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Biology

Third Edition

D G Mackean
Dave Hayward

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Cambridge IGCSE® Biology Third Edition aims to provide an up-to-date and comprehensive coverage of the Core and Extended curriculum in Biology, specified in the current Cambridge International Examinations IGCSE® syllabus.

This third edition has been completely restructured to align the chapters in the book with the syllabus. Each chapter starts with the syllabus statements to be covered in that chapter, and ends with a checklist, summarising the important points covered. The questions included at the end of each chapter are intended to test your understanding of the text you have just read. If you cannot answer the question straightaway, read that section of text again with the question in mind. There are past paper examination questions at the end of the book.

To help draw attention to the more important words, scientific terms are printed in bold the first time they are used. As you read through the book, you will notice three sorts of shaded area in the text.

Material highlighted in green is for the Cambridge IGCSE Extended curriculum.

Areas highlighted in yellow contain material that is not part of the Cambridge IGCSE syllabus. It is extension work and will not be examined.

Questions are highlighted by a box like this.

The accompanying Revision CD-ROM provides invaluable exam preparation and practice. We want to test your knowledge with interactive multiple choice questions that cover both the Core and Extended curriculum. These are organised by chapter.

Together, the textbook and CD-ROM will provide you with the information you need for the Cambridge IGCSE syllabus. I hope you enjoy using them.

I am indebted to Don Mackean for a substantial amount of the content of this textbook. Since 1962, he has been responsible for writing excellent Biology books to support the education of countless students, as well as providing an extremely useful source of information and inspiration for your teachers and their teachers. Don's diagrams, many of which are reproduced in this book, are legendary.

Dave Hayward

1 Characteristics and classification of living organisms

Characteristics of living organisms
Listing and describing the characteristics of living organisms

Concept and use of a classification system
How organisms are classified, using common features
Defining species
Using the binomial system of naming species

Features of organisms
Identifying the main features of cells

The five-kingdom classification scheme
The basic features of plants and animals
The main features of groups in the animal kingdom

The main features of groups in the plant kingdom
The main features of viruses

Dichotomous keys
Use of keys based on easily identifiable features
Construction of dichotomous keys

Characteristics of living organisms

Key definitions

Movement is an action by an organism causing a change of position or place (see Chapter 14).
Respiration describes the chemical reactions in cells that break down nutrient molecules and release energy (see Chapter 12).
Sensitivity is the ability to detect and respond to changes in the environment (see Chapter 14).
Growth is a permanent increase in size (see Chapter 16).
Reproduction is the processes that make more of the same kind of organism (see Chapter 16). Single-celled organisms and bacteria may simply keep dividing into two. Multicellular plants and animals may reproduce sexually or asexually.
Excretion is the removal from organisms of toxic materials and substances in excess of requirements (see Chapter 13).
Nutrition is the taking in of materials for energy, growth and development (see Chapters 6 and 7).

All living organisms, whether they are single-celled or multicellular, plants or animals, show the characteristics included in the definitions above: movement, respiration, sensitivity, growth, reproduction, excretion and nutrition.

One way of remembering this list of the characteristics of living things is by using the mnemonic **MRS GREN**. The letters stand for the first letters of the characteristics.

Mnemonics work by helping to make the material you are learning more meaningful. They give a structure which is easier to recall later. This structure may be a word, or a name (such as MRS GREN) or a phrase. For example, 'Richard of York gave battle in vain' is a popular way of remembering the colours of the rainbow in the correct sequence.

Key definitions

If you are studying the extended syllabus you need to learn more detailed definitions of some of the characteristics of living things.

Movement is an action by an organism or part of an organism causing a change of position or place.
Most single-celled creatