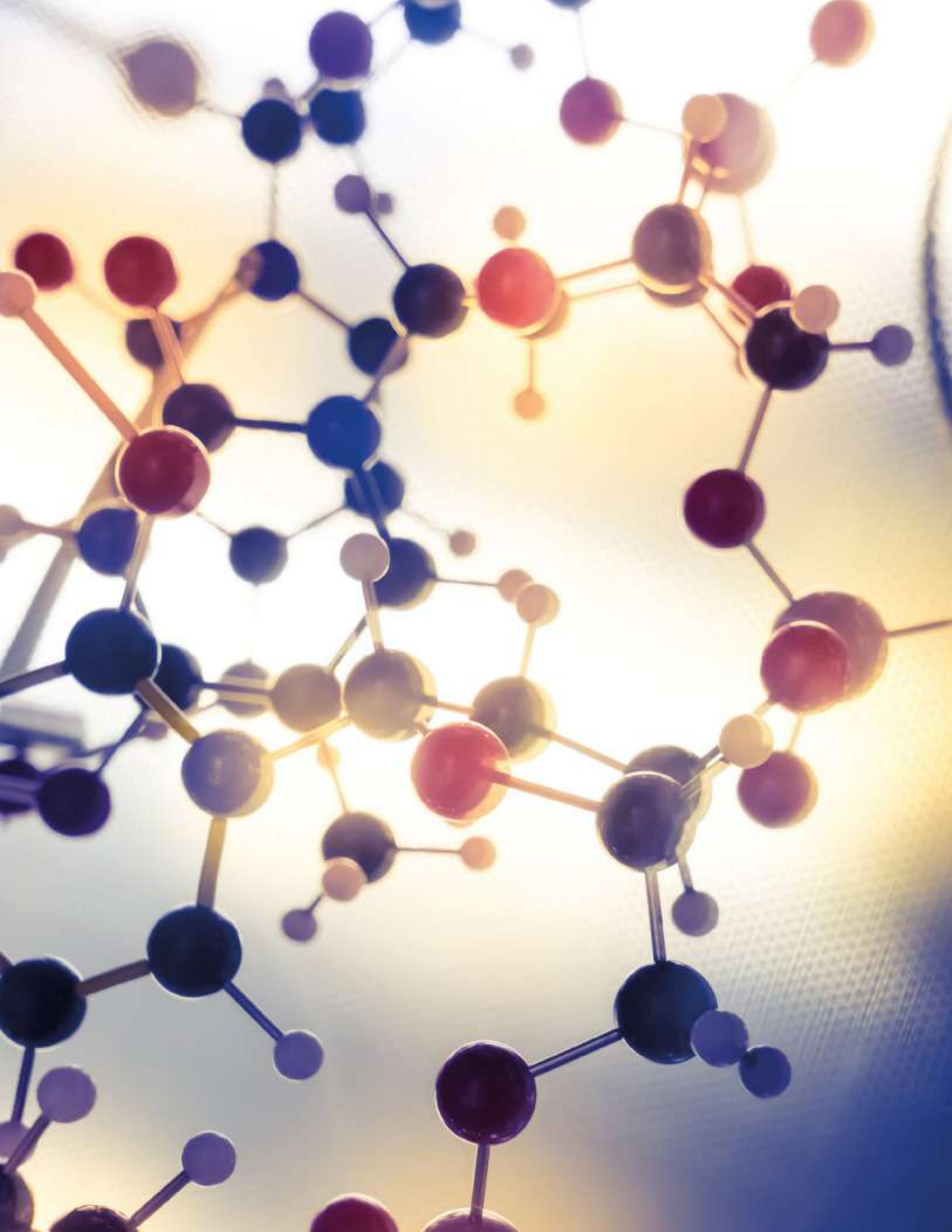


- **a** On the graph, write the letter D where DNA replication is occurring, and the letter C where cytokinesis is occurring.
- **b** On the graph, continue the line to show what would happen to the amount of DNA if fertilisation occurred and the cell carried on with one mitotic cell division.
- **c** Distinguish between mitosis and meiosis.

19 Consider the following cross-section of an embryo, showing the three primary germ layers.



- **a** What is the difference between an embryo and a foetus?
- **b** Identify each of the germ layers P, Q and R.
- **c** State one type of tissue that will arise from each of the germ layers.
- **d** Can the cells from this embryo be used as embryonic stem cells? Explain your answer.
- **e** Describe the different types of stem cells.
- **f** Outline the advantages and disadvantages of using embryonic stem cells and adult stem cells.



CHAPTER

10 The nature of genes

Sexual reproduction results in offspring with a set of unique characteristics that are inherited from their parents. In this chapter you will learn how an organism inherits a complete set of genes from their parents, how these genes influence how the organism looks and behaves, and the structure of DNA that contains all of an organism's genes.

You will also learn how genomic research has influenced what we know about how genes function, how species are related, how genetic disorders occur and how they are expressed, and how we can apply our knowledge to detect and diagnose genetic disorders.

Key knowledge

- distinguish between a genome, gene and allele
- identify the genome as the sum total of an organism's DNA measured in the number of base pairs contained in a haploid set of chromosomes
- describe the role of genomic research since the Human Genome Project, with reference to the sequencing of the genes of many organisms, comparing relatedness between species, determining gene function and genomic applications for the early detection and diagnosis of human diseases
- describe the role of chromosomes as structures that package DNA, their variability in terms of size and the number of genes they carry in different organisms, the distinction between autosome and a sex chromosome and the nature of a homologous pair of chromosomes (one maternal and one paternal) as carrying the same gene loci
- describe the presentation of an organism's set of chromosomes as a karyotype that can be used to identify chromosome number abnormalities including Down syndrome, Klinefelter syndrome and Turner syndrome in humans
- use symbols in the writing of the genotypes for the alleles present at a particular gene locus
- distinguish between a dominant and recessive phenotype
- describe the relative influences of genetic material, environmental factors and interactions of DNA with other molecules (epigenetic factors) on phenotypes
- describe qualitative treatment of polygenic inheritance as contributing to continuous variation in a population as illustrated by the determination of human skin colour through the genes involved in melanin production or by variation of height.

10.1 Genes and DNA

FIGURE 10.1.1 Representation of part of the molecule of DNA (deoxyribonucleic acid), showing its double helix structure.

Throughout history, people have wondered why children resemble their parents more than they resemble unrelated individuals. Today we know that many characteristics are inherited, such as the colour of our hair, eyes and skin, and also that many conditions such as Down syndrome are inherited. Children are not identical to their mother or father, and they are not identical to their sisters or brothers (except in the case of identical twins).

In this section you will learn about the difference between a gene, genome and allele. You will also learn about the genome as the complete set of genetic material (DNA) present in an organism, measured in the number of base pairs contained in a haploid set of chromosomes.

THE STRUCTURE OF DNA

All cells contain genetic material in the form of **DNA** (deoxyribonucleic acid) (Figure 10.1.1). DNA carries **hereditary** information, directs the cell's activities, and is passed on from generation to generation. The DNA molecule has certain regions known as **genes**, which contain the genetic information that determines what you look like and the function of each cell in your body. To understand how genes work, it is important to understand the basic structure of DNA.

Nucleotides—building blocks of DNA

DNA is a large (macro) molecule, which is made up of a series of chemical building blocks called nucleotides (Figures 10.1.2 and 10.1.3). As shown in Figure 10.1.2, a nucleotide is composed of a phosphate, the sugar deoxyribose, and one of four bases (adenine, cytosine, guanine or thymine). For example, the nucleotide adenosine monophosphate includes the base adenine.

DNA (deoxyribonucleic acid) is a complex molecule that contains all the genetic information necessary to build and maintain an organism.

Hereditary information refers to genetic material that is passed on from parent to offspring (or from one generation to the next).

A gene is a unit of heredity that determines the characteristics of an organism. At the molecular level, a gene is a section of DNA with a unique sequence.

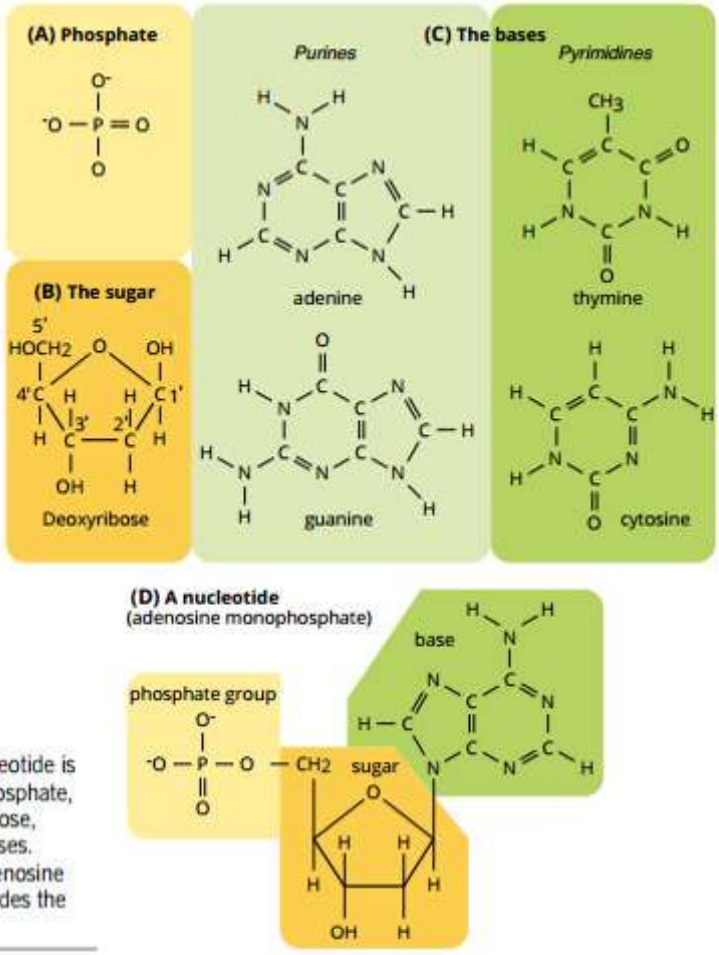


FIGURE 10.1.2 A nucleotide is composed of (a) a phosphate, (b) the sugar deoxyribose, and (c) one of four bases. (d) The nucleotide adenosine monophosphate includes the base adenine.

Figure 10.1.3 shows a single polynucleotide chain (strand) in which individual nucleotides are joined by phosphodiester bonds. Each nucleotide consists of:

- a phosphate group (Figure 10.1.2a)
- a five-carbon sugar (deoxyribose; Figure 10.1.2b). The five carbon atoms are numbered 1' – 5'. In an individual nucleotide, a phosphate is attached to the 5' carbon, and a base is attached to the 1' carbon.
- one of four nitrogen-containing **bases**: **adenine** (A), **guanine** (G), **thymine** (T) and **cytosine** (C) (Figure 10.1.2c). There are two types: **purines**, with a double ring structure, and **pyrimidines**, with a single ring. The purine bases are adenine and guanine, and the pyrimidine bases are thymine and cytosine.

Nucleotides are distinguished from one another by the nitrogen-containing base (Figure 10.1.2d). One nucleotide is joined to the next nucleotide by a covalent phosphodiester bond between the phosphate group on the 5' carbon of one nucleotide and the 3' carbon of the other nucleotide. When many nucleotides are joined together, a polynucleotide chain which runs from 5' to 3' is formed (Figure 10.1.3). Different nucleotides can occur in any order within a strand: if a particular base is A, the next base in the sequence could be A, G, T or C.

DNA is a double-stranded helix

A DNA molecule is made up of two polynucleotide chains. The two polynucleotide chains of DNA are held together by hydrogen bonds between **complementary base pairs** (Figure 10.1.4). There is a direct pairing between A and T, and between G and C in the DNA molecule. This complementary base pairing results in the two polynucleotide strands joining together to form the double stranded DNA molecule. Given the base sequence of one strand you can determine the sequence of the other by this complementary base pairing rule.

In order for the bases to face each other and form hydrogen bonds, one polynucleotide strand must run **antiparallel** to the other (meaning that one strand runs from 5' to 3' and the other runs from 3' to 5'). The two polynucleotide strands will then spiral around an imaginary axis, forming a **double helix** (Figure 10.1.5). It is like a rope ladder that is held at one end and twisted, or a spiral staircase. The 'steps' are only about 2 nm wide.

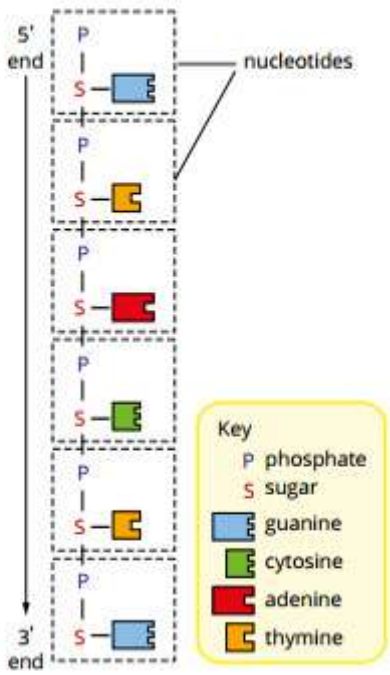


FIGURE 10.1.3 A single polynucleotide chain (strand). Individual nucleotides (shown in boxes) are joined by phosphodiester bonds.

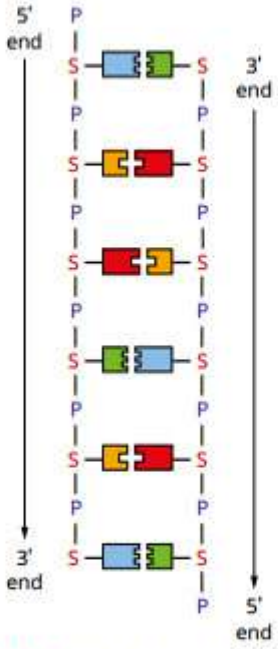


FIGURE 10.1.4 A two-dimensional representation of the DNA molecule. Hydrogen bonds between the complementary base pairs hold the two antiparallel polynucleotide strands together. The base symbols are the same as for Figure 10.1.3.

BIOFILE

DNA length

The 23 human haploid chromosomes contain about 3200 million base pairs. So an 'average' human chromosome contains about 140 million base pairs of DNA. Ten base pairs are about 3.4 nm long, so the DNA in an average chromosome is about 4.76 cm long. This is an extraordinary length considering that a DNA molecule has a very small diameter (2 nm). If you built a model of this molecule using a scale of 1 cm = 1 nm, the model would be 2 cm wide and 476 km long!

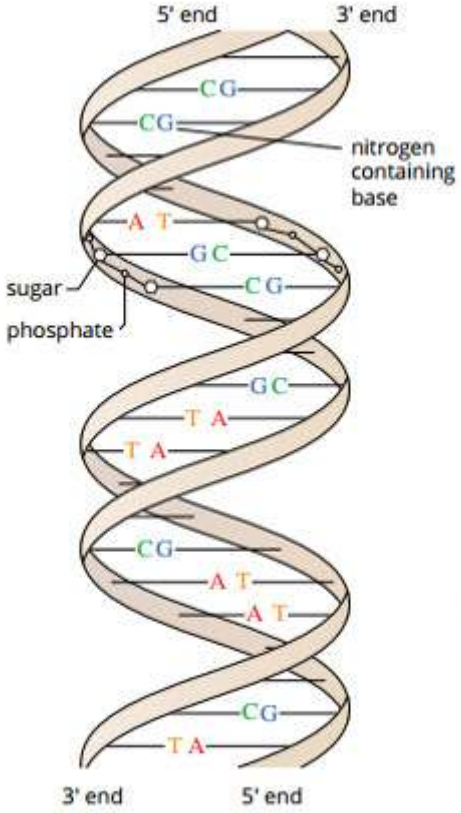


FIGURE 10.1.5 The structure of DNA. Two complementary strands form a double helix. The bases of each strand form a pair: A pairs with T and G pairs with C.

The genome of an organism is the total of an organism's DNA measured in the number of base pairs contained in a haploid (n) set of chromosomes, plus the DNA in organelles (mitochondria and chloroplasts).

Gene expression is the process by which the information in a gene is used to produce a functional product. The products are usually proteins.

GENOMES

The **somatic cells** (all cells in a body except gametes) of most organisms are **diploid** ($2n$). This is because they contain two sets of chromosomes (one set from each parent). These chromosomes range in size from about 50 million to 300 million base pairs. Because both sets of chromosomes are almost identical, the **genome** of an organism is the total of an organism's DNA measured in the number of base pairs contained in a **haploid** (n) set of chromosomes. A typical human cell has two similar sets of chromosomes and each set has DNA totalling 3234 million base pairs. In other words, the human genome has approximately 3234 million DNA base pairs.

GENES AND ALLELES

Genes

DNA is the molecule of life that encodes the information on which organisms are built. The DNA molecule consists of many genes, and these genes determine the characteristics of an organism. At a molecular level, a gene is a unique sequence of DNA. Each gene carries a particular instruction for a cell; for example, how to make silk for a spider web (Figure 10.1.6). The web is made of silk fibroin, which is a structural protein. The genetic information on how to make this protein is in one particular gene, called the silk fibroin gene. The process by which the information in the gene is decoded to assemble silk fibroin is called the gene expression.

A gene is a unit of heredity, made up of a unique sequence of DNA that determines a characteristic of an organism.

Nearly all genes specify the production of a polypeptide chain or **protein**, which perform essential functions in our body's cells. For example, enzymes are proteins that catalyse chemical reactions within the body, such as the reaction that produces sugars from starch. Carrier proteins found in the cell membrane control the movement of essential elements and molecules into and out of the cell. The protein haemoglobin in red blood cells carries oxygen.

FIGURE 10.1.6 Genes carry instructions for a cell. A spider's web is made of the structural protein silk (a fibroin protein).

EXTENSION

Transcription and translation

Protein synthesis consists of two main stages: transcription and translation (Figure 10.1.7). The first stage is transcription and occurs in the nucleus. The section of the DNA which contains the base sequence for the gene is transcribed (copied) into a molecule known as messenger RNA, or mRNA. When the mRNA is produced, it leaves the nucleus and enters the cytoplasm. The second stage of protein synthesis, translation, then occurs in the cytoplasm. Ribosomes in the cytoplasm read the nucleotide sequence on the mRNA in groups of three (known as codons) and specific amino acids are brought together to form a polypeptide chain. Eventually the polypeptide chain is folded or modified to form a fully functioning protein.

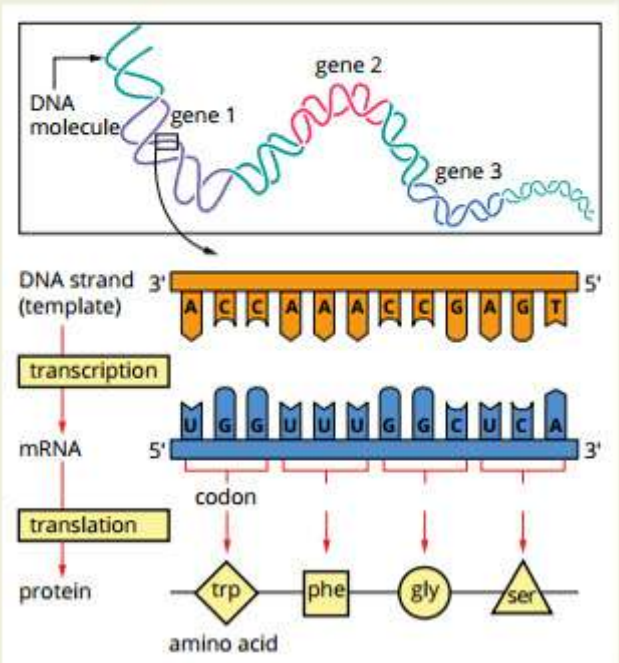


FIGURE 10.1.7 Summary of protein synthesis: transcription and translation.

Proteins control cellular functions and genes control the production of proteins; therefore inherited genes ultimately govern the functions of organisms. Genes vary in size from about 100 to 2.5 million base pairs. The length of the sequence of DNA and the precise order of the base pairs in a gene are the critical factors that determine what the gene product will be like and what it will do in a cell.

Alleles

You can see, simply by looking, that there is variation in the human population. Physical characteristics or **traits** such as skin colour, eye colour and hair colour all vary within populations and even within families. Although an individual gene may be responsible for a specific trait, that gene can exist in different forms known as **alleles**. For example, there is a gene that codes for the amount of pigment in the eye, and therefore eye colour. Alternative forms (alleles) of the gene exist, including one for blue eye colour and another for brown eye colour (Figure 10.1.8). This means that the DNA sequence of bases for these two alleles is slightly different. Both alleles still code for the eye colour gene and are found in the same place (locus) on the chromosome (DNA strand). Somatic cells of a diploid organism contain two alleles for every gene, with one allele for every gene in an organism inherited from each parent.

BIOFILE

Despite the importance of proteins, only 1.5% of human DNA contains genes for making proteins. The remainder is called non-coding or 'junk' DNA and has no known biological function.

A trait is a particular characteristic or feature of an organism.

An allele is one form of a gene.

FIGURE 10.1.8 Eye colour is a complex trait: many genes are involved in producing the variety of eye colours in humans. Each of these genes has different alleles.

BIOFILE

DNA sequencing

DNA sequencing is a procedure that determines the order of nucleotides in an allele. When DNA sequence analysis is used to compare the sequences of two alleles, it often picks up differences in the order of the nucleotides. These differences mean each allele will produce slightly different polypeptides. The sequences of some alleles can produce a polypeptide that is too short to be any use to the cell. For example, many people have an allele that produces the protein called melanin. If a lot of melanin is produced, the person will have brown eyes (Figure 10.1.9). If a person has the allele that does not produce a functional melanin protein, then their hair, skin and eyes will appear white. This is called albinism (Figure 10.1.10). The eyes of a person with albinism may look red because light reflects off normal blood vessels in the back of the eye and the red blood vessels can be seen through the pale iris.

FIGURE 10.1.9 The protein melanin is responsible for brown eyes in humans.

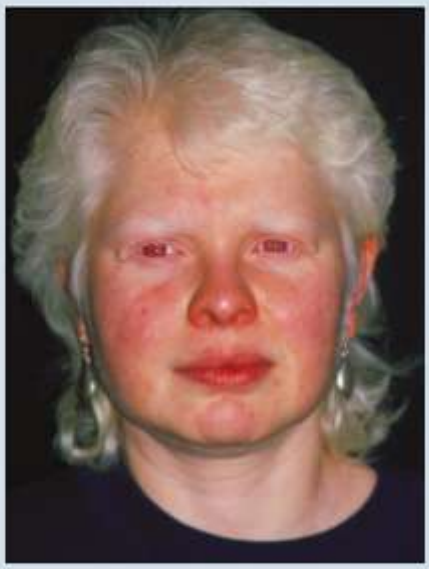


FIGURE 10.1.10 Albinism is a genetic disorder caused by an allele that does not produce a functional melanin protein. This results in white hair and pale skin, and eyes that look red.

DNA sequencing is the process of determining the precise order of nucleotides within a DNA molecule.

10.1 Review

SUMMARY

- Deoxyribonucleic acid (DNA) is the genetic material that contains the instructions for cells to make proteins.
- The genome of an organism is the total of an organism's DNA, measured in the number of base pairs contained in a haploid (*n*) set of chromosomes.
- A gene is a unit of heredity made up of a unique sequence of DNA that determines characteristics of an organism.
- Genes can have many alternate forms, known as alleles.
- There are two alleles for a particular trait: one allele is inherited from each parent.

KEY QUESTIONS

1 Outline the structure of the DNA molecule. In your answer, include:
- the name and components of the unit (building block) of DNA
- the names of the four bases found in DNA
- how nucleotides are joined to build a single stranded DNA molecule
- how a double stranded DNA molecule is formed
- what is meant by 5' and 3' ends of a DNA strand, and the two strands of DNA being antiparallel.

2 A strand of DNA has the sequence ATTCCGTA. Write this out, and under it write the sequence of the complementary strand.

3 Distinguish between DNA, genome, gene and allele.

10.2 Genomes and genomic research

The **Human Genome Project** (HGP) was the biggest worldwide biological project ever undertaken. It involved thousands of people globally, all working towards one common goal—sequencing the human genome.

In this section you will learn about the Human Genome Project. You will also learn about the role of genomic research since the Human Genome Project in:

- sequencing the genes of many organisms
- exploring the relatedness between species
- determining gene function.

The genomic applications for the early detection and diagnosis of human diseases will also be explored.

Figure 10.2.1 shows a computer display of a human DNA sequence as a series of coloured bands. This was created as part of the Human Genome Project.

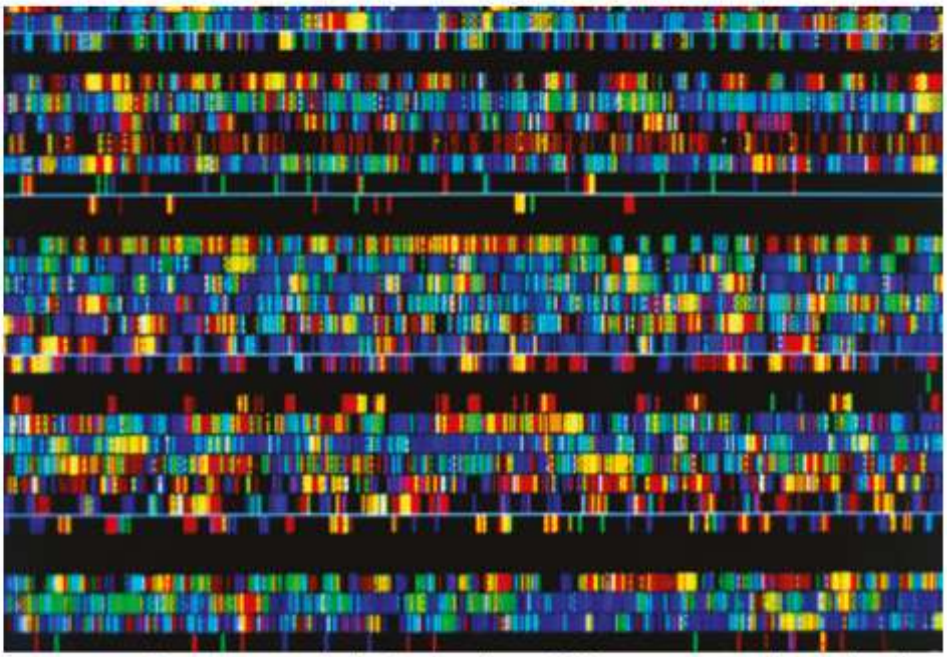


FIGURE 10.2.1 Computer screen display showing a human DNA sequence as a series of coloured bands.

THE HUMAN GENOME PROJECT

The Human Genome Project (HGP) was a worldwide project started in 1990. The goal of HGP was to determine the complete human genome, the precise order of nucleotides within a DNA molecule (known as DNA sequencing) and the number of genes in one human individual. It was the world's largest collaborative biological project and involved biologists from at least 20 universities globally and one private company. The project was completed in 2003 and has paved the way for many advances in genetic research in both humans and other organisms.

THE ROLE OF GENOMIC RESEARCH

When the Human Genome Project began in 1990, approximately 100000 bases were sequenced with the participation of a few laboratories. Since then, technological improvements and automation have increased the speed of DNA sequencing enormously. New methods could reportedly sequence a human genome in 10 days, compared to more than 10 years for the first full human genome sequence! These methods are now being used to sequence many other organisms.

In genetics the term 'cloning' also refers to the production of identical copies of a gene.

BIOFILE

The first genome

The first free-living organism to have its genome sequenced was a bacterium, *Haemophilus influenzae*. The work was completed in 1995 at the J. Craig Venter Institute in the United States. The genome consists of about 1.8 million base pairs in a circular chromosome.

FIGURE 10.2.2 *Haemophilus influenzae* (shown here in yellow) was the first free-living organism to have its genome fully sequenced.

EXTENSION

Determining the DNA sequence

The first stage of DNA sequencing involves replicating a piece of purified DNA in a test tube, in a controlled set of reactions called a polymerase chain reaction, or PCR. The DNA sample is added to a mixture containing two primers (short lengths of DNA, one for the 5' end of the required sequence, and one for the 3' end), DNA polymerase (an enzyme used in DNA replication), normal nucleotides, and terminating nucleotides that are tagged with coloured fluorescent markers. Each type of terminating nucleotide (A, T, G or C) is tagged with a different coloured marker.

During the PCR reaction the DNA strand is split and one strand is used to build the section of DNA required. When a primer binds to a DNA strand, the DNA polymerase begins to replicate the sequence by adding nucleotides. However, when it uses a terminating nucleotide the replication stops. This can happen at any point during the replication, so the process results in many different lengths of DNA fragments (Figure 10.2.3).

After the PCR is completed the DNA mixture is cleaned up to remove any unused nucleotides and other substances, so that it contains only fragments of the DNA sequence required.

In the next stage, the DNA fragments are injected into very fine capilllaries filled with a polymer. A large voltage is then applied, causing the negatively charged DNA fragments to be drawn towards the positive electrode. Smaller fragments move faster than larger ones. Just before reaching the positive electrode the fragments pass through a laser beam that causes the terminating nucleotide to fluoresce. The colour and strength of the fluorescence is recorded, and the data is assembled into a data file.

The data file is then analysed by a computer program that arranges the detected bases in the correct sequence. The output from the software is the sequence of bases and a matching chromatogram showing the strength of the fluorescence and the base that produced it (Figure 10.2.4). Because the data from the fluorescence detector is sometimes misread (especially if the quality or volume of DNA is low), the sequence must be checked manually by the researcher. Sequences are always obtained in both directions (5' to 3', and 3' to 5'), and the two sequences are matched up by the program.

The order of bases in the original sample of DNA can be read by the order of the peaks. Figure 10.2.5 shows how the terminating nucleotides on DNA fragments are read and converted into a chromatogram.

DNA template to be sequenced: AGCTTGGATT
Sequence of the complementary strand: TCGAACCTAA

If the terminating nucleotide is for A, four fragments are produced:
TCGA
TCGAA
TCGAACCTA
TCGAACCTAA

If the terminating nucleotide is for T, two fragments are produced:
T
TCGAACCT

FIGURE 10.2.3 Example showing how different fragment sizes are produced when terminating nucleotides are added at different points in the sequence during a polymerase chain reaction.

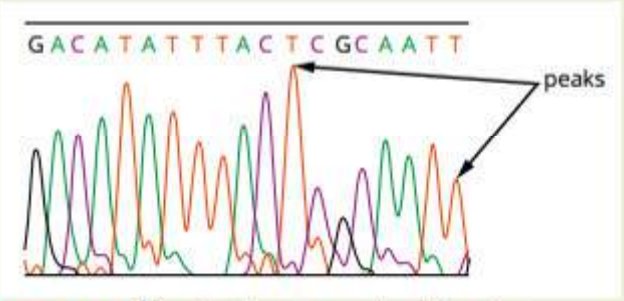


FIGURE 10.2.4 The output from sequencing software is a sequence of bases (top row) and a matching chromatogram that shows the strength of the fluorescence detected. The bases are colour-coded to make them easy to identify in the chromatogram.

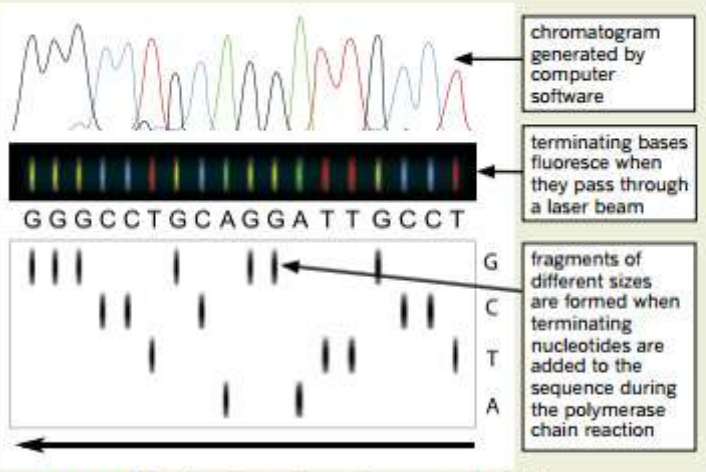


FIGURE 10.2.5 Capillary electrophoresis separates the DNA fragments according to size. The fragments pass through a laser beam, causing the terminating nucleotides to fluoresce. Computer software then transforms the data into a sequence and a matching chromatogram.

Sequencing genes of many organisms

Besides sequencing the human genome, genome sequences have now been generated for some key model organisms (organisms commonly used in scientific research). Examples of organisms whose genome has been sequenced include the house mouse (*Mus musculus*), brown rat (*Rattus norvegicus*), fruit fly (*Drosophila melanogaster*) (Figure 10.2.6), rice (*Oryza sativa*) and wild mustard cress (*Arabidopsis thaliana*).

Scientists have used gene sequencing to understand the function of many important genes used in agriculture. For example, researchers have found that fragrant varieties of rice such as jasmine and basmati rice have a change in the allele of a gene on chromosome 8. This different allele causes a fragrant protein to be produced. Some forms of rice do not have this allele and therefore are not fragrant. The difference does not affect any other part of the development of the plant.

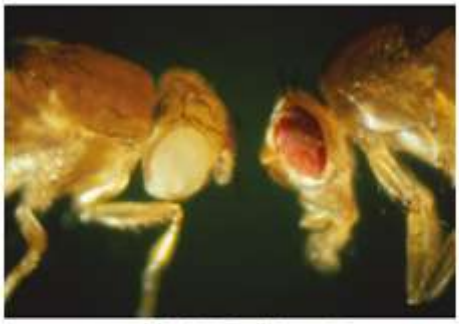


FIGURE 10.2.6 The fruit fly (*Drosophila melanogaster*) is a model organism often used in genetic research. The fly on the right is a normal fruit fly with red eyes and the fly on the left is a mutant with white eyes.

Comparing relatedness between species

The DNA sequence of a gene determines the amino acid sequence of a protein, which is the functional unit of the cell. Humans have many proteins that are similar to proteins in other organisms. Although this means that the amino acids in human proteins may be slightly different to those in another organism's protein, the proteins can carry out the same function.

BIOLOGY IN ACTION

Unlocking the secrets of the wallaby genome

An international team of researchers have sequenced the genome of the Tammar wallaby (*Macropus eugenii*). The first results found a 68% similarity between humans and wallabies.

The availability of the genome sequence provides important knowledge for understanding human and animal health. It will help to unravel the biology of some interesting traits such as the regulation of lactation (the formation and secretion of milk from the mammary glands) and embryonic diapause (a period of suspended development).

For example, researchers noted that the lactating female wallaby is capable of feeding newborn and older joeys at the same time. Remarkably, each joey is delivered milk that has the correct composition for its particular stage of development. Understanding the control mechanisms involved here is of major interest to the dairy industry.

In diapause, wallaby embryos develop to a stage of about 100 cells and then go into a state of suspended animation for 9–10 months until an environmental change spurs the older joey to leave the pouch. Leaving the pouch reduces the sucking stimulus and initiates the development of the 'suspended' early-stage embryo. Understanding the mechanisms that control this phenomenon could lead to new treatments for infertility or methods of contraception in humans.

Figure 10.2.7 shows Doctor Sue Forrest, head of the Australian Genome Research Facility (AGRF), a major national research facility. She works in the field of genomics with a focus on deciphering the genetic basis of common human disorders. The AGRF took up the challenge to drive the first large genome sequencing project ever undertaken in Australia.

FIGURE 10.2.7 Doctor Sue Forrest and a young Tammar wallaby.

Scientists often compare the gene sequence responsible for the proteins that are common to different species. Cytochrome c is an example of one such protein. It is a protein involved in cellular respiration and is produced by most eukaryotes. Table 10.2.1 shows an amino acid sequence for a section of the cytochrome c protein in a number of different eukaryotic animals. For the amino acids shown, it is possible to see there are only a few differences in the cytochrome c of these organisms.

	Amino acid position									
Organism	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Gorilla	Ala	Leu	Glu	Gly	Pro	Gly	Thr	Asp	Phe	Tyr
Chicken	Ala	Leu	Glu	Met	Pro	Gly	Arg	Cys	Phe	Try
Iguana	Ala	Leu	Glu	Met	Pro	Gly	Arg	Cys	Phe	Cys
Bullfrog	Ala	Leu	Glu	Met	Pro	Gly	Cys	Glu	Phe	Cys
Shark	Thr	Leu	Glu	Leu	Pro	Gly	Cys	Glu	Phe	Ala

TABLE 10.2.1 An amino acid sequence for a section of the cytochrome c protein in a number of different eukaryotic animals.

The comparison of DNA (gene) and amino acid (protein) sequences allows evolutionary relationships to be deduced (for example, by the construction of a phylogenetic tree; see Chapter 6). Differences in a DNA or protein sequence arise because of random mutations. The number of differences in a sequence of two species depends on how long ago the species' lineages diverged. Species whose lineages diverged long ago, such as humans and turtles, are less closely related than species whose lineages diverged more recently, such as horses and donkeys.

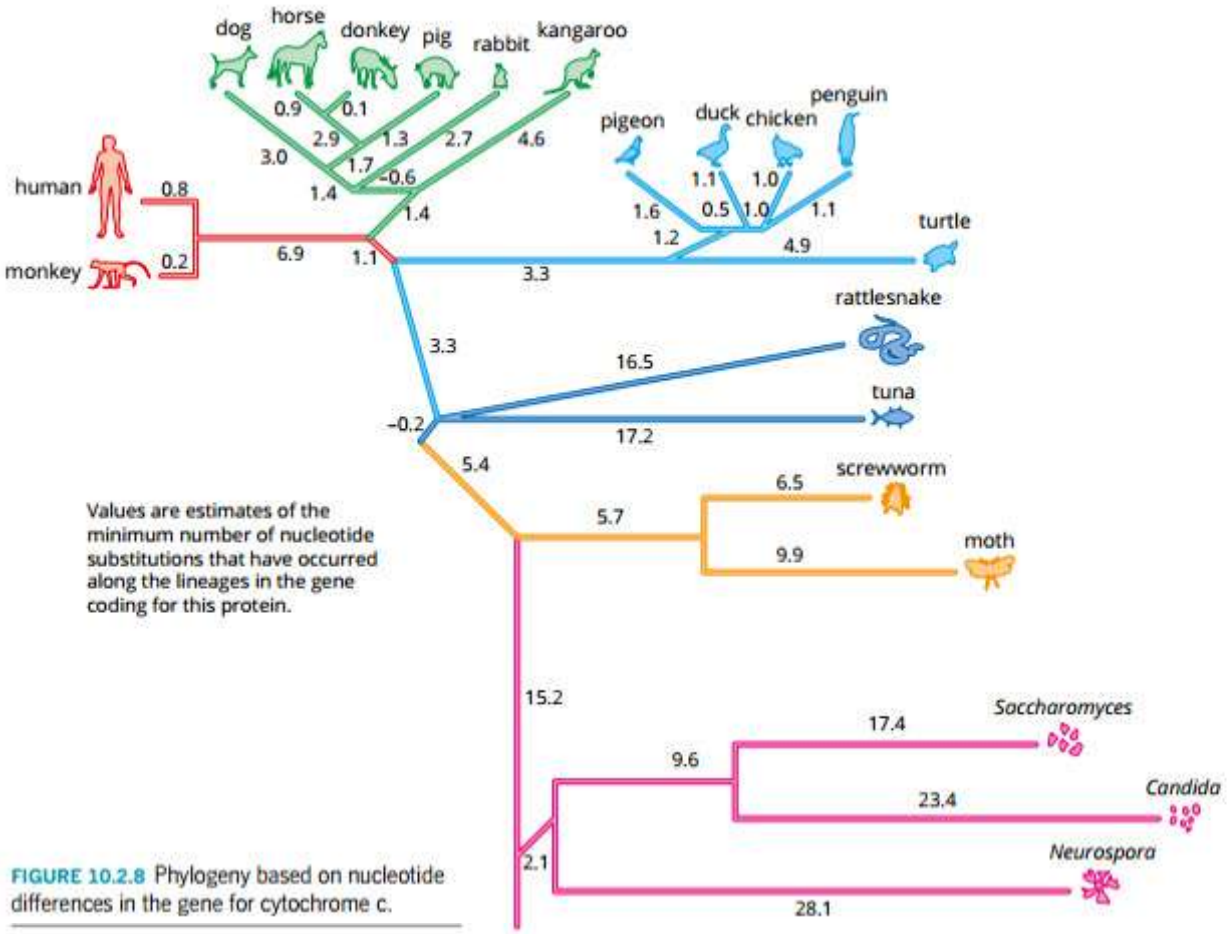


FIGURE 10.2.8 Phylogeny based on nucleotide differences in the gene for cytochrome c.

Figure 10.2.8 shows a phylogeny based on nucleotide differences in the gene for cytochrome c. Many species evolved from a common ancestor and all have a cytochrome c gene. The species that have been separated for a longer time have accumulated more differences in the cytochrome c gene than those separated for a shorter time. As a result they are further apart on the phylogenetic tree.

The spread of pathogenic organisms can also be traced by comparing sequences. For example, the strain of influenza H1N1 virus (which is a RNA virus) that spread across the world in 2009 could be traced to the human, swine and avian strains. The RNA could be sequenced to determine that the various strains had evolved from a common ancestor. Sequencing is an important tool in tracking the evolution of influenza viruses around the world each year. This helps the World Health Organization predict new strains and develop suitable vaccines to prevent major outbreaks of disease.

Finally, comparing of DNA sequence between humans and model organisms also allows scientists to find out which aspect of the model organism is similar to human. For example, the house mouse is often used to gain insights into gene function, disease and drug development. However, not all aspects of mouse biology reflect human biology. Comparing DNA sequences between human and mouse will allow scientists to identify which aspects are similar and allow them to identify when mice can be best used as a useful model organism.

RNA viruses, like influenza virus, use ribonucleic acid as their genetic information molecule. RNA is built of four nucleotides: A, C, G and U (uracil) in place of T. Like DNA, it encodes the proteins needed by the virus and its sequence can be determined using laboratory techniques similar to those used for DNA sequencing.

BIOLOGY IN ACTION

The origin and future of the Australian dingo

Most theories about how the dingo, *Canis lupus dingo* (Figure 10.2.9), came to inhabit Australia have assumed Asian seafarers introduced it between 3500 and 5000 years ago, and that the dingo is therefore a kind of dog domesticated from Chinese wolves. These theories were supported by the fact that fragments of wolf DNA were found in the genomes of dogs. However, the results of a study that determined and compared the full genome of the dingo with the basenji (from central Africa), the domesticated boxer (from Europe) and grey wolves (from China, Croatia and Israel), suggests these theories are wrong.

The study found that the wolves were all more closely related to each other than to the dogs, and that the dogs (the dingo, basenji and boxer) were all more closely related to each other than to the wolves. From this researchers can infer that dogs evolved earlier than previously thought, from a relative of grey wolves that has since become extinct, and that the fragments of wolf DNA in the genomes of dogs are the result of more recent interbreeding.

The study also suggested that dogs were probably domesticated by nomadic hunter-gatherers, rather than groups of people who had settled to farm the land, as previously thought. Unlike domestic dogs, most dingoes do not have the genes needed to digest starch, which is found in farmed grains. So the dingo appears to have branched off from the other dogs before humans settled into farming societies. What this means is that the dingo is probably the closest animal to dogs that lived 10000 to 35000 years ago. However, interbreeding between dingoes and domestic dogs is changing this. Indeed, hybridisation may soon send pure dingoes extinct, which could have ecological impacts. For example, there is some evidence that the breeding season of dingoes has become longer as a result of domestic dog genes, leading to a large increase in their numbers.

FIGURE 10.2.9 An Australian dingo.

Determining gene function

Finding the sequence of the entire human genome does not tell us about the functions of the genes. The protein encoded by the gene must be identified in order to study its location and function. A gene sequence can be analysed and compared to other species where its function is already understood.

Molecular techniques based on gene sequences allow scientists to identify alleles and mutant forms of a gene that may cause a malfunction. The gene sequence can be modified and inserted into model organisms, and studying the effects of the modification helps to understand the normal function. Alternatively, genes can be disabled to provide direct evidence for the function of the gene and the protein it encodes. The complete human genome sequence provides the raw data for scientists to search for sequences that are related to genes already identified in other organisms that may be useful for therapeutic purposes.

BIOLOGY IN ACTION

Diagnosing cystic fibrosis

In the disease cystic fibrosis (CF), an individual carries two alleles of the CF gene. The normal copy of the CF gene produces a protein named CFTR (cystic fibrosis transmembrane conductance regulator), which forms a channel in the outer cell membrane. The CFTR channel controls the flow of chloride out of the cell. Changes in the gene can lead to defective CFTR channel proteins being produced or, for some alleles, no protein being produced at all.

The symptoms of CF vary from person to person. Sufferers have high salt levels in their sweat and frequently produce sticky mucus in the lungs, which blocks the airways and increases the chance of infection. The pancreas does not work efficiently in most sufferers, and some individuals may also have liver problems.

Breathing difficulties and lung infections present the greatest threat to the lives of people with cystic fibrosis (Figure 10.2.10). The lung-related symptoms can be so severe that lung transplants (and even triple transplants of heart, lungs and liver) are performed. The cells of their transplanted lungs carry two normal copies of the CF gene. All other somatic cells in the body have two defective alleles of the CF gene.

Lung transplants greatly enhance the capacity to breathe for a person with CF. This improves the quality of life and extends life expectancy. However, it does not deal with the other symptoms of cystic fibrosis, such as digestive difficulties and male sterility. Transplant recipients also face problems associated with tissue rejection and therefore need ongoing treatment with immuno-suppressant drugs.

If a couple knows that they both carry a copy of the defective CF allele or any other genetic disease or disorder, there is now an option for them to screen the embryo. In order for this to happen, in vitro fertilisation (IVF) is used to create an embryo (Figure 10.2.11). The embryo is then screened using pre-implantation genetic diagnosis (PGD). PGD involves removing 1 or 2 cells from an embryo at the 8-cell stage. DNA in these cells is tested for genetic disorders, while the embryo continues to develop normally. This allows the selection of embryos that do not contain genetic disorders, which can then be implanted into the uterus to develop.

FIGURE 10.2.10 A physiotherapist using an intermittent positive pressure breathing (IPPB) machine to help clear the lungs of a patient with cystic fibrosis.

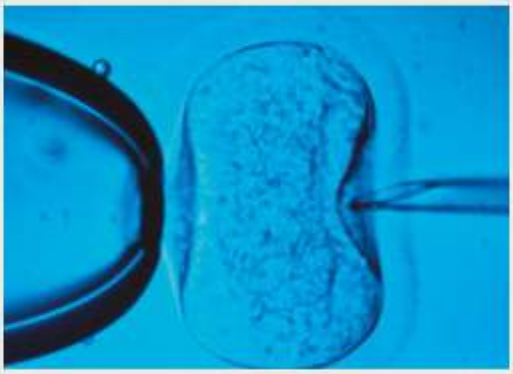


FIGURE 10.2.11 In vitro fertilisation (IVF) research. Here an ovum is held steady with a pipette (left) while a sperm cell is being injected directly into it.

Early detection and diagnosis of human diseases

Using DNA sequencing, scientists can identify base differences in a gene suspected to be the cause of a genetic disorder. This is done by comparing the candidate gene in a DNA sample from a healthy person with a sample from those with the disorder. For example, an inherited form of breast cancer is caused by the *BRCA1* gene on chromosome 17. The gene is responsible for the production of enzymes that repair damaged DNA. As a result, the cells are more likely to develop additional genetic mutations that can lead to cancer. In such cases, determining exactly how a gene differs in affected and healthy individuals of a family is important for predicting who may be at risk of developing cancer, and in developing a cure.

A person with a family history of an inherited disease such as cancer can have their DNA sequenced to determine if they carry the allele that caused the cancer in other family members. They can then take preventative measures or have treatment to prevent the onset of disease.

10.2 Review

SUMMARY

- The Human Genome Project determined the genome, the precise order of nucleotides within a DNA molecule and number of genes in one human individual.
- DNA technology from the Human Genome Project allowed for the DNA sequencing of other species.
- DNA sequencing of different species allows for comparison between species to determine evolutionary relationships and also determine which model organism to use for different diseases.
- DNA sequences of different species can be compared to detect genes and also determine gene function.
- The gene (or genes) responsible for a human disease can be determined by comparing the DNA sequence of a healthy individual with that of an individual suffering from the disease. Knowledge of the genes involved enables diseases to be detected early, and some may even be prevented.

KEY QUESTIONS

1 What was the original goal of the Human Genome Project?

2 Outline three outcomes of the Human Genome Project.

3 What major question does the Human Genome Project not answer?

4 The statements below describe the process of DNA sequencing. Reorder the statements in the correct order, from first to last.
- a chromatogram is produced
- DNA is replicated and the test tube mixture ends up with a range of fragments of DNA of different sizes (lengths)
- DNA is added to a mixture containing DNA polymerase, nucleotides, and terminating nucleotides that are tagged with fluorescent markers
- gel from gel electrophoresis is read by computers
- terminating nucleotides fluoresce as they pass through a laser beam

10.3 Chromosomes

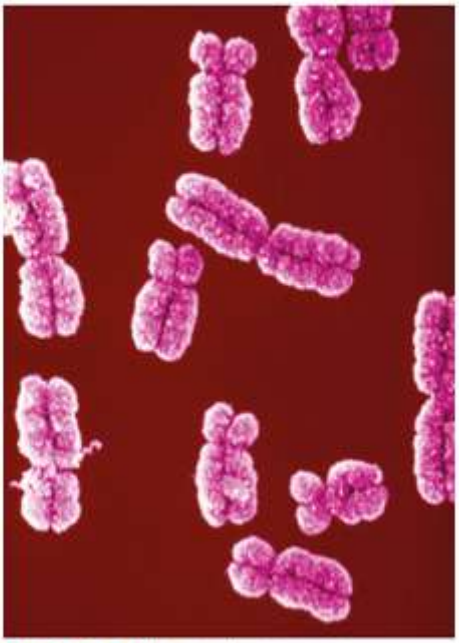


FIGURE 10.3.1 Human chromosomes photographed just before alignment along the metaphase plate (metaphase) in mitosis.

In all organisms, inherited characteristics are determined by genes located on DNA in chromosomes (Figure 10.3.1). In this section you will learn about the role of chromosomes as structures that package DNA. You will learn about their variability in terms of size and the number of genes they carry in different organisms. You will also learn about the distinction between an autosome and a sex chromosome and the nature of a homologous pair of chromosomes.

The presentation of an organism's set of chromosomes to identify chromosome number abnormalities in humans will also be explored.

THE ROLE AND STRUCTURE OF CHROMOSOMES

A **chromosome** is a structure containing a single DNA molecule and its associated proteins. Chromosomes therefore carry genes. Chromosomes can have various shapes and sizes, and their appearance changes during the life of a cell.

Eukaryotic organisms have sets of linear chromosomes located in the nucleus, and the number of chromosomes is constant in each species. Each chromosome carries a unique set of genes. These chromosomes are passed on to daughter cells during mitosis and to germ cells during meiosis.

Prokaryotes have a single circular chromosome. Prokaryotes may also contain smaller circular DNA molecules called plasmids, which can move between cells.

Structure of chromosomes

In eukaryotes the DNA is coiled around small proteins called **histones**, forming a particle about 10 nm in diameter, called a **nucleosome**. Figure 10.3.2 shows DNA and associated proteins located in chromosomes. The eukaryotic chromosome shown in the image is at a stage in cell division where it is slightly condensed. The diagram shows a section of the chromosome unravelled to show how DNA is wrapped within it. The DNA is coiled and super coiled around structural proteins.

Nucleosomes give the DNA strand the appearance of a string of beads. This arrangement of DNA wrapped around histones serves to package the DNA efficiently and to protect it from enzymatic degradation.

A chromosome is a structure containing a single DNA molecule and associated proteins.

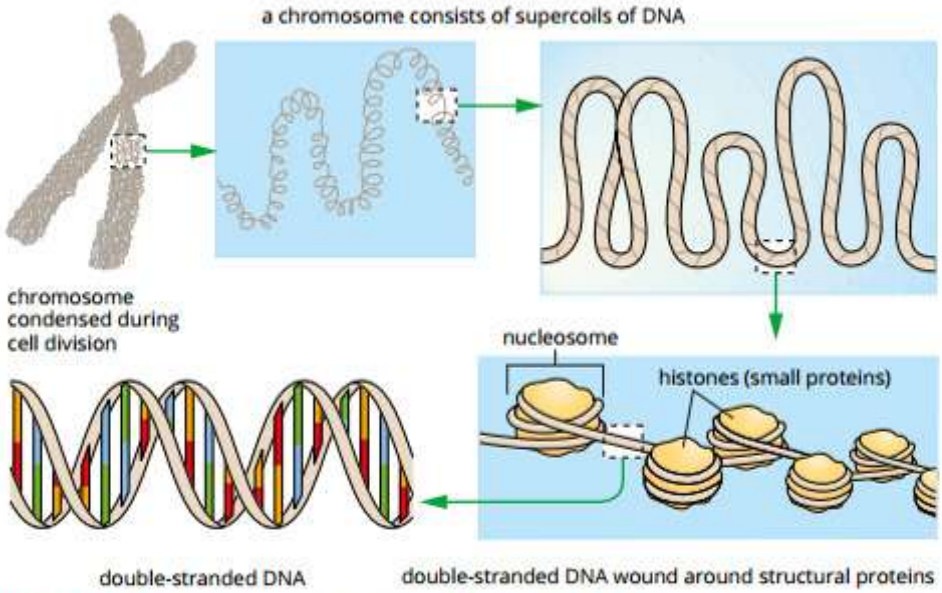


FIGURE 10.3.2 A chromosome unwound to reveal the complex substructure of supercoils of DNA. Each coil consists of histones that are structural proteins, which package and order the DNA into structural units called nucleosomes. Further unwinding of a nucleosome reveals the double-stranded DNA structure.

When a eukaryotic cell is preparing to divide, chromosomes become condensed and are visible when the cell is stained and viewed at high magnification under a light microscope. The nucleosomes fold in a regular manner, producing supercoils (Figure 10.3.2). When chromosomes are highly condensed they are visible under a light microscope.

In comparison, the DNA in prokaryotic cells is usually present in a single circular chromosome that is located in the nucleoid region of the cytoplasm. Prokaryotic chromosomes are less condensed than their eukaryotic counterparts. Prokaryotic chromosomes do not have features that are easily identifiable when viewed under a light microscope.

This can be seen in Figure 10.3.3, which shows *Legionella pneumophila*, the bacterium responsible for legionnaires' disease. Under light micrograph, the nucleoid region can be seen but not the features of the chromosomes.

A histone is a small protein that binds to DNA and plays a key role in chromatin structure.

A nucleosome consists of histone proteins around which DNA is coiled.

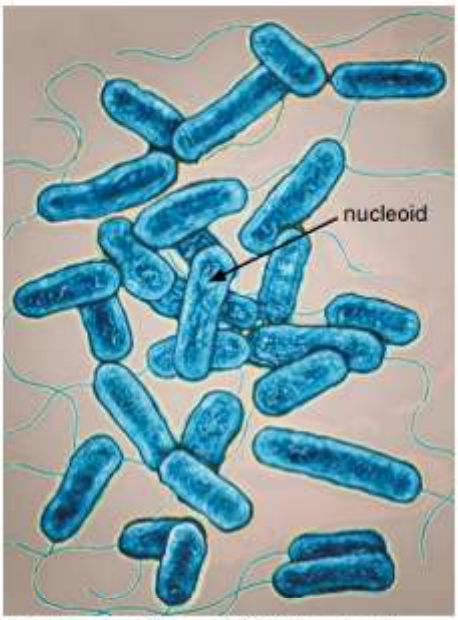


FIGURE 10.3.3 Coloured TEM of *Legionella pneumophila*. Although the nucleoid region can be seen, the features of the chromosomes cannot.

Types of chromosomes

Each chromosome has a constriction point called the **centromere**, which divides the chromosomes into two sections. The regions on either side of the centromere are referred to as the chromosome arms (Figure 10.3.4). The shorter arm is called the p arm and the longer arm is called the q arm. Photographs or diagrams of chromosomes are always arranged so that the p arm is at the top.

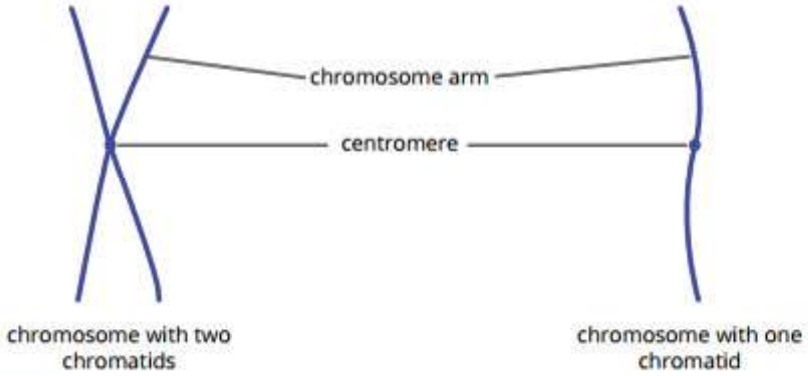


FIGURE 10.3.4 Each chromosome has a constriction point called a centromere. The regions on either side of the centromere are called arms. The shorter arm is called the p arm and the longer arm is called the q arm.

There are four major types of chromosomes, based on the position of the centromere (Figure 10.3.5):

- Metacentric chromosomes have the centromere centrally positioned, giving arms of equal length.
- Submetacentric chromosomes have the centromere towards one end, resulting in arms of unequal length, with a long arm approximately twice the length of the short arm.
- Acrocentric chromosomes have the centromere very close to one end.
- Telocentric chromosomes have the centromere at the tip of the arms.

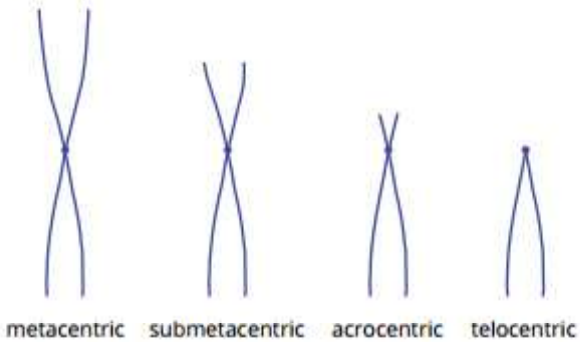


FIGURE 10.3.5 There are four major types of chromosomes based on the position of the centromere.

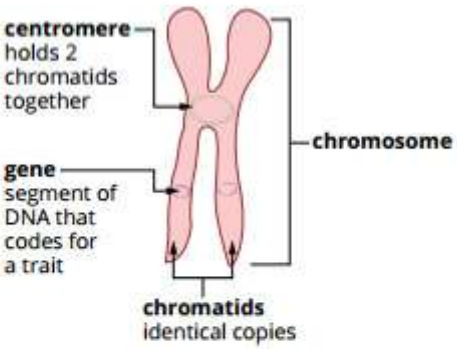


FIGURE 10.3.6 Each gene occupies a fixed locus on a chromosome. The gene indicated here is on the q arm at a precise distance from the centromere.

The position of a gene on a chromosome is called a locus.

Chromosome size

Each DNA molecule contains many genes; for example, there are 20 000 to 25 000 genes in the human genome. The longest human chromosome (chromosome 1) has about 2000 genes. Each gene has a particular position, called a **locus**, on a specific chromosome (Figure 10.3.6). The genes of each DNA molecule are separated by regions called spacer DNA. Figure 10.3.7 shows a short stretch of double-stranded DNA. Genes are highlighted in red and the spacer regions of DNA separating the genes are shown in blue. Spacer regions include DNA that does not encode a protein product. However, they may function in spacing genes far enough apart to enable enzymes or other molecules to interact easily with them. Chromosomes differ in size because of differences in the number of genes and the amount of spacer DNA between the genes.

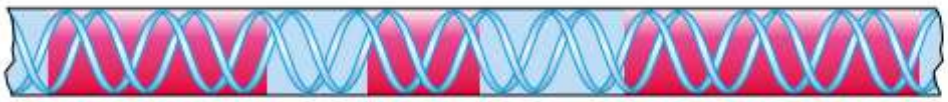


FIGURE 10.3.7 A short stretch of double-stranded DNA. Genes are highlighted in red and the spacer regions of DNA separating the genes are shown in blue.

BIOLOGY IN ACTION

Chromosome numbers of Australian plants

Chromosomes were first observed by Walther Fleming in 1882. While he was examining cells of a salamander larva under a light microscope, he saw minute threads in the nucleus. Since Fleming's time, the chromosome numbers of many plants and animals have been documented. This information is important for crossing species to breed new varieties of plants for horticulture and for understanding evolutionary patterns.

The family Proteaceae is a conspicuous and important part of the Australian bush, from heathlands to rainforests. It includes banksias, grevilleas, waratahs and the macadamia nut tree. The Australian waratahs (Figure 10.3.8) and their relatives in South America are characterised by a diploid number of 22. In contrast, all grevilleas (Figure 10.3.9) and their relatives such as hakeas (tribe Grevilleae) have one pair of chromosomes less, with a diploid number of 20. Chromosome number provides important evidence about the evolution and relationships of these plants.

FIGURE 10.3.8 Members of the family Proteaceae include waratahs (*Telopea* species), which have a diploid chromosome number of 22.

FIGURE 10.3.9 Grevilleas (*Grevillea* species) have a diploid chromosome number of 20.

Variation in number of chromosomes between species

In eukaryotic organism (plants, fungi, animals), cells that have a nucleus contain a fixed number of chromosomes. The number of chromosomes in somatic cells is characteristic of a species.

The **ploidy** level of a cell is the number of chromosome sets that it carries. Gametes have nuclei that contain only one set of chromosomes and they are called **haploid** (designated as n). Somatic cells are **diploid** ($2n$) because they contain two sets of chromosomes: one from each parent.

The diploid chromosome numbers of organisms vary widely, as shown in Table 10.3.1. In humans the diploid number is 46. In some species of Australian ants (*Myrmecia* species) the diploid number is 2; each ant has only one pair of chromosomes ($n = 1$). Some ferns have more than a thousand chromosomes in each somatic cell.

The number of sets of chromosomes in a cell is called the ploidy level. Haploid cells have one set, diploid cells have two sets, and polyploid cells have three or more sets.

Organism	Diploid number ($2n$)
Animals	
Horse nematode worm, *Parascaris equorum*	2
Fruit fly, *Drosophila melanogaster*	8
Koala, *Phascolarctos cinereus*	16
Cat, *Felis catus*	38
Human, *Homo sapiens*	46
Chimpanzee, *Pan troglodytes*	48
Platypus, *Ornithorhynchus anatinus*	52
Dingo, *Canis lupus dingo*	78
Plants and algae	
Pipe-cleaner moss, *Ptychomnion aciculare*	14
Garden pea, *Pisum sativum*	14
Cabbage, *Brassica oleracea*	18
All eucalypts, *Eucalyptus* spp.	22
Blackwood, *Acacia melanoxylon*	26
Pink rock orchid, *Dendrobium kingianum*	38
Single-celled alga, *Euglena gracilis*	90
Coconut palm, *Cocos nucifera*	596
Fern, *Ophioglossum reticulatum*	1260
Fungi	
Mould, *Penicillium* species	2
Rust fungus, *Puccinia graminis*	6
Oyster mushroom, *Pleurotus ostreatus*	22
Edible mushroom, *Agaricus bisporus*	26
Brewer's yeast, *Saccharomyces cerevisiae*	32

TABLE 10.3.1 Diploid numbers of chromosomes in various species of eukaryotes.

Homologous chromosomes

Humans have 46 chromosomes, comprising 23 inherited from their mother and 23 inherited from their father. Forty-four of these chromosomes form 22 matching pairs. The same genes are found at the same locations (loci) on the two chromosomes in a matching pair. They are referred to as **homologous chromosomes** or homologues.

Figure 10.3.10 shows metaphase chromosomes, which are classified according to the position of the centromere, in this case as either metacentric or acrocentric. These are homologues because they contain the same gene sets. The sex chromosomes for all females are also homologues because they have a matching pair of X chromosomes. The sex chromosomes for males are not homologous because they have an X and a Y chromosome, which contain different gene sets.

Nevertheless, in most mammals the X and Y chromosomes behave as a homologous pair during meiosis because some small regions of these chromosomes are homologous.

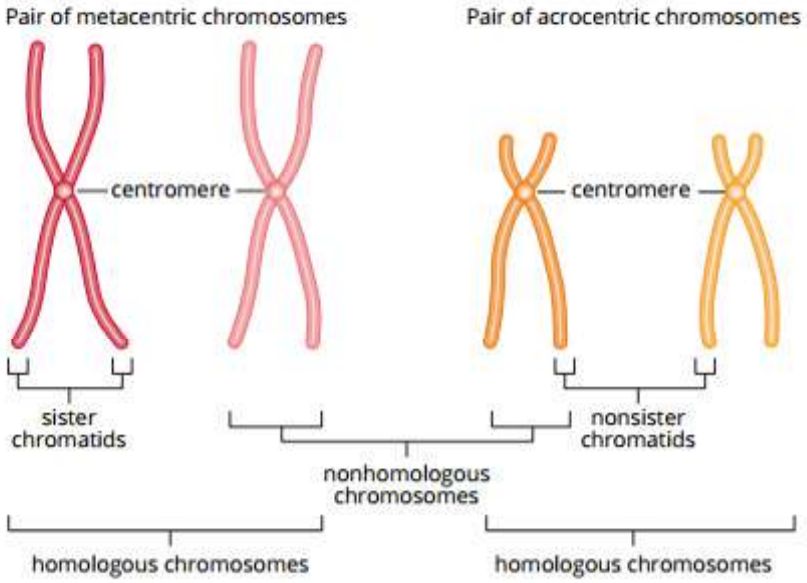


FIGURE 10.3.10 Metaphase chromosomes are classified according to the position of the centromere, in this case as either metacentric or acrocentric.

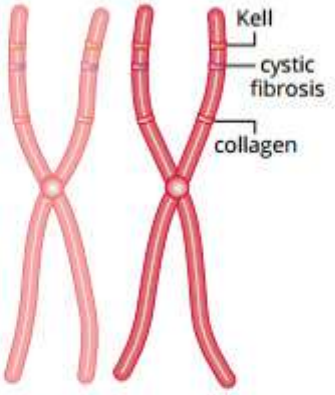


FIGURE 10.3.11 The two human chromosome homologues during metaphase. The locus for three genes is shown: a collagen gene, the cystic fibrosis gene and the Kell gene.

In Figure 10.3.11, two human chromosome homologues are shown during metaphase. The loci for three genes are shown: a collagen gene, the cystic fibrosis gene, and the Kell gene which produces a protein involved in determining the Kell blood groups. The three genes would be in this same position in all cells in most individuals.

The two **chromatids** of a chromosome in a somatic cell contain matching DNA molecules. Non-dividing cells have two copies of each gene, so they have two copies of alleles (which may be identical or different) for each gene. However, in actively dividing cells there is a period during the cell cycle, after chromosome replication (S) and before cytokinesis, when there are four copies of each gene in the diploid nucleus (Figure 10.3.11), but there can be no more than two alleles in total (one from each parent).

Sex chromosomes

Sex chromosomes (also called or allosomes) are chromosomes involved in sex determination. Chromosomes that are not involved in sex determination are called **autosomes**. In humans and all other mammals, a pair of chromosomes known as the X and Y chromosomes determine the sex of an individual. Other types of organisms may have different types of sex-determining chromosomes.

Some organisms (such as fungi and algae) do not have sex-determining chromosomes and therefore do not have sexes; instead they have 'mating types'. Table 10.3.2 shows different patterns of sex determination by segregation of sex chromosomes. Individuals with two similar sex chromosomes are the **homogametic** sex. Individuals with different sex chromosomes are the **heterogametic** sex.

Examples of organisms	Female	Male
humans, other mammals, fruit flies	XX	XY
birds, butterflies, strawberries	ZW	ZZ
grasshoppers, moths	XX	XO
plants	XX	XY

TABLE 10.3.2 Sex determination varies across groups of organisms. Different types and combinations of sex chromosome are involved in determining the sex of an organism.

In humans, females have two X chromosomes, i.e. XX. This is described as homogametic. Males have one X and one Y chromosome, i.e. XY. This is described as heterogametic. Sex is determined by the presence or absence of the Y chromosome. The gametes of females (eggs) carry an X chromosome. They also have one copy of each of the other 22 chromosomes, the autosomes, which are not involved in sex determination. During meiosis (see Section 9.2) in males, the X and Y chromosomes pair at the equator, ensuring equal segregation of X and Y chromosomes into sperm. So 50% of male gametes (sperm) will have an X chromosome and 50% will have a Y chromosome, together with a copy of each autosome.

Figure 10.3.12 shows that human females are genotypically XX and therefore produce gametes carrying an X chromosome. Human males are genotypically XY, so 50% of the sperm produced carry an X chromosome and the remainder carry a Y chromosome. Therefore you could expect the male to female ratio in human populations to be approximately 1:1. A number of syndromes in humans are caused by an incorrect number of sex chromosomes, resulting from errors in meiosis (see Section 9.2).

Segregation of sex chromosomes also determines sex in other species. For example, in birds and strawberries the females are heterogametic (ZW) and males are homogametic (ZZ). The Z and W notation is used to distinguish this system from the XX/XY system.

In grasshoppers there is only one sex chromosome. Females are XX but males are XO, where the O refers to the absence of a matching sex chromosome. The diploid chromosome number in grasshoppers is therefore even in females and odd in males.

Sex chromosomes (also called allosomes) are chromosomes involved in sex determination.

Autosomes are chromosomes that are not involved in sex determination.

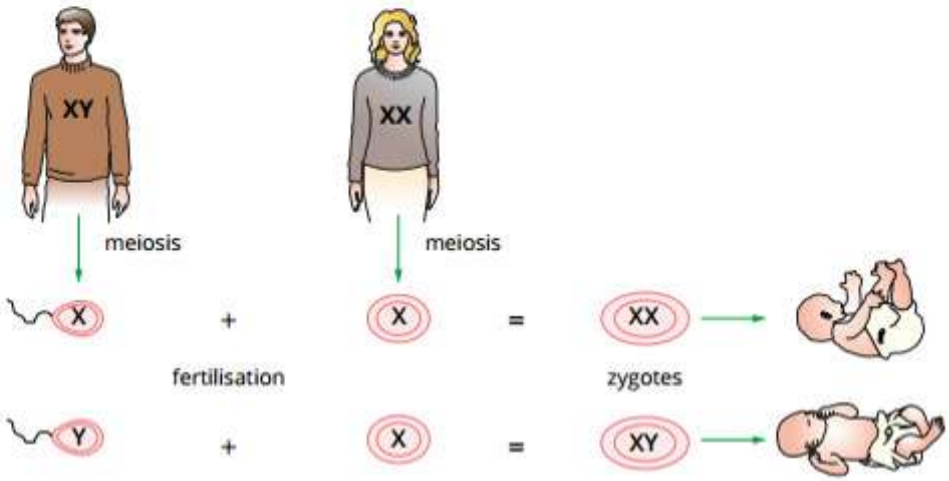


FIGURE 10.3.12 In humans, the inheritance of an X chromosome from both parents results in female offspring (XX). The inheritance of an X chromosome from the mother and a Y chromosome from the father results in male offspring (XY). The sex of a baby is determined by the sperm (X or Y) that fertilises the egg.

KARYOTYPES

Scientists examine eukaryotic chromosomes when they are most visible in the cell—at the metaphase stage of the cell cycle (Figure 10.3.16). The chromosomes are stained so that characteristic patterns of light and dark bands (G bands) appear along the arms of the chromosomes. The bands reflect regional differences in the amounts of bases A and T versus G and C. Banding patterns are specific and consistent. They can be used to distinguish between chromosomes and to identify subtle changes in chromosome structure that may be associated with genetic abnormalities.

Figure 10.3.13 shows the striking similarity in banding patterns in a chromosome from human, chimpanzee, gorilla and orangutan.

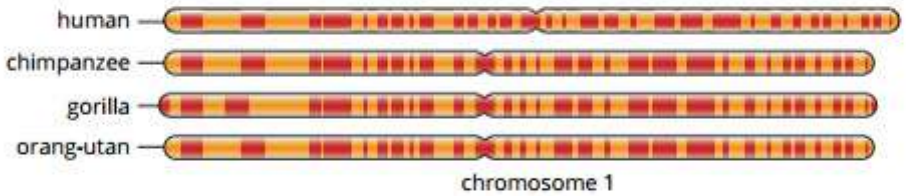


FIGURE 10.3.13 The banding patterns in chromosome 1 from human, chimpanzee, gorilla and orangutan show striking similarities.

A **karyotype** is the image or picture of the full set of chromosomes from an individual's cell. A karyotype is represented by photographs or diagrams of the chromosomes arranged in pairs according to their length and the position of the centromere. Karyotypes allow scientists to compare the chromosome sets of related species. Karyotypes also allow scientists to identify changes that may be associated with genetic abnormalities such as:

- changes in chromosome number (the loss or gain of whole chromosomes)
- changes in structure (such as the duplication, inversion or deletion of part of a chromosome).

EXTENSION

Sex determination that does not involve sex chromosomes

In some species, sex is determined by haplodiploidy. Males develop from unfertilised eggs, so they are haploid. Females develop from fertilised eggs, so they are diploid. This ploidy system occurs in a number of insects, including wasps and bees (Figure 10.3.14).

Alleles of a single gene may determine sex in some species (e.g. midges), while in other species sex is environmentally determined. In the latter case, sex determination may depend on temperature (e.g. turtles, crocodiles), day length (e.g. *Gammarus duebeni*, a shrimp) or richness and availability of food resources (e.g. mermithid nematode worms).

Loggerhead sea turtles lay their eggs on a beach above the high water mark (Figure 10.3.15), then cover the eggs with sand and return to the sea. The eggs incubate under the sand. The ratio of male to female young emerging depends on the incubation temperature. For loggerhead turtles (*Caretta caretta*), temperatures between 32 °C and 34 °C will result in only female hatchlings, while temperatures between 26 °C to 28 °C will result in only male hatchlings.

FIGURE 10.3.14 Female bees (workers and queens) are diploid and male bees (drones) are haploid.

FIGURE 10.3.15 Loggerhead turtles lay their eggs on a beach above the high water mark.

The human karyotype

In humans (and some other organisms), sex chromosomes are distinguished from the remaining chromosomes (autosomes). Human somatic cells have a diploid chromosome number of $2n = 46$. A karyotype for a human female shows that there are 22 pairs of autosomes and two sex chromosomes XX (Figure 10.3.16). The autosomal pairs are numbered 1–22 and are ordered from largest to smallest. The sex chromosomes are usually shown after the autosomes.

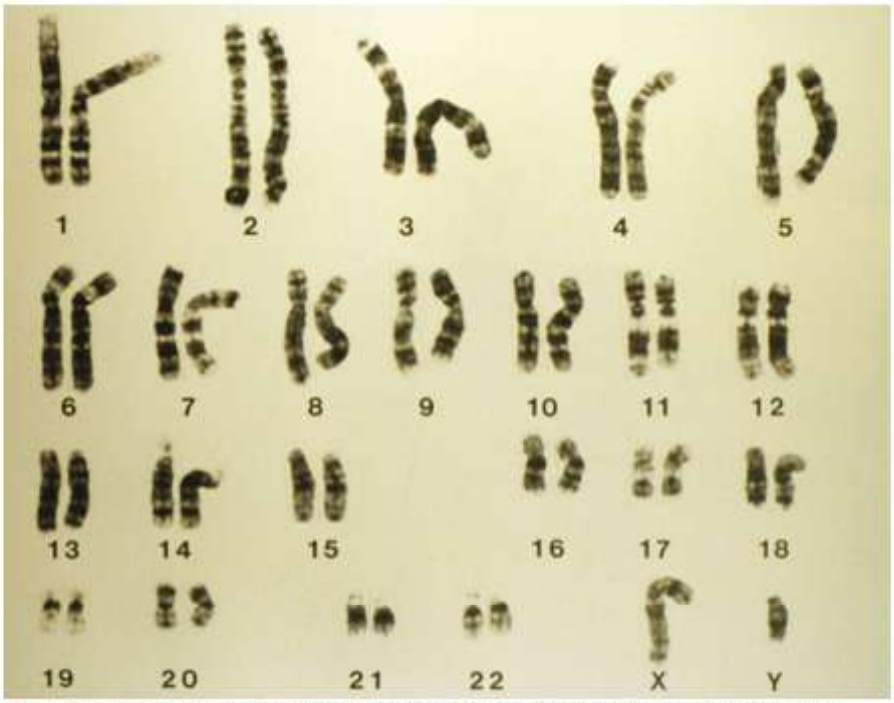


FIGURE 10.3.16 To construct a karyotype chart, metaphase chromosomes are stained and photographed. The chromosome images are arranged by size and centromere position, with the shorter arm (p arm) up.

Aneuploidy refers to an abnormal number of chromosomes, such as 45 or 47 chromosomes in humans instead of 46. In monosomy one chromosome is missing. In trisomy there is an extra copy of a chromosome.

Using karyotypes to identify chromosomal number abnormalities

A number of syndromes result from an increase or decrease in chromosome number. Down syndrome is a typical example of a syndrome that results from having one extra chromosome. It results from one extra copy of chromosome 21 which will be shown up on a karyotype (Figure 10.3.17). This type of abnormality is called a trisomy, because there are three copies of the chromosome.

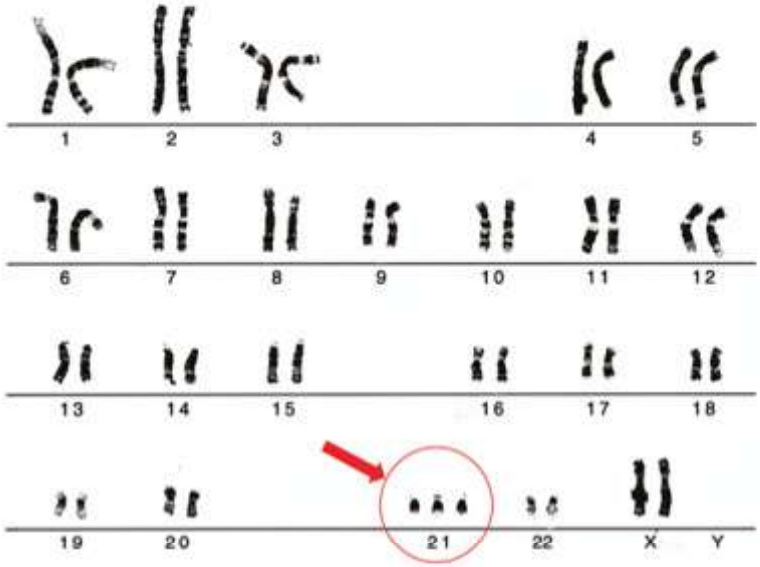
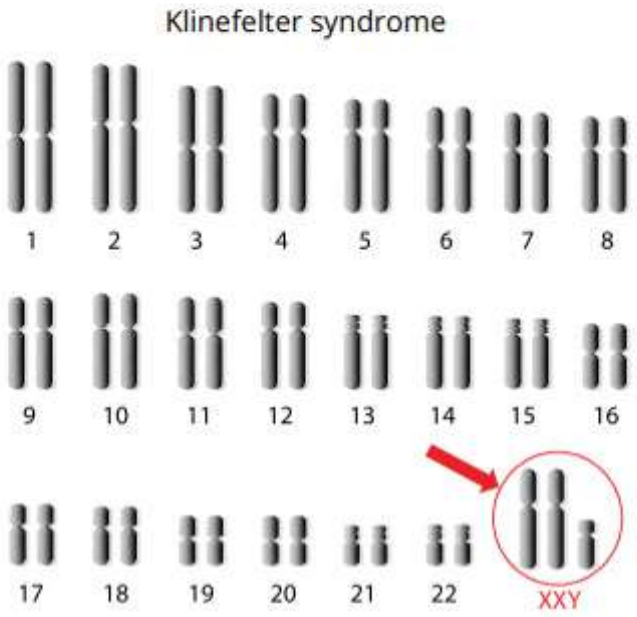


FIGURE 10.3.17 The Down syndrome karyotype, showing an extra copy of chromosome 21.

Two other abnormalities formed as a result of an abnormal chromosome number are Klinefelter syndrome and Turner syndrome. In Klinefelter syndrome (also called XXY syndrome), males have two X chromosomes and one Y chromosome instead of one X and one Y chromosome (Figure 10.3.18). As a result they have 47 chromosomes. Males with Klinefelter syndrome are infertile and have other characteristics such as breast development and a tall stature.



10.3.18 Klinefelter syndrome karyotype, showing an extra copy of the X chromosome.

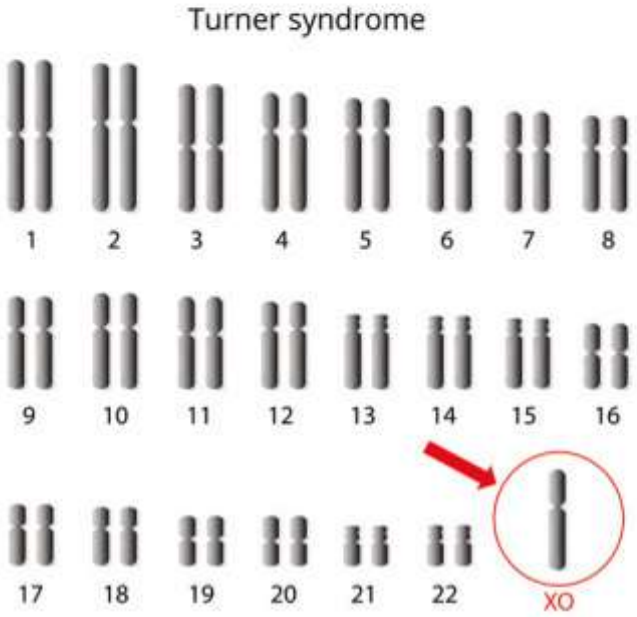


FIGURE 10.3.19 Turner syndrome karyotype, showing only one copy of the X chromosome.

In Turner syndrome (also called monosomy X), which occurs only in females, there is one X chromosome instead of two (Figure 10.3.19). People with Turner syndrome are infertile and have a short stature.

Table 10.3.3 shows some of the consequences in humans of an extra, or a missing member of a chromosome pair. This is the result of abnormal meiosis in one of the parents of the person with the condition.

Condition	Chromosome change	Traits of person with condition
Down syndrome	Three copies of chromosome 21 present (trisomy 21) (47 chromosomes)	Male or female, some intellectual disability, characteristic palm prints and facial features, may be infertile.
Klinefelter syndrome	Extra X (XXY) (47 chromosomes)	Male, sterile, often some intellectual disability, with female secondary sex traits (e.g. breast enlargement).
Patau syndrome	Three copies of chromosome 13 present (trisomy 13) (47 chromosomes)	Male or female, small skull, intellectual disability, cleft lip, cleft palate, usually has heart defects, seldom survives more than four months after birth.
Turner syndrome	All or part of one X chromosome is altered or missing (monosomy) (45 complete chromosomes)	Female, short stature, infertile, fluid retention and puffiness in hands and feet, kidney and heart problems, some learning difficulties but most people with Turner syndrome have normal intelligence.

TABLE 10.3.3 Conditions in humans that are a result of errors during meiosis and genetic recombination.

10.3 Review

SUMMARY

- Chromosomes are structures that contain DNA coiled around histones.
- Chromosomes vary in size, banding pattern and centromere position.
- Chromosome size is affected by the number and length of genes and the length of spacer DNA.
- Homologous chromosomes are matching pairs of chromosomes (one set from each parent) that have the same genes.
- Genes on homologous chromosomes occur at the same loci but may have different alleles.
- Sex chromosomes (allosomes) are chromosomes that are involved in sex determination.
- In humans the sex chromosomes are X and Y.
- Other organisms may have other sex chromosomes, or not at all.
- Females have two X chromosomes and males have an X and Y.
- Autosomes are chromosomes that are not involved in sex determination.
- A karyotype is the number and appearance of a cell's chromosomes.
- A karyotype can identify:
  - the number of chromosomes in a cell
  - the gender of the individual
  - whether an individual has an extra chromosome, such as in Down Syndrome and Klinefelter syndrome
  - where an individual is missing a chromosome, such as in Turner syndrome
  - the position of the centromere
  - the size of the chromosome.

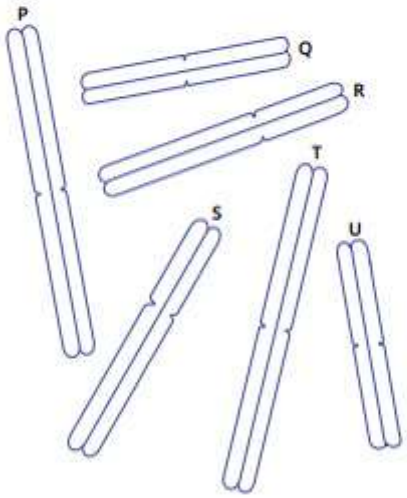
KEY QUESTIONS

1 Using the terms chromosome, histone, DNA and nucleosome, describe how DNA is packaged into a cell nucleus.

2 Outline the variations seen in eukaryotic chromosome structure.

3 Distinguish between the following terms:
- autosome and sex chromosome (allosome)
- sex chromosome and homologues

4 The figure below shows 6 chromosomes belonging to 3 homologous pairs.



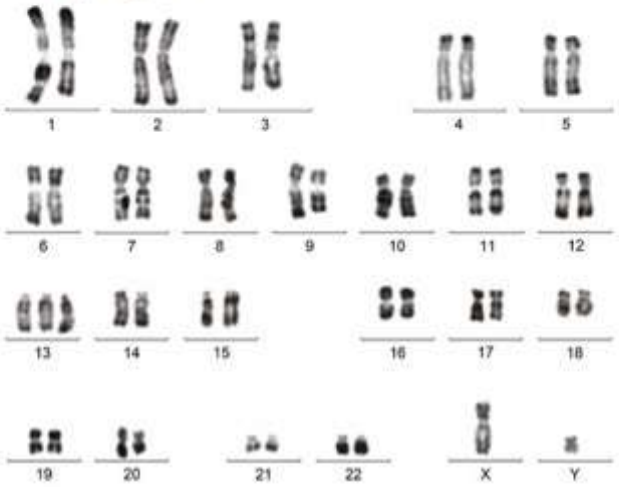
a Identify the three pairs of homologous chromosomes.

b Explain which features you used to match the chromosomes.

5 How many homologous pairs of chromosomes would you expect to find in the cells of most
a human females?
b human males?

6 For each of the conditions listed below, state which chromosome is affected and whether the chromosome is in excess or missing.
a Down syndrome
b Turner syndrome
c Klinefelter syndrome

7 The figure below shows a human karyotype.
a State whether this individual is a male or female.
b Is there any evidence of aneuploidy in this person? Explain your answer.



10.4 Genotypes and phenotypes

FIGURE 10.4.1 Hydrangeas are a well-known example of the effects the environment can have on phenotype. Differences in soil pH result in differences in flower colour.

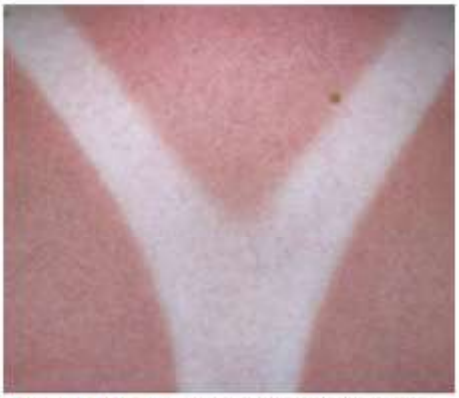


FIGURE 10.4.2 The effect of sun exposure on skin colour. The darker part of the skin has been exposed and has produced more melanin, causing it to darken. Unexposed skin (the Y shape) does not produce extra melanin.

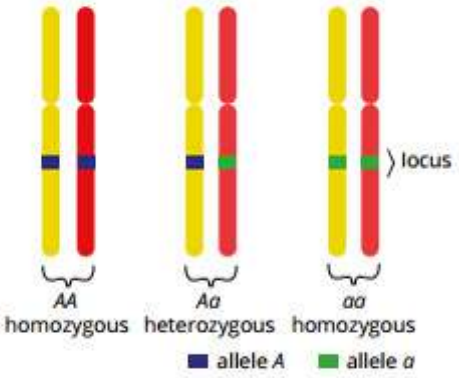


FIGURE 10.4.3 On homologous chromosomes, alleles of a gene occur at the same locus. If a gene has two alleles, there can be three different combinations or genotypes. Two of these combinations are homozygous, and one is heterozygous.

You inherited many of your physical features or traits from your parents. You share certain traits with your mother and others with your father. You might even appear to have a totally different version of a trait.

In this section you will look at what determines the traits and characteristics that humans have and how they are passed to children from parents. You will also learn the difference between genotype and phenotype, the use of symbols for writing of genotypes for the alleles present at a particular gene locus, and the distinction between dominant and recessive phenotypes. You will also learn about the influences of genetic material, environmental factors (Figure 10.4.1) and interactions of DNA with other molecules on phenotypes.

You will also explore how polygenic inheritance contributes to continuous variation in a population, through examples such as human skin colour and variation in height.

GENOTYPE AND PHENOTYPE

A **genotype** is the set of alleles present in the DNA of an individual organism. It is the result of inheritance. In Section 10.1 you learned that an allele is an alternative form of a gene. Each individual usually only has two alleles for each trait: one inherited from their mother and one inherited from their father. But one gene may have many alleles, and this is what leads to variation in a population.

The genotype is the set of alleles present in the DNA of an individual organism. The genotype is the result of inheritance.

An organism's **phenotype** is all of its observable characteristics. It is the result of inheritance and the effects of the organism's environment. An example of a phenotype is skin colour. Your skin colour depends on how much skin pigment (melanin) is produced. But skin colour also depends on environmental factors such as exposure to sunlight, especially in pale-skinned people. The greater the exposure, the more melanin is produced (Figure 10.4.2).

An organism's phenotype is all of its observable characteristics. It is the result of inheritance and the effects of the organism's environment.

Genotype

You will recall from Section 10.3 that a diploid cell has two sets of chromosomes (one set from each parent). You have two sets of autosomes, which are denoted by the numbers 1 to 22. Each pair of these chromosomes are homologous because they are identical and carry the same genes.

Consider a gene, which might be called gene *A*, that has two alleles. Different alleles are represented by different symbols. One allele can be represented by a capital *A*, and the other by a lower-case *a*. The names of genes and alleles are always italicised.

If gene *A* is in a homologous chromosome, there will be two copies of the gene. If you inherited the allele *A* from both parents, your genotype for gene *A* will be *AA*. On the other hand, if you inherited the *A* allele from one parent and the *a* allele from the other parent, you will have the genotype *Aa*. If you inherited the allele *a* from both parents, you will have the genotype *aa*.

Therefore there are three different combinations or genotypes of gene *A*: *AA*, *Aa* or *aa* (Figure 10.4.3). Genotypes *AA* and *aa* contain only one type of allele, so the individual is said to be **homozygous** for that gene and is called a **homozygote**. Genotype *Aa* contains two different alleles, so the individual is said to be **heterozygous** for that gene and is called a **heterozygote**.

Now consider a gene, which might be called gene *B*, on the X chromosome. This gene also has two alleles, *B* and *b*. Figure 10.4.4 shows the symbols used to record genotypes of autosomal and X-linked genes. To show that this gene is on the X chromosome, the symbol X (an X-linked gene) is used, with a superscript to represent the gene. So the two alleles are named X^B and X^b.

Because females have two copies of the X chromosome they can be homozygous (X^BX^B or X^bX^b) or heterozygous (X^BX^b) for gene *B*.

Males only have one copy of the X chromosome, so they are referred to as being **hemizygous** ('hemi' = 'half'). This term is used to indicate that the human male has only half the number of copies of genes on the X chromosome compared with a female. The Y chromosome is used in describing the genotype to emphasise that the individual is a male.

The two possible genotypes of gene *B* for a male are X^BY and X^bY.

> An organism that has two copies of the same allele of a gene is said to be homozygous for that gene; 'homo' means 'the same'.
>
> An organism that carries two different alleles of a gene is said to be heterozygous for that gene; 'hetero' means 'different'.

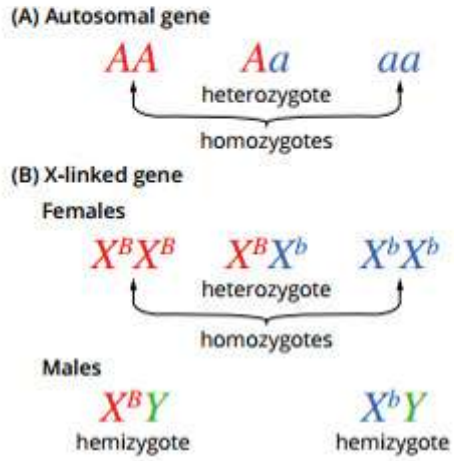


FIGURE 10.4.4 These are the symbols used to record genotypes of autosomal and X-linked genes.

Multiple alleles at a single gene locus

A single gene locus may have more than two alleles. The human ABO blood group system is based on such alleles (Figure 10.4.5). In this case there are three alleles, represented as I^A, I^B and *i*. Allele I^A produces the A antigen, I^B produces the B antigen, and *i* produces no antigen. Each person carries two copies of these three possible alleles. There are therefore six possible genotypes and four phenotypes, as shown in Figure 10.4.5. (See the Extension box on page 442 for a further discussion of human blood alleles and how these four phenotypes occur.)

ABO blood groups				
Blood type	**Type A**	**Type B**	**Type AB**	**Type O**
Possible allele combinations	I^AI^A I^Ai	I^BI^B I^Bi	I^AI^B	ii
Antigen (on RBC)	A antigen	B antigen	AB antigens	no antigens

FIGURE 10.4.5 The ABO blood group system is based on three alleles. The production of antigens A and B depends on the combination of alleles present.

Phenotype

When studying inheritance it is important to know the genotypes of parents and offspring. However, it is equally important to know the specific observable characteristics that can result from a given genotype; that is, the phenotype. The phenotype includes any distinct property of an organism: physical, chemical, physiological or behavioural. In experimental crosses (matings), such as those carried out by Gregor Mendel, phenotypes are observed to determine the underlying genotypes.

Importantly, environmental conditions can affect the phenotype of certain genotypes. In these cases, the genotype determines the possible range of phenotypes for a particular characteristic or trait, and the environment influences where in that range the actual phenotype will be.

For example, in Arctic foxes (*Vulpes lagopus*), two fur colour genotypes occur, called 'white morph' and 'blue morph'. The fur of the blue morph remains dark blue-grey throughout the year, but the fur of the white morph varies from dark brown or grey to pure white. In summer the fur is dark, but as winter approaches the fur gradually changes to white in response to the increasing cold and shorter day length (Figure 10.4.6, page 440). At the end of winter the fur gradually returns to its summer colour.

BIOFILE

Naming genes

There are internationally accepted names for genes and their abbreviated forms. For example, the gene that codes for phenylalanine hydroxylase, an enzyme involved in the inherited disorder phenylketonuria, is abbreviated to *PAH*. The gene name is always italicised, to distinguish them for the proteins they encode. For example, BRCA1 is an enzyme expressed in the cells of breast and other tissue, where it helps repair damaged DNA or destroy cells if DNA cannot be repaired. The gene that codes for this enzyme is known as *BRCA1*.

Although the phenotype is relevant to the functioning of an individual organism, the genotype is what is passed on to the next generation.

FIGURE 10.4.6 The fur of the white morph genotype of Arctic fox (*Vulpes lagopus*) changes from dark brown or grey (a) to pure white (b) as winter approaches, in response to the increasing cold and shorter day length.

BIOLOGY IN ACTION

Gregor Mendel, the founder of genetics

The birth of modern genetics began in an abbey garden, where a monk named Gregor Mendel proposed a mechanism for inheritance (Figure 10.4.7). Mendel developed his theory of inheritance before chromosomes were observed under the microscope and the significance of their behaviour was understood.

Mendel's work began with breeding garden peas to study inheritance. His choice of breeding peas was fortunate. There were a number of easily observable phenotypes, and the plants were self-fertile but could also be outcrossed (that is, crosses could be carried out within and between pure-breeding lines). Furthermore, large numbers of offspring could be counted for each cross, the generation time was short, and the peas were easy to maintain.

Figure 10.4.7 shows some of the discrete traits that Mendel observed in his breeding experiments with peas: flower colour, pod colour, pod shape, seed colour and seed shape. Each of these traits was important in the choice of peas used for crossings. It was likely that Mendel devised his model of inheritance theoretically and used the data from peas to confirm the model.

Mendel presented his results to the Brunn Natural Science Society in 1865 and they were published by the society in 1866. But the results were ignored until three other scientists independently produced similar data in 1900. Only then was Mendel's scientific contribution recognised—16 years after his death.

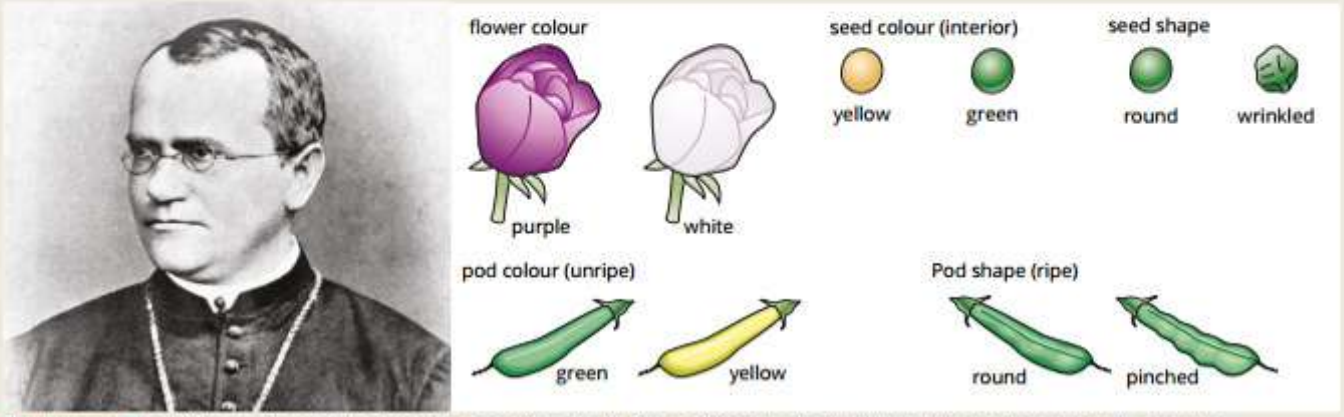


FIGURE 10.4.7 Left: Gregor Mendel, the founder of genetics. Right: Some of the discrete traits that Mendel observed in his breeding experiments with peas: flower colour, pod colour, pod shape, seed colour and seed shape.

DOMINANT AND RECESSIVE PHENOTYPES

The relationship between genotype and phenotype gives an insight into an important property of phenotypes known as **dominance**. For a given gene, the phenotype of the heterozygote compared with the appearances of each homozygote allows us to determine whether a phenotype is completely dominant, co-dominant or **recessive**. It is important to understand that dominance (and recessiveness) are properties of alleles, not genes. They are expressed as dominant or recessive phenotypes. Genes are neither dominant nor recessive.

Dominance and recessiveness are properties of alleles, not genes. They are expressed as either dominant or recessive phenotypes.

Complete dominance

To understand complete dominance it is useful to consider the white eye gene in blowflies. There are two alleles for the white eye gene, *W* and *w*. Individuals with genotype *WW* have red eyes, while individuals with genotype *ww* have white eyes (Figure 10.4.8). Individuals with genotype *Ww* do not show an in-between trait such as pink eyes but instead have red eyes, making them indistinguishable from those of the *WW* genotype.

Blowflies with genotype *Ww* display the red eye because the *W* allele makes enough membrane transporter protein to give the eye normal red pigment levels. The red eye colour phenotype is referred to as the **dominant phenotype**, because it only needs one *W* allele for that phenotype to be displayed. The white phenotype is referred to as the **recessive phenotype** because it is not observed in the heterozygote. It needs two copies of the *w* allele for it to be observed in the phenotype. This example shows that scientists can determine which phenotype, if any, is dominant only by examining the heterozygote.

By convention, the allele associated with the dominant phenotype is represented by an upper-case symbol (e.g. *W*). The allele associated with the recessive phenotype is represented by a lower-case symbol (e.g. *w*). The blowfly's white eye is an example of complete dominance. *Ww* individuals have the same eye colour as *WW* flies.

FIGURE 10.4.8 Blowflies with the WW and Ww genotypes have a red-eye phenotype (top). Blowflies with the ww genotype have a white-eye phenotype (bottom).

A dominant phenotype is one that is observed in the heterozygote and homozygote conditions.

A recessive phenotype is one that is observed only in the homozygous condition.

POLYGENETIC INHERITANCE

For some traits, such as skin colour and height in humans, more than one gene contributes to the phenotype of an individual. This is known as **polygenic inheritance** and results in a much greater range of phenotypes. Polygenic traits in non-human animals include wing shape and bristle count in *Drosophila*; birth weight, temperament and milking ability in cattle; and plumage and beak size in birds. When the phenotypes of a polygenic trait are shown on a graph, the result is a bell-shaped curve (typical of continuous variation), which is referred to as a normal distribution.

Polygenic inheritance is the inheritance of an observable trait that is controlled by many genes.

Height in humans

It has been found that height in humans is controlled by about 50 genes or regions of the genome (Figure 10.4.9). Some individual characteristics controlled by some of these genes include the secretion of thyroid gland hormones and human growth hormones. A deficiency in the amount of these hormones during childhood and puberty can result in stunted growth. On the other hand, too much of them can cause excessive growth resulting in exceptional height. The greater the number of genes that control a characteristic, the more possible gene combinations exist and as a result, the more phenotypes.

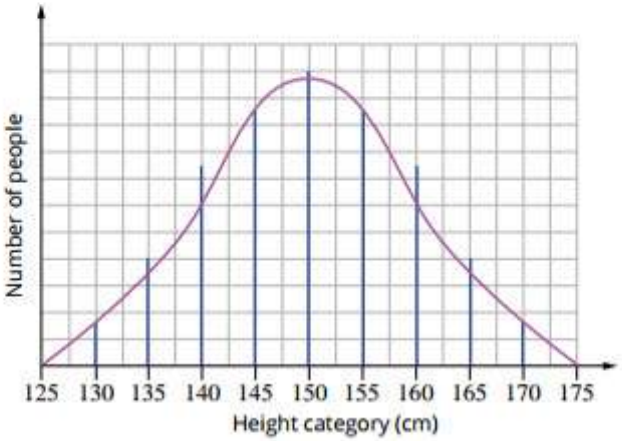


FIGURE 10.4.9 An example of continuous variation resulting from polygenetic inheritance: height in humans.

EXTENSION

Phenotypes that are not fully dominant or recessive

The relationship of genotype to phenotypes is rarely as simple as dominant and recessive. As the study of inheritance expanded, biologists began to notice a variety of relationships between alleles that code for the same trait. These allelic interactions were not exclusively recessive or dominant.

Co-dominance

In co-dominance the full phenotypic expression of both alleles is observed. The classic example is the ABO human blood group system. Figure 10.4.10 shows red blood cells displaying the four possible phenotypes: AB, A, B and O. In the ABO blood group system there are three allelic forms (I^A, I^B and i) at the same locus and individuals can have A, B, AB or O phenotypes (see Table 10.4.5). Those with the less common AB blood group are heterozygotes carrying one allele (I^A), that produces the A antigen (a polypeptide) and one allele (I^B) that produces a B antigen (a different polypeptide).

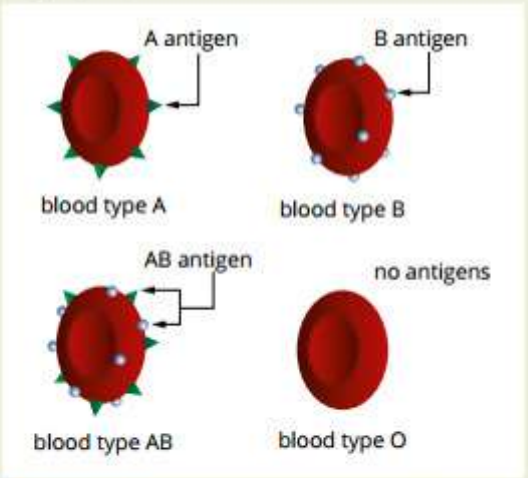


FIGURE 10.4.10 The four possible phenotypes of red blood cells: AB, A, B and O.

Because both the A and B antigens are present on the surface of red blood cells and can be detected using appropriate antibodies, neither phenotype (presence of A antigen or the presence of the B antigen) is truly dominant. This is co-dominance. Thus, A and B phenotypes are co-dominant and the O phenotype is recessive.

Sometimes neither phenotype is completely dominant, so that intermediate phenotypes occur.

For example, snapdragons (Figure 10.4.11) can have a red flower phenotype (R_1R_1) or a white flower phenotype (R_2R_2). In this case upper-case letters and subscripts are used to distinguish the alleles because neither phenotype is completely dominant. Plants of the R_1R_2 genotype have pink flowers. In R_1R_1 flowers, both copies of the R_1 allele produce an enzyme required to produce red pigment. In R_2R_2 flowers, no pigment is produced because the R_2 allele produces no enzyme or a defective enzyme.

Since the R_1R_2 flower has one R_1 allele, which produces the active enzyme, and one R_2 allele, which does not, it will produce half the amount of pigment as the R_1R_1 flower. Hence the flower is pink.

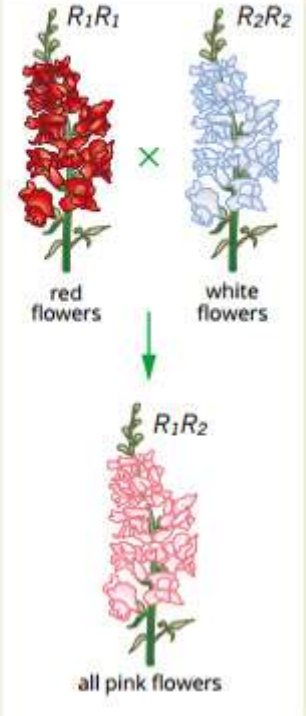


FIGURE 10.4.11 Above: Red, white and pink snapdragons.
Right: When pure-breeding red (R_1R_1) and white (R_2R_2) snapdragons are crossed, the resulting heterozygotes are pink (R_1R_2) because only half the amount of red pigment is produced.

Human skin colour

The colour of human skin is determined by the amount of melanin (dark pigment) it contains, and there are three types of melanin: eumelanin, pheomelanin and neuromelanin. At least four genes are involved in melanin production. For each gene, one allele codes for melanin production while the other does not. For example, the melanocortin 1 receptor gene (*MC1R*) is primarily responsible for determining whether pheomelanin and eumelanin is produced in the human body. The agouti signalling peptide gene (*ASIP*) inhibits eumelanin production. The tyrosinase gene (*TYR*) is responsible for making an enzyme called tyrosinase. Tyrosinase converts tyrosine to dopaquinone. A series of additional chemical reactions convert dopaquinone to melanin in the skin. The presence or absence of the different gene affects the level of melanin production and hence dark skin colour.

Besides levels of melanin production, the formation of melanin producing cells, melanocytes, would also affect skin colour. The KIT ligand gene (*KITLG*) is involved in the permanent survival, proliferation and migration of melanocytes to the skin surface.

The different combination of melanin producing alleles, number of melanocytes determines the degree of pigmentation, leading to a normal variation.

INFLUENCES ON PHENOTYPE

The examples discussed so far show that the phenotype is determined by the genotype but may also be affected by the environment. So if an individual with a given genotype develops in one environment, its phenotype may be different than if it had developed in some other environment. For example, the average height of humans has gradually increased in the last few hundred years because of the effect that improvements in nutrition have had on growth.

Phenylketonuria

The inherited disorder phenylketonuria (PKU) is a consequence of the build up of an amino acid called phenylalanine in the blood. This is toxic to developing neurons, leading to abnormal development of the nervous system and intellectual disability. PKU is caused by a mutation in the *PAH* gene, which codes for an enzyme that converts phenylalanine into another amino acid, tyrosine. If an individual inherits two copies of the mutant allele (that is, they are homozygous for the gene), they will develop PKU. Fortunately, development of the symptoms can be prevented by modifying the diet (environment) of babies that test positive for PKU shortly after birth. If homozygous individuals reduce their intake of dietary phenylalanine, particularly during childhood, they show normal brain development. Newborns in Victoria are routinely tested for genetic disorders like PKU.

Fur colour in Himalayan rabbits

Coat colour of Himalayan rabbits provides an example of the effect of environmental temperature on phenotype. The Himalayan rabbit is homozygous for a mutant allele that encodes a heat-sensitive tyrosinase. Tyrosinase is produced but it is inactivated at normal body temperature, resulting in no melanin produced and hence a white coat. At low temperatures, tyrosinase is activated and results in the formation of melanin, causing black fur to form. When a small section of fur is shaved from a white region on the back, the fur grows back black if the animal is kept at low temperatures, but white if the animal is kept at high temperatures (Figure 10.4.12).

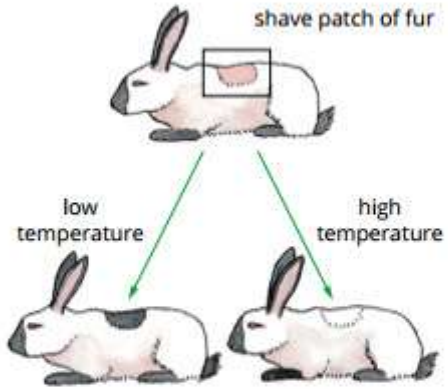


FIGURE 10.4.12 The relationship between temperature and fur colour in Himalayan rabbits.

EXTENSION

Discontinuous variation

In contrast to the continuous variation seen in polygenic traits, when only one gene with a few alleles controls the trait, discrete variation (also known as discontinuous variation) is observed as only a few phenotypes are observed. This is called a monogenic trait. One example of this is the ABO blood system (Figure 10.4.13).

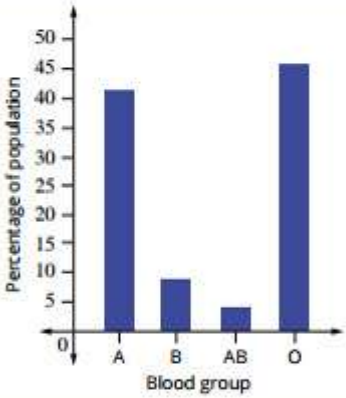


FIGURE 10.4.13 An example of discontinuous variation: ABO blood groups.

Flower colour in hydrangeas

Hydrangeas are a commonly seen example of environmental effects on phenotype. If cuttings of a single hydrangea plant are grown in very acidic soil (pH 5.5 or less), the flowers produced are blue; if the cuttings are grown in weakly acidic or alkaline soil (pH 6.5 or more), the flowers are pink (Figure 10.4.14). The cuttings are of identical genotype, so it must be the environment (the pH of the soil) that affects the phenotype of the hydrangea.

FIGURE 10.4.14 Flower colours of cuttings of the same hydrangea plant grown in an acid soil (left) and an alkaline soil (right).

FIGURE 10.4.15 All the honeybees in a colony are genetically identical to each other. The queen bee (marked with blue paint on her head) looks different to the worker bees because of epigenetics.

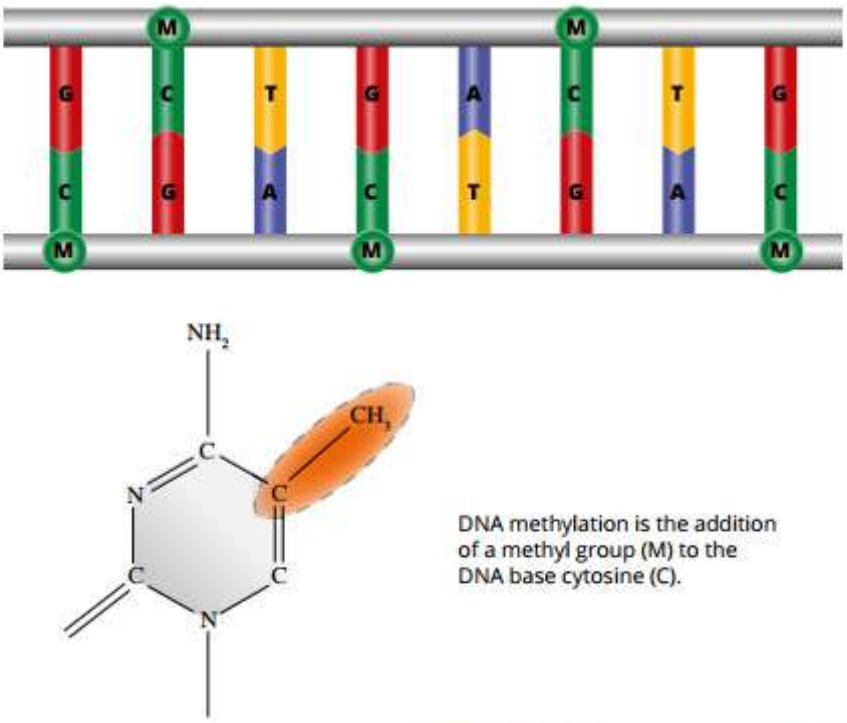
This effect is caused by the relationship between soil pH, a pigment called anthocyanin, and the availability of aluminium in the soil for uptake by the plant. At a soil pH of 5.5 or less, aluminium is free to be taken into the plant. Anthocyanin is normally red, but it binds to aluminium in the plant to form a blue pigment called metalloanthocyanin, resulting in blue flowers. At a soil pH of 6 or more the aluminium binds to soil particles and is less available to the plants. This leaves most of the anthocyanin in the plant in its red form, resulting in pink flowers.

Epigenetics

Phenotypes can sometimes be affected by the interaction of DNA with other molecules. For example, the queen and worker honeybees (*Apis mellifera*) are genetically identical, but their behaviour, physiology, and appearance are different (Figure 10.4.15). The phenotype differences are due to the differences in the diet of the bees. Queen bees are fed royal jelly while worker bees are fed nectar.

Royal jelly contains ingredients that inhibit an enzyme which adds a methyl group ($-CH_3$) onto cytosine bases in honeybee DNA, allowing for certain genes to be expressed (Figure 10.4.16). When scientists mimicked the effects of royal jelly on worker bees, worker bees exhibited characteristics of queen bees.

This effect of royal jelly in the honeybee is an example of **epigenetics**. Epigenetics is a term used to describe molecular events, such as adding methyl groups, that occur on DNA without altering the DNA sequence. Such modifications are called 'epigenetic marks' and result in changes in gene expression and variations in phenotype. Other forms of epigenetic modification include addition of methyl or phosphate groups to histones, which affect how DNA is coiled and whether particular genes are expressed. Another example of epigenetics is X-inactivation.



DNA methylation is the addition of a methyl group (M) to the DNA base cytosine (C).

FIGURE 10.4.16 When a methyl group ($-CH_3$) is attached to cytosine bases, it prevents the expression of genes.

X-inactivation occurs in females that have two copies of the X chromosomes. It is a process in which one of the two copies of the X chromosome is inactivated. One of the X chromosomes must be inactivated to ensure that females do not end up with twice as many X chromosome gene products compared to males. The inactive X chromosome, Xi, is silenced by the addition of methyl groups to DNA and histones, resulting in Xi being coiled in such a way that it has an inactive structure called heterochromatin.

During the formation of gametes, epigenetic tags are usually erased during meiosis to ensure the growth of a healthy embryo. This process is known as **reprogramming** (Figure 10.4.17). However, there is some evidence suggesting that certain epigenetic changes can be inherited. For example, feeding pregnant laboratory rats vinclozolin (a fungicide used on grape plants) results in lifelong epigenetic changes to the offspring. The male offspring have low sperm count and the sperm have abnormally high levels of methyl tags. The great-grandsons of the exposed male offspring also have low sperm count with abnormally high levels of methyl tags.

Researchers are amassing more and more evidence for the importance of epigenetic information in the regulation of gene expression. Epigenetic variations might help explain why one identical twin acquires a genetically based disease, while the other twin does not.

A methyl group is a carbon with three hydrogen atoms bound to it. The attachment of a methyl group to DNA, referred to as DNA methylation, can affect gene expression; the gene might not be 'turned on' to produce the protein, or it might be silenced.

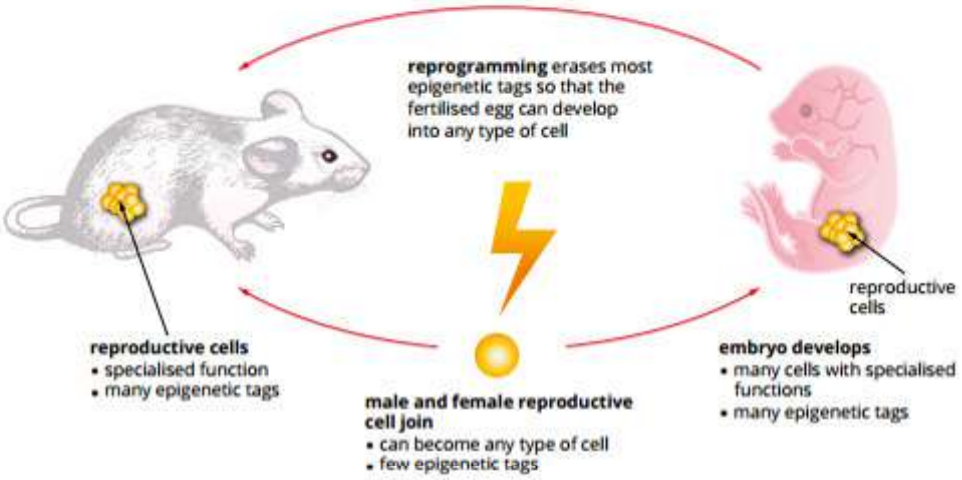


FIGURE 10.4.17 Reprogramming removes the epigenetic tags of the early embryo so that it can form every type of cell in the body.

10.4 Review

SUMMARY

- Genotype is the combination of alleles at a particular locus.
- An organism that has two copies of the same allele is homozygous for that allele.
- An organism that carries two different alleles is heterozygous.
- Phenotype is an observable characteristic or trait that results from the genotype under the influence of the environment.
- Dominance and recessiveness are properties of alleles and are expressed as dominant or recessive phenotypes.
- A phenotype can be dominant or recessive depending on its appearance in the heterozygote.
  - A dominant phenotype is one that is visible in the heterozygote and one homozygote.
  - A recessive phenotype is only observed in the homozygous condition.
- An italic capital letter is used to signify the allele for a dominant phenotype.
- An italic lowercase letter is used to signify the allele for a recessive phenotype.
- When more than one gene influences a trait, it is called polygenic inheritance.
- Polygenic inheritance causes a wide variety of phenotypes. This is called continuous variation.
- Discontinuous variation occurs when a single gene determines a trait.
- Phenotype is influenced by:
  - genotype
  - interaction between genotype and the environment
  - interaction between DNA with other molecules (epigenetic factors).
- Fur colour in rabbits, flower colour in hydrangeas and the management of PKU are examples of how environment can affect an organism's phenotype.
- Epigenetics refers to molecular events that affect the expression of genes without altering the DNA sequence. These events usually involve switching genes on or off. Examples of epigenetic events are the addition of methyl or phosphate groups to histones, which affect how DNA is coiled.

KEY QUESTIONS

1 Explain the difference between the genotype and phenotype of an individual.

2 What factors contribute to an individual's phenotype? Give an example.

3 *E* and *e* are alleles of a particular autosomal gene. Write down the possible combinations of these alleles and state whether each is homozygous or heterozygous.

4 Use an example to explain how two organisms can have the same phenotype but different genotypes.

5 Use an example to distinguish between dominant and recessive phenotypes.

6 Describe an example where an organism's phenotype can be affected by the environment in which it is raised.

7 Mutations are changes in a DNA sequence, and can result in new alleles for a gene. Outline the difference between epigenetic events affecting phenotypes and mutations affecting phenotypes.

Chapter review

10

KEY TERMS

adenine (A)
alleles
antiparallel
autosomes
base
centromere
chromatid
chromosome
complementary base pair
complete dominance
cytosine (C)
diploid
DNA
DNA sequencing
dominance
dominant phenotype
double helix
epigenetics
gene
genome
genotype
guanine (G)
haploid
hemizygous
hereditary
heterogametic
heterozygote
heterozygous
histones
homogametic
homologous chromosomes
homozygote
homozygous
Human Genome Project
in vitro fertilisation (IVF)
karyotype
locus
nucleosome
phenotype
ploidy
polygene
polygenic inheritance
polypeptide
pre-implantation genetic diagnosis (PGD)
protein
purines
pyrimidines
recessive phenotype
reprogramming
sex chromosomes
somatic cell
thymine (T)
trait

KEY QUESTIONS

1 What is the difference between the alleles of a gene?
- **A** their locus on the chromosome
- **B** their amino acid sequence
- **C** the type of sugar on the nucleotides
- **D** the sequence of bases

2 A human cell has approximately 25 000 genes and E. coli has approximately 4000 genes. Explain why the number of genes is not an indicator of the size of the genome.

3 What was the aim of the Human Genome Project?
- **A** to identify human infectious diseases
- **B** to make improvements to the human genome
- **C** to allow transfer of genes from other species to humans
- **D** to sequence genetic information in humans

4 What does a nucleosome consist of?
- **A** DNA and histones
- **B** DNA and chromatid
- **C** Chromatid and nucleotides
- **D** RNA and histones

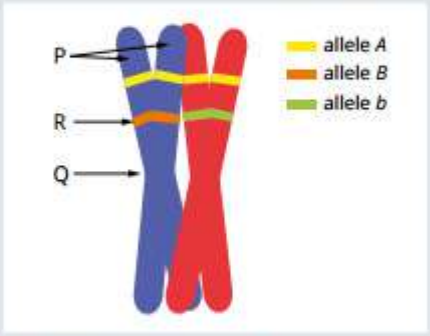
5 Most of the DNA of a human cell is contained in the nucleus. Distinguish between unique and spacer DNA sequences in DNA found in the nucleus.

6 State the number of autosomes and homologous chromosomes in a human
- **a** female somatic cell
- **b** male somatic cell.

7 Explain what is meant by DNA being coiled and supercoiled within a chromosome. Include a diagram in your answer. What benefit is there in DNA being packaged in this way in a cell?

8 In mice, coat colour is controlled by a single gene. Black coat colour is dominant to white coat colour.
- **a** Assign allele symbols for the gene responsible.
- **b** How many genotypes are possible with respect to these alleles? State the genotypes and phenotypes.

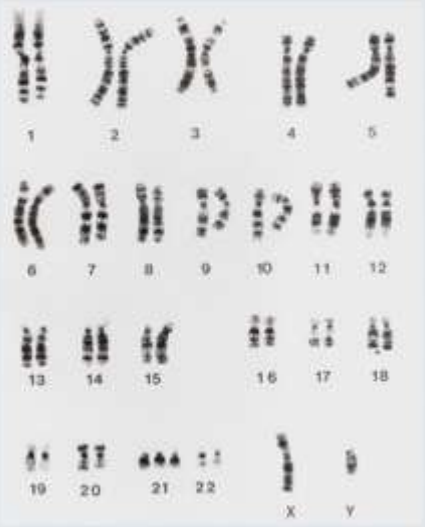
9 The diagram below shows a pair of chromosomes during meiosis to form a human sperm. The position of the alleles of some of the genes is shown.



- **a** Identify the chromosome structures labelled P and Q.
- **b** Suggest with reasons, whether the chromosomes are:
  - **i** sex chromosomes or autosomes
  - **ii** homologous or non-homologous
  - **iii** homozygous, hemizygous or heterozygous with respect to the B gene locus?

10 Describe karyotyping and one application of its use.

11 The figure below shows a human karyotype.

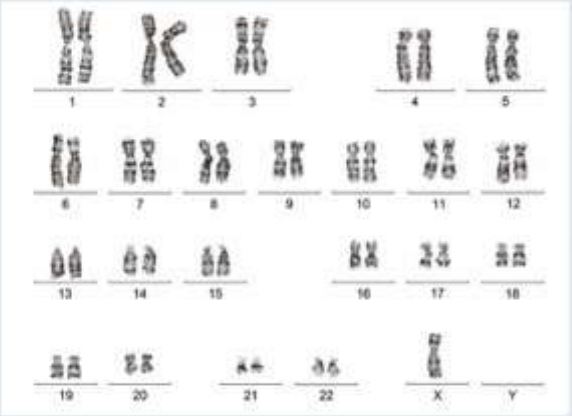


What conclusions can be deduced from the karyotype?

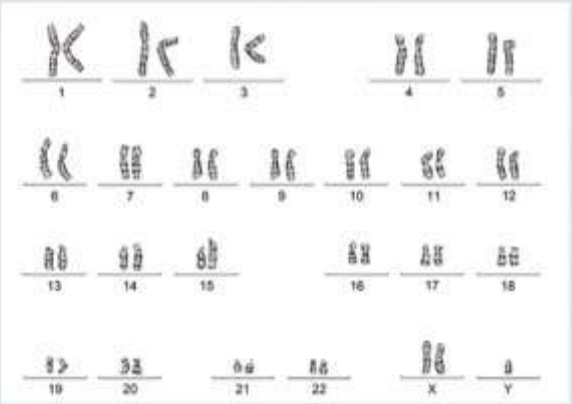
12 Describe how human skin colour is determined genetically.

13 Consider the following images of karyotypes. In each case identify the sex of the individuals and the conditions that they have.

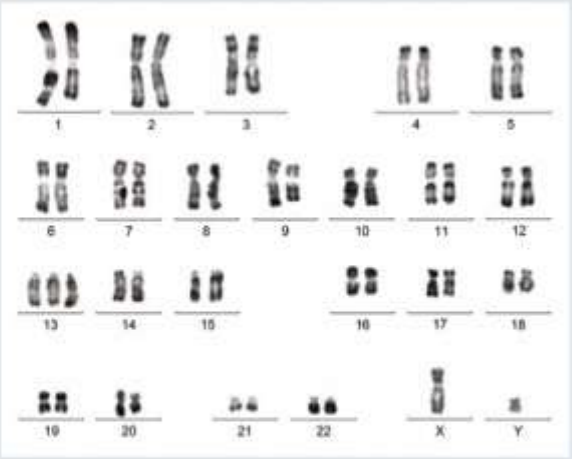
a



b



c



CHAPTER

11 Patterns of inheritance

In this chapter you will learn about the transmission of biological information from generation to generation. You will use chromosome theory and terminology from genetics to explain the inheritance of characteristics, analyse patterns of inheritance, learn about the differences between independent and linked genes, interpret pedigree charts and predict the outcomes of genetic crosses. You will also learn about the social and ethical issues involved in genetic screening and testing.

Key knowledge

- pedigree charts and patterns of inheritance including autosomal dominant, autosomal recessive, X-linked and Y-linked traits
- the determination of genotypes and prediction of the outcomes of genetic crosses including monohybrid crosses and monohybrid testcrosses
- the inheritance of two characteristics as either independent or linked, and the biological consequence of crossing over for linked genes
- the nature and uses of genetic testing for screening of embryos and adults, and its social and ethical implications.

11.1 Monohybrid crosses

FIGURE 11.1.1 After carefully studying the results of crossing different pea plants (*Pisum* species) in his garden over two years, Gregor Mendel deduced the basic principles of inheritance.

Much of what is now understood about natural variation and patterns of inheritance in sexually reproducing organisms was originally gained through the work of Gregor Mendel in the 1860s. Mendel accurately deduced the basic principles of inheritance by studying several inheritable traits in pea plants (*Pisum* species) (Figure 11.1.1), using precise experimentation and careful observations over many years.

In this section you will learn about the basic principles of inheritance, focusing on autosomal and sex-inked inheritance.

MENDEL'S STUDY OF PATTERNS OF INHERITANCE

Mendel demonstrated that traits are passed from parents to offspring, and that these traits form specific patterns over generations of cross-breeding.

Mendel made several observations in his pea experiments: purple flowers were **dominant** over white flowers, a round seed shape was dominant over a wrinkled seed shape, and a green pod colour was dominant over a yellow pod colour. These variant or alternative forms (phenotypes) occur because of variations (alleles) of genes on **autosomes**. Autosomes are chromosomes that are not involved in sex determination. (The difference between autosomes and sex chromosomes is explained in Section 10.3.)

Dominant phenotypes are expressed if the individual carries at least one allele for the dominant trait. **Recessive** phenotypes are expressed only if the individual carries two alleles for the recessive trait.

A **cross** of the traits being studied can be carried out to determine which trait is dominant. A monohybrid cross is a cross between two individuals with different alleles at a single locus. In the standard monohybrid cross, homozygous parents (P) with different phenotypes of the same trait (e.g. white fur and black fur) are crossed first to produce heterozygous offspring (the first filial generation, or F1). These heterozygous offspring are then crossed with each other to produce the second filial generation (F2). The phenotypic ratios in the offspring of F1 and F2 generations indicate which phenotypes are dominant or recessive. Mendel used monohybrid crosses to discover the dominance relationships of traits in pea plants.

The symbols for filial generations are sometimes written in the form F_1, F_2 etc.

Phenotype refers to the observable characteristics of an organism. The phenotypic features of an organism are an expression of their genes (genotype) and their interaction with the environment. They may be structural, behavioural or physiological features.

P Homozygous dominant × Homozygous recessive

↓

F1 First filial generation Heterozygous offspring

↓

F2 Second filial generation

AUTOSOMAL DOMINANT INHERITANCE

Autosomal dominant inheritance (complete dominance) refers to a dominant trait that is passed on to offspring via an autosomal gene. Only one copy of the allele from one parent is needed to express a dominant phenotype.

Parent (P) generation

The inheritance of eye colour in the Australian sheep blowfly is an example of a single gene with two alleles (found on an autosomal chromosome) coding for the trait. In the blowfly, red eye colour is dominant over white eye colour. The homozygous genotypes are *WW* and *ww*. Homozygous genotypes produce only one type of gamete. *WW* individuals produce only *W* gametes and *ww* individuals produce only *w* gametes.

In a cross between two red-eye homozygous (*WW*) individuals, all the offspring would be homozygous *WW* (red eye). As long as *WW* individuals were crossed together, it would be a **true-breeding** strain. Similarly, as you can see on the right side of Figure 11.1.2 crosses between two homozygous white-eye (*ww*) individuals would yield a true-breeding white eye (*ww*) strain.

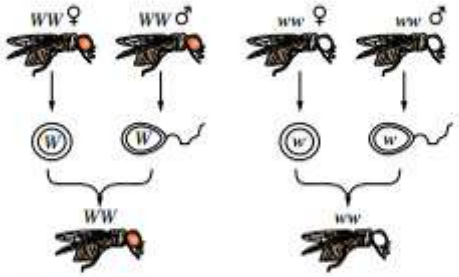


FIGURE 11.1.2 Homozygous genotypes produce only one type of gamete. By crossing homozygotes of the same genotype together, a true-breeding strain can be established.

Punnett squares

In 1905, geneticist Reginald Punnett devised a simple method for showing the random combination of gametes and the genotypes of the resulting offspring. In a Punnett square (Figure 11.1.3) the alleles of each parent are first written in the top and side cells. Then by going down each column and across each row, the alleles are combined and written into the remaining cells.

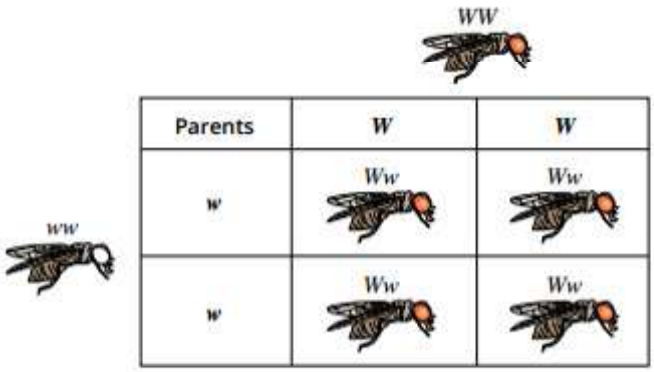


FIGURE 11.1.3 A Punnett square for a cross between two homozygous parents to produce an F1 generation. All F1 individuals are heterozygous.

Punnett squares make it easy to establish all the possible combinations of alleles carried by the gametes and, therefore, all the possible genotypes of the offspring. This is useful in fields such as animal husbandry and horticulture because it allows breeders to select individuals to cross according to the desired traits of the offspring.

The F1 generation

To test the principle of dominance, two true-breeding parents with two different traits can be crossed. This type of cross is known as hybridisation, and the offspring are known as **hybrids**.

In the blowfly example, two true-breeding strains (one with red eyes, *WW*, and one with white eyes, *ww*) can be crossed to produce an **F1 generation**. The results of the cross can be shown in a Punnett square, as shown in Figure 11.1.3.

Each of the offspring in the F1 generation has the heterozygous genotype *Ww*. The phenotype resulting from this genotype is red eyed. From this, it can be deduced that the red-eye phenotype is dominant over the white-eye phenotype.

BIOFILE

Choosing symbols for alleles

When choosing symbols for alleles, it is common practice to select one that relates to the dominant phenotype. For example, if the dominant phenotype is grey fur, the dominant allele would be given the symbol *G* and the recessive phenotype would be *g*.

However, the symbols *W* and *w* are traditionally used for eye colour alleles in flies, even though red eye colour is dominant. This is because other genes are involved in eye colour in flies, and the discoverers of this gene named it 'white eye gene'.

BIOFILE

Genotypic and phenotypic ratios

Genotypic and phenotypic ratios are used to express the expected frequency of genotypes and phenotypes in the offspring from a genetic cross. Punnett squares are used to calculate the expected outcomes of a cross and the possible genotypes and phenotypes generated in the offspring.

The ratio of genotypes in the offspring is written in the following order: homozygous dominant : heterozygous : homozygous recessive

The ratio of phenotypes observed in the offspring is written as: dominant phenotype : recessive phenotype

The genotypic and phenotypic ratios sometimes differ because the dominant or recessive nature of traits means that different genotypes can result in the same phenotype; for example, both WW and Ww result in red eyes in flies.

The F2 generation

The **F2 generation** is the result of crossing the individuals from the F1 generation. In this example, half of the gametes produced by an F1 individual (*Ww*) will be *W* and half will be *w*. So three different combinations of alleles are possible in the F2 generation: *WW*, *Ww* and *ww*, as shown by the Punnett square in Figure 11.1.4.

In the F2 generation the dominant phenotype is likely to occur in 3 out of 4 crossings, and the recessive phenotype only once.

Parents	*W*	*w*
W	*WW*	*Ww*
w	*Ww*	*ww*

FIGURE 11.1.4 Punnett square of a cross between two F1 individuals to produce the F2 generation.

The Punnett square shows that the F2 genotypic pattern is:

WW : *Ww* : *Ww* : *ww* or 1*WW* : 2*Ww* : 1*ww*

Because red eye colour is dominant over white eye colour, the F2 phenotypic pattern is:

3 red-eyed flies (*WW* : *Wr* : *Wr*) : 1 white-eyed fly (*ww*)

From this information it can be determined that the wild type is red-eyed.

BIOLOGY IN ACTION

The Law of Segregation

In the 1860s Gregor Mendel conducted breeding experiments on 34 different varieties of pea plants. During this time he carefully collected data and made many observations that would later lay the foundations for modern genetics and the study of inheritance.

One of his most significant observations was that the offspring of the pea plants did not always have the same phenotype as the parents, and that offspring from the same parents were often different from one another. Mendel hypothesised that hereditary units or 'factors' (now called genes) must have different forms (now called alleles) that separate randomly during the production of gametes. These forms would then unite after fertilisation, with each parent contributing one allele to the offspring. Mendel's hypothesis became known as the Law of Segregation or Mendel's first law.

With the advancement of cell biology, we now have a better understanding of the process of the Law of Segregation. During meiosis, each daughter cell (or gamete) receives one chromosome from each homologous pair. The alleles for each trait are separated into different gametes. Because gametes are haploid, they carry only one of the two alleles of a genotype. Offspring then receive one allele from each parent at fertilisation (Figure 11.1.5).

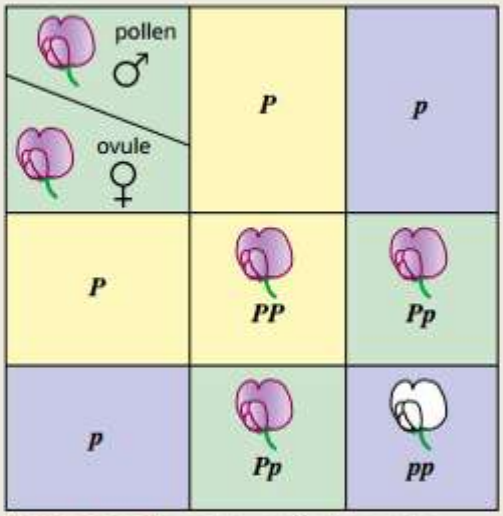


FIGURE 11.1.5 Punnett square for flower colour resulting from a cross between two heterozygous pea plants (*P* = purple flowers, *p* = white flowers). The resulting offspring have a 3 : 1 phenotypic ratio.

The wild type is the typical or standard form of an organism, gene or characteristic that is the most common in natural or normal populations. It is distinguished from forms that may result from selective breeding.

The genotypic pattern 1 : 2 : 1 ratio of the F2 generation resulting from a monohybrid cross occurs because of the following reasons.

In meiosis, heterozygous (Ww) individuals (both male and female) produce two gametes (a *W* gamete and a *w* gamete). This is because of the separation of pairs of alleles during the formation of reproductive cells.

Fertilisation occurs at random. For example, a W sperm has equal chance of fertilising a *W* egg or a *w* egg, because these eggs are produced in equal frequency. A *w* sperm also has an equal chance of fertilising a *W* egg or a *w* egg. So the four equally possible genotypic outcomes are *WW*, *Wr*, *wW*, *ww*.

The Punnett square accounts for both of these factors in demonstrating the possible outcomes of the cross.

TEST CROSSES

It is not immediately obvious whether an individual with a dominant phenotype is homozygous, because it might be either *AA* or *Aa*. Apart from sequencing the gene involved (which is very expensive and time-consuming), the only way to determine this is to do a **test cross**. This involves crossing the individual with another that has the recessive trait and is therefore homozygous. Homozygous individuals produce gametes with one type of allele, whereas heterozygous individuals can produce gametes with two types of alleles.

If the offspring from the test cross all have the dominant phenotype, then both the parents are likely to be homozygous. (It is not possible to be certain because of the random nature of fertilisation.) If the offspring have both dominant and recessive phenotypes, then the parent with the dominant phenotype must also carry a recessive allele and is therefore heterozygous.

Example: coat colour in guinea pigs

The coat colour of guinea pigs is determined by the alleles of one gene, and black fur is the dominant phenotype. If a true-breeding white guinea pig (*bb*) is crossed with a true-breeding black guinea pig (*BB*), the resulting F1 has black fur (*Bb*). But if the genetic history of a black guinea pig is unknown, its genotype can be determined by crossing the black guinea pig with a white-coated guinea pig, which must be *bb* (homozygous recessive).

Figure 11.1.6 illustrates the test cross that would be carried out. Of the resulting offspring in this example, half are white and half are black. This ratio of about 1 : 1 is consistent with the results of a heterozygote crossed with a homozygote if the trait is determined by the alleles of one gene and one trait is dominant. So the black guinea pig is likely to be heterozygous. If all the offspring of the test cross were black-coated (all *Bb*), the F1 guinea pig in question would have been shown to be homozygous.

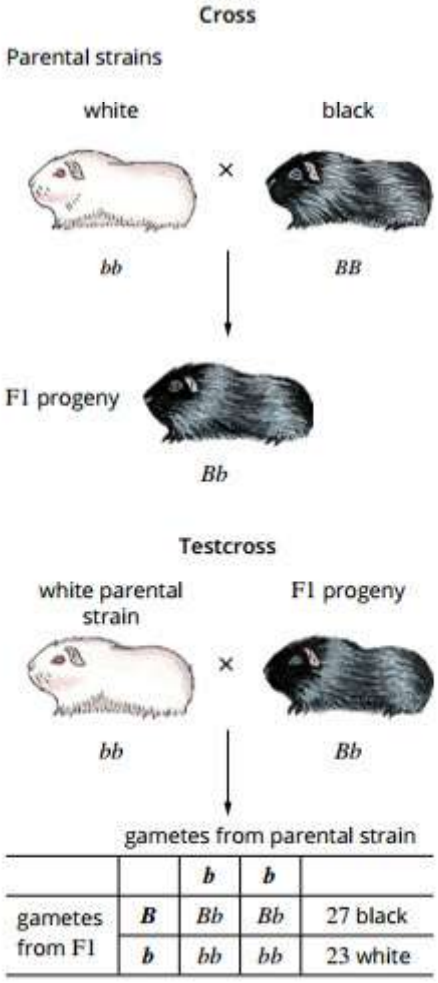
The predicted outcome for a cross between heterozygote black guinea pigs is 1 black (*Bb*) : 1 white (*bb*). However, as the diagram shows, the resulting ratio of the test cross was 27 black (*Bb*) : 23 white (*bb*) rather than, for example, 23 : 23 (which is equal to a 1 : 1 ratio). The difference between predicted and observed ratios is due to chance.

BIOFILE

Punnett squares vs experimental data

Punnett squares provide only the theoretical results of a cross; the actual results from an experiment may be different. Fertilisation can be compared to tossing a coin—for most genes there are two possible outcomes. If a coin is tossed, there is a 50% chance of getting heads and a 50% chance of getting tails. If the coin is tossed 10 times, you might not get 5 heads and 5 tails, but if it is tossed 1000 times, a heads : tails ratio very close to 1 : 1 would be observed.

Similarly, the more fertilisation events (data) there are in a breeding experiment, the closer the results will be to the theoretical ratio.



		b	*b*	
gametes from F1	***B***	*Bb*	*Bb*	27 black
	b	*bb*	*bb*	23 white

FIGURE 11.1.6 A cross and test cross between true-breeding strains of guinea pigs and their progeny (F1).

AUTOSOMAL CO-DOMINANT INHERITANCE

Some traits do not show simple dominance or recessiveness. These are instances in which both alleles are expressed to varying degrees in the phenotype of heterozygous individuals. This is called **co-dominance**.

Autosomal co-dominance

One example is co-dominance in snapdragons, where in the case of flower colour, neither trait is dominant. In the individual heterozygous for this trait, neither allele is completely expressed and the result is a blending effect of the two phenotypes.

In snapdragon flowers, R_1 represents the red colour allele and R_2 represents the white colour allele. In this case, because neither is completely dominant, upper case letters and subscripts are used to distinguish the alleles.

Crossing red-flowering snapdragons (R_1R_1 genotype) with white-flowering snapdragons (R_2R_2 genotype) will yield an F1 generation in which all individuals have the genotype R_1R_2 and are pink-flowering:

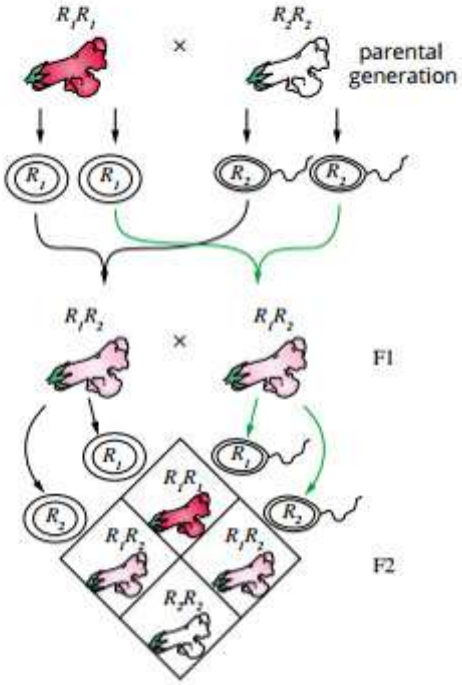


FIGURE 11.1.7 A cross between homozygous red and white snapdragons produces pink-flowering progeny in the F1 generation. If plants from the F1 are then crossed, a phenotypic ratio of 1 red : 2 pink : 1 white would be expected in the F2 generation.

Parents		Red flowers	
		R_1	R_1
White flowers	R_2	R_1R_2	R_1R_2
	R_2	R_1R_2	R_1R_2

If the F1 plants ($R_1R_2 \times R_1R_2$) are crossed, an F2 generation with a 1 : 2 : 1 genotypic ratio (1 R_1R_1 : 2 R_1R_2 : 1 R_2R_2) would be expected:

Parents		Pink flowers	
		R_1	R_2
Pink flowers	R_1	R_1R_1	R_1R_2
	R_2	R_1R_2	R_2R_2

The heterozygote pink-flowering snapdragon (R_1R_2) can be distinguished from the two homozygotes, red R_1R_1 and white, R_2R_2 due to the co-dominance of both the red and white alleles resulting in a pink-flowering phenotype.

Genotype ratio: 1 R_1R_1 : 2 R_1R_2 : 1 R_2R_2

Phenotype ratio: 1 white : 2 pink : 1 red

This phenotypic ratio of 1 : 2 : 1 (Figure 11.1.7) is different to the 3 : 1 ratio of two phenotypes observed in complete dominance (see Figure 11.1.5 on page 452).

> To represent co-dominance in a cross, the alleles are written as capital letters with subscript numbers (e.g. R_1 represents the red flowers in snapdragons and R_2 represents the white flowers). This is because neither phenotype is completely dominant or recessive. In the case of blood typing, the alleles are written as superscripts.

ABO blood grouping

As described in Section 10.4, page 439 human blood type is an example of autosomal co-dominant inheritance. In this case, depending on the allele inherited, the expression of the genotype differs. There are three alleles for blood type at the same locus, and individuals can have A, B, AB or O phenotypes. Those with the less common AB blood group are heterozygotes carrying one allele that produces an A antigen and one allele that produces a B antigen.

Because both the A and B antigens are present on the surface of red blood cells, which can be detected using antibodies, neither phenotype is fully dominant. This is another example of co-dominance. So A and B phenotypes are co-dominant, while the O phenotype is recessive.

Multiple alleles at a single locus

Blood group systems, provide a demonstration of the effects of multiple alleles at the same locus. In this case, the three alleles are represented as I^A, I^B and i. I^A codes for the A antigen, I^B codes for the B antigen while i does not produce either antigen. Therefore the effects of I^A and I^B dominate over i. Each person carries copies of one or two of these three possible alleles. Table 11.1.1 shows the possible genotypes and phenotypes for the ABO blood group system.

Genotype	Phenotype (blood group)	Diagram of red blood cell
I^AI^A I^Ai	A	
I^BI^B I^Bi	B	
I^AI^B	AB	
ii	O	

TABLE 11.1.1 Possible genotypes and phenotypes in the ABO blood group system.

From this table it can be seen that there are six possible genotypes and four phenotypes, with the A and B blood groups both having two possible genotypes.

The possible genotypes and phenotypes of the offspring of a parent with blood type O and a parent with blood type AB can be determined using a Punnett square, as shown below.

Parents		Blood type AB	
		I^A	I^B
Blood type O	i	I^Ai	I^Bi
	i	I^Ai	I^Bi

The F1 generation in this example would be either blood type A or B, but all would be heterozygous.

If a heterozygous individual for blood type A and a heterozygous individual for blood type B were to have children, four possible combinations of blood type are possible, as shown in the following Punnett square.

Parents		Blood type B	
		I^B	i
Blood type A	I^A	I^AI^B	I^Ai
	i	I^Bi	ii

The F1 generation would show all of the phenotypes possible: AB, A, B and O. The important principle illustrated by this example is that phenotypes are not always dominant or recessive. The dominance of a phenotype is always in relation to another phenotype. Thus, phenotype A is co-dominant with B, but dominant to O.

Dominance relationships can also vary with a change in the environment.

SEX-LINKED INHERITANCE

So far you have examined the inheritance of genes located on autosomes. However, the patterns of inheritance are not the same for genes located on either of the two sex chromosomes. Phenotypes inherited through genes on sex chromosomes are said to be 'sex-linked' and they show **sex-linked inheritance**. It is important to remember that sex chromosomes also carry other genes which are not related to sex determination.

Figure 11.1.8 shows how sex chromosomes are transferred to the offspring, with an equal probability of the offspring being female or male. The XY system determines sex in humans, most other mammals, some insects and some plants. In this system, females are homogametic (XX) and males are heterogametic (XY). The female passes one X chromosome on to her offspring, while the male can pass on either an X or Y chromosome; an X chromosome produces female offspring and a Y chromosome produces male offspring. It is therefore the father's genetic contribution that determines the sex of the offspring. In birds, some fish, some insects and some reptiles, sex is determined by ZW chromosomes. In this system females are the heterogametic sex (ZW) and males are the homogametic sex (ZZ).

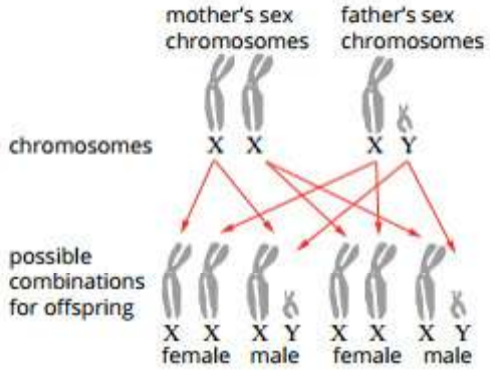


FIGURE 11.1.8 Inheritance of the sex chromosomes in the XY sex-determination system. The outcome of this inheritance is two possible arrangement—XX or XY with half the offspring being female and half being male.

X-linked recessive inheritance

In humans, X-linked recessive traits are predominantly expressed in males, because males carry only one X chromosome. Females carrying an X-linked recessive allele might not express the trait, or show only mild expression. This is because the second X chromosome that females carry could mask the recessive trait. The probability in humans of a female carrying two X-linked recessive alleles is very low.

The pattern of sex-linked inheritance is evident when a **reciprocal cross** is performed. This is an experiment to investigate the role of parental sex on the inheritance of genotypes. Two crosses are performed: one crossing a male with the trait of interest with a female not expressing the trait (usually homozygous wild type), and another crossing a female with the trait of interest (homozygous) with a male that does not express the trait (usually wild type). If the trait is sex-linked (carried on the X chromosome), the phenotypic ratios of the male and female offspring will be different.

Paralysis in Drosophila

The temperature-sensitive paralytic gene, named after the mutant phenotype, is on the X chromosome of the fruit fly (*Drosophila melanogaster*). A mutant phenotype arises from a genetic mutation that causes phenotypic change from the normal wild type phenotype. Individuals with the mutant allele are paralysed when incubated to a temperature of 29 °C, whereas wild type flies (see page 472) show normal behaviour at this temperature. The paralytic phenotype is recessive to wild type. For this trait, wild type flies move around normally, are not paralysed, when the temperature is 29 °C.

The alleles are defined differently for sex-linked traits. An *X* is used to indicate that the trait is carried on the X chromosome, and the allele is written in superscript next to the X. In the example of the vinegar flies, the alleles can be written as:

X^P = wild type

X^p = paralysis

As the paralytic phenotype is recessive, females that are homozygous for the mutant allele (X^pX^p) express the mutant paralysis phenotype; females that are homozygous dominant (X^PX^P) and females that are heterozygous (X^PX^p) are both wild type phenotype.

As males have only one X chromosome there are only two male genotypes: X^pY males are paralytic and X^PY males are wild type.

If paralytic females (X^pX^p) are crossed with wild type males (X^PY), all of the F1 male offspring will be paralytic (X^pY) and all of the F1 female offspring will be wild type phenotype (X^PX^p) (Figure 11.1.9a, page 458). This pattern of transmission of the mutant phenotype from the female parent to male offspring is characteristic of X-linked recessive inheritance.

EXTENSION

Dominance relationships can vary

Whether a phenotype associated with a particular allele is dominant, recessive or co-dominant can be determined at the biological level (e.g. protein or cell) and also influenced by the environment of the organism. One example of this is sickle cell anaemia, which is caused by a mutation of the gene that codes for the production of the protein beta-haemoglobin.

The phenotype can be examined at three different levels: the protein (production of beta-haemoglobin), the cell (shape of the red blood cells) and the organism (susceptibility to malaria). Furthermore, these can be looked at in two environments—at sea level and at high altitude.

The following table illustrates that dominance, as shown by the phenotype of the heterozygote, varies at different biological levels and that these relationships may be different again at high or low altitudes.

Phenotypes	Normal Hb^AHb^A	Heterozygote Hb^AHb^S	Homozygote Hb^SHb^S	Dominance relationships
ß-globin polypeptide production				Normal and sickle-cell phenotypes are co-dominant
Red blood cell shape at sea level	 Normal	 Normal	 Sickle cells present	Normal phenotype is dominant, sickle-cell phenotype is recessive
Red blood cell shape at high altitudes	 Normal	 Sickle cells present	 Severe sickling	Normal and sickle-cell phenotypes show co-dominance
Susceptibility to malaria	Normal susceptibility	Resistant	Resistant	Sickle-cell phenotype is dominant, normal phenotype is recessive

TABLE 11.1.2 Phenotypic expression of the genotypes of sickle cell at different levels of biological organisation and in different environments. *Hb* is the gene for beta-haemoglobin, with alleles Hb^A (normal beta-haemoglobin) and Hb^S (mutation in beta-haemoglobin causing sickle-shaped cells).

The reciprocal (reverse) cross, shown in Figure 11.1.9b, produces a different outcome. If a wild type homozygous female (X^PX^P) is crossed with a paralytic male (X^pY) all of the offspring (male and female) are wild type (X^PX^p and X^PY).

These different outcomes of the reciprocal crosses are characteristic of X-linked recessive inheritance. In contrast, reciprocal crosses give the same outcome for autosomally inherited genes.

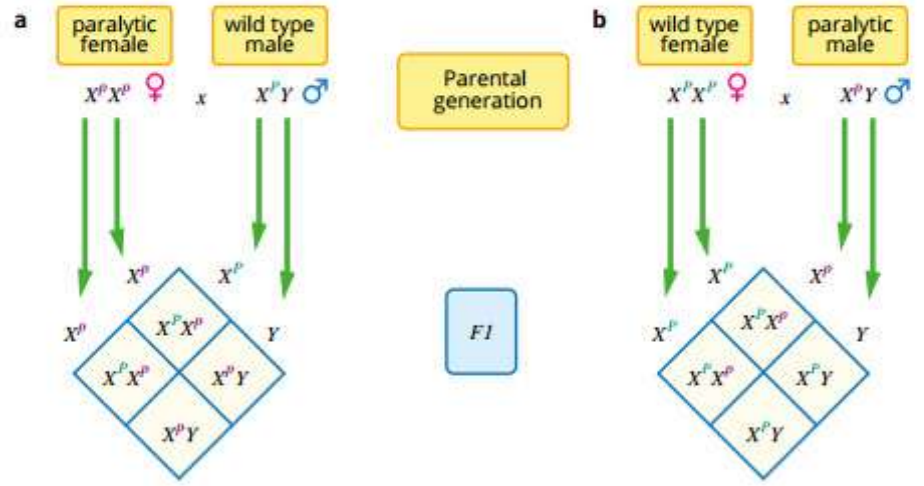


FIGURE 11.1.9 The characteristics of X-linked inheritance are evident in a reciprocal cross. (a) A male receives an X chromosome from the female parent, so males are paralytic (X^pY) and females are wild type (X^PX^P or X^PX^p). (b) In the reciprocal cross, both the male and female offspring are wild type. The outcome of the reciprocal cross is always different for X-linked traits.

Haemophilia in the British royal family

Figure 11.1.10 shows part of the family tree of the British royal family, including Queen Victoria, whose eighth child Leopold was born with haemophilia. Haemophilia is a blood disorder in which blood clotting is slow, resulting in excessive bleeding. It results from a mutation in a gene on the X chromosome that is involved in the production of a blood clotting protein that controls bleeding.

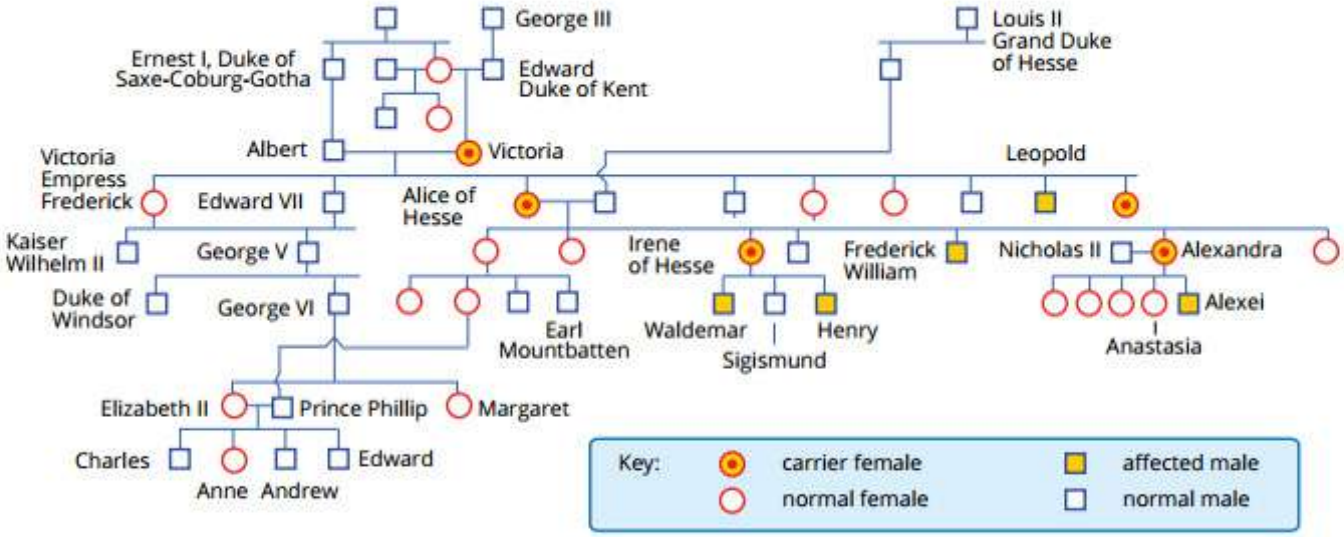


FIGURE 11.1.10 Queen Victoria was a carrier of a mutation that causes haemophilia. The affected gene codes for a blood-clotting protein. She had one copy of the normal allele and one copy of the mutant allele. Some of Queen Victoria's female descendants have been carriers, and some male descendants have had the disease.

The incidence of haemophilia in the descendants of Queen Victoria shows the hallmarks of X-linked recessive inheritance. All of the haemophiliacs shown in the tree are male. The female **carriers** of the disease are heterozygous, carrying one haemophiliac allele and one normal allele. Given that the haemophilia phenotype is recessive, carrier females are phenotypically normal. However, because females produce eggs carrying the normal and haemophiliac alleles with equal frequency, and males receive their single X chromosome from the egg, there is a 50 per cent chance that the son of a carrier will have haemophilia.

Through marriage, some of Victoria's phenotypically unaffected daughters who carried this mutation spread haemophilia to other royal families in Europe. For example, Irene of Hesse transmitted the haemophilia allele to her eldest and youngest sons Waldemar and Henry, and the normal allele to her other son, Sigismund. This form of haemophilia occurs at a frequency of 1 in 10 000 males and 1 in 100 million females.

Pedigree charts are discussed further in Section 11.2.

In general, X-linked recessive disorders occur at much higher frequencies in males than females because females need to inherit a copy of the allele from both parents (that is, the mother must be a carrier and the father must be affected by the disorder). Males, however, need only inherit one copy of the X-linked allele from their carrier mother (Figure 11.1.11).

X-linked dominant inheritance

X-linked disorders may also display a dominant phenotype. Consider the inheritance of vitamin D-resistant rickets disorder, which causes bone deformities. This is shown in the pedigree chart in Figure 11.1.12. The mother of the first generation is heterozygous and affected by the condition. Her children had a 50% chance of having vitamin D-resistant rickets, regardless of whether they were male or female.

When a father is affected and a mother is normal (as in the first generation), all female offspring will show the condition, and all male offspring will be normal. This is because female children all receive an X chromosome, which carries the allele for the disease, from their father (refer back to Figure 11.1.8, page 456).

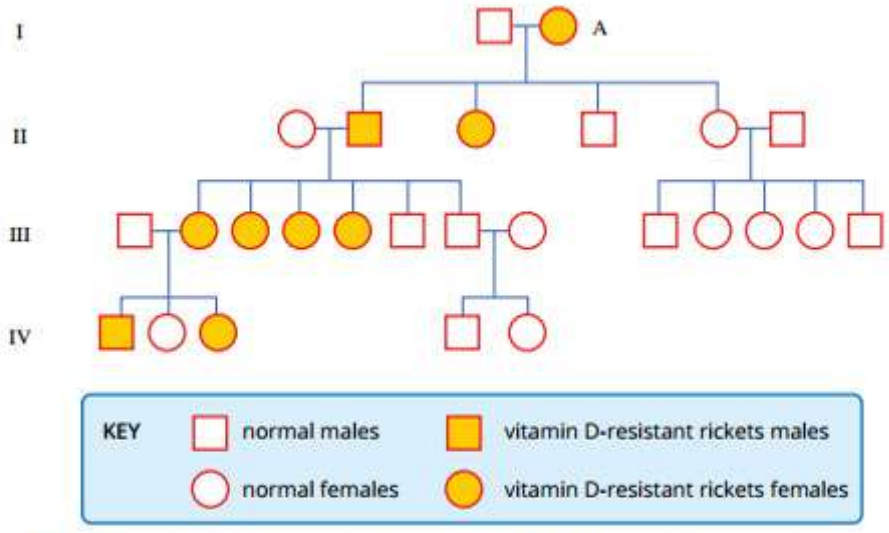


FIGURE 11.1.12 Pedigree chart showing the inheritance of the X-linked dominant condition vitamin D-resistant rickets. The mother (A) of the first generation is heterozygous for the gene that controls the condition.

The alleles for this trait could be shown as:

X^D = vitamin D-resistant (rickets) allele

X^d = normal allele

BIOFILE

Spontaneous mutations

Spontaneous mutations are mutations in DNA that have not been inherited. In the case of Queen Victoria there is no history of haemophilia in her ancestry, so it seems likely that she (or possibly her mother, Victoria, Duchess of Kent) was the source of the mutation. Spontaneous mutations are believed to cause about one third of all haemophilia occurrences.

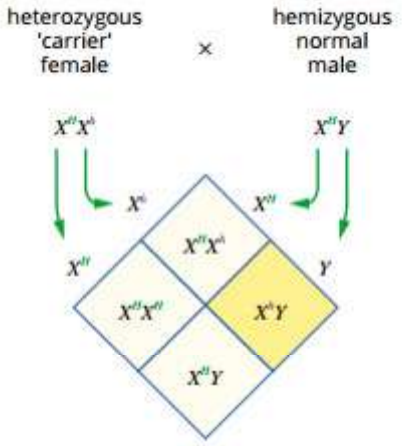


FIGURE 11.1.11 Diagram highlighting the typical situation for the inheritance of X-linked recessive diseases such as haemophilia. A female who is phenotypically normal carries one copy of the allele for the dominant normal phenotype X^H and one for the recessive (mutant) phenotype X^h. All of the female offspring will be normal, but there is a 50% chance that each male offspring will inherit the disease.

BIOFILE

Male pattern baldness

It is estimated that 80% of hair loss is genetic, and though the causes are not yet well understood, it is known that several genes are involved (that is, it is a polygenic trait).

Male pattern baldness is the most common type of baldness and affects around 40% of men by the age of 40 and around 60% by the age of 60. Affected males gradually start losing their hair, until eventually they have hair only on the sides and back of the head (Figure 11.1.13).

You may have heard that baldness is inherited from your mother's father. This is because one of the key genes associated with balding is on the X chromosome. If your mother's father has male pattern baldness, then your mother will carry the allele for this characteristic on the X chromosome that she inherited from her father. Because you inherited one of your X chromosomes from your mother, there is a 50% chance that you will inherit the affected X chromosome. However, males are much more likely to express the balding phenotype because females have a second X chromosome to mask the expression of the gene.

Balding can also be passed from fathers to offspring, indicating that autosomal genes must be involved. Two genes on chromosome 20 have been found to contribute to balding. The effects of these genes are neither dominant nor recessive, but have an additive effect—the more copies of the alleles you have, the more likely you are to go bald. Even though these genes are found on autosomes, males are affected more than females. This is because some of the genes are associated with male hormone receptors. This is an example of sex-limited inheritance—males and females may have the same genotype but express different phenotypes.

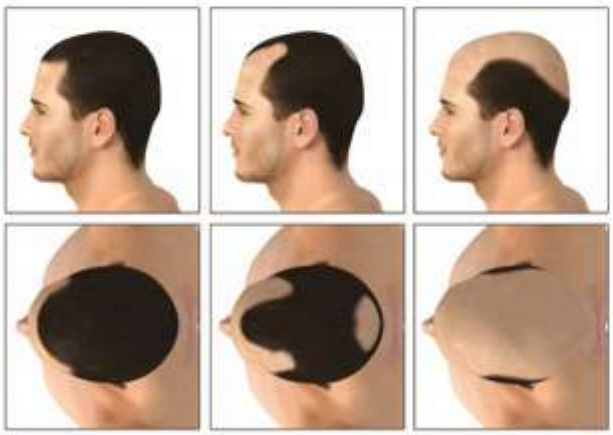


FIGURE 11.1.13 Head of a man showing the change over time of hairline with male pattern baldness. This phenotype can be caused by several genes located on autosomes and the X chromosome.

The following Punnett square shows the pattern of inheritance of offspring of a heterozygous female affected by the vitamin D-resistant rickets allele and a male with the normal allele.

Parents		Mother	
		X^D	X^d
Father	X^d	X^DX^d	X^dX^d
	Y	X^DY	X^dY

The possible genotypes of the offspring are:

$X^DX^d : X^dX^d : X^DY : X^dY$

1 : 1 : 1 : 1

The possible phenotypes are therefore:

female with vitamin D-resistant rickets : normal female : male with vitamin D-resistant rickets : normal male

1 : 1 : 1 : 1

The following Punnett square shows the pattern of inheritance of offspring between a homozygous unaffected female and a male with vitamin D-resistant rickets.

Parents		Mother	
		X^d	X^d
Father	X^D	X^DX^d	X^DX^d
	Y	X^dY	X^dY

The possible genotypes of the offspring are:

$X^DX^d : X^dY$

1 : 1

The possible phenotypes are therefore:

All females have vitamin D-resistant rickets : all males are unaffected

Y-linked inheritance

Compared to the X chromosome, the Y chromosome has few genes: it has only about 72 protein coding genes, compared to 800–900 on the X chromosome. Most of these genes are involved in male sex determination and fertility. Therefore there are far fewer **Y-linked** traits than X-linked traits.

If a trait is passed from father to son and never observed in females, it is likely to be Y-linked, meaning the gene for that trait is on the Y chromosome. Until recently hairy ears were thought to be controlled by a Y-linked gene, but recent studies suggest there are also autosomal genes involved in the trait.

Sex-limited inheritance

The Y-linked pattern of inheritance is sometimes confused with **sex-limited inheritance**. Sex-limited traits can only occur in one sex because the feature affected is unique to that sex. Therefore males and females have different phenotypes. For example, complete androgen insensitivity syndrome, in which the foetus is unresponsive to male hormones, can only occur in males, because only males carry the Y chromosome. This means that even if females have the genotype for this syndrome, they cannot express the condition.

11.1 Review

SUMMARY

- The Law of Segregation states that individuals carry pairs of alleles of each gene, which segregate into gametes during meiosis so that each gamete carries one allele of each gene.
- True-breeding strains are homozygous at the locus of interest and produce genetically identical progeny when crossed with each other.
- A phenotypic ratio approaching 3 : 1 will be observed in the F1 generation of a monohybrid cross between two heterozygous individuals for any trait controlled by a single autosomal gene, with two different alleles, controlling a dominant trait.
- A test cross involves crossing an individual displaying the dominant phenotype but unknown genotype with an individual displaying the recessive phenotype(s).
- Test crosses are used to determine whether an individual of dominant phenotype is homozygous or heterozygous.
- A phenotypic ratio approaching 1 : 2 : 1 will be observed in the F2 generation of a monohybrid cross for any trait controlled by a single autosomal gene, with two different alleles, displaying co-dominance.
- Co-dominant inheritance can be seen in ABO blood grouping.
- Phenotypes inherited through the action of genes located on either the X or Y chromosomes show sex-linked inheritance.
- X-linked recessive inheritance shows a pattern of transmission of the mutant phenotype from the female parent to male offspring.
- X-linked dominant inheritance shows a pattern of transmission of the dominant trait from an affected male parent to all female offspring and from an affected heterozygous female parent to 50% of all offspring.
- Y-linked inheritance shows a pattern of transmission of the trait from father to son, and it is never observed in females.

KEY QUESTIONS

1 What is meant by the term 'monohybrid cross'?

2 Why might the results of a monohybrid cross differ from the expected ratio of 3 : 1? Select the correct answer.

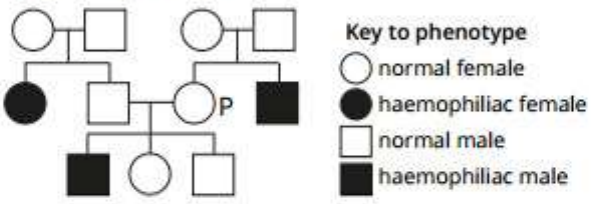
A mutations
B alleles not segregating
C chance
D incomplete meiosis

3 Freckles are an inherited trait which results in the formation of spots on fair skin. It is found on chromosome 4 and shows a dominant inheritance pattern.

a State the type of inheritance (autosomal / sex-linked, dominant / recessive).
b Using suitable symbols, draw a full genetic diagram to show how a mother and father, who have freckles, can have a child that does not have freckles. State the probability for the child not to have freckles.

4 Robert has blood type A and Lee has blood type B. Is it possible for them to have a baby of blood type O? What is the probability of this occurring? Draw a Punnett square to explain your answer.

5 The figure below shows the inheritance of haemophilia in a family. Haemophilia is a recessive X-linked inheritance.



What is the genotype of P? Show your working using a Punnett square and appropriate symbols.

6 Why do sex-linked disorders affect males more than females?

7 Why are there fewer Y-linked disorders than X-linked disorders?

FIGURE 11.2.1 Pedigree charts help to determine patterns of inheritance for different traits in families.

A pedigree is a record of the ancestry (also called the lineage) of an individual or a group of related individuals.

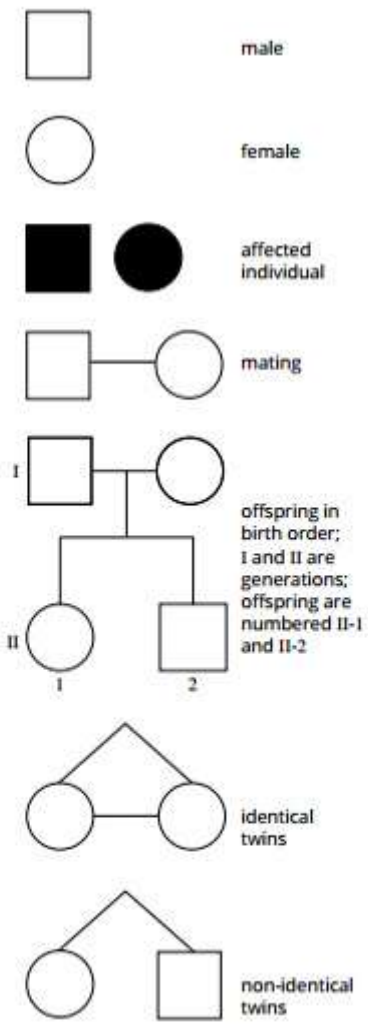


FIGURE 11.2.2 Conventions for pedigree charts.

11.2 Pedigree charts and inheritance patterns

Studying the patterns of inheritance in humans has its challenges. In this section you will learn how patterns of inheritance of alleles across generations of families (Figure 11.2.1) can be analysed using pedigree charts.

PEDIGREE ANALYSIS

Pedigree analysis can be used to follow the inheritance of traits through a family over a number of generations. Given sufficient data, the likely mode of inheritance can be determined; for example, dominance patterns and whether inheritance is autosomal or sex-linked. When it comes to studying the genetics of humans, pedigree analysis is often the only method available for the following reasons:

- Experimental crosses cannot be set up as required.
- The environment in which humans live cannot be controlled experimentally.
- There are strict legal and ethical laws concerning human experimentation.
- Humans tend not to have large families, so there are rarely large numbers of offspring to score.
- Each generation of humans takes many years to reach sexual maturity and produce offspring.

Some of the unique problems of human genetic analysis are being overcome as a result of the Human Genome Project, which you studied in Chapter 10. Knowledge of the mechanisms of inheritance in humans and other organisms continues to advance through research in model genetic organisms, such as the bacterium *Escherichia coli*, fruit fly *Drosophila melanogaster*, yeast *Saccharomyces cerevisiae*, mouse *Mus musculus*, nematode *Caenorhabditis elegans* and the plant *Arabidopsis thaliana*.

In the meantime, studying existing families can assist in tracing inheritance of traits. Pedigree analysis is a technique involving studying a family tree for the occurrence of a particular character or trait in one family over a number of generations. In practice it may be necessary to combine information gained from the pedigree data of several families to determine the most likely mode of inheritance of a particular character.

Pedigrees can be used to determine the pattern of inheritance of particular alleles, as well as the presence of particular alleles within a family and the chances of the allele occurring in offspring.

Pedigree charts

Pedigree analysis makes use of pedigree charts to track and organise data. When analysing a pedigree chart, key features in the pattern of inheritance can be used to distinguish between one type of inheritance and another.

Symbols and conventions used for pedigrees

Pedigree charts use a number of standard symbols and conventions (see Figure 11.2.2). The main ones you need to know are as follows:

- Circles represent females and squares represent males.
- Shapes are shaded or unshaded to represent the presence of a phenotype for a particular trait.
- A horizontal line represents a cross between the individuals.
- A vertical line represents a link from parents to offspring.
- Individuals are numbered from left to right (if required).
- Generations are represented with roman numerals (if required), with the first generation in the pedigree being generation I.
- A carrier of an X-linked trait is shown with a dot in the centre of the symbol.

RECOGNISING INHERITANCE PATTERNS

Autosomal inheritance

Autosomal recessive inheritance

Autosomal recessive inheritance of a trait is likely if two parents do not have a particular phenotype but one or more of their offspring does. Figure 11.2.3 shows the inheritance pattern of a particular trait in a population of unisexual plants (so plants are either male or female). Shaded individuals are affected (that is, they express the trait), and unshaded individuals are not affected.

For this exercise it may be assumed that the inheritance of the trait is not sex-linked. Consider the section of the chart highlighted by the square. This shows that:

- the cross between individuals II-3 and II-4 resulted in three offspring
- individuals II-3 and II-4 are unaffected
- offspring III-1 is female and unaffected, III-2 is male and unaffected, and III-3 is female and affected.

The parents both contribute one allele each for the trait to III-3 (white), so both parents must carry the allele responsible for the trait. Since the parents are both unaffected, both must be heterozygous. The trait is therefore autosomal recessive.

Another indicator of autosomal recessive inheritance is that the trait skips generations (that is, it does not appear in every generation). However, not skipping a generation (as in the pedigree shown above) does not rule out autosomal recessive inheritance.

Once the form of inheritance is determined, it is possible to work out the genotypes of the individuals in the pedigree. First, a symbol should be allocated for the two alleles. In this particular example:

- *P* can represent the allele for purple flower (dominant trait)
- *p* can represent the allele for white flower (recessive trait).

So III-3 (white flowers) must be *pp*, both parents must be heterozygous (*Pp*) and individuals III-1 and III-2 must be heterozygous (*Pp*) or homozygous (*PP*).

An example of autosomal recessive inheritance in humans is haemochromatosis, a disorder in which too much iron accumulates in the body, leading to tissue damage.

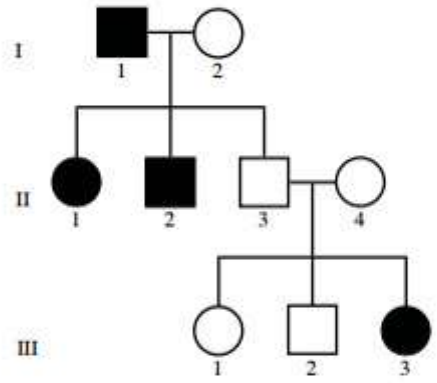


FIGURE 11.2.3 Example of autosomal recessive inheritance.

Pedigree analysis is the determination of the pattern of inheritance of a trait or condition (or disease) by reference to a family tree in which the presence or absence of the condition is recorded over generations.

The observable characteristic that is evident in the heterozygote is referred to as the dominant phenotype.

BIOFILE

Uses for pedigree analysis

Pedigree analysis can be extended to a number of animals that are difficult to study genetically for similar reasons to those for humans. Studbooks are records of parent and offspring phenotypes kept for many years for animals for which ancestry is important. Such animals include recognised dog and cat breeds, thoroughbred horses, and a number of breeds of farm animals. Zoos also keep studbooks for many of their animals to determine breeding programs for conserving the available genetic variation and to avoid inbreeding.

FIGURE 11.2.4 Pedigree analysis can be used to trace the inheritance of particular traits in animals, such as coat colour in horses.

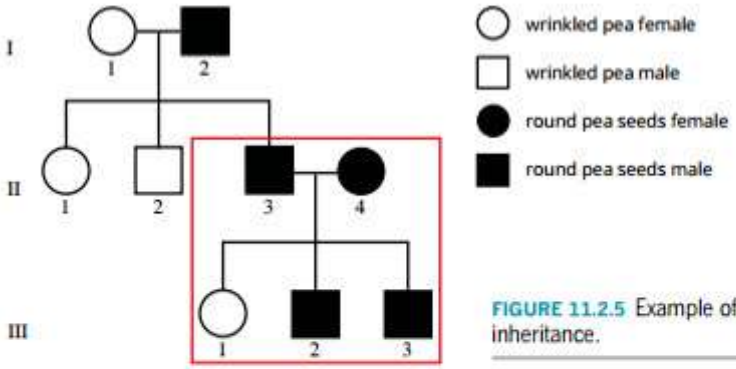


FIGURE 11.2.5 Example of autosomal dominant inheritance.

FIGURE 11.2.6 Hands holding two types of pea, with wrinkled ones at left and round ones at right.

Autosomal dominant inheritance

Autosomal dominant inheritance of a trait is likely if both parents show the trait but one or more of their offspring do not show the trait. The pedigree in Figure 11.2.5 shows the inheritance pattern of round (smooth) and wrinkled pea shape in pea plants (Figure 11.2.6). The shaded individuals represent round peas and the unshaded individuals represent wrinkled peas.

Again it may be assumed for this example that the trait is not sex-linked. Consider the section of the chart highlighted by the square. This shows that:

- II-3 and II-4 produce three offspring
- both II-3 and II-4 are affected
- offspring III-1 is female and unaffected, and III-2 and III-3 are male and affected.

Because both II-3 and II-4 contribute one allele each to III-1, each must carry the allele for the unaffected phenotype. Since each parent carries the wrinkled allele, they must both be heterozygous. As they are heterozygous and show the round phenotype, their phenotype (round) must be dominant.

Other indicators of autosomal dominant inheritance are that the trait may be seen in all generations, and individuals showing the trait must have at least one parent showing the trait. Examples of autosomal dominant inheritance in humans include Huntington's disease and neurofibromatosis Type 1. Examples in other animals include the hornless (polled) trait in cattle.

BIOLOGY IN ACTION

The principle of penetrance

Researchers in France in the 1990s conducted one of the largest pedigree analyses to date when they traced the inheritance of a particular form of blindness (juvenile glaucoma) in over 30 000 living descendants of a 15th century couple. The analysis accounted for almost half of the known cases of this disease in France. The massive pedigree clearly showed that juvenile glaucoma resulted from autosomal dominant inheritance. As a result, it might be expected that every individual who had at least one parent with the disease would also have the disease. However, the researchers noted that this was not always true; sometimes offspring of a parent who developed juvenile glaucoma did not develop the disease (Figure 11.2.7). This illustrates the principle of penetrance.

Complete penetrance of a phenotype means that all individuals with an affected genotype will have the affected phenotype. Incomplete penetrance describes the situation that occurred in the juvenile glaucoma pedigree, where a proportion of a population with an affected genotype does not show the expected phenotype. In the pedigree chart (Figure 11.2.7), individual V-2, whose father had the disorder, did not show the glaucoma phenotype yet passed it on to his daughter (VI-2).

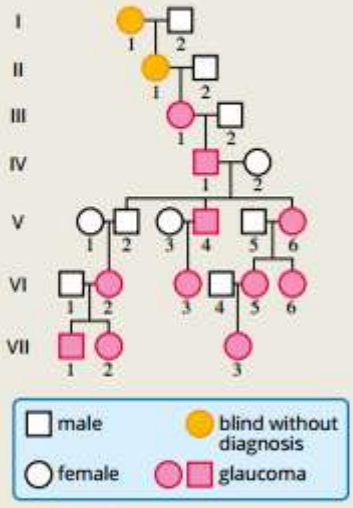


FIGURE 11.2.7 Part of a pedigree chart showing the pattern of transmission of juvenile glaucoma over several generations. Incomplete penetrance is demonstrated by the lack of juvenile glaucoma in V-2.

Sex-linked inheritance

Distinguishing between autosomal and sex-linked inheritance

In the previous examples of autosomal inheritance it was assumed that inheritance was autosomal. However, when investigating inheritance it is important to check whether the inheritance might be sex-linked, because similar patterns can occur in both types.

The inheritance pattern of colour blindness (Figure 11.2.8) in humans can be examined by studying the pedigree of a family in which some individuals are colour blind. By convention, if a mating partner is not shown in the pedigree, he or she is not affected by the phenotype (in this case, not colour blind).

Differences in the incidence of the trait between males and females, and the frequency of the trait across generations, are two inheritance patterns that help determine whether a trait is sex-linked or autosomal.

In the pedigree shown in Figure 11.2.9 only the males are colour blind. This demonstrates that the colour blind trait is not dominant and is potentially sex-linked (X-linked). Y-linked alleles affect only males and are very rare, and the phenotype will be present in every male offspring. Because of these factors, colour blindness cannot be a Y-linked trait.

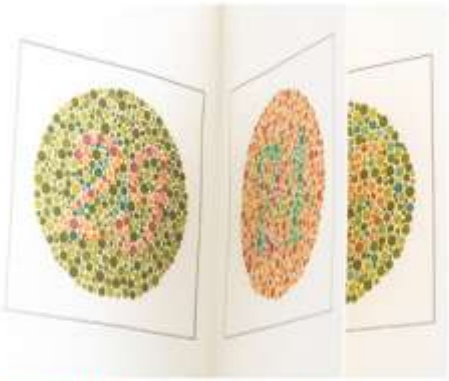


FIGURE 11.2.8 Colour blindness test. Ishihara test cards used to check for red-green colour blindness. Each card depicts a number formed from red dots on a background of green dots, or vice-versa. People suffering from red-green colour blindness cannot distinguish the numbers. Colour blindness is usually caused by an inherited genetic defect in the light-sensitive pigments of the eye. Up to 8% of the male population is affected, and ten times more men have colour blindness than women.

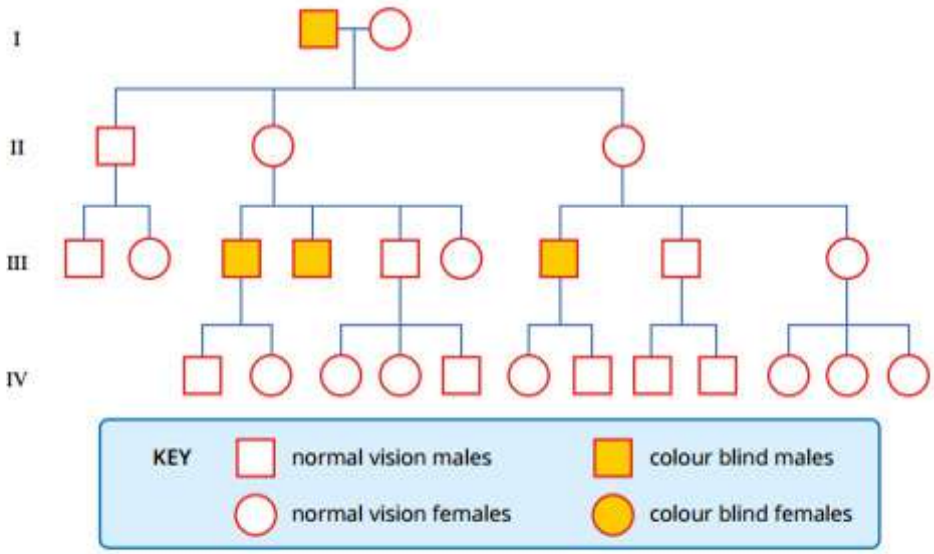


FIGURE 11.2.9 Pedigree of a family in which colour blindness is present. The inheritance of colour blindness is X-linked recessive and so males are affected more frequently than females. No colour blind females were observed in this particular pedigree.

X-linked recessive inheritance

The pedigree in Figure 11.2.9 also indicates that the inheritance of colour blindness is more likely to be X-linked recessive than autosomal recessive, because X-linked recessive traits affect more males than females. This is because males only inherit one X chromosome, while females inherit two. This second X chromosome has a masking effect on recessive alleles, resulting in females carrying the affected allele but not expressing the phenotype. In order for females to be affected by X-linked recessive traits, they must carry two copies of the allele, one on each X chromosome.

Given the low number of offspring, it is possible that all the colour-blind individuals are males purely by chance. However, in reality, many such pedigrees have been studied and show similar patterns, confirming that the inheritance of colour blindness is X-linked recessive.

X-linked dominant inheritance

Traits that are X-linked dominant are rare and affect more females than males. This is because females inherit two X chromosomes and so have twice the chance of inheriting an affected X chromosome compared to males, who inherit only one.

Evidence of X-linked dominant inheritance is seen in a pedigree in which affected males have daughters who are all affected and sons who are not affected. This is because daughters inherit their father's only X chromosome, while sons inherit their father's Y chromosome. If the X chromosome carries an allele for a dominant trait, then the daughter will express its phenotype. X-linked dominant inheritance can be seen in Figure 11.2.10.

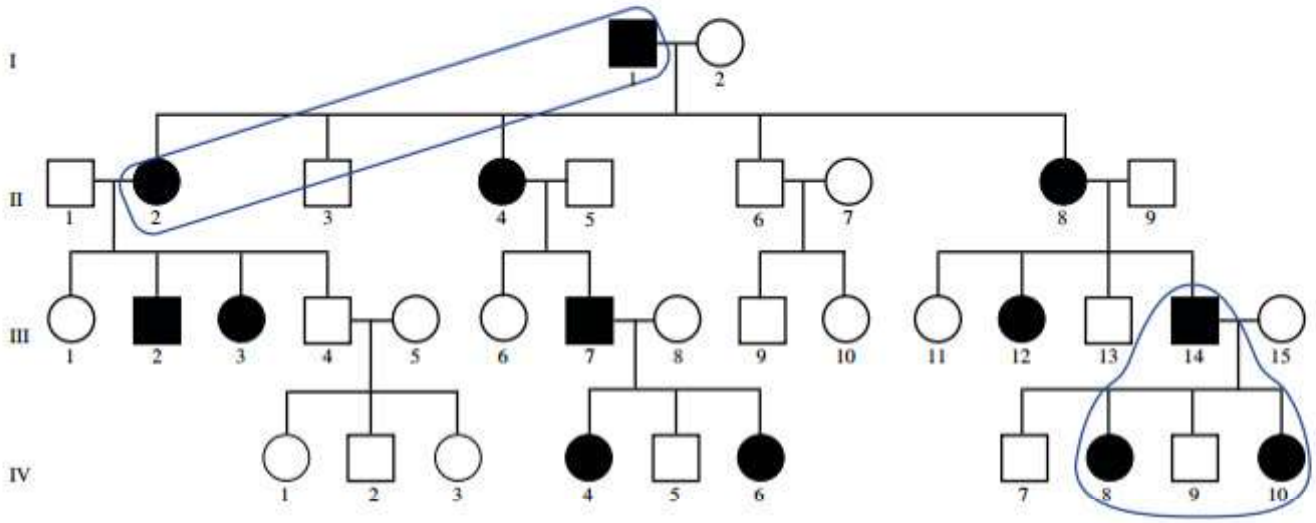


FIGURE 11.2.10 An example of X-linked dominant inheritance.

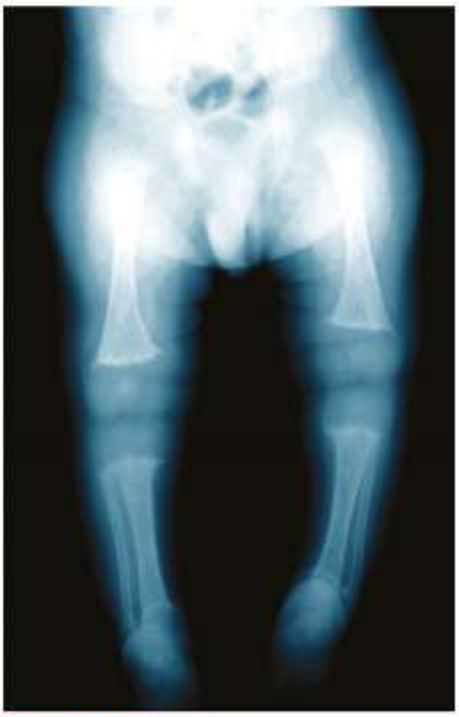


FIGURE 11.2.11 X-ray of the legs of a young child with vitamin D-resistant rickets.

Males I-1, III-7 and III-14 have daughters who are all affected and sons who are unaffected.

Because females pass on one of their two X chromosomes to both their daughters and sons, there is a 50% chance that they will pass on an X-linked dominant trait to their offspring. This pattern of inheritance is seen in female individuals II-2, II-4 and II-8, who have both affected and unaffected daughters and sons. An example of X-linked dominant inheritance in humans is Rett syndrome (RTT), a rare genetic neurological disorder of the grey matter of the brain. Another example is vitamin D-resistant rickets (see Figure 11.2.11, this page, and Figure 11.1.12, page 459).

Y-linked inheritance

Male offspring inherit their father's Y chromosome, so any alleles carried on this chromosome will be passed on from father to son. The phenotype of Y-linked disorders is, therefore, seen in fathers and all their sons. Females are never affected by Y-linked traits because they do not inherit a Y chromosome. As there is only one Y chromosome (hemizygous), and thus only one allele present, the general principles of dominant and recessive inheritance do not apply.

A Y-linked trait is likely if:

- only males are affected
- all male offspring are affected and
- the trait is observed in every generation in which males are born.

This pattern of inheritance can be seen in Figure 11.2.12 on page 467. Because the Y chromosome has far fewer genes that encode for proteins compared to the X chromosome, Y-linked inheritance of disorders is relatively rare.

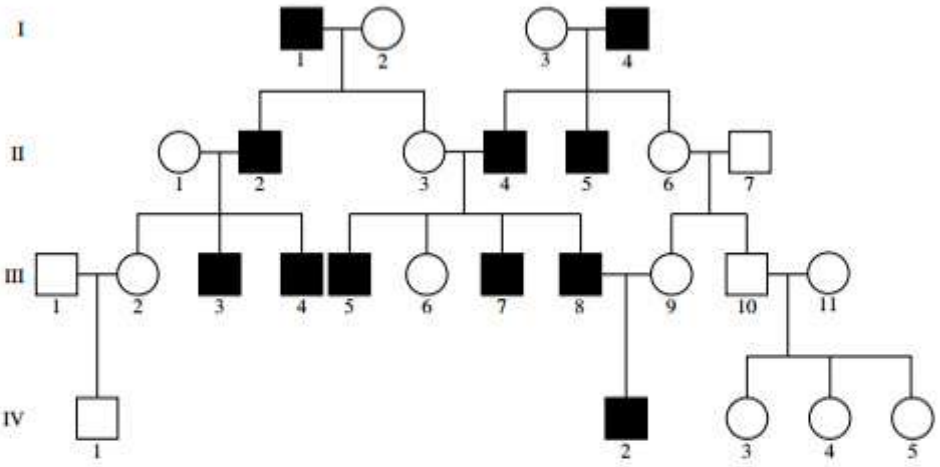


FIGURE 11.2.12 Pedigree chart for a trait with Y-linked inheritance. This pattern of inheritance is evident because only males are affected and the trait is present in males in every generation.

Ruling out sex-linked inheritance

Consider the following pedigree for a trait in humans. It is possible to rule out sex-linked inheritance in this pedigree (Figure 11.2.13) by looking for a pattern that will rule out each type of sex-linked inheritance in turn. (If no such pattern can be found, then that type of inheritance cannot be ruled out.)

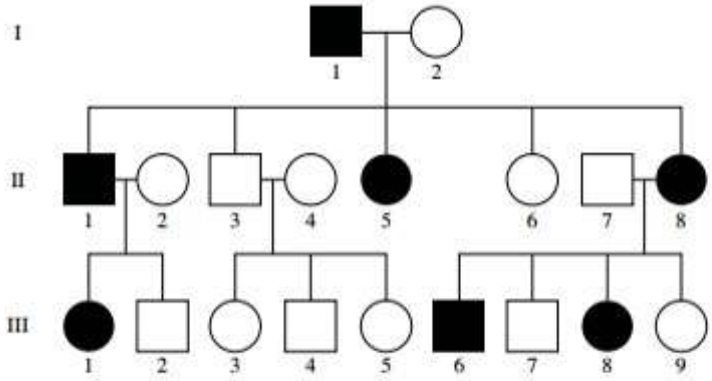


FIGURE 11.2.13 A pedigree chart for an inherited trait in humans. At this stage it is not known whether the inheritance is sex-linked or autosomal.

Ruling out X-linked recessive inheritance: In order for a trait to be X-linked recessive, affected mothers must have affected sons. In Figures 11.2.13 and 11.2.14, we can see that individual II-8 has two sons, one affected by the trait and the other unaffected. For the trait to be X-linked recessive, the mother would have to carry the allele on both her X chromosomes (X^hX^h) to be affected. The mother contributes one of these chromosomes to her offspring, so both sons would have to receive a chromosome with the affected allele. But one son does not show the trait (and therefore did not receive the affected allele), so X-linked recessive inheritance cannot be involved.

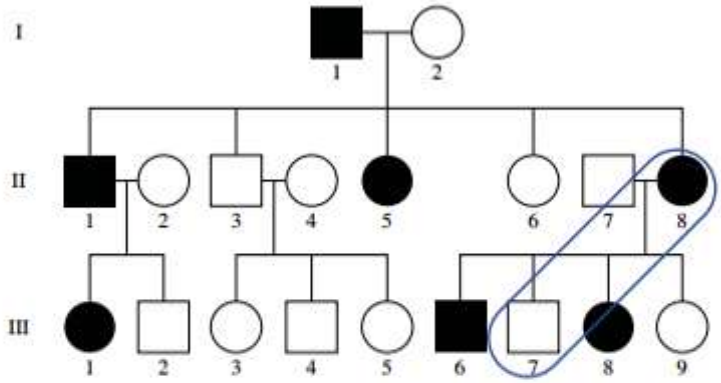


FIGURE 11.2.14 Ruling out X-linked recessive inheritance.

Ruling out X-linked dominant inheritance: For X-linked dominant inheritance to be involved, every daughter of an affected male must be affected. This is because the daughters must receive an X chromosome from their father, and the father has only one X chromosome. In the pedigree shown in Figure 11.2.15, male I-1 has the trait but one of his daughters (II-6) does not. X-linked dominant inheritance therefore cannot be involved in this pedigree.

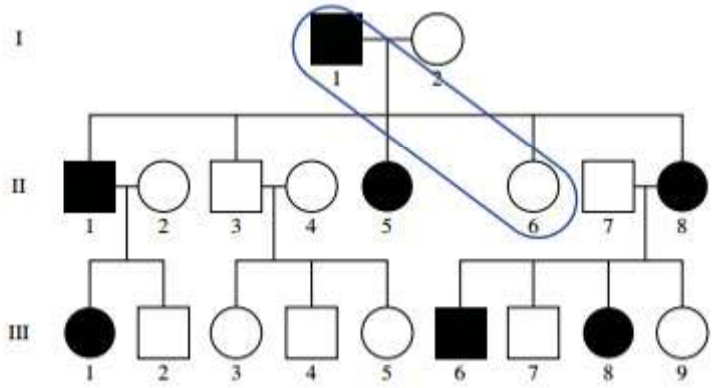


FIGURE 11.2.15 Ruling out X-linked dominance.

Ruling out Y-linked inheritance: If a trait is Y-linked, only males are affected (because females lack a Y chromosome) and affected fathers pass the trait on to all their sons. In the pedigree shown in Figure 11.2.16, some females have the trait, and not all fathers with the trait passed it on to their sons (e.g. male I-1 and son II-3; also II-1 and III-2). Y-linked inheritance is therefore not involved in this pedigree.

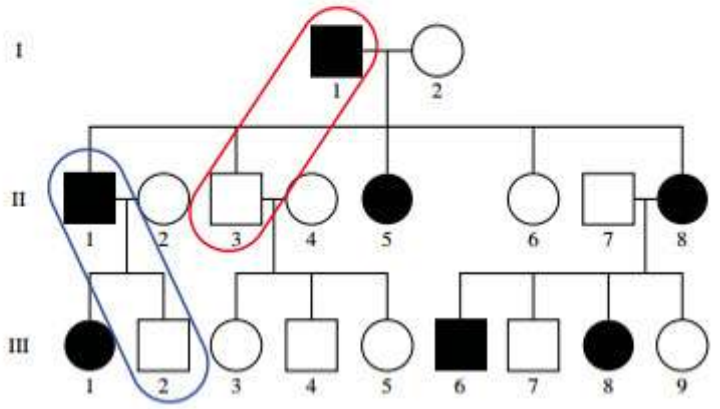


FIGURE 11.2.16 Ruling out Y-linked inheritance.

After ruling out X-linked recessive, X-linked dominant and Y-linked inheritance, it can be concluded that the trait shown in the previous figures must be the result of autosomal inheritance. Although the trait is observed in every generation, which often indicates dominant inheritance, in this case the trait could be autosomal dominant or autosomal recessive inheritance. Further information would be needed to determine which is involved in this pedigree.

STEPS IN PEDIGREE ANALYSIS

A pedigree analysis should be carried out in a methodical series of steps to determine the pattern of inheritance. These steps are outlined below and illustrated in Figure 11.2.17.

Step 1

Determine whether the condition is sex linked.

a Are mostly males affected? If only males are affected, and the trait passes from father to son in every generation, inheritance is most likely Y-linked.

b Do affected daughters have an affected father?

c Do affected mothers have affected sons but not affected daughters? If conditions in (b) or (c) are met, inheritance is most likely X-linked recessive.

d If you answered 'no' to either question in (b) and (c), go to step 2.

Step 2

Look for two affected/unaffected parents that have a child with a different phenotype.

a If two unaffected parents have an affected offspring, inheritance is autosomal recessive.

b If two affected parents have an unaffected offspring, inheritance is autosomal dominant.

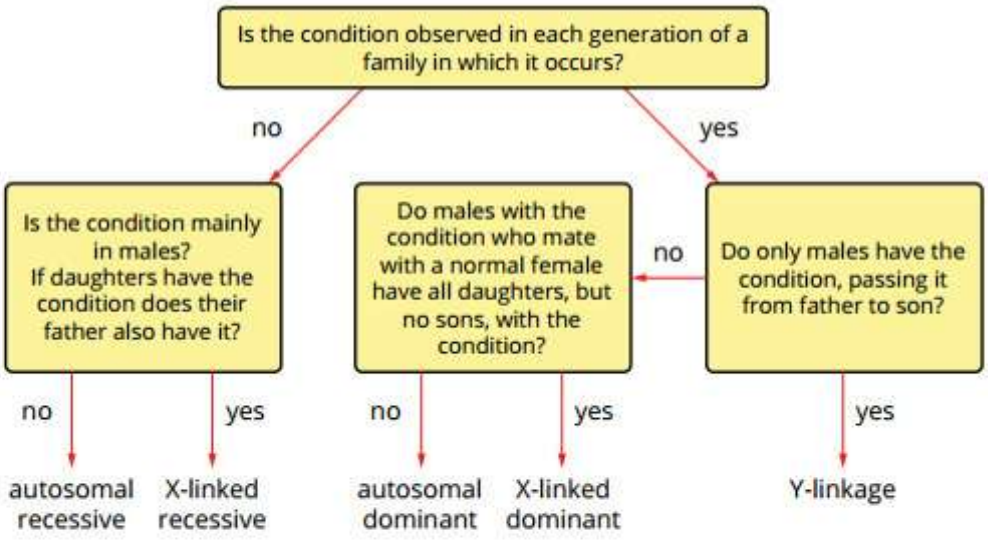


FIGURE 11.2.17 Flow diagram for pedigree analysis of simple modes of inheritance.

11.2 Review

SUMMARY

- Pedigree analysis is a technique of looking through a family tree (of humans or other organisms) for the occurrence of a particular characteristic in one family over a number of generations.
- Pedigrees can be used to determine the likely mode of inheritance, such as dominance patterns and whether inheritance is autosomal or sex-linked.

Autosomal recessive

- Both sexes display the trait in equal numbers in a pedigree.
- Offspring of unaffected parents have a 25% chance of being affected.
- Affected individuals are homozygous.

Autosomal dominant

- Both sexes display the trait in equal numbers in a pedigree.
- One parent must be affected to have an affected offspring.
- Two affected parents with an unaffected offspring indicate dominance: the parents need only one 'dominant' allele to express the trait, so their offspring may inherit their unaffected alleles.
- The trait is observed in each generation.

X-linked recessive

- The trait is rare within the pedigree, but males are more affected than females.
- Affected fathers do not pass the trait on to their sons, so the condition can skip generations.
- Females can be carriers and not show the condition; females pass the trait on to their sons.

X-linked dominant

- Males and females are affected (often more females than males).
- All affected sons have an affected mother.
- All affected daughters have an affected father.
- The trait is observed in each generation.

Y-linked

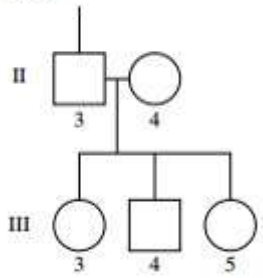
- Only males are affected, not females.
- Fathers pass the trait on to their sons.
- The trait is observed in each generation.

KEY QUESTIONS

1 Why is pedigree analysis often the easiest way to investigate inheritance patterns in humans?

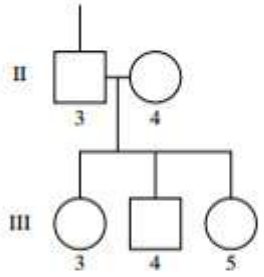
2 Which technology is changing the way we investigate inheritance?

3 The figure below shows part of a family pedigree. If individual III-3 was shaded, which of the following best describes the trait?



A dominant
B sex-linked
C recessive
D co-dominant

4 If individual III-5 was shaded, what would the genotypes of the parents be? Choose from options A–D and draw a Punnett square to show your reasoning.



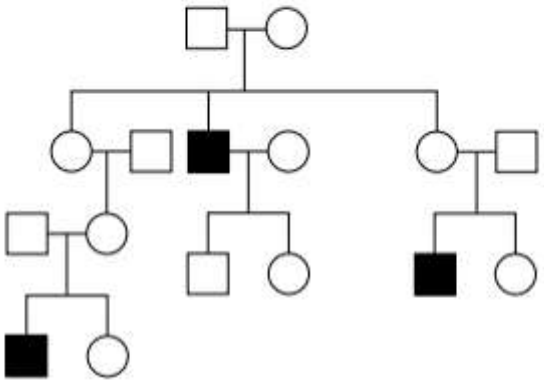
A *BB*, *BB*
B *Bb*, *Bb*
C X^BX^B, X^BY
D X^BX^B, X^bY

5 What does 'carried on the X-chromosome' and 'occurs more in males than females' suggest?

A a monohybrid cross
B a dihybrid cross
C Mendel's experiments
D sex-linked inheritance

6 Explain why Y-linked disorders are rare.

7 What type of inheritance is shown in the pedigree below? Give three reasons for your choice of inheritance pattern.



11.3 Linked genes and crossing over

The crosses discussed so far relate to one trait; for example, the colour of a flower. In this section, you will learn about the inheritance of two characteristics as either independent or linked, and the biological consequence of crossing over for linked genes.

INDEPENDENT ASSORTMENT

FIGURE 11.3.1 The fruit fly (*Drosophila melanogaster*) has red eyes and a brown body.

Mendel's second law of inheritance, the **Law of Independent Assortment**, states that the alleles of a gene controlling one trait assort independently of alleles of another gene controlling a different trait. This can be illustrated by considering crosses involving two genes that affect two distinct traits.

You can cross true-breeding strains of flies (*Drosophila*) that differ for two traits: eye colour and body colour (Figure 11.3.1) and then conduct a **dihybrid cross** ('di' meaning two). The two traits in this example are eye colour and body colour in *Drosophila*.

The eye-colour gene in this example is the yellow eye gene. (This is a different gene from the white eye-colour gene discussed in Section 11.1, and is located on a different chromosome). The 'yellow eye' gene is autosomal; the alleles are *Y* and *y*.

The wild type 'red eye' phenotype (genotypes *YY* and *Yy*) is dominant and the 'yellow eye' phenotype (genotype *yy*) is recessive.

The second trait is body colour and the gene in this example is called 'brown body'. It is an autosomal gene with two alleles *B* and *b*. The wild type green body phenotype (genotypes *BB* and *Bb*) is dominant and brown body phenotype (genotype *bb*) is recessive.

The eye-colour and body-colour genes are on different chromosomes.

F1 generation

In a dihybrid cross, a cross is first set up between a true-breeding red eye, green body (*YY*, *BB*) strain and a yellow eye, brown body (*yy*, *bb*) strain. The homozygous *YY*, *BB* strain will produce gametes carrying only the *Y* and *B* alleles and the homozygous *yy*, *bb* strain will produce only *y* and *b* alleles. The gametes fuse to produce F1 progeny, which are heterozygous for both genes (*Yy*, *Bb*). Following meiosis, a gamete will end up with any of four possible combinations of alleles: *YB*, *yb*, *yB* or *Yb*.

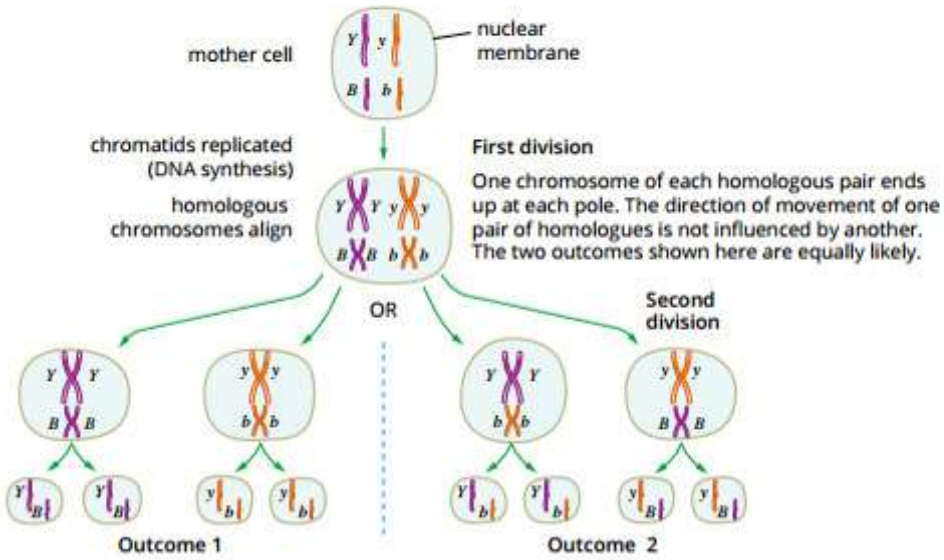


FIGURE 11.3.2 New combinations of alleles result from cells dividing by meiosis. Two genetic loci are shown, each on separate chromosomes within the cell nucleus. Daughter cells produced by meiosis may have any of four possible combinations of alleles.

During gamete formation in F1, the chance of a sperm or egg cell containing a *Y* allele is 0.5 (because half of the gametes contain a *Y* allele). The chance that a gamete will contain a *B* allele is also 0.5. Therefore, the chance of the gamete being *YB* is $0.5 \times 0.5 = 0.25$. The probability of each of the other three possible gametic combinations is also 0.25.

This is because the segregation of alleles of a gene on one chromosome in meiosis is independent of the segregation of alleles of a gene on another chromosome. The **homologue** (matching chromosome) carrying the *Y* allele can move to either pole, as can the homologue carrying the *y* allele. These homologues move independently of the chromosomes that carry the *B* and *b* alleles (Figure 11.3.2). This is the Law of Independent Assortment of genes.

The Law of Independent Assortment states that the alleles of genes that code for different traits are inherited independently from each other.

F2 generation

The heterozygotes generated in the F1 can be crossed together (a dihybrid cross) to produce an F2 generation. Figure 11.3.3 shows that the expected ratio of phenotypes in the F2 generation is:

- 9 red eye, green body
- 3 red eye, brown body
- 3 yellow eye, green body
- 1 yellow eye, brown body.

If these crosses were actually performed, the phenotypic ratio in the F2 generation should be close to the 9 : 3 : 3 : 1 ratio. There would be some difference between the expected and observed phenotypic ratios due to sampling error. The larger the number of F2 progeny scored, the closer the result will be to the 9 : 3 : 3 : 1 ratio.

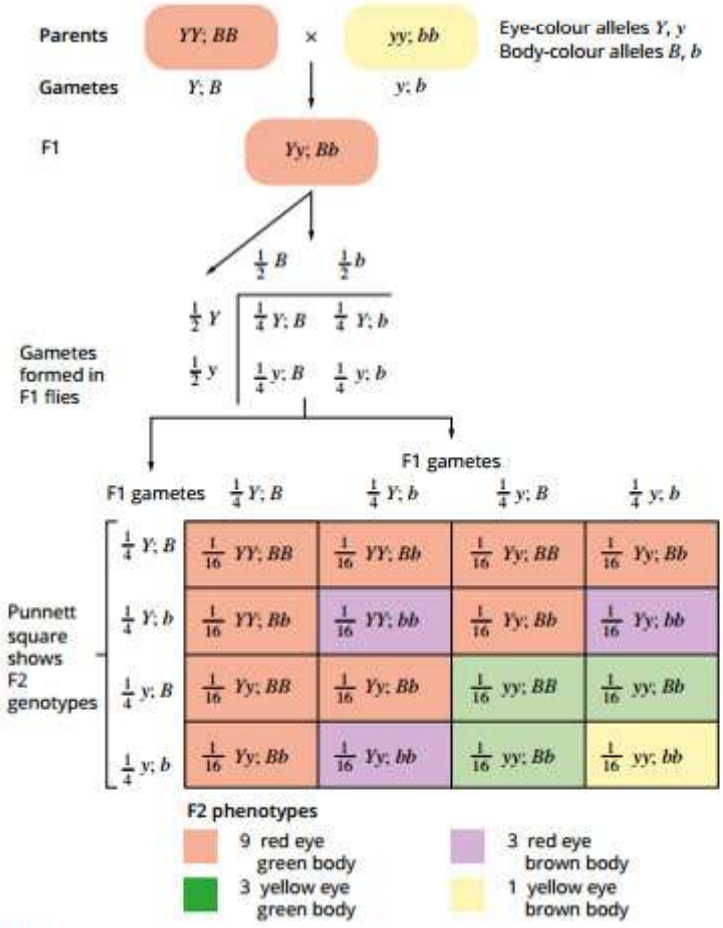


FIGURE 11.3.3 A Punnett square showing the genotypes and phenotypes of the F2 progeny. The F1 generation produces *YB*, *yB*, *yB* and *yb* gametes in equal frequency. When F1 individuals are crossed, the resulting F2 shows a 9 red eye, green body : 3 red eye, brown body : 3 yellow eye, green body : 1 yellow eye, brown body phenotypic ratio.

Dihybrid cross summary

In summary, a phenotypic ratio approximating 9 : 3 : 3 : 1 will be observed in the F2 generation of a dihybrid heterozygous cross if the following five conditions apply:

- the two genes control two distinct traits
- there are two alleles for each of the genes
- one phenotype is dominant for each trait
- both genes are on autosomes
- the two genes assort independently.

In this example, independent assortment occurs because the two genes are on different chromosomes. However, you will learn later in this section that independent assortment can occur via another mechanism.

LINKED GENES

Gregor Mendel was a truly outstanding scientist. His Law of Segregation and Law of Independent Assortment are the cornerstones upon which our current understanding of inheritance is built. Since the rediscovery of Mendel's work 16 years after his death, scientists have continued to refine and extend these Laws or principles to explain new and unexpected aspects of heredity, and more complex patterns of inheritance.

Linkage is the tendency for two or more genes located on the same chromosome to be inherited together.

Although many traits are inherited in accordance with Mendel's Laws, this is not always the case. The exceptions occur when two or more genes are located on a single chromosome and are inherited together. This is known as **linkage**, and is another key principle of inheritance. The closer the genes are, the more likely they are to be inherited together, or 'linked'. But linkage is never complete because of **crossing over**, which occurs during meiosis.

The consequences of gene linkage for phenotypes in offspring can be seen in the following example of maize seed shape and colour. These phenotypes are encoded by autosomal genes, each with two alleles.

Seed colour: Orange (genotypes *OO* and *Oo*) is dominant to white (genotype *oo*).

Seed shape: Round (genotypes *RR* and *Rr*) is dominant to flat (genotype *rr*).

A standard dihybrid cross was conducted, starting with two true-breeding parents, one with orange round seeds (genotype *OORR*) and the other with white flat seeds (genotype *oorr*). The F1 offspring all showed the dominant phenotypes (phenotype: orange, round seeds; genotype: *OoRr*)

If the two genes assort independently, the expected genotypes and phenotypes in the F2 generation can be predicted with a Punnett square for a cross between two F1 plants with orange, round seeds (*OoRr* × *OoRr*). The predicted phenotypic ratio is:

9 red, round seed : 3 red, flat seed : 3 white, round seed : 1 white, flat seed

The expected genotypic ratios are shown in the Punnett square in Figure 11.3.4.

Parents	OR	Or	oR	or
OR	*OR OR*	*OR Or*	*OR oR*	*Or oR*
Or	*OR Or*	*Or Or*	*OR or*	*Or or*
oR	*OR oR*	*OR or*	*oR oR*	*oR or*
or	*Or oR*	*Or or*	*oR or*	*or or*

FIGURE 11.3.4 Punnett square predicting the F2 genotypic outcomes of a dihybrid cross in maize.

However, when this cross was actually carried out, only orange, round and white, flat seeds were obtained, with a phenotypic ratio of 3 : 1. This phenotypic ratio is not in accordance with Mendel's Law of Independent Assortment because both genes are located on the same chromosome and are inherited together. They are linked genes.

Because the alleles are inherited together, there is no crossing over and so only two types of gametes are produced (*AB* and *ab*). In cases such as this, the correct Punnett square to use is seen in Figure 11.3.5:

Parents	*AB*	*ab*
AB	*AA BB*	*Aa Bb*
ab	*Aa Bb*	*aa bb*

FIGURE 11.3.5 Punnett square predicting the genotypic outcomes of a cross with two linked genes.

Linkage and recombination

Crossing over is a normal event that results in genetic exchange between non-sister chromatids. It will occur in most germ line cells going through meiosis. The probability of at least one cross-over event occurring somewhere on the chromosome is high because there is usually at least one chiasma (point of crossing over between chromosomes) for each homologous pair in meiosis (Figure 11.3.6).

Crossing over is the exchange of chromosomal material between members of a homologous pair of chromosomes during meiosis.

Non-sister chromatids are chromatids of paired homologous chromosomes, one from each parent. Paired non-sister chromatids form chiasmata (crossing points) during prophase I of meiosis.

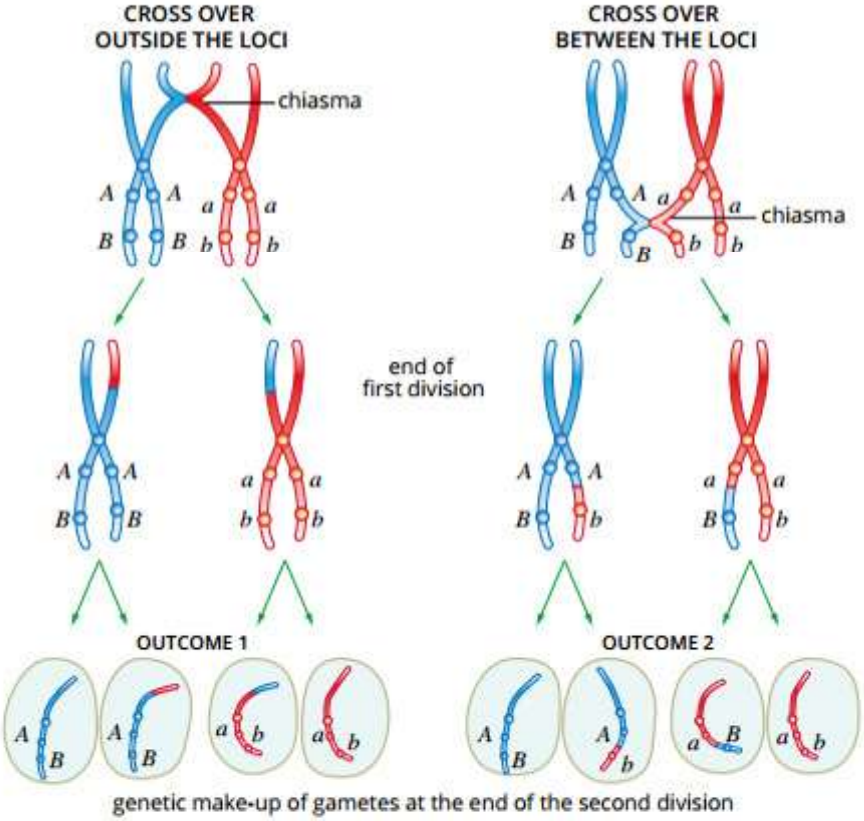


FIGURE 11.3.6 Illustration showing the consequences of crossing over. When two genes, A and B, are located on the same chromosome, crossing over may occur outside the loci (outcome 1) or between the two loci (outcome 2). The gametes produced in these two situations (outcome 1 and outcome 2) are very different.

Consider Figure 11.3.6, which features two hypothetical genes, A and B, with their pairs of alleles *A*, *a* and *B*, *b*. The A and B loci are on the same chromosome.

If a cross is initiated between *AA*, *BB* and *aa*, *bb* parents, the F1 of *Aa*, *Bb* (all heterozygote) individuals will be produced. The diagram shows two possible outcomes of meiosis in a cross of *Aa* and *Bb* heterozygotes.

- Outcome 1 is that crossing over does not occur between the A and B loci, but occurs elsewhere on the chromosomes. In this case:
  - only gametes of allelic combinations *AB* and *ab* are formed, and they are formed in equal frequencies
  - these gametes are referred to as being of the **parental type** because they are the gametes that the *AA*, *BB* and *aa*, *bb* parents of the F1 would have produced.
- Outcome 2 is when crossing over occurs between loci A and B. Gametes containing allelic combinations *AB*, *Ab*, *aB* and *ab* are observed in equal frequency.
  - Some parental type gametes (*AB* and *ab*) are formed.
  - **Recombinant gametes**, *Ab* and *aB* are also formed.
  - Recombinant gametes carry a combination of alleles not observed in the *AA*, *BB* and *aa*, *bb* parents.

If the A and B loci are very close together, the probability of a random cross-over event occurring between them (outcome 2) is very low.

If genes are close together, there will be fewer recombinant gametes and more parental gametes produced (outcome 1). The closer the two genes are together, the more rare the recombinant gametes will be.

If genes are so far apart (on the same chromosome) that close to 50% of the gametes are recombinants, then independent assortment is observed. If the percentage of recombinant gametes is less than 50%, the two genes are considered to be linked (Figure 11.3.7).

i Genes are said to be linked when the percentage of recombinant gametes falls below 50%.

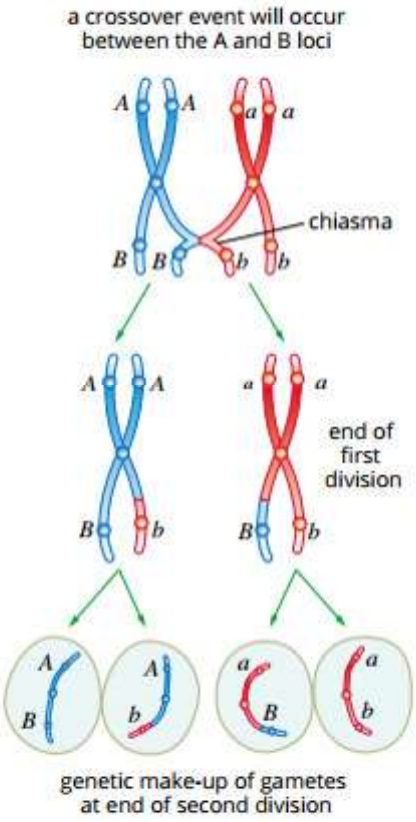


FIGURE 11.3.7 If the genes A and B are far enough apart on the same chromosome, there will be an average of one cross-over event between the genes in every cell, and 50% of the gametes will be recombinant. Therefore, the genes and their alleles assort independently.

BIOFILE

Linked traits: haemophilia and colour blindness

Pedigree analysis shows that the two X-linked traits of red–green colour blindness and haemophilia A (see Section 11.2, page 465) tend to be inherited together. This indicates that the genetic loci for these two genes are close , as seen in the pedigree below for Family A (Figure 11.3.8a).

In Family B, another X-linked trait, haemophilia B, was shown to assort independently from the colour-blindness trait (Figure 11.3.8b). In this family, traits found in one individual (I-1) were inherited separately in subsequent generations (III-2, who inherited haemophilia B, and III-3, who inherited colour blindness). This shows that these two loci are farther apart, and therefore assort and are inherited independently.

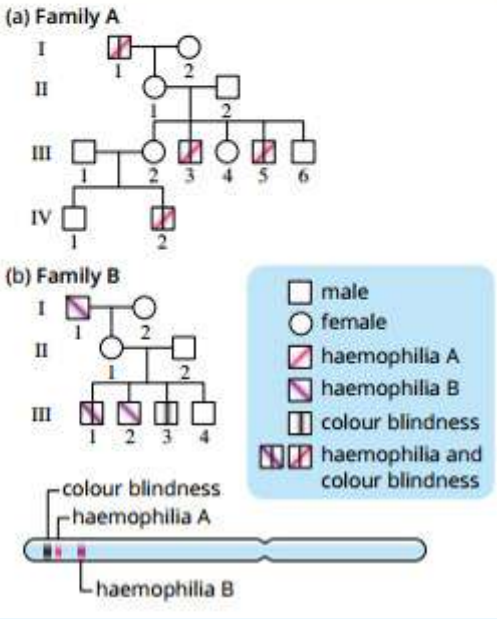


FIGURE 11.3.8 (a) Pedigree chart for Family A, affected by haemophilia A and colour blindness. (b) Pedigree chart for Family B, affected by haemophilia B and colour blindness. Alleles for these three traits are all on the X chromosome. The distance between the loci determines how likely they are to be inherited together. Colour blindness and haemophilia B are farther apart on the chromosome, so they are less likely to be inherited together than colour blindness and haemophilia A.

BIOLOGY IN ACTION

Cystic fibrosis and linkage mapping

Cystic fibrosis (CF) is an inherited disorder that affects the respiratory and digestive systems. It can significantly shorten the lifespan of people with the condition. In a person with cystic fibrosis, the mucus glands secrete thick, sticky mucus, which clogs the airways, leading to breathing difficulties, respiratory infections and lung damage (Figure 11.3.9). The mucus also affects the pancreas, inhibiting the release of important digestive enzymes, which causes a range of nutritional problems. There is currently no cure for the disorder, but modern treatments are continuing to improve life expectancy for those with cystic fibrosis.

The symptoms of cystic fibrosis were first identified in 1938. Finding the gene responsible was a difficult task because its protein product was not known at the time and the gene could have existed on any of the 23 human chromosomes.

In the 1980s, researchers conducting linkage analysis tracked and mapped five genes that were linked to the gene that causes CF (the CFTR gene). The data showed that the CFTR gene was located on the long arm of chromosome 7. The gene was subsequently cloned in 1989 and its gene product (protein) was identified as a membrane chloride channel protein in 1992. This protein regulates the movement of salt in and out of cells. Because the gene is faulty, the regulation of salt movement is inefficient and leads to a build up of salt in the cells, which causes the production of thick mucus.

It is now known that cystic fibrosis is an autosomal recessive disorder (Figure 11.3.10). It is the most common genetic life-threatening disorder in Australia; more than one million Australians carry a copy of the faulty CFTR gene.

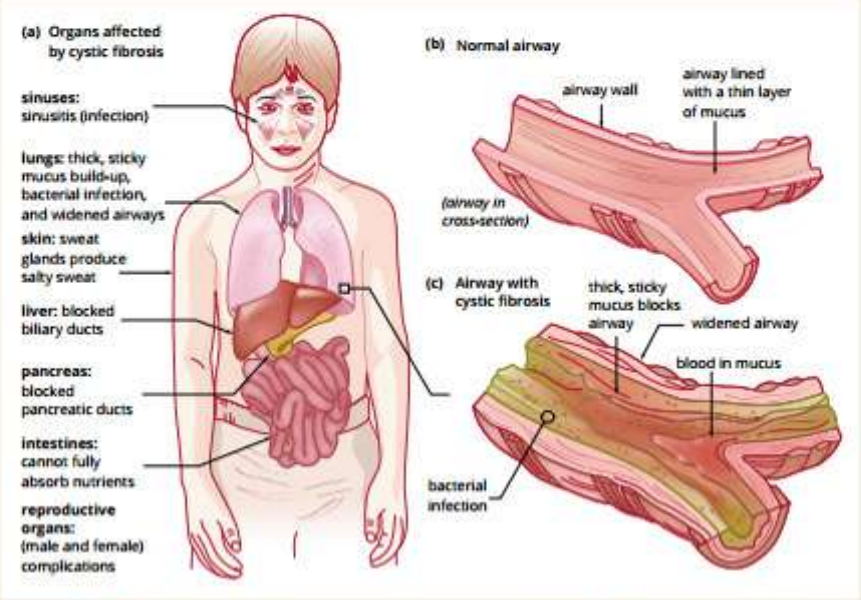


FIGURE 11.3.9 (a) The effects of cystic fibrosis on the systems of the human body and (b) a normal airway compared to (c) the airway of someone with cystic fibrosis.

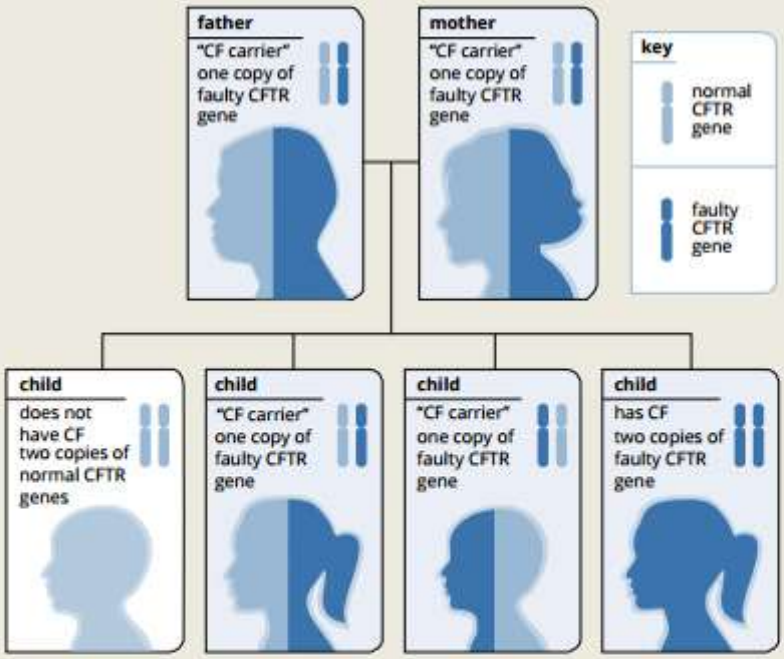


FIGURE 11.3.10 Autosomal recessive inheritance of cystic fibrosis. Regardless of their gender, an individual has a 25% chance of inheriting cystic fibrosis if both their parents are carriers of the CFTR gene.

The percentage of recombination between two linked genes is correlated with their physical distance apart along the length of the chromosome.

Recombination and distance between linked genes

By measuring the percentage of recombinant gametes produced by an F1 heterozygote when genes are linked, it is possible to estimate the distance between the two genes. The farther apart two genes are on the chromosome, the more frequently crossing over will occur and the higher the observed percentage of recombination. By repeating such measurements for different pairs of genes, the position of any identifiable gene on a particular chromosome can be found. This process is called **gene mapping**.

Making use of gene linkage

An important consequence of linkage is that very different traits can be inherited together. This can be extremely important in terms of understanding human health, and in plant and animal breeding.

Information about one locus provides us with the likely genotype at the other locus. A genetic marker is a sequence of DNA with a known location on a chromosome. If a gene of interest is closely linked to a genetic marker, then this can be used to determine if someone carries a mutation (a change in DNA sequence). The closer two loci are, the greater the linkage, and the more precisely a genotype can be used at one locus to predict the other.

Molecular techniques and genetic markers play an important role in this area. Linkage relationships are becoming increasingly important in providing information about the likelihood that a child will have a particular disorder. A marker locus closely linked with the gene that causes a disorder can be extremely useful in determining the genotype of a parent who has the disorder. If a child has the same marker as the parent with the disease, the child is also likely to have the disorder.

11.3 Review

SUMMARY

- A dihybrid cross is a cross between two individuals that carry alleles for different traits at two genetic loci.
- A phenotypic ratio approximating 9 : 3 : 3 : 1 will be observed in the F2 generation of a dihybrid cross if the two traits are each separately controlled by a single autosomal gene with two alleles, where for each trait one phenotype is dominant and the genes assort independently.
- Independent assortment occurs because the segregation of one pair of homologous chromosomes (and the alleles they carry) in meiosis, does not influence the segregation of other homologous pairs of chromosomes.
- Linkage is the tendency for two or more genes located on the same chromosome to be inherited together.
- Genes are 'linked' when the percentage of recombinant gametes falls below 50 per cent.
- Recombinant gametes carry a combination of alleles not observed in the parents.
- The percentage of recombinant progeny can be used to estimate the distance between two genes on chromosomes.

KEY QUESTIONS

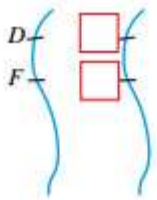
1 What is Mendel's second law, and what does it state?

2 Complete the sentences below about the principle of linkage.
The tendency for two or more _____ located on the same _____ is that they are inherited _____. The _____ the _____ are to each other, the more likely they are to be _____ together, and appear to be _____.

3 What are the possible outcomes of meiosis in a heterozygote individual with the genotype *AaBb*? List all the gametes that this individual could produce.

4 For each of the following statements, state whether it is True or False.
- **a** Genes are linked when the percentage of recombinant gametes falls below 50%.
- **b** Recombinant gametes are observed in the offspring.
- **c** If A and B loci are very close together, the probability of a random cross over event is very low.

5 Sheep blowfly chromosome 5 carries genes for resistance to the insecticide dieldrin (gene *D*). The same chromosome carries a gene called furrowed eyes (*F*).



- **a** Complete the allele symbols for a fly that is heterozygous at both loci.
- **b** If no crossing over occurs in meiosis, the gametes will carry either *DF* or *df* alleles. What combinations of alleles will be present in gametes if crossing over does occur?
- **c** Construct a Punnett square for a cross between the fly shown above (genotype *DdFf*) (after recombination has occurred in meiosis) and a homozygous recessive fly (*ddff*).
- **d** If dieldrin resistance is a dominant trait and furrowed eye is recessive, what proportion of the offspring with normal (wild type) eyes are resistant to the chemical dieldrin?

11.4 Genetic testing and screening

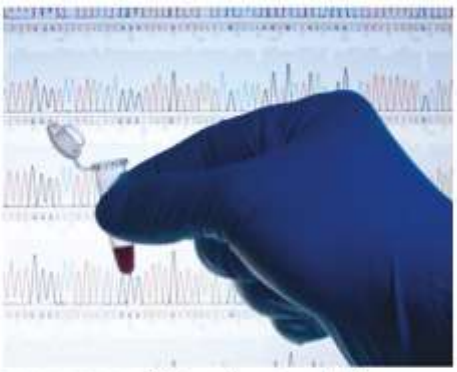


FIGURE 11.4.1 DNA can be extracted from tissue samples and sequenced to enable screening for genetic disorders.

Most cells contain the entire complement of an organism's DNA, known as its genome, which in humans includes thousands of genes. Today biologists are able to isolate fragments of DNA (Figure 11.4.1) and study a single gene or determine the base sequence of an entire genome. Although there are many benefits to this new technology, there are also many social and ethical implications. In this section you will look at the nature and uses of genetic testing and screening of embryos and individuals. The social and ethical implications of genetic testing and screening will also be explored.

GENETIC TESTING

Genetic testing is a type of medical test. It is used to detect specific alleles, mutations, genotypes or karyotypes that are associated with heritable traits, diseases or predispositions to diseases. Genetic testing may also be used as a method to determine parentage or ancestry and has become an important part of forensic analysis.

There are many different kinds of genetic tests, but the methodologies fall into three main categories: molecular genetic testing, cytogenetic testing and biochemical genetic testing.

MOLECULAR GENETIC TESTING

Genetic testing is a type of medical test used to detect specific alleles, mutations, genotypes or karyotypes that are associated with heritable traits, diseases or predispositions to diseases.

Molecular genetic testing is used to identify single genes or short lengths of DNA. Through molecular testing, variations or mutations that lead to a genetic disorder can be identified. Molecular genetic testing is the most effective method if the gene sequence of interest is known and the function of the protein is unknown.

Molecular genetic testing can be performed on any tissue sample and requires only a small sample. There are a few different kinds of procedures that can be used to analyse the sample. Two of the most common procedures used are the polymerase chain reaction (PCR) based assay and restriction fragment length polymorphism (RFLP) analysis.

Molecular genetic testing using the polymerase chain reaction

PCR is a technique used for DNA amplification (make many copies) of a piece of DNA (Figure 11.4.2). A DNA sample is mixed with primers (short lengths of DNA) and other chemicals in a special tube, and the mixture is heated and cooled in cycles. At each cycle of synthesis, the number of copies of the DNA fragment is doubled. In this way a large amount of DNA can be produced in less than an hour. The DNA primers used in PCR target the genes associated with the disorder. The amplified DNA product is then sequenced using DNA sequencing (see Section 10.2) to reveal the presence or absence of the disease-causing mutation.

PCR is a key tool for generating a DNA profile using DNA regions called STRs. STRs, or short tandem repeats, are short sequences of DNA that frequently appear throughout the genome. They are located in the spacer DNA rather than within the protein-coding genes, and vary in length in different people. These differences have no impact on the phenotype or the health of a person, but they are very useful for DNA comparisons. In forensic analysis, PCR is used to amplify 13 different STR regions (using different primers that target different STRs) to gain a DNA profile unique to each individual.

In molecular genetic testing, the DNA primers used in PCR target the genes associated with the disorder. Specific primers can target the CFTR gene when screening parents to identify carriers of cystic fibrosis. Different primers target the PAH gene when screening newborns carrying an allele that causes phenylketonuria. The amplified DNA product is then sequenced using DNA sequencing to reveal the presence or absence of the disease-causing mutation. Alternatively, the amplified DNA is treated with an enzyme (described further below) to identify specific alleles.

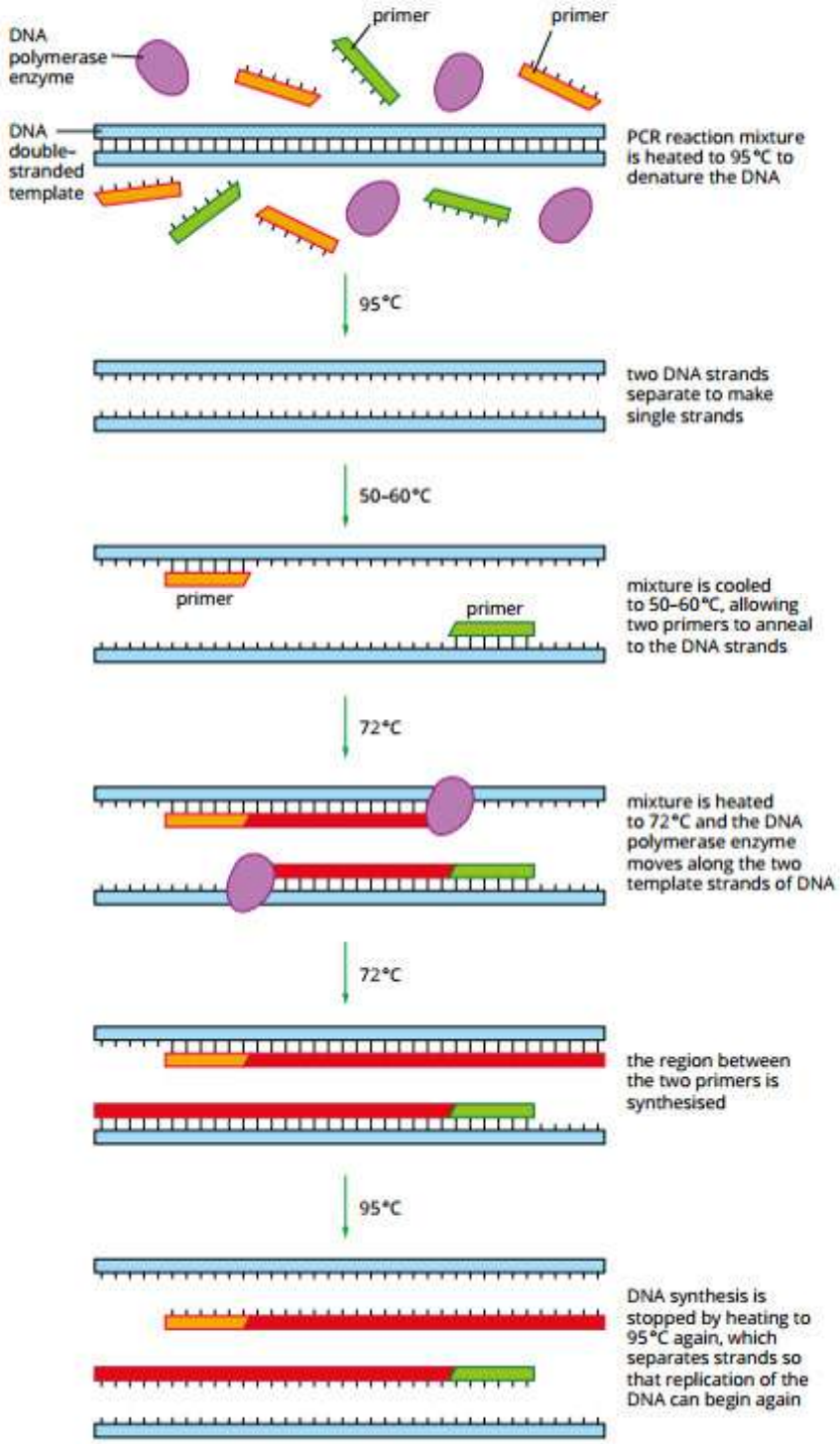


FIGURE 11.4.2 Synthesis of DNA by PCR. All of the components of the PCR reaction mixture are present in the tube. (The four nucleotides, containing bases A, T, C and G are also in the mixture, although they are not shown here.)

BIOFILE

The polymerase chain reaction

The polymerase chain reaction (PCR) is an extraordinarily sensitive technique for forensic investigations of crimes. A DNA sample of only a few cells can provide enough DNA for amplification. Scientists at the Victoria Forensic Science Centre have shown that merely touching an object deposits sufficient material for successful DNA amplification. In handling keys, opening a door or driving a car, the cellular material deposited by a criminal provides ample DNA for analysis following PCR.

After 40 cycles of amplification using the PCR technique, one target molecule of DNA will produce more than one million molecules.

Molecular genetic testing using restriction fragment analysis

FIGURE 11.4.3 Research biologist holding a DNA banding pattern produced by gel electrophoresis. Gel electrophoresis is used to observe differences in the banding patterns (fragment sizes) of an individual's DNA and is used in DNA profiling and gene mapping.

Restriction fragment analysis is a useful type of analysis that rapidly provides information about DNA sequences. There are two parts to this procedure: producing DNA fragments using restriction enzyme digestion (cutting) of a DNA molecule, then separation of the fragments using gel electrophoresis (Figure 11.4.3).

DNA can be cut into fragments by a set of enzymes called restriction enzymes or restriction endonucleases. These enzymes recognise short sequences of bases (a **recognition site**) in a DNA molecule. The different sequences of bases in individuals result in restriction enzymes cutting the target DNA at different sites (Figure 11.4.4). Therefore, DNA samples from two individuals that have been mixed with the same restriction enzymes will form different DNA fragments, giving each person a unique DNA profile (DNA fingerprint). This type of analysis has been used in forensic analysis and paternity testing.

FIGURE 11.4.4 Restriction enzymes act as molecular scissors that cut DNA into fragments at a restriction site.

When the mixture of DNA fragments has been produced, gel electrophoresis is used to separate the fragments of DNA (Figure 11.4.5). Different sized molecules will migrate at different rates through a gel with an electrical current running through it.

Restriction enzymes are frequently used in combination with PCR to identify specific alleles (Figure 11.4.5), such as in screening for carriers of inherited disorders. First, the gene locus is **amplified** using specific primers and PCR. Recall that an allele is a variant of a gene and the sequence may differ by only one nucleotide. If, by chance, this difference occurs at the recognition site for a restriction enzyme, or if a new recognition site is created, then the ability of the enzyme to cut the DNA can be used to identify the allele.

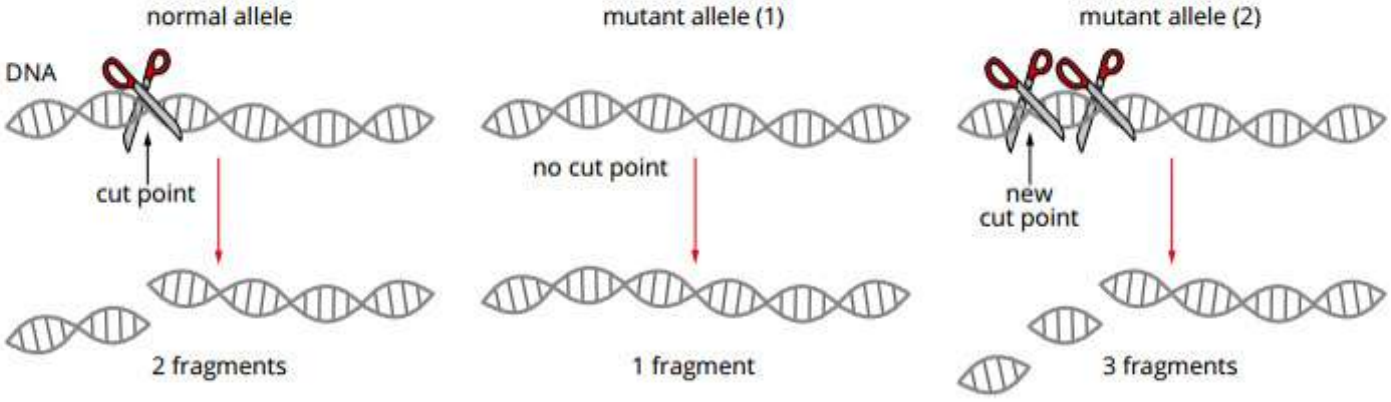


FIGURE 11.4.5 The ability of a restriction enzyme (indicated with scissors) to cut DNA can be used to identify the allele.

Comparing DNA by gel electrophoresis

When the mixture of DNA fragments has been produced, gel electrophoresis is used for separating fragments of DNA (Figure 11.4.6). DNA molecules are separated in a slab of jelly-like substance called agarose.

The gel is immersed in a buffered salt solution to keep the pH suitable for DNA molecules; salts are needed to conduct the electric current through the gel. The DNA is mixed with a fluorescing dye that attaches to the fragments, and a small amount is pipetted into wells along the top of the gel, together with a standard mixture of DNA fragments with different known molecular weights.

The phosphate groups in DNA fragments are negatively charged, so the fragments move through the gel towards the positive terminal when a large electric current is applied. Heavier (longer) fragments move more slowly than lighter (shorter) fragments, so the fragments become more and more separated with time. After a set time the current is turned off. The gel is removed from the bath and placed on an ultraviolet light box. When the light is switched on the dye attached to the DNA fragments fluoresces, so the various DNA fragments can be seen and their sizes estimated by comparing them to the fragments in the standard.

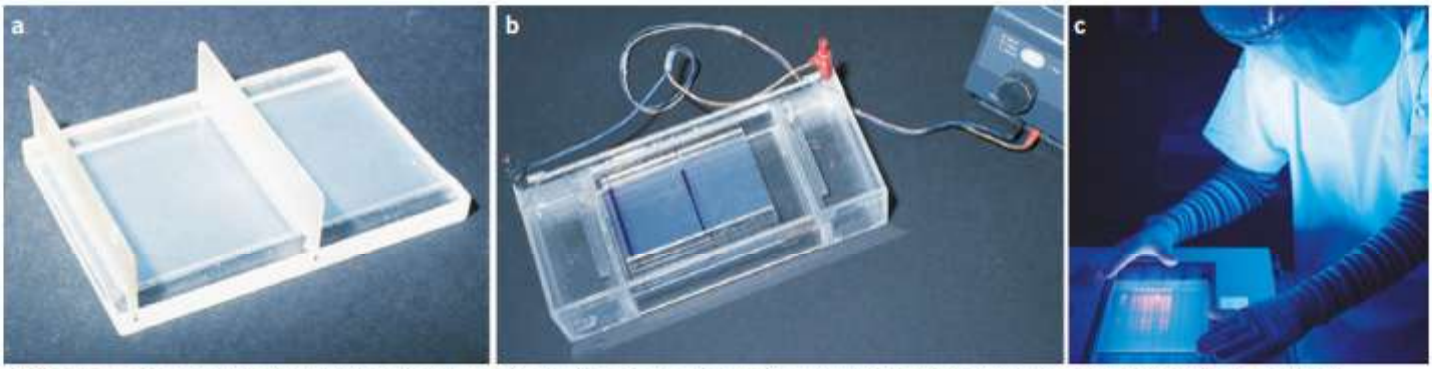


FIGURE 11.4.6 The process of gel electrophoresis. (a) The gel is made in a mould. The two combs shown have two rows of wells for samples and standards. (b) The gel is placed in an electrophoresis bath where it is covered with a buffer solution, and an electric current is applied. (c) The DNA in the gel can be observed when the gel is placed under ultraviolet light.

BIOLOGY IN ACTION

Discovery of heat-stable DNA polymerase

A field trip to Yellowstone National Park in the United States radically altered the course of molecular genetics research in the 1960s. Thomas Brock, a bacteriologist from the University of Wisconsin–Madison, found bacteria in water taken from a hot spring. He named the new species *Thermus aquaticus*.

Enzymes from most organisms are normally denatured (they unfold and stop working) if heated to temperatures of 95°C for more than a few seconds. For *T. aquaticus* to survive in the hot springs, its enzymes, including DNA polymerase, must be able to tolerate these high temperatures. Therefore the DNA polymerase from *T. aquaticus* (called Taq) has proved to be an ideal enzyme for PCR.

FIGURE 11.4.7 Thomas Brock, US microbiologist and discoverer of the bacterium *Thermus aquaticus*.

This technique can be used to compare DNA between individuals and identify relationships. The different sequences of bases in individuals result in restriction enzymes cutting the target DNA at different sites. So, a DNA sample from an individual will result in a unique banding pattern on a gel, showing their individual DNA profile (Figure 11.4.8).

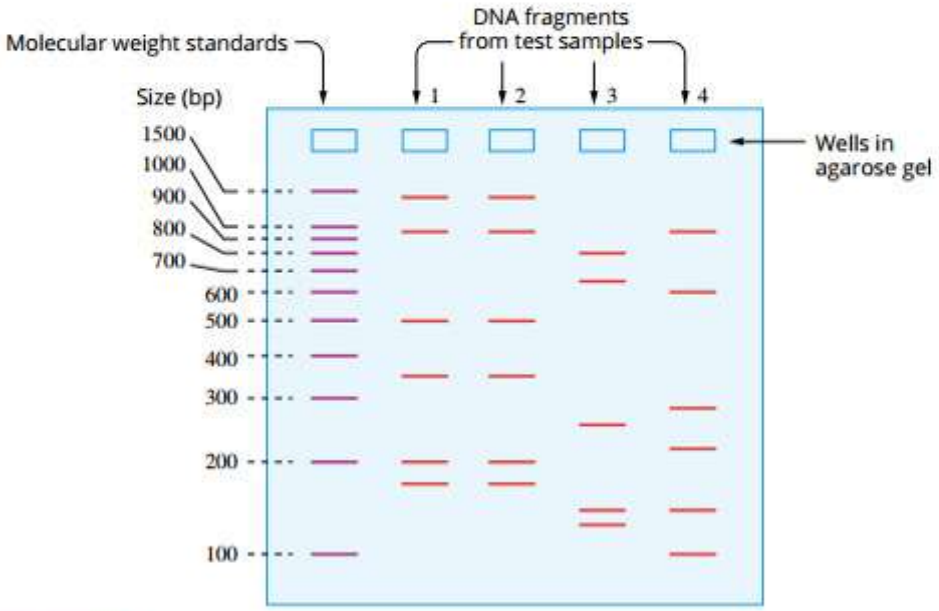


FIGURE 11.4.8 Diagram of a gel showing fragments of digested DNA from four different plant samples. The left lane contains a standard mixture of DNA fragments, which is used to compare the sizes of DNA fragments in the test samples. Plant samples 1 and 2 have identical banding, so they are genetically identical.

BIOFILE

Single nucleotide polymorphisms

New molecular genetics approaches to studying populations have emerged with the advances of the Human Genome Project and the genome projects for other species. These include identifying all the single base changes, called single nucleotide polymorphisms (SNPs, pronounced 'snips') in individual genomes. SNPs are used when comparing genomes in large studies called genome-wide association studies (GWAS) which examine common variants and help identify links between SNPs and disease alleles. They are also useful in identifying important characteristics for crop and livestock breeding.

In molecular genetic testing, restriction fragment analysis can be used to compare two different DNA molecules. For example, two alleles of a gene have slight differences in nucleotide sequence. If the nucleotide difference occurs at a restriction site, it will prevent a restriction enzyme from cutting there. As a result, there will be a difference in the banding patterns between the two alleles (Figure 11.4.9).

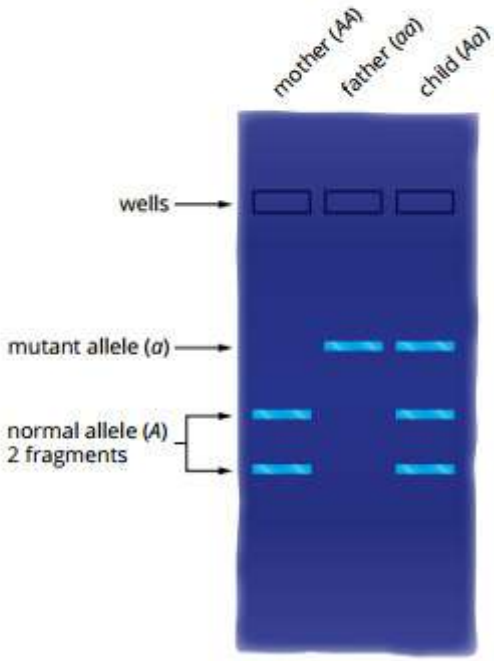


FIGURE 11.4.9 Using restriction fragment analysis to compare DNA samples. In this case a mutant allele, *a*, is present in the homozygous father's DNA and in the heterozygous child's DNA, but not in the homozygous mother's DNA.

Cytogenetic testing

There are two types of cytogenetic testing: conventional cytogenetic testing, also known as karyotyping, and molecular cytogenetic testing by fluorescence *in situ* hybridisation (FISH).

Conventional cytogenetic testing karyotyping

Conventional cytogenetic testing (Chapter 10, page 434) is used to detect numerical or structural chromosome abnormalities in metaphase cells. This method is useful in detecting large changes in chromosomes using light microscopic methods at approximately 1000× magnification (Figure 11.4.10).

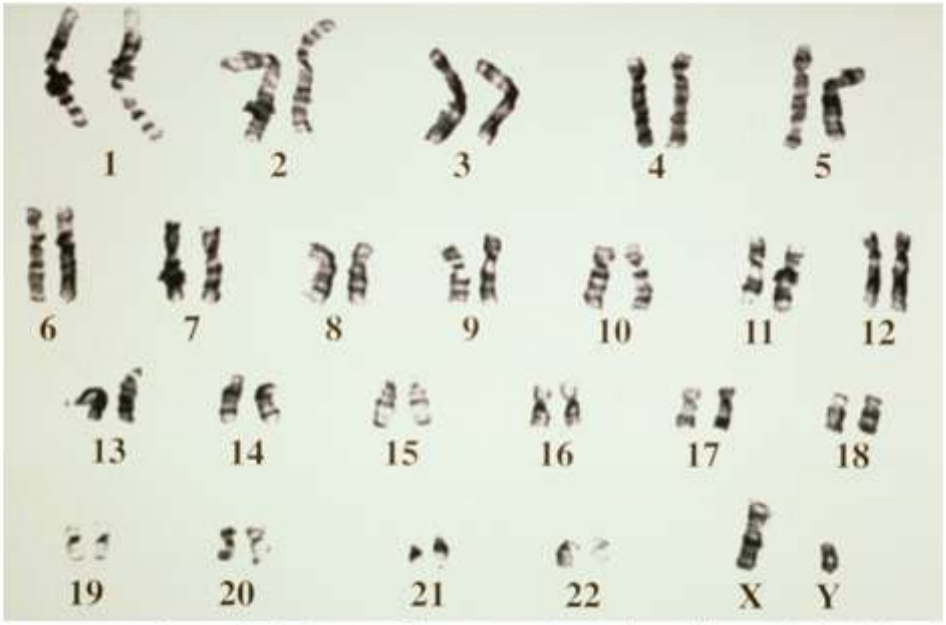


FIGURE 11.4.10 A normal male karyotype. Chromosomes in metaphase cells are stained and viewed under the light microscope. Chromosome photos are arranged in order, to construct the karyotype chart. Conventional cytogenetic testing allows for the determination of abnormal chromosome numbers (such as additional chromosome number 21 in Down syndrome) or large changes in chromosome structure (such as abnormally short or long chromosomes).

Molecular cytogenetic testing by FISH

Conventional cytogenetic testing does not detect other forms of genetic abnormalities such as molecular defects. Molecular cytogenetic testing by FISH is a method in which fluorescently labelled nucleic acid DNA fragments are allowed to hybridise, or attach, to whole chromosomes. This allows the chromosomes to be assessed for changes in their structure, such as the deletion or duplication of certain sections. For example, a chromosome that normally has sections in the order of A-B-C-D might have sections A-B-B-C-D (duplication of B), A-C-D (deletion of B) or A-B-C-P (replacement of D with another section from a different chromosome). These alterations of the chromosomes can be detected using FISH (Figure 11.4.11). Chromosomes can also be assessed for the presence of certain DNA sequences of interest (Figure 11.4.12).

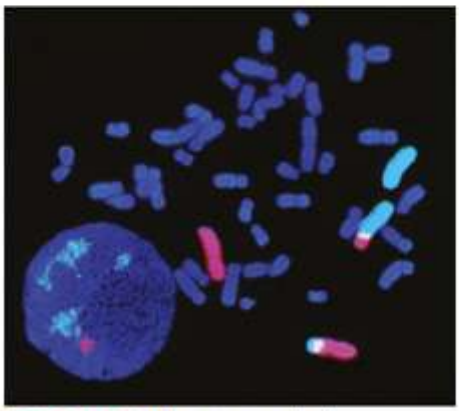


FIGURE 11.4.11 Fluorescence *in situ* hybridisation (FISH) micrograph of chromosomes. In this image, chromosomes 2 and 3 fluoresce pink and light blue. It can be seen that segments of these chromosomes have undergone translocation (exchanged location) so that part of chromosome 2 is attached to 3, and part of 3 is attached to 2.

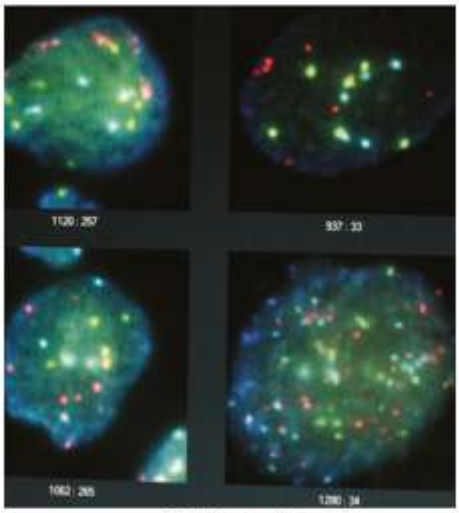


FIGURE 11.4.12 FISH is a technique for detecting the presence or absence of specific DNA sequences on chromosomes. Here it is being used as part of a breast cancer screening process to determine the presence of HER-2 (human epidermal growth factor receptor 2) gene, which codes for a protein that increases aggressiveness in breast cancers.

Biochemical genetic testing

Biochemical testing studies the amount or activity level of certain proteins. Any abnormality in the activity level of proteins is an indicator of changes to the DNA due to the presence of a genetic disorder. Biochemical tests may be used when the specific gene defect has not been identified, or when there are several possible causes of the disease, for example, different mutations in one or more genes. For example, a genetic disease called mucopolysaccharidosis I (MPS I) is caused by an enzyme deficiency that results in an accumulation of molecules called glycosaminoglycans (GAGs) within the lysosomes of cells. If GAGs are not broken down by the enzyme when entering the cells, they accumulate in the cells and cause permanent cell damage that progressively hinders physical development. MPS I leads to skeletal deformities (Figure 11.4.13), coarse facial features, enlarged liver and spleen, and mental retardation. There is no known cure and individuals rarely live past the age of 10 years. If a person is suspected of having MPS I, biochemical testing can be done to determine if there is evidence of the enzyme deficiency associated with the disorder.

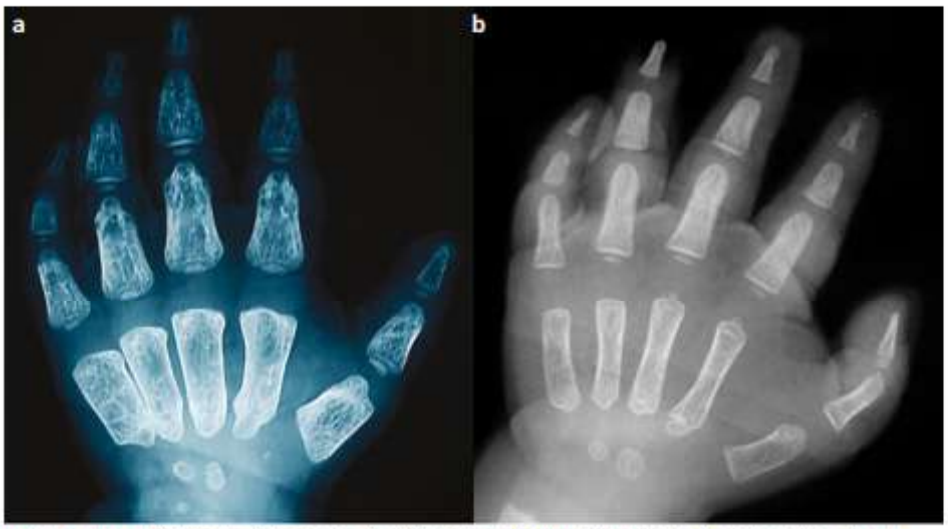


FIGURE 11.4.13 (a) X-ray of the hand of a 28-month-old child with mucopolysaccharidosis type I (MPS I). MPS I is caused by a defective enzyme that is unable to break down glycosaminoglycans (GAGs). GAGs are large molecules normally found in the fluid lubricating the joints. (b) X-ray of a normal child's hand.

APPLICATION OF GENE TECHNOLOGIES IN MEDICINE

Our use of gene technologies means we are capable of intervening in evolutionary processes related to our own and other species. Gene cloning and bacterial transformations, for example, to cultivate insulin-producing bacteria for the treatment of patients with diabetes, represents just one application. **DNA profiling** is commonly used today in paternity cases and to identify or exonerate individuals in crime investigations, but it is also used in **genetic screening** for particular genetic diseases, such as Huntington's disease.

Genetic screening is genetic testing of a large number of individuals or embryos to identify those who are carriers for a particular disease, or who are at risk of a particular disease.

Reproductive technology and genetic screening of embryos

With increased knowledge of the molecular structure of genes and their positions on chromosomes, scientists are able to predict the likelihood of inheriting a disease or whether a mother is carrying a girl or boy. A parent may choose not to carry a particular foetus.

Reproductive technology, such as in vitro fertilisation (IVF), improves some people's chances of having children. This practice affects the human gene pool and may be seen as intervening in human evolution. Check-ups before birth (antenatal) also increase the chance of babies being born that may not otherwise have survived.

In IVF, genetic screening of embryos can be conducted before implantation. This is known as **pre-implantation genetic diagnosis** (PGD). In PGD for cystic fibrosis, for example, one or two cells are removed from an early embryo in vitro and tested for the specific cystic fibrosis mutation (Figure 11.4.14). Only embryos that do not have the mutations would be transferred to the mother's uterus for development. Healthy embryos that are not implanted may be used as donors of embryonic stem cells.

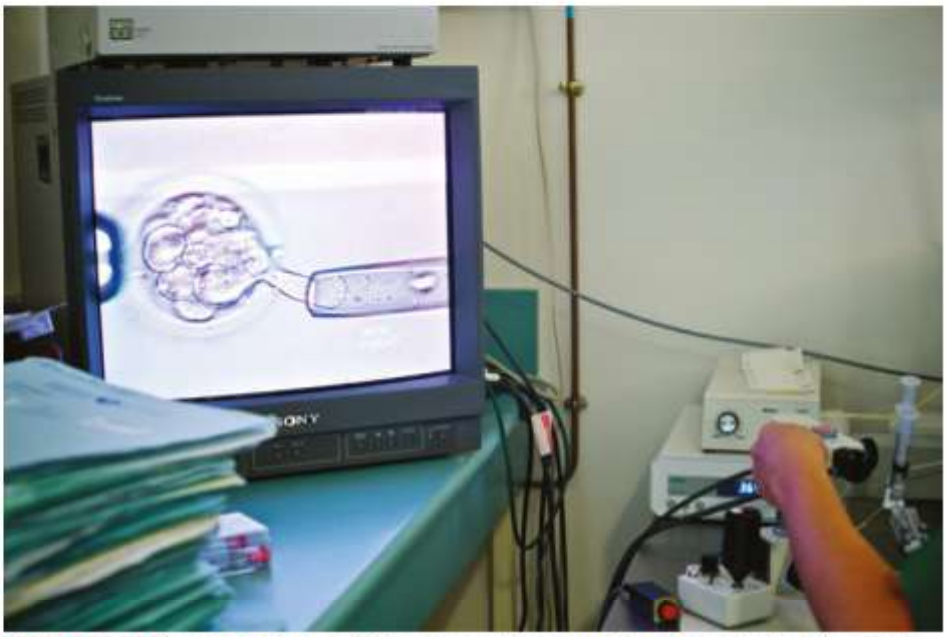


FIGURE 11.4.14 Screen showing a cell being removed from an embryo for pre-implantation genetic testing (PGD). The cell that is removed will be screened genetically for disorders. Only a healthy embryo will be transferred into the uterus for development.

PGD has numerous advantages:

- Parents can choose to avoid having children with a disorder.
- Parents can mentally and physically prepare for a child with a disorder.
- Treatment for the child can start early to prevent symptoms.
- Fewer children with the disorder are born.
- Healthy embryos that are not implanted may be used as a donor of embryonic stem cells instead.

However, there are also some disadvantages:

- The frequency of abortion can increase because parents know about the potential genetic disorder.
- Parents can select embryos for the sex of the child.
- There is the possibility of harmful side effects such as depression if the child knows that he or she will develop a disorder later.

Social and ethical implications of genetic testing and screening

Genetic testing and screening have many applications and benefits, allowing people to seek early treatment and make decisions regarding family planning and health care. However there are also many social, ethical and legal responsibilities and implications that need to be considered when using this technology. The limitations of genetic testing, availability of treatments and privacy concerns, along with the ethical debates surrounding the use of embryos and gene therapy, are just some of the issues that are associated with use of genetic screening.

Limitations of genetic testing

Some genetic tests do not identify all possible gene mutations that can cause a particular condition, or they may have limited predictive value. As a result, the tests may require difficult decisions without full information. For example, genetic testing can determine whether an embryo or foetus has inherited the cystic fibrosis mutation, but it cannot predict the severity of cystic fibrosis in the baby (Figure 11.4.15). Parents are then faced with the ethical dilemma of whether to terminate or continue a pregnancy without knowledge of the severity of the disorder.

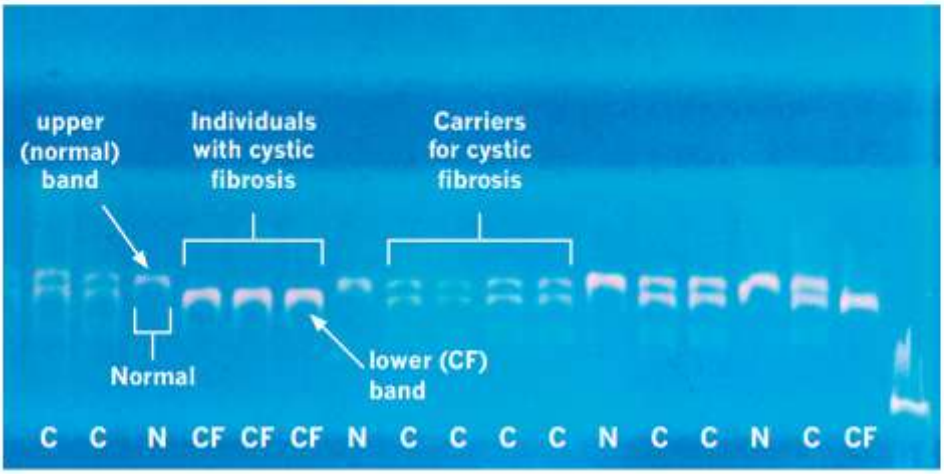


FIGURE 11.4.15 DNA test results from cystic fibrosis (CF) patients and their relatives, showing patterns for patients, carriers and non-carriers. The region of the CFTR gene affected by a mutation was amplified by PCR. A person without CF (homozygous for the normal allele) has only the upper DNA band. Individuals with cystic fibrosis have a 3 base pair section of DNA missing from their cystic fibrosis gene; they are homozygous for the mutation and show only the lower DNA band. Carriers are heterozygous and show a normal allele (upper band) plus the mutant allele just underneath. Genetic testing can only inform whether an individual carries the defective gene but not the severity of the condition. (Abbreviations in figure are: C = carrier, N = not affected, CF = affected.)

There is treatment for some but not all conditions

Genetic testing can lead to specific treatments for some conditions but not all conditions. For example, genetic testing for phenylketonuria (PKU), a genetic disorder that prevents the breakdown of the amino acid phenylalanine, can allow for dietary intervention from birth so that the child can lead a healthy and productive life.

In Australia, every newborn baby can have a Guthrie blood test, which provides early detection and treatment of some serious conditions. The blood, taken from the heel of the foot, is blotted onto thick paper. The blood samples are tested for the presence of particular genetic or metabolic disorders, including PKU, hypothyroidism and cystic fibrosis (see Figure 11.4.16).

FIGURE 11.4.16 Guthrie blood test; taking a blood sample from the heel of a newborn baby.

Haemachromatosis is an inherited disorder in which iron levels in the blood are too high, causing tissue damage (e.g. to the liver, pancreas and joints). It is a fairly common disorder in Australia. A DNA test can detect the disorder before any symptoms are evident. There is no cure, but iron levels can be kept within the normal range simply by having blood taken regularly. This prevents long-term tissue damage and the resulting side effects.

Availability of treatments

Genetic testing can lead to positive outcomes for individuals who have treatment options available to them, however there are many conditions for which there is currently no treatment available. This leads to the ethical dilemma of whether infants should be screened for disorders that cannot be treated. For example, a disease for which there is currently no effective treatment or preventative measures available is Huntington's disease (Figure 11.4.17, page 489). This condition is a genetic disorder that results in degeneration of the basal ganglia of the brain. This brain degeneration leads to chorea (jerky and involuntary movements) and dementia. Although the disease may start in childhood, symptoms do not usually appear until 35 to 50 years of age. As a result, an affected person may have children before realising they have the disease.

Knowledge that they have the Huntington's disease gene mutation can help some individuals with reproductive and career planning. However, testing can also lead to psychological and potential discriminatory harm with regards to employment and insurance.

Genetic testing of some conditions is not diagnostic

Genetic testing can identify individuals who are at risk of certain diseases, but it does not mean for certain that they will develop the disease. For example, genetic testing can identify people with BRCA1 and BRCA2 mutations. These people have a 26 to 85 per cent lifetime risk of developing breast cancer. However, the genetic test is not diagnostic (that is, it does not confirm that you have the disease, only that you have a higher risk of developing the disease) and may lead to decisions that cannot be reversed, such as removal of breast tissue.

Privacy issues

Privacy is a major consideration in genetic testing and screening, and there is continuing debate about access rights to DNA samples and profiles. The outcomes of genetic tests may affect entire families; family members may be at risk of developing the disease or may be carriers of the genetic mutation and potentially pass the disease on to their offspring. Whether or not information from genetic tests should be disclosed to family members remains a controversial area.

Parents deciding to have their children tested for carrier status is also controversial. The outcomes of these tests can significantly affect individuals' life choices, and many ethicists argue that individuals have the right to informed consent (making a decision based on knowledge of the risks and benefits) and confidentiality, both of which are difficult in cases involving young children.

Another concern with the use of this technology is the possibility of discrimination by employers or health insurers, based on genetic test results. Anti-discrimination legislation in Australia offers some protection, but there is still a need for progress in this area to meet the growing availability of genetic testing.

Embryonic stem cells and ethical issues

Embryonic stem cells are cell lines derived from early embryos that can differentiate into any tissue type (Section 8.4). This offers the possibility of treating diseases of different tissues from one source of stem cells, and may be the only treatment available to individuals suffering from some genetic disorders. However, some people oppose the use of embryonic stem cells on ethical grounds because they involve the destruction of embryos at the blastocyst stage.

Gene therapy and ethical issues

It is possible to treat serious inherited disorders by inserting the normal gene into a patient who has a mutant allele. This is called gene therapy. For example, a person suffering from haemophilia could receive the gene that produces the missing blood-clotting factor.

There are both medical and ethical issues as well as technical problems in gene therapy, including getting the normal gene into the target tissue, the possibility of the patient's immune system reacting to the virus vector used to carry the gene, and the potential increased risk of dying from the therapy. A social and ethical dilemma associated with gene therapy is whether the gene should be inserted only into somatic tissue and not the germ line, which could affect the patient's offspring.

Many ethical issues surround the debate of whether we should be able to make choices that will affect the genetic health of future generations, and how we can use this technology effectively and responsibly to benefit society.

FIGURE 11.4.17 This elderly woman suffers from Huntington's disease, a genetic disorder that results in brain degeneration, jerky and involuntary movements and dementia. There is currently no cure for the disease.

BIOLOGY IN ACTION

Nutrigenomics: genetic testing for personalised nutrition

The relationship between nutrition and genetics is a complex one that works in two ways: the nutrients you consume can affect if and how different genes are expressed, while your genes influence how your body responds to different nutrients. Genetic variation between individuals can play an important role in how people's bodies respond to food differently, with implications for their nutrition and health.

A new field of science, known as nutrigenomics, aims to address this need for a personalised approach to nutrition by combining the study of genetics with nutrition science. Nutrigenomics works to understand molecular interactions with nutrients and how an individual's genetic variation influences the absorption, metabolism and elimination of nutrients. With this information, scientists can begin to understand why people respond differently to the same foods and create nutritional plans to suit an individual's genotype.

Researchers from the University of Toronto in Canada have shown that people are more likely to make positive changes to their diets if the dietary advice they receive is based on results from their genetic test. The researchers investigated the intake of caffeine, sodium, sugar and vitamin C in 138 healthy young adults over 12 months. The subjects who took part in the study were randomly assigned to two groups. One group received standard nutritional advice (control group) while the other group received personalised DNA-based nutritional advice.

FIGURE 11.4.18 Information from your DNA could be used to create a personalised nutrition plan that is optimal for your genetic make-up.

Some of the participants were found to have a variant of a gene associated with a higher risk of high blood pressure and heart failure (ACE gene) and were advised to reduce sodium in their diets. These participants did reduce their sodium intake significantly over 12 months, compared to those who did not have the risk-version of the ACE gene and those in the control group.

This study demonstrates the positive impact that nutrigenomics can have in the field of health care, with implications for treating and reducing rates of diseases such as obesity, type 2 diabetes and heart disease.

11.4 Review

SUMMARY

- Genetic testing is a type of medical test used to detect specific alleles, mutations, genotypes or karyotypes that are associated with heritable traits, diseases or predispositions to diseases.
- Genetic screening is genetic testing carried out on a large number of individuals or embryos to determine whether they are carriers of a particular disease, or are at risk of having the genetic disease.
- Genetic testing may also be used as a method to determine parentage or ancestry.
- There are three main categories for genetic testing:
  - Molecular genetic testing is used for identifying single genes or short lengths of DNA.
  - Conventional cytogenetic testing, also known as karyotyping, analyses whole chromosomes to see if there are any major genetic changes such as an extra copy of a chromosome.
  - Molecular cytogenetic testing via FISH allows for the chromosomes to be assessed for changes in their structure, such as the insertion, deletion or duplication of sections. Chromosomes can also be assessed for the presence of DNA sequences of interest.
- Biochemical testing studies the amount or activity level of certain proteins. Any abnormality in the amount or activity of proteins is an indication of a genetic disorder, due to changes in the DNA.
- Genetic testing of certain conditions is a useful tool but there are many social and ethical implications that need to be considered. Some of these issues are:
  - the limitations of genetic testing
  - the availability of treatments
  - privacy concerns and the impacts of disclosure of test results
  - ethical issues associated with the use of embryos
  - technical and ethical issues associated with gene therapy.

KEY QUESTIONS

1 Define genetic testing.

2 What are the three main methodologies used in genetic testing?

3 Outline the social and ethical issues associated with genetic testing and screening.

4 Define gene therapy and discuss some of the ethical issues surrounding this technology.

Chapter review

11

KEY TERMS

adenine (A)
amplified
antigen
autosome
biochemical testing
carrier
chiasma (plural chiasmata)
chromatid
co-dominance
cross
crossing over
cytogenetic testing
dihybrid cross
DNA amplification
DNA polymerase
DNA profiling
DNA sequencing
dominant
endonuclease
fluorescence-in situ hybridisation (FISH)
F1 generation
F2 generation
gel electrophoresis
gene mapping
genetic screening
genetic testing
genome
heterogametic
heterozygous
homogametic
homozygous hybrid
incomplete penetrance
Law of Independent Assortment
Law of Segregation
linkage
locus (plural loci)
molecular genetic testing
monohybrid cross
mutant
nucleotide
parental type
pedigree analysis
penetrance
polymerase chain reaction (PCR)
pre-implantation genetic diagnosis (PGD)
primer
progeny
recessive
reciprocal cross
recognition site
recombinant gametes
restriction enzyme (endonuclease)
restriction fragment analysis
sex-limited inheritance
sex-linked inheritance
single nucleotide polymorphism (SNP)
spontaneous mutation
testcross
true-breeding
wild type
X-linked
Y-linked

KEY QUESTIONS

1 The shape of a human earlobe is determined by a single autosomal gene. Free lobe is dominant to attached lobe.
- **a** Write appropriate allele symbols for this gene.
- **b** How many genotypes are possible with respect to these alleles? How many phenotypes are possible?
- **c** A homozygous man with free lobes married a heterozygous woman. Show the genotypes and phenotypes possible in their children.
- **d** Can two people with free lobes have a child with attached lobes? Explain your answer.
- **e** Two parents heterozygous for earlobe shape have a child. What is the probability that the child has attached lobes? Write your answer as a percentage, and as a ratio.

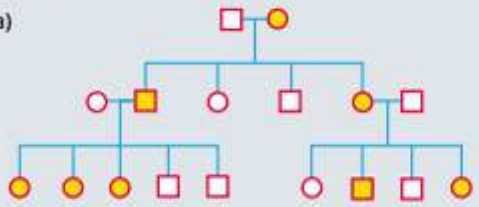
2 In mice, black coat colour is dominant to white coat colour. Calculate the expected genotypic and phenotypic ratio for a cross between two heterozygotes. Use appropriate notation.

3 A genetics student undertakes a study of inheritance patterns of feather colour in domestic chickens. The student observes the following:
- Matings between black-feathered adults always result in black-feathered offspring.
- Matings between white-feathered adults always result in white-feathered offspring.
- Matings between black-feathered adults and white-feathered adults produce only blue/grey-feathered offspring.
- Matings between blue/grey-feathered adults results in black, blue/grey and white offspring in a ratio of 1 : 2 : 1.
- **a** Describe the mode of inheritance of this trait. Outline the evidence that leads you to this conclusion.
- **b** How many genes and alleles control this trait? Outline the evidence that leads you to this conclusion.
- **c** Use appropriate notation to set up a model that explains the student's observations.

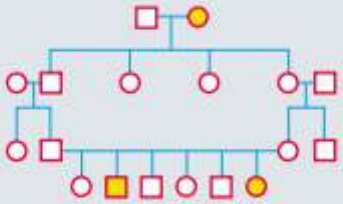
4 Using the key terms that relate to different sorts of crosses (testcross, monohybrid cross and other crosses), make a poster that distinguishes between the different crosses.

5 What is the most likely mode of inheritance for each of the diseases shown in the following pedigrees? Explain your choices.

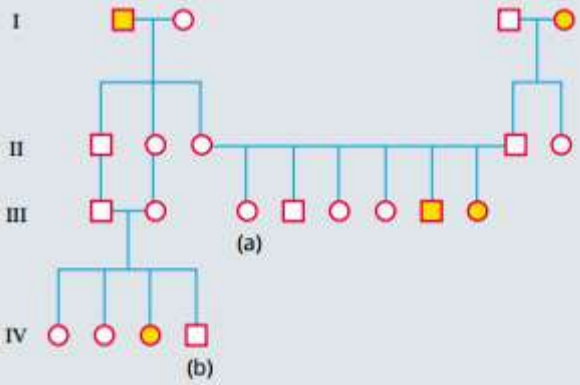
(a)



(b)



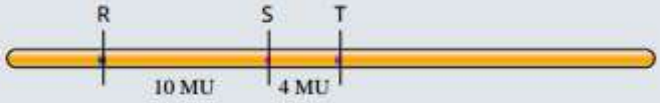
6 The following pedigree shows the inheritance of albinism.



a What is the most likely mode of inheritance of the condition? Explain.

b If III(a) and IV(b) were to have offspring, what would you need to know about these individuals to calculate the chances of their offspring having albinism?

7 This diagram represents a linkage group on a chromosome from a common crop plant. R, S and T represent different loci on the chromosome. MU = map units (the distance between loci).



Would you expect the greatest percentage of recombination to occur between RS, ST or RT? Explain your reasoning.

8 If a woman is a carrier for a sex-linked recessive disease, only a son can suffer from the disease if the father does not have the disease. In vitro fertilisation enables the sex of the embryo to be determined very early in development. It is therefore possible to implant only female embryos into the woman's uterus so that the disease will not occur in her children.

a Does this approach mean the disease will not occur in subsequent generations of the family? Explain.

b Discuss the short-term and long-term benefits and disadvantages of implanting only female embryos of a mother who is a carrier for a sex-linked recessive disease.

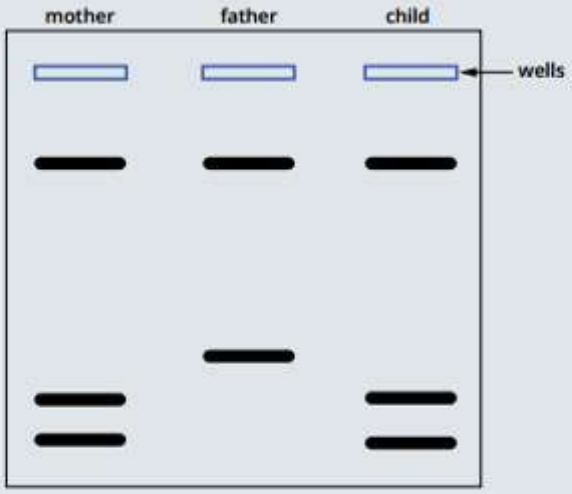
9 Which one of the following best describes restriction enzymes?

A enzymes that cut DNA at particular base sequences
B enzymes that replicate DNA
C enzymes involved in gene expression
D digestive enzymes involved in protein breakdown

10 Which one of the following lists chemicals used in polymerase chain reactions?

A restriction enzymes and a primer to copy a DNA sequence
B DNA polymerase to produce a primer
C DNA polymerase and a primer to produce many copies of DNA
D restriction enzymes to produce a primer

11 A couple wishes to find out if their unborn child has sickle cell anaemia. The figure below shows the results from the gel electrophoresis of the restriction fragments of the sickle cell gene (located on chromosome 11) for the family. The mother carries the mutation, which results in sickle cell anaemia, while the father is normal.



a How does restriction fragment analysis of the alleles of a gene result in different banding patterns?

b Does the child carry the mutation for sickle cell anaemia? Explain your answer.

c Using this scenario, outline some of the ethical implications of genetic testing of embryos.

REVIEW QUESTIONS

How is inheritance explained?

Multiple choice questions

1 Which of the following statements about genes or alleles is correct?

A Alleles randomly segregate during meiosis.
B Genes randomly segregate during meiosis.
C Alleles represent specific information coded at a defined locus on homologous chromosomes.
D Genes and alleles mean the same thing.

2 Which of the following best describes the aim of the Human Genome Project?

A To identify all the genetic diseases on human chromosomes.
B To map the DNA sequence of all human chromosomes.
C To locate the gene for each human feature on chromosomes.
D To identify the location of alleles for dominant traits.

3 Which of the following describes the composition of a eukaryotic chromosome?

A one DNA molecule and one large protein
B many DNA molecules and many proteins
C one DNA molecule and many proteins
D many DNA molecules and one large protein

4 How many autosomes are there in a human sperm?

A 1
B 22
C 23
D 44

5 What is the difference between the X chromosome and Y chromosome in humans?

A The X chromosome is much shorter.
B Many genes found on the X chromosome are absent from the Y chromosome.
C Both chromosomes carry the same genes but the loci of the genes are different.
D Only the X chromosome determines sex.

6 Consider the following types of information:

i size of the chromosomes
ii gene mutations of the chromosomes
iii age of the individual

Which one or more of these are needed to construct a karyotype?

A i only
B ii only
C i and ii only
D i, ii and iii

7 To make a karyotype, which phase of cell division is photographed?

A anaphase of mitosis
B anaphase I of meiosis
C metaphase of mitosis
D metaphase I of meiosis

8 Which of the following genotypes shows alleles for a heterozygous trait?

A *AA*
B *Bb*
C *CD*
D *Cd*

9 'Carried on the X-chromosome' and 'occurs more commonly in males than in females' suggests:

A monohybrid cross
B dihybrid cross
C autosomal-linked inheritance
D sex-linked inheritance

10 The cross-over percentage between linked genes *P* and *Q* is 40%, between *Q* and *R* it is 20%, between *R* and *S* it is 10%, between *P* and *R* it is 20%, and between *Q* and *S* it is 10%. What is the sequence of genes on the chromosome?

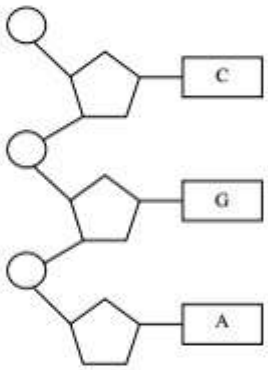
A *P, Q, R, S*
B *P, R, S, Q*
C *P, Q, S, R*
D *P, S, R, Q*

Short answer questions

11 Following the completion of the Human Genome Project in 2003, the DNA technologies developed were used to sequence the genomes of non-human organisms. Answer the following questions.

a Distinguish between the terms 'genome' and 'genes'.
b What is the purpose of sequencing the genomes of non-human organisms?
c Compare the use of the Human Genome Project and karyotypes as ways to identify the location of harmful genes in humans.

12 The following diagram shows a short section of a polynucleotide.

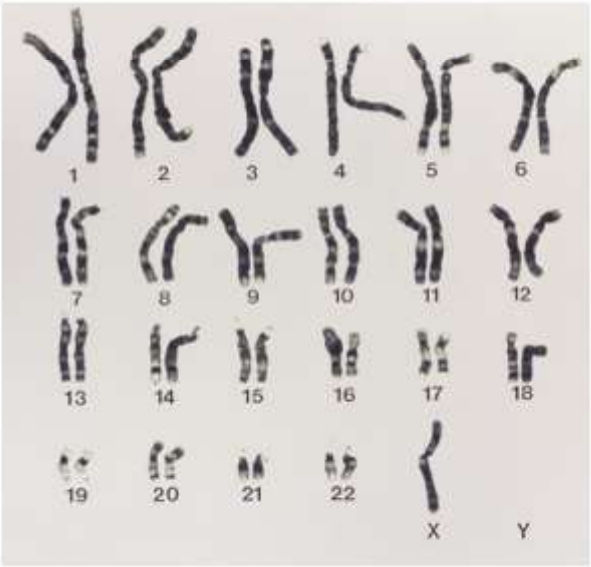


a On the diagram, label a nucleotide, a phosphate group, a deoxyribose sugar, and a nitrogenous base.

b Draw on the diagram the complementary strand of polynucleotide.

c Describe how DNA is packaged in a chromosome.

13 The figure below shows a karyotype of a human baby.



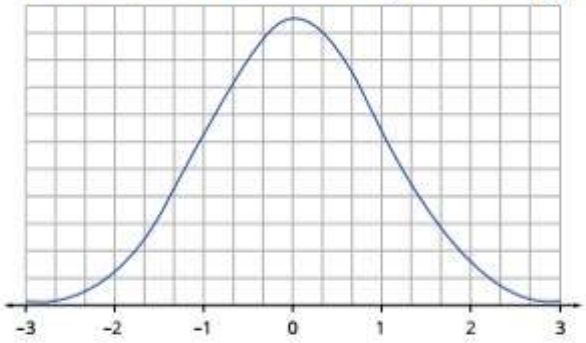
a The chromosomes are arranged in pairs. State the name given to chromosomes that contain the same gene loci.

b Explain the term 'diploid' and why all human somatic cells are diploid.

c Is there any chromosome abnormality with this baby? Explain your answer.

d Describe the types of variation seen in chromosome structure and number between species.

14 The variation exhibited by a particular genetic characteristic can be summarised by the following graph.



a Give an example of a characteristic with a distribution indicated by the graph.

b What term is used for this type of inheritance?

c Outline the genetic principle of this form of inheritance.

15 In humans, the adenomatous polyposis coli (APC) gene is located on chromosome 5. APC controls cell division and is also known as a tumour suppressor gene. Mutations of APC will cause a genetic disease called Familial Adenomatous Polyposis (FAP).

a Is FAP a sex-linked genetic disease? Give an explanation for your answer.

b 50% of the gametes produced by a person with FAP have an APC gene with the mutation. State whether FAP is a dominant or recessive phenotype. Give an explanation for your answer.

c A male who is heterozygous for FAP and an unaffected female are planning to have children. Predict the possible phenotypes and genotypes of the children, showing your working.

16 Boys can inherit the X-linked allele (*Xc*) that causes the recessive phenotype red–green colour blindness.

a Explain the following terms:

i X-linked allele

ii recessive phenotype.

b Write down the possible genotypes for red-green colour blindness in:

i men

ii women.

c A boy inherited red–green colour blindness from one of his grandfathers. Which of the boy's grandfathers (maternal or paternal) was also colour blind? Explain your reasoning.

d A red–green colour-blind woman and an unaffected man had five children: three boys and two girls. The three boys and the elder girl did not marry. The younger girl married a man with normal colour vision, and they had four children: two boys and two girls. Draw a pedigree chart to illustrate the inheritance of the X-linked condition in this family. Use conventional symbols.

17 The snowshoe hare's fur is brown in summer and white in winter. The change in fur colour is caused by epigenetic factors.


a Outline what is meant by epigenetic factors.

b Besides epigenetic factors, what other factors can influence an organism's phenotype?

18 In the garden pea, *Pisum sativum*, the phenotype for tall plants (allele represented as *T*) is dominant over the phenotype for short plants (*t*). The phenotype for round seeds (*R*) is dominant over the phenotype for wrinkled seeds (*r*). The alleles are unlinked.
Pure-breeding tall plants with round seeds were crossed with pure-breeding short plants with wrinkled seeds.
The F1 plants were then crossed with plants that had the genotype *ttrr*. The table below shows the results obtained in the F2 generation.

Phenotype	Frequency
tall plants with round seeds	22%
short plants with round seeds	26%
tall plants with wrinkled seeds	25%
short plants with wrinkled seeds	27%

a State the genotype and the phenotype of the F1 individuals.

b Draw up a Punnett square to show the expected ratio of phenotypes in the F2 generation.

c Are the results listed in the table exactly as you expected? If not, suggest an explanation for the differences.

d Outline an experiment to investigate the genotype of a tall *Pisum sativum* whose genetic history is unknown.

19 In fruit flies (*Drosophila melanogaster*) the grey body phenotype (allele *G*) is dominant to black body (*g*), and normal wing shape (*N*) is dominant to vestigial wings (*n*). The genes for these traits are linked. Male flies heterozygous for both grey body and normal wings were mated with black-bodied and vestigial winged females. Five thousand offspring were examine for body colour and wing type. The following table shows the results obtained.

Offspring	Frequency
grey body, normal wings	36%
black body, vestigial wings	38%
grey body, vestigial wings	12%
black body, normal wings	14%

a Contrast linked and unlinked genes.

b The genotype for the female parental flies can be represented as *ggnn*. Suggest a possible genotype designation for the male parentals.

c Describe the process of recombination (crossing over).

d Does the experiment provide evidence for recombination of linked genes? Explain your answer.

e Identify which offspring are the result of recombination in this cross.

Glossary

A

abiotic Relating to the non-living (physical and chemical) parts of the environment, such as water, soil and sunlight, as opposed to the biological (biotic) parts.

abiotic environment The non-living parts of the environment, such as air, water, soil and rock.

abiotic factors The non-biological parts of an environment that influence ecosystems and the organisms that live in them.

accuracy The ability to obtain a correct value.

active transport The movement of substances across membranes that involves the use of energy.

adaptation (1) An inherited character that increases the likelihood of survival and reproduction of an organism or species. (2) The process by which a species becomes well-suited to its lifestyle and environment.

adenine (A) Nitrogen-containing base (a purine) that occurs in nucleotides of DNA and RNA.

adenosine diphosphate (ADP) A molecule produced by the release of energy from ATP. ADP be converted back to ATP for re-use.

adenosine triphosphate (ATP) A molecule that provides energy for immediate use by a cell. It is produced during glycolysis and cellular respiration.

ADP See *adenosine diphosphate*.

adrenaline (epinephrine) A hormone released by the adrenal gland in response to activity and stress. It stimulates a number of tissues to increase the heart rate, blood flow and blood glucose level.

aerobic Requiring oxygen.

aestivation A long period of torpor in hot and dry conditions. See also *hibernation*.

aldosterone A steroid hormone produced by the adrenal cortex. Its main function is to regulate blood pressure and sodium and potassium levels.

allele One of the alternative forms of a gene. Most genes have two alleles, but more than two alleles are possible.

allosome See *sex chromosome*.

alternative hypothesis The hypothesis that there is a relationship between two variables, such that a change in one causes a change in another. It is the usual type of hypothesis proposed for an experiment, and is the opposite of the *null hypothesis*.

alveoli Small air sacs in the lungs of mammals, located at the ends of the bronchioles. Alveoli have very thin cell walls surrounded by a network of capillaries, which enables efficient gas exchange across their surface.

amensalism A relationship between organisms of different species in which one of the organisms benefits and the other is harmed or killed. An example is a paralysis tick and its host. The tick benefits by feeding on the blood of its host, and the host suffers by becoming ill or possibly dying from the effect of neurotoxins injected by the tick.

amino acid An organic compound containing an amino group ($-NH_2$) and a carboxyl group ($-COOH$) at opposite ends of the molecule. Linked amino acids form the peptide chains in protein molecules.

ammonia A compound (formula NH_3) that is the first nitrogenous waste to be formed from the breakdown of proteins. Ammonia is highly toxic and it is excreted mainly by aquatic animals.

amniotic cavity The fluid-filled cavity of the amniotic sac that surrounds the developing embryo and foetus.

amplify Make many copies of a piece of DNA using the polymerase chain reaction (PCR) technique.

amylase An enzyme that breaks down starch molecules.

anaerobic Not requiring or involving oxygen.

angiosperm A vascular plant that produces flowers and seeds enclosed within an ovary (fruit, grain or nut). Angiosperms include most trees, shrubs, herbs and grasses.

anther A structure containing chambers called pollen sacs in which pollen grains develop following meiosis. Anthers are located at the tips of stamens.

antidiuretic hormone (ADH) A hormone that increases the permeability of the collecting duct of the kidney to water. This increases the amount of water reabsorbed, resulting in a smaller volume (and therefore more concentrated) urine. ADH is secreted by the pituitary gland. Also called vasopressin.

antifreeze proteins (AFPs) A group of polypeptides that inhibit the growth and recrystallisation of ice crystals by binding to them.

antigen A substance that stimulates antibody production and is capable of binding with an antibody produced by the immune system.

antiparallel In DNA, meaning that one strand runs from the 5' end to the 3' end, and the other runs from the 3' end to the 5' end.

aorta The large artery that carries blood from the left ventricle of the heart to the body.

apoptosis A process of cell death that involves a characteristic series of steps. Also called programmed cell death.

Archaea A domain of living things consisting of bacteria that can live at high temperatures (thermophiles), in acidic environments (acidophiles) or very salty environments (halophiles). See also *Bacteria*, *prokaryote*.

arteriole A small blood vessel that stems from an artery and leads to capillaries.

artery A blood vessel with thick, elastic walls, through which blood flows from the heart to the rest of the body.

asexual reproduction Reproduction in which one parent gives rise to a new individual from its body cells. The resulting offspring are genetically identical to their parent.

atmosphere The layer of gases surrounding the Earth, consisting of about 78% nitrogen, 21% oxygen, and 1% other gases and water vapour.

ATP See *adenosine triphosphate*.

atrium (pl. atria) A chamber of the heart that receives blood returning from the body or the lungs, before passing the blood into a ventricle. The left atrium receives oxygenated blood from the lungs, and the right ventricle receives deoxygenated blood from the rest of the body.

autoimmune disorder A disorder or disease resulting from the persistent presence of antibodies directed against particular parts of the body. It occurs as a result of an impaired ability of the immune system to recognise self.

autonomic nervous system In vertebrates, the part of the nervous system that supplies nerves to the visceral organs and is under involuntary control.

autosomes Chromosomes that are not sex chromosomes.

autotroph An organism that is able to produce its own food from inorganic materials, using light or chemical energy. Plants that photosynthesise are the most common autotrophs. All autotrophs are producers.

B

Bacteria A domain of living things consisting of bacteria that live on or in animals, plants, soil or water, in environments of moderate conditions. See also Archaea, prokaryote.

bar graph A graph in which categorical data are represented by horizontal bars. Each bar represents one category of independent variable (such as a range of values, or a particular type of thing), and the length of the bar represents the value of the dependent value for that range or thing.

baroreceptor A receptor that detects blood pressure in vertebrates, sending the information to the brain to regulate blood pressure.

basal metabolic rate The rate at which energy is used by an animal at rest.

base Any of the four compounds adenine (A), thymine (T), guanine (G) and cytosine (C) present in the nucleotides of the nucleic acids DNA and RNA, forming the linking points between strands.

bilateral symmetry The symmetrical arrangement of body parts on either side of a central axis.

bile A secretion produced by the liver and stored in the gall bladder, from where it is released into the small intestine. Bile acts as an emulsifying agent, physically breaking up large fat droplets into smaller droplets to increase the surface area of food being digested.

binary fission A form of asexual reproduction in unicellular organisms, in which the parent cell divides into two approximately equal parts.

binomial system The system for naming species, invented by Carl Linnaeus in the 18th century. The two-word (binomial) name for a species consists of two Latinised words: the first word is the name of the genus (e.g. *Eucalyptus*), and the second word is the name of the species (e.g. *regnans*). The combined name (in this example, *Eucalyptus regnans*) is unique.

biochemical testing Testing for the amount or activity of certain proteins, in order to detect any abnormality. An abnormality may be an indicator of a genetic disorder caused by changes in DNA.

biodiversity The variety of all life forms—the different plants, animals and micro-organisms, the genes they contain, and the ecosystems in which they exist.

biogenesis The principle that cells are formed only from pre-existing cells.

biological agent Any bacterium, virus, protozoan or other organism or particle that can affect the function of cells, tissues or organs, causing injury or death.

biological classification Grouping organisms on the basis of features they have in common, and naming these groups in a hierarchical system consisting of domains, kingdoms, phyla, classes, orders, families, genera and species. See also *taxonomy*.

biological control The use of a natural predator, parasite or other agent to limit and control the growth of a pest species. An example is use of the myxoma virus and calicivirus to control the European rabbit in Australia.

biological species A group of organisms that interbreed in the wild (or could do so) and produce viable, fertile offspring, but cannot produce viable, fertile offspring if they interbreed with organisms outside the group.

bioluminescence The production and emission of light by an organism, such as sea jellies, fireflies and luminous fungi. It is a form of chemiluminescence, in which light energy is produced following a chemical reaction.

biomass The mass of living matter per unit area (e.g. kg/m²), or the equivalent amount of chemical energy bound in the mass of tissue (e.g. kJ/m²). Biomass measurements may be for total biomass, or for the biomass of a particular group of organisms such as plants.

bioprospecting The exploration of biodiversity for new resources that may have social or commercial value, such as new medicines.

biosphere The region of the Earth's land, sea and atmosphere that is occupied by living things.

biotic Relating to the biological parts of the environment, as opposed to the abiotic (physical and chemical) parts.

bladder A muscular organ that receives urine from the kidneys and holds it before it is excreted through the urethra.

blastocyst The blastula stage in the development of a mammalian embryo. The blastocyst consists of an outer layer of cells that will develop into the placenta, an inner mass of cells that will develop into the embryo, and a fluid-filled cavity.

blastula An early stage of embryonic development in animals, coming after the morula stage. The blastula consists of a sphere of cells surrounding a fluid-filled cavity. It is during this stage that cell differentiation begins. In mammals the blastula is referred to as a blastocyst.

Bowman's capsule The region of a nephron into which filtered plasma flows from the glomerulus.

brumation A type of torpor undergone by many reptiles. It is similar to hibernation but differs in the metabolic processes involved. Brumation begins just before winter and lasts between 1 and 8 months.

budding A form of asexual reproduction in which a new individual arises as an outgrowth or bud from the parent.

bulb A large, often spherical underground bud of a plant, surrounded by fleshy leaves. The bulb stores food for the growing shoot of the plant.

C

caecum An intestinal pouch at the junction of the small and large intestine. In some herbivores, such as koalas, it is very enlarged and acts as a fermentation chamber for the digestion of cellulose.

CAM photosynthesis Crassulacean acid metabolism, a form of photosynthesis that occurs in many plants growing in hot, dry environments. Stomata open at night to take in carbon dioxide, which is incorporated into malate. During the day the stomata are closed to reduce transpiration, and malate is metabolised to release carbon dioxide, which is then used by cells.

capillary A tiny blood vessel with a wall only one cell thick, across which exchange occurs between blood and tissues.

carbohydrate An organic compound consisting only of carbon, hydrogen and oxygen atoms, with the hydrogen and oxygen atoms in the same proportion as in water (2 to 1). Carbohydrates include sugars and starches.

carbon fixation The incorporation of carbon into organic compounds by living organisms.

carcinogen Any substance that is known to cause abnormal tissue growth or neoplasms.

carnivore An organism that feeds only on other animals.

carotid rete system A network of blood vessels that cools the brain by counter-current heat exchange. It is present in humans and many other vertebrates.

carrier (1) An organism infected by a pathogen, and capable of transmitting the pathogen to another organism, usually without itself being affected by the pathogen. See also *channel protein*. (2) An individual that has an allele for a condition but does not express the condition because it is masked by a dominant phenotype. The carrier can pass the allele to its offspring, who will express the condition if they receive the same allele from the other parent.

carrier protein A transport protein that changes shape when molecules bind to it, so that the molecules can pass through the plasma membrane. Carrier proteins take part in facilitated diffusion and active transport.

carrying capacity The maximum population of a species that can be supported indefinitely by an ecosystem.

Casparian strip A water-resistant strip in the endodermis of roots that regulates the entry of water and solutes.

cell The smallest structural and functional unit in a living thing. All cells have a plasma membrane and contain cytoplasm, organelles and genetic material (DNA). In plants, fungi and monerans, cells also have a cell wall.

cell compartmentalisation The formation in the cytosol of specialised structures enclosed by membranes, including the nucleus, mitochondria, endoplasmic reticulum, Golgi apparatus, endosomes, lysosomes and chloroplasts.

cell cycle The events in the life of a cell, from its formation by cell division through its growth and function until it divides again. It begins with the G1 stage and proceeds through S, G2, mitosis and finally cytokinesis. A G0 resting stage may also be entered during G1.

cell cycle control system A system within the eukaryotic cell that operates cyclically to trigger and coordinate the events of the cell cycle. The system is controlled by a set of molecules.

cell differentiation The process by which a cell changes from one type to another. This is usually an unspecialised cell becoming a specialised cell.

cell plate A partition that forms in a plant cell during cell division. It divides the cell into two parts, each of which develops into a daughter cell.

cell replication The process by which a single cell divides into two or more daughter cells.

cell specialisation The specialised function performed by a cell. Examples of specialised cells are red blood cells, nerve cells and muscle cells in animals, and root hair cells and guard cells in plants.

cell theory The scientific theory which states that all organisms consist of cells, and that all cells come from pre-existing cells. Cell theory is a fundamental principle of modern biology.

cellular respiration The energy-releasing processes that occur in cells. In particular, the aerobic stage in the complete breakdown of glucose to produce ATP, which occurs in mitochondria and produces 36 or 38 molecules of ATP per molecule of glucose.

cellulose A complex carbohydrate molecule consisting of a chain of many glucose molecules. It is the main component of plant cell walls. Its formula is $(C_6H_{10}O_5)_n$.

central nervous system (CNS) The system of nerve tissues that controls most of the activities of an organism. In vertebrates it consists of the brain and spinal cord.

centriole A small cylindrical organelle consisting of a group of microtubules, and occurring as a pair in the centrosome in the cells of animals and some other organisms. Centrioles are replicated in the S phase, and the two pairs formed separate during mitosis and move towards the opposite ends (poles) of the cell.

centromere A part of the chromosome that attaches to spindle fibres during mitosis, and where the two sister chromatids of a double-stranded chromosome are joined.

cervix The lower part of the uterus in the female reproductive system, separating the uterus from the vagina.

channel protein A transport protein that molecules do not usually bind to. Channel proteins allow specific molecules to pass through the plasma membrane, and are used in facilitated diffusion. See also *carrier protein*.

chemical communication Communication between cells involving the release of specific signalling molecules and their detection by matching receptors on the target cells.

chemical digestion The action of enzymes in breaking down complex compounds into simple compounds that can be used for metabolism.

chemical energy Energy stored in the chemical bonds that join atoms together in molecules, and which can be released by breaking the bonds apart.

chemoheterotroph A consumer organism (heterotroph) that gains its energy by carrying out energy-releasing reactions between inorganic molecules.

chemosynthetic Able to synthesise organic compounds from inorganic materials using the energy released by simple chemical reactions. Chemosynthesis occurs in some prokaryotes.

chemotropism Growth or movement in response to a chemical substance, either towards or away from the substance.

chiasma (pl. chiasmata) A point of crossing of strands of non-sister chromatids observed during the first division of meiosis.

chlorophyll A light-absorbing pigment involved in photosynthesis.

chloroplast A green organelle in plant cells in which photosynthesis takes place. A chloroplast consists of many folded layers of membrane and contains chlorophyll.

cholesterol A steroid lipid found in most body tissues. Cholesterol is an important component of cell membranes in animals and is used to form other steroid compounds.

chromatid One of two copies of a chromosome formed during the S stage of interphase. The two copies, called sister chromatids, are joined at a centromere.

chromatin A large molecule consisting of DNA, protein and RNA, located in the cell nucleus.

chromatophore In animals, a light-reflecting cell or group of cells containing a pigment. Chromatophores enable an animal to change colour in response to changes in its surroundings, or in response to its physical state (e.g. reproductive state or stress).

chromosome A complex structure consisting of DNA strands coiled around histone proteins, carrying the hereditary information of the cell in the form of genes. All body cells in a particular species have the same number of chromosomes.

cilium (pl. cilia) A hairlike structure on the surface of some eukaryotic cells, consisting of a '9 + 2' arrangement of microtubules enclosed by an extension of the cell membrane. Cilia move with an oar-like motion and are usually shorter and more numerous than flagella.

class In the classification of organisms, the taxonomic category above the level of order. Similar classes are grouped together into a kingdom.

classification The grouping of organisms on the basis of features they have in common, and naming these groups in a hierarchical system of domains, kingdoms, phyla, classes, orders, families, genera, species and subspecies. See also *taxonomy*.

cleavage The early division of a zygote into smaller cells by mitosis.

clone A biological entity (such as a gene, cell, tissue or organism) that is a genetically identical copy of another entity.

cloning (1) The process of replication that creates a new biological entity, such as a gene, cell, tissue or organism. (2) In animals, the creation of a new individual by transferring the nucleus of a somatic cell into an enucleated egg, which is then implanted for development. The resulting individual will be genetically identical to the parent that provided the nucleus.

closed circulatory system A circulatory system in which the fluid (blood) is confined to vessels and is kept separate from the interstitial fluid.

co-dominance The occurrence of a phenotype in a heterozygote that results from the expression of both alleles. An example is the AB blood group in humans.

cohesive Tending to stick together. Cohesiveness is a property of water molecules.

cohesive bond A bond between molecules of a substance resulting from the shape and structure of the molecules.

colony A group of organisms of the same species that live together.

column graph A graph in which categorical data are represented by vertical columns. Each column represents one category of independent variable (such as a range of values, or a particular type of thing), and the length of the column represents the value of the dependent value for that range or thing.

commensalism A relationship between two organisms in which only one benefits, but the other organism is not harmed.

community A group of species that occur in the same area and interact, or could interact, with each other.

competition An interaction between organisms that are seeking to use the same resource, such as food, water, shelter, sunlight or mates.

complementary base pair Either of only two possible pairs of bases in a double-stranded DNA molecule. Adenosine (A) paired with thymine (T), or guanine (G) paired with cytosine (C).

complete dominance In sexual reproduction, the expression of only one phenotype in all heterozygous individuals.

complete penetrance The expression of a condition in all individuals carrying the allele for that condition. An example of such a condition is neurofibromatosis type 1, in which every person who carries a mutation in the NF1 gene shows symptoms of the condition.

concentration gradient A difference in the concentration of a solute between one region and another; for example, across a membrane.

conidium (pl. conidia) A fungal spore that is produced asexually by budding.

conjugation In eukaryotes, a form of sexual reproduction in which two single-celled organisms fuse together and exchange genetic material.

connective tissue Tissue that connects, separates or supports tissues or organs in the body.

consumer An organism in a food chain that feeds on other organisms.

continuous variable A variable that can have any number value within a given range.

control centre The part of a feedback mechanism that determines the response required and sends an appropriate signal to the effector.

control group A group of subjects in an experiment that is identical to the experimental group and is treated in an identical way, except that the variable of interest (the independent variable) is kept constant.

controlled experiment An experimental design that includes a control group as well as an experimental group.

cord blood Blood taken from the umbilical cord after the birth of a baby.

corm A solid, bulb-like underground stem that stores food for a plant and also sends down a root at the start of each growing season.

coronary circulation The movement of blood through the heart muscles. Blood is supplied via arteries from the base of the aorta, and returns to the lungs via veins from the right atrium.

corpus luteum The remains of a Graafian follicle after ovulation. The corpus luteum becomes an endocrine organ in the ovary, secreting oestrogen and progesterone during the latter part of the oestrous cycle in mammals.

cotyledon Embryonic leaves in the seeds of flowering plants. Two cotyledons are present in dicotyledons, and one in monocotyledons.

cross The intentional breeding of two genetically different organisms which results in offspring that inherit genetic material from each parent.

crossing over The exchange of chromosomal material between non-sister chromatids of a homologous chromosome pair during prophase I of meiosis.

cytogenetic testing A genetic testing method used to identify chromosomal abnormalities.

cytokinesis The division of a cell following mitosis or meiosis, when the cytoplasm divides and the cell splits into two daughter cells.

cytoplasm The fluid cytosol of a cell, together with the organelles that it surrounds.

cytosine (C) A nitrogen-containing base (a pyrimidine) that occurs in nucleotides of DNA and RNA.

cytosol The fluid part of cytoplasm, surrounding all of a cell's organelles except the nucleus.

D

data The measurements or observations collected during an investigation.

daughter cell A new cell formed by cell replication.

decomposer An organism that breaks down dead or decaying organisms or organic wastes. Decomposers are mainly bacteria and fungi.

dehydrin A protein produced in plants in response to cold or drought. Dehydrins bind to proteins and water molecules inside the cell and stabilise the cell membrane and enzymes.

density-dependent factor A limiting factor whose effect depends on the size of the population.

density-independent factor A limiting factor whose effect does not depend on the size of the population.

deoxyribonucleic acid (DNA) A nucleic acid made up of a sequence of nucleotides, each with a deoxyribose sugar, phosphate and base (adenine, cytosine, guanine or thymine), linked by phosphodiester bonds. DNA is the carrier of genetic information in all living things and most viruses. It occurs in chromosomes in the nucleus or nucleolus, and also in mitochondria and plastids.

dependent variable The variable that is measured to study the effect of changes in the independent variable.

detritivore An organism that obtains its nutrients from decomposing organisms or wastes expelled by animals.

detritus Organic matter consisting of the remains of dead organisms or wastes expelled by animals.

diastole The period of relaxation of a heart chamber, during which it refills with blood. There are ventricular diastoles and atrial diastoles.

diffusion The passive movement of a solute from a region of higher concentration to a region of lower concentration.

digestion The breakdown of food into a form that can be used by an organism for metabolism. Digestion involves mechanical digestion and chemical digestion.

digestive enzyme An enzyme that assists in the digestion of otherwise indigestible matter.

dihybrid cross A cross between pure lineages that exhibit two different phenotypes. An example is a cross between a pea with dominant phenotypes of yellow seeds and red flowers, and a pea with recessive phenotypes of green seeds and white flowers.

diploid Having two sets of chromosomes ($2n$). All somatic cells are diploid.

disaccharide A sugar formed when two monosaccharides are joined together, with the loss of a water molecule. Sucrose and lactose are common examples of disaccharides.

discrete variable A variable that can have only certain values. For example, the number of individuals in a population can only be whole numbers.

dispersal (1) In animals, the movement of individuals away from their place of birth. (2) In plants, the distribution of seeds or other propagules away from the parent plant.

distribution The geographic extent of a group of organisms. It is commonly applied to the extent of a population or species.

DNA See *deoxyribonucleic acid*.

DNA amplification The production of a large number of copies of a DNA fragment. The most common method of DNA amplification is the polymerase chain reaction, which can generate thousands of millions of copies in a short time.

DNA polymerase An enzyme that catalyses the elongation of a new DNA strand in DNA replication, using an existing strand of DNA as a template.

DNA profiling The identification of an individual by the characteristics of their DNA. DNA profiling originally involved a comparison of the pattern of DNA fragments separated by gel electrophoresis. Modern DNA profiling involves the comparison of highly variable segments of DNA called short tandem repeats. Also called DNA fingerprinting.

DNA sequencing The determination of the sequence of bases in a fragment of DNA. DNA sequencing can be used to determine relationships between individuals of a species, and for determining the entire genome of an organism.

DNA thermocycler A machine used in the laboratory to amplify segments of DNA by the polymerase chain reaction (PCR).

domain The largest grouping in the classification of living things. See *Bacteria*, *Archaea* and *Eukarya*.

dominance (adj. dominant) The expression of one allele of a gene rather than another allele of the same gene. See also *complete dominance*, *co-dominance*.

dominant phenotype The phenotype expressed in a heterozygous individual; that is, an individual carrying different alleles of the same gene.

double helix The structural shape of a DNA molecule, consisting of two linear lengths of nucleotides twisted spirally about each other, and connected by phosphodiester bonds.

E

ecosystem A system formed by organisms interacting with one another and their physical environment.

ectoderm The outermost layer of the three primary germ layers in the early embryo.

effector A cell or tissue that responds to a stimulus.

egestion Elimination of food that has not been absorbed by the gut.

egg (ovum) An unfertilised reproductive cell containing a haploid nucleus.

embryo The stage in the development of a vertebrate, between the fertilisation of the ovum and the development of the characteristics of the adult organism (the foetus).

emigration The movement of individuals out of a population.

endemic Occurring only in a particular area. For example, the Tasmanian devil is endemic to Tasmania.

endocytosis The movement of material into a cell by enclosing it in plasma membrane, which then pinches off to form a vesicle within the cell. Endocytosis includes phagocytosis (the entry of solids) and pinocytosis (the entry of liquids).

endoderm The innermost layer of the three primary germ layers in the early embryo.

endometrium The inner lining of the uterus in mammals. It is the site of implantation of the embryo after fertilisation.

endonuclease See *restriction enzyme*.

endosperm The tissue in a plant seed that provides nutrition for the developing embryo.

endotherm An animal that maintains a more or less constant body temperature, which is usually higher than the temperature of the surrounding environment.

enteric nervous system The part of the nervous system that controls the gastrointestinal system.

enzyme A protein molecule that catalyses (speeds up) biochemical reactions.

epidermis The outermost layer of cells of a multicellular organism.

epigenetics The study of molecular events such as methylation that occur on DNA but do not alter the DNA sequence, but result in different phenotypes.

epiglottis A thin flap of cartilage that covers the entrance to the larynx, preventing food from entering the trachea while eating.

epithelium (adj. epithelial) A thin layer of tissue covering the external surfaces of a multicellular organism, and also lining the inner surfaces of internal structures such as intestines and lungs.

equilibrium A state of stability in which opposing factors are balanced.

error The difference between the true value and the measured value.

essential amino acid An amino acid that cannot be produced from other amino acids and therefore must be obtained in the diet. Essential amino acids for humans are histidine, isoleucine, leucine, methionine, phenylalanine, threonine, tryptophan, valine and lysine.

ethogram A list of the specific behaviours of an animal in its natural environment.

ethology The study of the behaviour of organisms in their natural environment.

Eukarya The domain that includes all eukaryotes.

eukaryote An organism whose cells contain a membrane-bound nucleus and other membrane-bound organelles. Protists, fungi, plants and animals are eukaryotes.

evolution The cumulative change in the inheritable characteristics of organisms, expressed as the development of new forms or species.

excretion The removal of waste substances from the body of an organism.

exocytosis A type of active transport in cells in which molecules such as proteins are expelled from a cell. The molecules are enclosed by a vesicle, which then fuses with the cell membrane and expels the contents into the extracellular fluid.

experimental group The group of subjects in an experiment in which one variable (the independent variable) is altered in order to measure its effect on another variable (the dependent variable). See also *control group*.

exponential growth The growth of a population in which rate of growth is proportional to population size. A graph of exponential growth shows an increasing gradient over time.

exponential relationship A mathematical relationship in which the rate of change of one variable is proportional to the value of the other variable.

external environment The environment immediately surrounding an organism.

exteroreceptor A sensory receptor that detects external stimuli.

extracellular digestion Chemical digestion in which the enzymes are secreted into a cavity, where digestion takes place.

extracellular fluid The fluid outside the cells in a multicellular organism.

extracellular matrix In animals, a lattice of molecules in the space between cells that provides structural and organic support to the cells around it.

extremophile An organism that lives in an extreme environment, such as somewhere with a very high pressure, temperature or salinity.

F

F1 generation The generation consisting of offspring of a cross between members of the parental generation.

F2 generation The offspring of a cross between members of the F1 generation.

facilitated diffusion Diffusion of ions and molecules through a plasma membrane via ion channels and channel proteins. Facilitated diffusion does not require chemical energy from the conversion of ATP to ADP.

facultative mutualism Mutualism in which the individuals do not depend on each other for survival, but both benefit from the relationship.

fallopian tube See *oviduct*.

family In the classification of organisms, the taxonomic category above genus. Similar families are grouped together into an order.

fermentation The stage in the breakdown of glucose that follows glycolysis when there is no oxygen present. Fermentation produces either lactic acid (in most animals) or alcohol (in most plants and micro-organisms).

fertilisation Penetration of an egg by sperm and fusion of the egg and sperm nuclei.

filament The stalk of a stamen that bears the anther.

filtration In the kidney, the process by which the primary kidney filtrate is formed, from fluid passing from Bowman's capsule into the nephron.

fluorescence in situ hybridisation (FISH) A method used in genetic testing to identify the specific location of a gene or allele on a chromosome, and to detect changes in chromosome structure such as deletion or duplication of certain sections. A fluorescent DNA probe binds to the target sequence on the chromosome.

fission A form of asexual reproduction in unicellular organisms, in which the parent cell divides into two parts. See also *binary fission*.

foetus The stage in the development of a mammal, following the embryonic stage. The foetus has all of the major structures of the adult mammal. In humans, this stage lasts from the eighth week of gestation until birth.

follicle A mature ovarian follicle that ruptures during ovulation to release the ovum. Also called Graafian follicle.

food chain A sequence of feeding relationships, beginning with a producer and ending with a higher order consumer. The producer is eaten by a first-order consumer, the first-order consumer is eaten by a second-order consumer, and so on.

food web A network of interlinked food chains that describes the feeding relationships between all organisms in an ecosystem.

fragmentation A form of asexual reproduction in which an organism breaks into two or more parts, each of which regenerates the missing pieces to form a complete new organism.

Fungi One of the five kingdoms of eukaryotic organisms, consisting of heterotrophs that are composed of hyphae and reproduce by spores. They include mushrooms, lichens (lichenised fungi), yeasts and moulds.

G

gamete A haploid cell capable of fusion with another haploid cell to form a zygote. In vertebrates the gametes are sperm and egg cells.

gametophyte The gamete-forming haploid stage in the life cycle of a plant.

gastrula An early stage in the development of an embryo, consisting of three layers of cells: ectoderm (outer layer), mesoderm (middle layer) and endoderm (inner layer).

gastrulation A series of cell and tissue movements at the blastocyst stage of animal development, during which the embryo is reorganised to form a gastrula.

gel electrophoresis A technique used for separating fragments of DNA, or different proteins, based on their size. DNA molecules are negatively charged, so they migrate through the agarose gel towards the positive electrode; lighter molecules migrate faster than heavier molecules, so the different sizes of molecules separate out in the gel.

gene A section of DNA that contains instructions for making a protein. Particular genes have specific locations on chromosomes. Genes are copied and passed from one generation to the next during reproduction.

gene expression The process by which the genetic instructions encoded in genes synthesise products such as proteins.

gene mapping The determination of the location of genes, and the distance between them, on a chromosome.

genetic marker A sequence of DNA with a known location on a chromosome.

genetic screening Genetic testing of a large number of individuals or embryos to identify carriers for a particular disease (such as breast cancer, phenylketonuria or haemophilia A in individuals, or Down syndrome and Turner syndrome in embryos) or those at risk of developing the genetic disease.

genetic testing DNA analysis to determine the genetic status of an individual or embryo. Genetic testing is carried out to detect specific alleles, mutations, genotypes or karyotypes that are associated with heritable traits, diseases or predispositions to diseases, such as cystic fibrosis, Down syndrome or Turner syndrome.

genome The DNA in one full set of chromosomes present in the nuclei of normal cells of a species, plus the DNA in mitochondria and (in plants) chloroplasts.

genophore A single, usually circular DNA chromosome in a prokaryote, containing the genetic material.

genotype (1) The total set of genes of an organism. (2) The combination of alleles for a trait carried by an individual.

genus (pl. genera) In the classification of organisms, the category above the species level. Similar genera are grouped into families.

geotropism Plant growth in response to gravity.

germ cell Any cell in an organism that gives rise to gametes.

germ layer The primary layer of cells that are formed during embryogenesis. Animals with bilateral symmetry have three layers: endoderm, mesoderm and ectoderm. Animals with radial symmetry have two layers: endoderm and ectoderm.

germination The initial growth of a seed. Germination is usually triggered by environmental factors such as temperature or moisture.

glucagon A hormone produced in the pancreas that causes glycogen to be broken down in the liver, releasing glucose into the blood, thus opposing the effect of insulin.

glucose A simple sugar (formula $C_6H_{12}O_6$) that is a product of photosynthesis. It is the main source of energy for cells in living things, and is essential for cellular respiration.

glycogen A complex carbohydrate molecule consisting of glucose subunits. Glycogen is the main carbohydrate storage molecule in animals.

glycolipid A lipid with a carbohydrate group attached. It is a component of the cell membrane and is a marker for cell recognition.

glycolysis The first stage in the breakdown of glucose to produce ATP. Glycolysis occurs in the cytoplasm and produces two molecules of ATP for each glucose molecule.

glycoprotein A protein that has a carbohydrate group attached to the polypeptide chain. Glycoproteins are components of the cell membrane and are receptors for molecules such as hormones.

goitre An enlarged thyroid gland, which is usually a symptom of iodine deficiency.

Graafian follicle See *follicle*.

granum (pl. grana) A stack of thylakoids in the chloroplast.

guanine (G) A nitrogen-containing base (a purine) that occurs in nucleotides of DNA and RNA.

guttation The loss of liquid water from leaves as a result of root pressure.

H

habitat The environment where an organism lives.

haemoglobin A protein molecule in red blood cells that carries oxygen from the lungs, and returns carbon dioxide from the tissues to the lungs. Haemoglobin occurs in mammals and many other animals, and gives red blood cells their characteristic colour.

halophyte A plant adapted to growing in a salty environment.

haploid Containing one set of chromosomes (half the normal number of chromosomes of a diploid cell).

heat capacity the amount of heat that one gram of water must absorb or lose to change its temperature by 1 °C. Water has a high heat capacity, meaning that it needs to absorb a great deal of heat before there is any change in water temperature.

heat exchanger A mechanism for exchanging heat between an organism and its environment.

hemizygote (adj. hemizygous) A diploid cell or organism with only one copy of a particular chromosome. Human males are hemizygotes because they have one X chromosome rather than two.

herbivore An animal that feeds only on producers, such as plants or algae.

hereditary Able to be passed from parent to offspring, or from one generation to the next.

hermaphrodite (1) In plants, having both stamens and carpels in the same flower. (2) In animals, producing both male and female gametes.

heterogametic Having different sex chromosomes; for example, human males with XY.

heterotroph An organism that must obtain nutrients from other organisms.

heterozygote (adj. heterozygous) A diploid individual with different alleles for a particular gene.

hibernation A long period of torpor during the colder months of the year. See also *aestivation*.

hierarchy The different levels of classification of living things, from domain to species.

histone One of various alkaline proteins that arrange DNA into nucleosomes.

homeostasis The maintenance of a more or less stable internal environment, even when external conditions change.

homogametic Having two similar sex chromosomes; for example, human females with XX.

homologous chromosomes Matching pairs of chromosomes in a diploid organism. Homologous chromosomes carry the same genes in the same loci.

homozygote (adj. homozygous) A diploid individual with two identical alleles at a particular genetic locus.

hormone A molecule that regulates the growth or activity of those cells capable of responding to it (target cells). Hormones are produced by specialised groups of cells within an organism.

host An organism that carries a parasite.

Human Genome Project A worldwide project started in 1990 to determine the human genome. The project was completed in 2003.

hybrid An individual produced by a cross between parents with different genotypes.

hydrolysis A chemical reaction involving the splitting of a molecule by the addition of a water molecule at a particular point.

hydrophobic Repelling water. Hydrophobic substances do not wet easily and do not dissolve in water.

hydrosphere The watery region of the Earth, consisting of the oceans, seas, lakes, streams and groundwater.

hydrothermal vent A fissure in the Earth's crust from which extremely hot water escapes.

hydrotropism Plant growth in response to a water concentration gradient.

hyperglycaemia A higher than normal blood glucose level.

hypersecretion An increased secretion of a substance, such as thyroid hormone.

hyperthyroidism A disease resulting from an overactive thyroid gland.

hyphae (sing. hypha) Minute thread-like structures that make up the mycelium of a fungus.

hypoglycaemia A lower than normal blood glucose level.

hyposecretion A deficiency in secretion of a substance, such as insulin.

hypothalamus In vertebrates, the base and part of the sides of the brain immediately below the thalamus. In mammals the hypothalamus directly or indirectly controls aspects of the internal environment, particularly through the secretion of various hormones such as anterior pituitary hormones.

hypothesis A suggested explanation for observed facts. An experimental hypothesis is used to make predictions that can be tested experimentally.

I

immigration The movement of individuals into a population.

immuno-suppressant drug A drug that inhibits the immune response against foreign particles or tissues. Immuno-suppressant drugs are used to prevent the rejection of transplanted organs or tissues.

implantation Attachment and embedding of the blastocyst into the lining of the uterus. Implantation commences the development of the blastocyst into a foetus, and occurs in all mammals except monotremes.

in vitro fertilisation (IVF) The fertilisation of an ovum outside the body, in laboratory glassware. IVF is used particularly if normal fertilisation cannot occur.

incomplete penetrance Penetrance is said to be incomplete when some individuals carrying the allele for a trait do not express the trait.

independent variable The variable that is altered during an experiment to test its effect on another variable (the dependent variable). Also called experimental variable.

infer To deduce something from evidence or reasoning.

inference Something that is inferred.

inorganic compound Any compound that does not include carbon. However, oxides, carbonates, bicarbonates, carbides and cyanides are usually also considered to be inorganic compounds.

insulin A hormone secreted by β cells in the pancreas, controlling the concentration of glucose in the blood. Insulin is secreted in response to high glucose levels, and acts by suppressing the breakdown of glycogen to glucose in the liver, stimulating the storage of glucose as glycogen in the liver and muscles, and stimulating the formation of fat using glucose.

integral protein A protein that is a permanent part of the cell membrane.

internal environment The watery extracellular fluid that surrounds the cells of a multicellular organism.

interneuron A neuron that transmits information from a sensory neuron to a motor neuron. Most of the nerve cells of the brain and spinal cord are interneurons.

interoreceptor A sensory receptor that detects internal stimuli.

interphase The phase in the cell cycle when the cell is not undergoing mitosis.

interspecific Occurring between or involving two or more species.

intracellular digestion The breakdown of particles that takes place in the cytoplasm of a cell.

intracellular fluid The fluid inside a cell.

intraspecific Occurring between or involving two or more individuals of a species.

inverse relationship A mathematical relationship in which one variable increases when the other decreases.

K

karyotype A visual depiction of the number, size and shape of chromosomes in an individual.

karyotyping A method used in genetic testing that analyses whole chromosomes to identify large genetic changes, such as an extra copy of a chromosome. Also called conventional cytogenetic testing.

keystone species A species on which the entire structure and functioning of an ecosystem depends. Without the keystone species, the ecosystem structure would change significantly, and the ecosystem would function in a very different way.

kingdom The second-highest category in a biological classification, below domain. The five major kingdoms recognised are Monera, Protista, Fungi, Plantae and Animalia.

L

lacteal Vessels of the lymphatic system close to the small intestine. Lacteal capillaries absorb digested fats from the small intestine, giving the lacteals a milky appearance.

larynx The organ in the upper trachea that contains vocal cords and is responsible for speech in humans. It is also involved in breathing and in preventing the aspiration of food or other large particles into the lungs.

law of independent assortment The principle, first stated by Gregor Mendel, that individual inherited traits assort independently, so that the occurrence of a trait (such as brown eyes) in an offspring is independent of the occurrence of any other trait (such as attached ear lobes). Because of linkage, the law applies only to alleles on different chromosomes. Also called Mendel's second law of inheritance.

legume Any plant of the pea family Fabaceae. Legumes are important in fixing nitrogen from the atmosphere into forms that can be used by organisms, and are important agricultural crops.

lenticel A porous group of cells that allows gas exchange across the otherwise airtight and waterproof cork layer covering the stems and roots of woody plants.

lichen An organism consisting of a fungus and an alga growing together in symbiosis. The fungus protects the alga from the external environment, and the alga produces nutrients for the fungus by photosynthesis.

light compensation point The light intensity at which the rate of oxygen produced by photosynthesis equals the rate of oxygen use in cellular respiration in a plant.

lignin A complex organic compound deposited in the cell walls in the xylem vessels, tracheids and supporting tissue of vascular plants. Lignin gives strength to the stem and other plant parts. It is not present in non-vascular plants such as mosses.

limiting factor Any factor that prevents a population from growing larger. Common limiting factors are the availability of water, food, shelter, nesting sites and mates.

line graph A graph in which the relationship between the variables is represented by a straight line, curved line, or series of line segments.

linear relationship A mathematical relationship between variables in which a change in one variable produces a proportional change in the other variable. The graph of a linear relationship is a straight line.

linkage The tendency for two or more genes on the same chromosome to be inherited together because they are close together on the chromosome. Linked genes may be separated if crossing over occurs between them.

Linnaean system A classification system created by Carl Linnaeus. In the Linnaean system, organisms were divided into three kingdoms, which were further divided into classes, orders, families, genera and species.

Linnaeus, Carl An 18th century Swedish botanist who created the binomial system for naming plants, as well as a classification of living things on which modern classification is based.

lipase An enzyme that digests lipids.

lipid An organic compound that is insoluble in water but soluble in alcohol, ether or chloroform. Lipids include fats, oils, sterols, some hormones, fat-soluble vitamins, glycerides and phospholipids.

lithosphere The solid outer layers of the Earth, including the crust and the solid part of the mantle below it.

liver A large organ in vertebrates that is involved in many important metabolic processes, including protein manufacturing, fat storage and processing, bile secretion, and metabolism of toxins.

locus (pl. loci) The site on a chromosome where a particular gene is located.

logistic growth Population growth in which the growth rate decreases as the population approaches the carrying capacity. A graph of logistic growth is an S-shaped curve.

longitudinal fission A form of asexual reproduction in which the organism splits along its longest axis, and each half forms a new organism. It occurs mainly in unicellular organisms, such as the protist *Euglena*.

loop of Henle A U-shaped loop in a mammalian kidney between the proximal and distal convoluted ducts, dipping into the medulla. Its main function is to recover water and sodium chloride from urine, thus making the urine more concentrated and reducing the amount of water that needs to be taken in.

lumen (1) The region enclosed by the plasma membrane of a cell. (2) The inside of a tubular structure such as a blood vessel or xylem tube.

lymph The fluid that circulates in the lymph system. It consists mainly of interstitial fluid (fluid forced from capillaries by blood pressure into the spaces between tissues) and contains lymphocytes, macrophages, proteins and fats. It has an important role in defending the body against harmful bacteria and other particles, and also in the absorption and transport of fatty acids.

M

maltose A sugar formed by the digestion of starch. It is a disaccharide consisting of two glucose molecules.

Materials Safety Data Sheet (MSDS) A document that provides health and safety information about hazardous chemicals or products.

mean The average value of a set of values, calculated by dividing the sum of the values by the number of values.

median The value in the middle of an ordered list of values.

meiosis A division of a nucleus that results in one copy of each homologous chromosome and one sex chromosome in each daughter cell. Meiosis produces four genetically unique daughter cells, each with half the number of chromosomes of the parent cell.

meniscus The curved upper surface of liquid in a tube or container, caused by surface tension. A meniscus can be concave (as in water in a glass tube) or convex (as in mercury in a thermometer).

meristem Tissue in plants that contains undifferentiated cells and is the site of cellular differentiation and specialisation. Meristem tissue usually occurs at the tips of roots and shoots of plants, where most tissue growth occurs.

mesoderm The middle layer of the three primary germ layers in the early embryo. The mesoderm is present only in animals with bilateral symmetry; animals with radial symmetry have only two primary germ layers.

metabolic rate The rate at which energy is required by an organism to maintain homeostasis.

metabolism The total of the physical and chemical processes by which energy and matter are made available by an organism for its own use. Metabolism is controlled by enzymes.

methanogen A prokaryote that uses carbon dioxide to produce methane (CH_4).

microclimate The climate of a small, restricted area, in contrast to the general climate of the region.

microvillus (pl. microvilli) A microscopic fold of the inner surface of intestinal epithelial cells. Microvilli increase the surface area for the absorption and secretion of substances.

migration The geographic movement of organisms.

mineral Any naturally occurring inorganic substance. In nutrition, important minerals include elements such as magnesium, potassium, calcium, iron and sodium. Minerals in foods are essential for maintaining biological functions.

mitochondrion (pl. mitochondria) Organelles in which cellular respiration occurs. Each mitochondrion is composed of many layers of folded membrane.

mitogen A molecule that stimulates mitosis (cell division).

mitosis A division of a nucleus that results in two cells that are genetically identical to the parent cell. Asexual reproduction and cell replication for growth occur by mitosis.

mitospore A spore produced asexually by mitosis.

mode The value that occurs most often in a data set.

molecular genetic testing A genetic testing method to identify single genes or short lengths of DNA.

Monera The kingdom of living things that includes all bacteria. See also Archaea, Bacteria.

monohybrid cross A cross between individuals that have different pairs of alleles of a particular gene. For example, one individual might have T and t alleles, and the other might have t and t alleles. Monohybrid crosses are used to study the inheritance of one characteristic.

monosaccharide Any of various simple sugars that are the basic unit of carbohydrates. They include glucose, fructose and galactose.

monosomy A condition in which part or all of one chromosome of a particular diploid pair is missing in the karyotype. An example of monosomy is Turner syndrome, in which all or part of an X chromosome is missing.

mortality The death rate in a population, usually expressed as number of deaths per unit of population in a given time period. For example, the death rate in Australia in 2013 was 6.4 per 1000 population.

morula An embryo consisting of an unorganised mass of 16 cells, resulting from a series of divisions of the zygote.

mRNA (messenger RNA) An RNA molecule that is transcribed from DNA in the nucleus, then passes into the cytoplasm and binds to a ribosome, where it is used to build an amino acid sequence (polypeptide).

multicellular Consisting of two or more specialised cells that have identical DNA, are responsible for specific functions, and depend on each other for survival. Also called pluricellular.

multipotent (cell) A cell that can develop only into cells of a similar type. For example, stem cells in bone marrow are multipotent because they can develop into different blood cells but not into other types of cells.

murein A giant molecule that forms a mesh-like layer on the outside of the plasma membrane of most bacteria. Each molecule consists of glycans (large-molecule sugars) linked by chains of amino acids. Also called peptidoglycan.

mutagen A physical, chemical or biological agent that can cause mutations in DNA.

mutant (1) A cell or organism carrying an altered (mutated) gene. (2) An individual with a phenotype that is different from the wild type.

mutation A permanent change in the base sequence of DNA. Mutations may occur spontaneously or in response to radiation or harmful substances.

mutualism A symbiotic relationship between two organisms in which both organisms benefit. An example is pollination of flowers by insects, in which the insect receives nutrition and the plant is able to reproduce.

mycorrhiza (pl. mycorrhizae) A mutualistic association between a fungal mycelium and the roots of a plant. Mycorrhizae enable the roots to absorb water and nutrients more efficiently, while the fungus gains access to nutrients such as sugars.

myoglobin A red respiratory pigment that occurs in muscles. Myoglobin carries oxygen that can be used when other oxygen reserves are depleted.

N

nastic movement A movement of plant tissues in response to an environmental stimulus, such as a change in humidity or temperature. Nastic movements are independent of the direction of the stimulus.

natality The birth rate in a population, usually expressed as number of births per unit of population in a given time period. For example, the birth rate in Australia in 2014 was 12.8 per 1000 population.

natural selection The mechanism by which evolution is believed to occur. Some individuals in a population have inherited characteristics that make them more likely to survive and reproduce than others in the population. These individuals then pass these characteristics on to their offspring. Over time this removes less suitable variations, so that evolutionary change gradually occurs.

negative feedback loop A control system in which the response produced by a stimulus reduces the size of the original disturbance. This eventually leads to homeostasis.

neoplasm Abnormal tissue growth, caused by unusually rapid cell replication. Neoplasms may be malignant (cancerous) or benign (not cancerous).

nephron The functional unit of the kidney; consisting of a Bowman's capsule surrounding a glomerulus and a tubular region leading into a collecting duct. About one million nephrons are found in each human kidney.

neuron A nerve cell, including its various processes and attachments. The neuron is the fundamental unit of the nervous system in animals.

niche The role of an organism or group of organisms in an ecosystem, including its position in the food web, how it obtains its food, and how it reproduces.

nitrogen fixation The conversion of atmospheric nitrogen into nitrogenous compounds that can be used by plants. Nitrogen fixation is brought about by specialised bacteria and cyanobacteria, especially Rhizobium bacteria that live symbiotically in the roots of legumes.

nitrogenous waste Waste products from the breakdown of proteins, including ammonia, urea and uric acid.

nocioception The detection of harmful stimuli, such as pain, that alerts the organism to potential harm.

nominal variable A categorical variable in which there is no inherent order. Nominal variables can be counted but not ordered.

non-shivering thermogenesis The production of body heat by an increase in metabolic rate in brown fat. Brown fat is rich in mitochondria and is capable of high rates of aerobic metabolism.

nucleic acid A long-chain molecule formed from nucleotides. The nucleic acids DNA and RNA are the genetic material of all organisms. They determine the physical appearance of an organism and how it functions.

nucleolus (pl. nucleoli) A dark-staining body in the nucleus, where ribosomal RNA is synthesised.

nucleosome A particle made up of histone proteins around which DNA is coiled. Nucleosomes occur in chromosomes.

nucleotide A molecule consisting of a 5-carbon sugar (ribose in RNA, or deoxyribose in DNA), a nitrogenous base (purine or pyrimidine) and a phosphate group. Nucleotides are the building blocks of nucleic acids such as DNA and RNA.

null hypothesis The hypothesis that there is no relationship between two variables, so that any change that occurs in one variable when the other variable is changed is entirely random. It is the opposite of the *alternative hypothesis*.

O

obligate mutualism Mutualism in which one of the organisms cannot survive without the other.

observation A value or other information obtained during an experiment.

oestrogen Any of a group of hormones, produced mainly in the ovaries, that initiate the development of secondary sex characteristics and control the ovarian cycle.

omnivore An organism that feeds on both plants and animals.

oocyte A precursor egg cell in the ovary that undergoes meiosis, resulting in the formation of a single egg cell.

open circulatory system A system for fluid circulation in animals in which there is no clear distinction between circulatory and interstitial fluids, so that fluids flow more or less freely between the cells of the tissues.

order In the classification of organisms, the taxonomic category above the level of family. Similar orders are grouped together into classes.

ordinal variable A categorical variable in which there is an inherent order. Ordinal variables can be counted as well as ordered.

organ A structure, consisting of different tissues, that carries out one or more specific functions.

organelle Any specialised structure in the cytoplasm of a cell, including Golgi apparatus, mitochondrion, endoplasmic reticulum, vacuole, chloroplast and nucleus.

organic compound Any chemical substance containing carbon, once thought to come from living organisms. Common organic compounds are proteins, carbohydrates and lipids. However, oxides, carbonates, bicarbonates, carbides and cyanides are usually not considered to be organic compounds.

organism A living system that functions as an individual, whether unicellular or multicellular.

origin In prokaryotes, the point at which the chromosome is attached to the plasma membrane.

osmolality The osmotic pressure of a liquid, measured in osmoles of solute per kg of water.

osmolarity The concentration of a solution, measured in osmoles of solute per litre of solution. Also called osmotic concentration.

osmoreceptor A sensory receptor that detects changes in osmotic pressure in the internal environment. Most osmoreceptors are located in the hypothalamus.

osmosis Passive diffusion of free water molecules across a semi-permeable membrane from a more dilute solution to a more concentrated solution.

osmotic gradient A difference in the concentration of a solute (dissolved substance) on each side of a semi-permeable membrane.

osmotic pressure The pressure that causes free water molecules to move along a concentration gradient (osmotic gradient) across a semi-permeable membrane. It is caused by a difference in concentration of the solutions on each side of the membrane.

outcompete To displace another species in the competition for space, food, or other resources.

outlier A data point that lies outside the main group of data.

ovary A female gonad into which precursor egg cells migrate and develop into ripe eggs. The two ovaries are important hormone-secreting organs during pregnancy.

oviduct The duct that collects eggs from an ovary after ovulation and transports it to the uterus. Fertilisation usually occurs in the oviduct. Also called fallopian tube or uterine tube.

ovulation The release of a ripe egg from its follicle in the ovary. Ovulation usually occurs spontaneously during each period of oestrus in response to a cyclic surge of luteinising hormone.

oxygen-carrying capacity The amount of oxygen that can be carried by a particular medium, such as blood.

P

parasit(adj. parasitism) An organism that lives in or on another organism and benefits by feeding on nutrients.

parasympathetic division A division of the autonomic nervous system that is responsible for directing the unconscious actions of the body and inhibiting the effects of the sympathetic nervous system; for example, by dilating blood vessels and decreasing the heart rate.

parental type A gamete that has the same alleles that are present in the parent. Also called parental gamete.

parthenogenesis The development of an egg in the absence of fertilisation by sperm. It is a normal part of the life cycle in some insects and crustaceans.

pedigree analysis The determination of the pattern of inheritance of a characteristic or condition by reference to a family tree in which the presence or absence of the characteristic is recorded over generations.

penetrance The extent to which a particular phenotype is expressed among individuals with the genotype for that phenotype. In complete penetrance, all such individuals will express the phenotype. In incomplete penetrance, some individuals will not express the phenotype.

peripheral nervous system (PNS) Nerve pathways and neurons located outside the central nervous system of a vertebrate. The peripheral nervous system includes spinal and sensory nerves and nerves supplying the internal organs.

peripheral protein A protein that is a temporary part of the cell membrane. Peripheral proteins bind to integral proteins or penetrate the periphery (outside layer) of the cell membrane.

peristalsis Coordinated muscular contractions and relaxations of the wall of the digestive tract that move a bolus of food from the oesophagus to the intestines.

pest organism An organism that can cause harm to the environment or to humans or human activities.

pH A measure of the acidity or alkalinity of an aqueous solution. It is measured on a logarithmic scale from 0 (most acid) to 14 (most alkaline). A solution that is neither acid nor alkaline has a pH of 7, and is said to be neutral.

phagocytosis The process by which a solid particle in the extracellular fluid is taken into a cell. The particle is enclosed by a section of plasma membrane, which then pinches off to form a vesicle within the cell's cytoplasm. Phagocytosis is a type of endocytosis.

phenotype (1) An observable character or trait of an organism. (2) The overall appearance of an organism.

phloem Plant tissue through which sugars and other organic compounds are distributed to different parts of a plant. In flowering plants, phloem consists of sieve tubes, companion cells and fibres.

phospholipid A fat-like substance, usually based on glycerol. Phospholipids are essential components of cell membranes. They are involved in the uptake of fats and fatty acids from the products of digestion.

photoheterotroph A consumer (heterotroph) that obtains its energy from light.

photometer An instrument that measures the intensity of light.

photonasty Plant movement in response to a change in light intensity.

photosynthesis (adj. photosynthetic) The process by which plants and other photosynthetic organisms convert energy from sunlight into chemical energy for biological functions. It occurs in plastids.

phototropism Plant growth in response to light.

phylogeny The evolutionary relationship between organisms, commonly represented by a diagram called a phylogenetic tree.

phylum (pl. phyla) In the classification of organisms, the taxonomic category above class. Similar phyla are grouped together into a kingdom.

pie chart A circular diagram divided into sectors, with each sector representing the value of one set of data as a proportion of the total data set.

piloerection The erection of hair cells in response to cold, fright or shock. The sympathetic nervous system triggers this reflex.

pinocytosis The process by which a mass of fluid is taken into a cell. The fluid is first surrounded by a section of plasma membrane, which then pinches off to form a vesicle within the cell. Pinocytosis is a type of endocytosis.

pistil The female reproductive organ of a flower, consisting of the stigma, style and ovary.

plasma membrane A bilayer (double layer) of phospholipids that encloses the contents of a cell and controls the movement of substances into and out of the cell. Also called cell membrane or plasmolemma.

plasmid A fragment of DNA that is outside the chromosomes, in the cytoplasm. Plasmids usually include genes and can replicate independently. In genetic engineering, bacterial plasmids can be used to produce recombinant DNA.

plasmodesma (pl. plasmodesmata) A microscopic channel that connects the cytoplasm of adjacent cells in plants and some algae.

plasmodium A protist whose cells can contain two or more nuclei during particular periods of its development. Also called a slime mould. See also *syncytium*. (Note: the genus *Plasmodium* comprises malarial parasites and is not related to slime moulds.)

ploidy The number of full sets of chromosomes in an organism's karyoptye. Haploid (one set, or n) and diploid (two sets, or $2n$) are the most common ploidy states, but other states are possible. See also *polyploid*.

pluripotent (cell) A cell that can develop into several different cell types. An example is a human embryonic stem cell, which can form all adult cell types.

pneumatophore An aerial root of a mangrove that increases the surface area exposed to the air at low tide for oxygen uptake.

pollination The transfer of pollen from one flower to another.

polygene A gene that acts together with one or more other genes to control a quantitative character, such as height in the human population.

polygenic inheritance The inheritance of an observable trait that is determined by many genes.

polymerase chain reaction (PCR) A technique used to make millions of identical copies of a segment of DNA in a short period of time.

polypeptide A long, chain-like molecule consisting of many amino acids linked together. Each amino acid loses a water molecule when it is linked, so a polypeptide is actually a chain of amino acid residues. The group of atoms (–NH–CO–) that links each amino acid to the next one is called a peptide bond.

polyploid Having more than one copy of the full complement of chromosomes. Common polyploid states are diploid (two copies), triploid (three copies) and tetraploid (four copies).

polysaccharide A long chain of linked monosaccharides. Polysaccharides include starch, glycogen and cellulose. Also called glycan.

population A group of organisms of the same species that interact with each other.

population explosion A very rapid increase in the size of a population of organisms.

positive feedback loop A control system in which the response produced by a stimulus increases the size of the original disturbance.

pre-implantation genetic diagnosis (PGD) Genetic testing conducted before implantation of a fertilised egg, to determine whether there are any genetic abnormalities that might lead to a disorder in the resulting individual.

precision The ability to consistently obtain the same measurement.

predation The killing and consumption of an animal by another animal.

predator An animal that kills and consumes other animals.

prey An animal that is a food source for another animal.

primary source A source that includes first-hand information, such as the results of an original experiment. See also *secondary source*.

primer A short, synthetic segment of DNA that is complementary to the sequences of bases at one end of a DNA region to be amplified. Primers specify the starting and finishing points for DNA replication. A primer is added to single-stranded DNA to start DNA synthesis during a polymerase chain reaction.

principle A scientific theory that is so strongly supported by evidence that it is considered unlikely to be shown to be untrue in the future.

processed data Data that has been mathematically manipulated.

producer An organism that obtains its nutrition from non-living sources by photosynthesis or chemosynthesis. Plants, algae, phytoplankton and some bacteria are producers.

progeny Offspring or descendants of an organism.

progesterone The hormone that regulates the oestrus and menstrual cycles and maintains a pregnancy. Progesterone is produced in the corpus luteum of the ovary, and in the placenta.

prokaryote An organism with cells that do not have a membrane surrounding the nucleus and lack most organelles. All prokaryotes are bacteria. See also *Archaea*, *Bacteria*.

proprioception The unconscious sense of the body's position and spatial orientation.

protease An enzyme that digests proteins.

protein A nitrogenous organic compound consisting of one or more long chains of amino acids.

protein synthesis The process by which cells assemble new proteins. Protein synthesis occurs in two stages: (1) transcription, in which DNA information is copied into messenger RNA, and (2) translation, in which proteins are synthesised from amino acids using the information in messenger RNA.

Protista One of the three kingdoms of eukaryotic organisms, consisting of mostly unicellular organisms. Protists include protozoa, slime moulds, water moulds and many algae.

proto-oncogene A normal cellular gene which could become a gene that triggers molecular events that lead to cancer.

Protozoa See *protozoan*.

protozoan A single-celled heterotrophic protist. Although once grouped into the phylum Protozoa, protozoans are now considered to belong to all the main lineages of protists. Also called protozoon.

pulmonary vein In humans, a blood vessel that carries oxygen-rich blood from the lungs to the left atrium of the heart.

purine A group of chemical bases that include adenine (A) and guanine (G), which are present in the nucleotides of DNA and RNA.

pyrimidine A group of chemicals that include the bases thymine (T), cytosine (C) and uracil (U) that are present in the nucleotides of DNA (C and T) and RNA (C and U).

pyrogen A toxin, produced by bacteria, that causes a fever by acting directly on the brain.

Q

quadrat An area (usually a square) within which a biological survey (such as counting plants or identifying species) is carried out.

qualitative data Data that consists of categorical variables.

quantifiable Able to be measured or counted.

quantitative data Data that consists of numerical variables.

R

radial symmetry The arrangement of body parts around a central point. An example of radial symmetry is the body shape of a sea star.

random selection A selection that is not affected by bias.

range The difference between the highest and lowest values.

raw data The data recorded during an experiment.

reabsorption In the kidney, the process by which the primary kidney filtrate is taken back into the tissues via nephrons.

reagent A chemical used to produce a change in an organic compound.

receptor A specialised structure that can detect a specific stimulus and initiate a response.

recessive Relating to a trait or phenotype (encoded by an allele or gene) whose appearance is subordinate to a dominant trait.

recessive phenotype A phenotype that is observed only in homozygous individuals.

reciprocal cross A cross in which a male of strain A is crossed with a female of strain B, and a female of strain A is crossed with a male of strain B.

recognition site A short segment of DNA that is recognised by a restriction enzyme. Different restriction enzymes recognise different sites.

recombinant DNA DNA formed artificially from fragments of DNA from different sources.

recombinant gametes Gametes carrying a combination of alleles not observed in the parents, as a result of crossing over during meiosis.

recombination In offspring, the formation of a new combination of alleles from the total alleles available from the parents.

reduction division A nuclear division that halves the number of chromosomes in the daughter cells. Reduction division occurs in meiosis.

reliability The ability to reproduce your results.

renin An enzyme that is produced and stored in the kidneys. It plays a role in regulating blood pressure by catalysing the conversion of angiotensinogen to angiotensin I. This is then converted to angiotensin II, an effective vasoconstrictor.

repeat trial An experiment that is conducted again, in exactly the same manner as a previous experiment.

replication (1) Experimentation carried out on more than one set of subjects at the same time. (2) The production of new cells by cell division.

reprogramming The conversion of one cell type into another cell type, such as a somatic cell into a pluripotent cell.

resource (1) Anything required by an organism for its survival and reproduction. (2) A source of information.

response A physiological or behavioural change in an organism as a result of receiving a stimulus.

restriction enzyme An enzyme that can cleave molecules of DNA at a particular site. Restriction enzymes are widely used in DNA analysis, genetic testing and genetic engineering. Also called an endonuclease.

restriction fragment analysis A type of analysis that provides information about DNA sequences based on how restriction enzymes cut the DNA. Patterns of DNA fragments are generated to compare individuals.

rhizome A creeping stem from which vertical stems arise from buds. Rhizomes enable plants to regenerate when the above-ground parts have died.

ribonucleic acid (RNA) Nucleic acids involved in ribosome structure and protein synthesis. There are three forms: messenger RNA (mRNA), ribosomal RNA (rRNA) and transfer RNA (tRNA).

ribosomal RNA (rRNA) The RNA part of a ribosome. It is synthesised in the nucleolus and is essential for protein synthesis.

ribosome A small organelle composed of protein and RNA. Ribosomes are often attached to rough endoplasmic reticulum and are the site of protein synthesis.

risk assessment A systematic way of identifying the potential risks associated with an activity.

RNA See *ribonucleic acid*.

root hair A very thin extension of an epidermal cell of a root. Root hairs increase the root's surface area, making the absorption of water and minerals from soil more efficient.

root pressure Osmotic uptake of water that accompanies the active uptake of mineral salts and contributes to the movement of water up xylem in some plants.

rough endoplasmic reticulum Layers of intracellular membranes associated with ribosomes. Rough endoplasmic reticulum is involved in protein synthesis.

rRNA See *ribosomal RNA*.

rumen A large fermentation chamber for the digestion of cellulose, located before the stomach in many herbivorous animals, such as cattle and sheep.

ruminant An animal with a rumen.

S

salinity The concentration of salts (mainly sodium chloride) in water or soil.

saprotroph An organism that feeds on dead or decaying organic matter.

scatterplot A graph in which two variables are plotted as points. The x coordinate of a particular point is one measured value of the independent variable and the y coordinate is the corresponding measured value of the dependent variable.

scavenger An animal that feeds on other animals that are already dead.

scientific method The systematic, objective collection of data by experiment in order to determine whether predictions based on a particular hypothesis are correct.

secondary source A source of information that does not include first-hand information. See also *primary source*.

secretion (1) The release of specific substances from a cell or group of cells. (2) In kidneys, the active excretion of particular substances by the cells of the duct walls.

semi-permeable membrane A membrane that allows only some molecules to pass across it by osmosis or diffusion. Also called partially permeable membrane, selectively permeable membrane.

semen A secretion of the testes that contains sperm. Also called seminal fluid.

sepal One of the outer parts of a flower that form the calyx, which encloses and protects the other parts of a flower during the bud stage. Sepals are usually green and often act as support for the petals when the flower opens.

sex chromosome A chromosome that is involved in sex determination. In humans the sex chromosomes are the X and Y chromosomes. Also called an allosome.

sex-limited inheritance The inheritance of a trait that is expressed only in one sex, even though both sexes carry the gene. An example is haemophilia A, an X-linked trait that occurs almost exclusively in males (cases in females are extremely rare).

sex-linked inheritance Inheritance related to genes that occur on the sex-chromosomes (X and Y in humans). An example is red-green colour blindness, which is caused by a mutation in a gene on the X chromosome. See also *X-linked*, *Y-linked*.

sexual reproduction Reproduction involving the fusion of two gametes (egg and sperm), which are the haploid products of meiosis.

shivering thermogenesis The production of heat energy through the involuntary movement of muscles (shivering).

single nucleotide polymorphism (SNP) A single base difference in DNA, used for genome comparison and studies of the association between genes.

sink A site where something is stored or consumed.

solute A substance dissolved in a fluid (the solvent).

solvent A fluid in which a substance (the solute) is dissolved.

somatic cell Any cell of an organism except a cell that gives rise to gametes (eggs and sperm). Somatic cells in mammals are diploid ($2n$); that is, they contain a full set of paired chromosomes.

source (1) A site where something is produced. (2) A document or person from which information has been obtained.

species The basic category or group in the binomial system. Organisms that are grouped into species usually closely resemble each other and can interbreed. Different species usually do not interbreed with one another in the wild, and if they do interbreed then their offspring are not capable of reproduction.

speculation The formation of a theory or conclusion without supporting evidence.

sperm The male gamete in animals, which can move by the motion of a flagellum. Also called spermatozoon.

spermatocyte Cells in the testes that divide by meiosis to produce four sperm cells.

spindle An arrangement of microtubules that binds to a centromere of a chromatid, enabling the chromosome to be divided equally between two daughter cells during mitosis and meiosis.

spiracle (1) In insects, the external opening of the trachea, through which gases are exchanged with the environment. (2) In fish, the small anterior (first) gill-slit, which is usually closed in most bony fishes.

spontaneous mutation Any naturally occurring random change in DNA.

sporangium (pl. sporangia) The structure in a spore-bearing plant in which spores develop. Also called spore case, spore capsule.

spore A haploid cell that can develop into a new organism without sexual reproduction. In plants, algae and fungi, spores are the products of meiosis, but fungi and some algae can also produce spores by mitosis.

stamen The male reproductive organ of a flower, composed of a filament and an anther. Stamens produce pollen, which is the male gamete.

starch A complex carbohydrate consisting of glucose subunits. It is the main form of energy storage in plants.

stem cell A cell that can differentiate into a specialised cell.

stem cell therapy Medical treatment based on the use of stem cells.

stigma The receptive surface for pollen at the tip of the style in a flower.

stimulus An environmental factor that an organism can detect and respond to.

stolon A thin, horizontal branch that serves to propagate a plant. Stolons usually grow along the ground, giving rise to roots and aerial branches at node points. An example of a plant with stolons is the strawberry. Also called a runner.

stoma (pl. stomata) Pores in the leaf epidermis, bounded by specialised guard cells that open and close the pore. Stomata are the main routes through which gas exchange occurs in plants, and through which water loss is regulated.

short tandem repeat (STR) A variable region of DNA used in modern DNA profiling.

strobilation A method of asexual reproduction in multicellular organisms, in which the organism divides along its shortest axis, and each part grows into a new individual. See also *longitudinal fission*, *transverse fission*.

style The organ in a flower that bears the stigma and through which, after pollination, pollen tubes grow towards the ovules.

subspecies A geographically separate group within a species that are morphologically or genetically different from other members of the species.

substrate A molecule that is acted on by an enzyme.

surface tension Bonds between surface molecules that inhibit molecules from leaving the surface, and other particles from penetrating the surface.

symbiosis A close association between two different organisms, in which at least one of the organisms benefits from the association. Symbiosis includes mutualism, commensalism and parasitism.

sympathetic division A division of the autonomic nervous system that is responsible for directing the unconscious actions of the body and inhibiting the effects of the parasympathetic nervous system (e.g. contracting blood vessels and increasing the heart rate).

synapsis The process of pairing of two homologous chromosomes during meiosis.

syncytium A cell containing two or more nuclei, resulting from a fusion of cells.

system A group of organs in animals that work together for a particular purpose. The major systems in humans are the integumentary system, skeletal system, circulatory system, muscular system, digestive system, nervous system, endocrine system, respiratory system and excretory system.

systole The period of contraction of a heart chamber, when blood is forced out under pressure. There are ventricular systoles and atrial systoles.

T

taxon (pl. taxa) A named taxonomic unit at any given level of classification, such as species or genus.

taxonomy The classification and naming of organisms according to their similarities and differences. Modern taxonomy uses both the appearance of organisms (morphology) and their DNA structure (genetics) to classify organisms.

telomere An area of repetitive DNA at either end of the DNA molecule of a eukaryotic chromosome. Telomeres protect the end of the chromosome from deteriorating and from clumping together with other chromosomes.

testcross A type of backcross in which an individual with the dominant phenotype is crossed with an individual of the recessive phenotype for the character being studied. A testcross is used to identify whether the individual with the dominant trait is homozygous or heterozygous.

testes (sing. testis) The male gonads into which precursor sperm cells migrate and develop into sperm. The testes are important hormone-secreting organs.

testosterone A hormone produced in male vertebrates. It is produced by the testes in male mammals, and to a lesser extent by the ovaries in females, and is responsible for the development of various sex characteristics.

theory A hypothesis that is supported by a great deal of evidence from a wide variety of sources.

thermonasty Plant movement in response to temperature change.

thermoreceptor A sensory receptor that detects and responds to temperature.

thigmonasty Plant movement in response to touch.

thigmotropism Plant growth in response to touch.

thylakoid A membrane-bound compartment inside a chloroplast. Thylakoids are the site of light-dependent reactions in photosynthesis.

thymine (T) A nitrogen-containing base (a pyrimidine) that occurs in nucleotides of DNA, but not RNA.

tidal volume The volume of air moved into and out of lungs during breathing.

tissue A group of similar cells functioning together.

tissue culture A method of growing cells or tissues in an artificial medium containing essential nutrients, salts and growth factors.

tolerance range The range of environmental conditions (such as temperature or salinity) that an organism can tolerate without injury.

tonoplast The membrane surrounding the vacuole in a plant cell.

torpor A state of inactivity or dormancy in animals, in which the body temperature is lower and the metabolism is slower than normal.

totipotent (cell) A cell that can give rise to any cell type and potentially a complete new organism.

tracheid A long, hollow cell with a thickened wall and tapering ends, found in the xylem of vascular plants. Tracheids transport water and nutrients to the living cells of the plant.

trait A particular characteristic or feature of an organism.

transect A line along which a biological survey is conducted. Transects are used mainly in botanical surveys.

translocation The transport of organic substances in the phloem of a vascular plant.

transmembrane protein An integral protein that spans both phospholipid layers of the plasma membrane.

transpiration The loss of water from the leaves of plants through stomata. Transpiration causes suction, which draws water up xylem vessels from the roots.

transpiration stream The flow of water within a plant, from the uptake by the roots to the loss of water to the environment via the leaves.

transverse fission A form of asexual reproduction in unicellular organisms in which the cell divides across its shortest axis.

trisomy An abnormality in which a cell has three copies of a particular chromosome. An example is trisomy of chromosome 21, which causes Down syndrome in humans.

trophic level The position of an organism in a food chain. For example, an organism that feeds on producers is a first-order consumer, and an organism that feeds on that first-order consumer is a second-order consumer.

tropism Plant growth in response to an external stimulus such as gravity, light or water. The plant might grow towards the stimulus (positive tropism) or away from it (negative tropism).

true-breeding Producing only progeny with a particular characteristic or trait seen in the parent. Also called pure-breeding.

tuber A starchy, underground stem that stores food for the plant. Tubers often grow just under the surface of the soil. Examples of plants with tubers are the potato and cassava.

tumour-suppressor gene A gene whose protein product inhibits cell division, thus preventing uncontrolled cell growth that would result in a cancer.

turgor (adj. turgid) The rigid state or fullness of a plant cell caused by internal fluid pressure (turgor pressure) acting on the cell wall. Turgor is maintained by the osmotic intake of water into the cell.

turgor pressure Internal fluid pressure in a cell that has a cell wall. It is the result of the osmotic intake of water into the cell, whose volume is limited by the cell wall.

type 1 diabetes An autoimmune disease in which the pancreas does not make insulin. Type 1 diabetes has a genetic basis, but appears to also require an environmental factor such as a viral infection in order to be expressed.

type specimen A sample of an organism on which the scientific name and description is based.

U

uncertainty The range of values within which the true value of a measured quantity probably occurs. Uncertainty is caused by random and systematic errors.

ungulate A hoofed mammal. Ungulates are classified as odd-toed (order Perissodactyla: horses, zebras, donkeys, rhinoceroses and tapirs) or even-toed (order Artiodactyla: all other ungulates, including pigs, deer, giraffes and sheep).

unipotent (cell) A stem cell that can differentiate only into one cell type.

urea A water-soluble molecule (CH_4N_2O) that is a major product of protein breakdown. It is excreted by many vertebrates, including mammals.

ureter The tube that carries urine from a kidney to the bladder for storage, before release via the urethra.

urethra The tube that carries urine from the bladder to the exterior for excretion.

uric acid A complex nitrogenous compound ($C_5H_4N_4O_3$) that is produced and excreted by birds and most land reptiles.

uterus The hollow, muscular organ of the female reproductive system, in which the foetus develops.

V

validity How real your results are, and whether they apply to all situations.

valve A specialised structure in circulatory systems that allows movement in one direction only. In humans, valves occur in the heart, veins and lymph vessels.

variable A factor or condition that can change during an experiment.

variance The square of the standard deviation of a random variable. Variance is a measure of the spread of values of the variable.

vas deferens A muscular duct that moves sperm from the epididymis into the urethra before ejaculation.

vascular (adj. vascularised) Having vessels that transport fluids.

vascular bundle A grouping of vascular tissues in vascular plants, containing both xylem and phloem. Vascular bundles are continuous, from the roots into the stem, branches and leaves.

vascular plant A plant that has vascular tissues (xylem and phloem) in which the cell walls contain lignin. All living plants, except bryophytes, are vascular plants.

vascular tissue The tissue that conducts water and nutrients from the roots to the leaves in vascular plants. It consists of two types of tissue: xylem and phloem. Vascular tissue also provides structural support to a plant.

vasoconstriction The narrowing of the internal diameter of a blood vessel.

vasodilation The widening of the internal diameter of a blood vessel.

vegetative reproduction A form of asexual reproduction found in plants, in which a piece of a plant (usually a growing tip of a stem) is separated from the plant and grows into a new plant. It is a method used widely in horticulture to produce new plants.

vein A blood vessel that carries blood towards the heart. All veins except the pulmonary veins carry deoxygenated blood.

ventilation Active movement of air or water past gas exchange surfaces in animals. In land animals it is called breathing.

ventricle A muscular chamber of the heart that pumps blood from the heart to the rest of the body. In a four-chambered heart (as in humans) the right ventricle pumps deoxygenated blood to the lungs, and the left ventricle pumps oxygenated blood to other body tissues.

venule A small vessel that connects capillaries to a vein.

vertebrate An animal belonging to the phylum Vertebrata. Vertebrates have a brain enclosed in a skull, and a segmented spinal column consisting of vertebrae. They include fish, amphibians, reptiles, birds and mammals.

vesicle A small organelle consisting of a membrane filled with fluid. Vesicles are often involved in transport within the cell, but may have other functions.

villus (pl. villi) A tiny fold in the lining of the intestine. Villi increase the surface area available for the absorption of food.

virion A complete mature virus particle that is metabolically inert and is in the transmission (infectious) phase.

vital capacity The maximum volume of air that can be moved into and out of the lungs in one breath.

vitamin Any organic compound required in small amounts for cell processes. In humans there are 13 such compounds, called vitamins A, B group (eight vitamins), C, D, E and K.

viviparous Having offspring that develop inside the mother and are released as live young. Viviparity occurs in most mammals, and in plants in which the seeds germinate while still attached to the parent plant (e.g. in some mangroves).

WXYZ

weed A plant that is growing where it has the potential to cause environmental or economic harm.

wild type The phenotype most commonly observed in a natural population.

X-linked Resulting from the inheritance of a gene on the X chromosome. An X-linked trait may be inherited from either parent, because both have an X chromosome.

xerophyte A plant adapted to dry conditions.

xylem The tissue in vascular plants that transports water and nutrients upwards from the roots. It consists of hollow chains of dead cells.

xylem vessel A long tube consisting of cells joined end to end, through which water and nutrients are transported from the roots to the leaves in a vascular plant.

Y-linked Resulting from the inheritance of a gene on the Y chromosome. A Y-linked trait is passed from father to son. It is never observed in females because they do not have a Y chromosome.

zygote The diploid cell resulting from the fusion of an egg and sperm. It is the first stage of the development of a unique new organism.

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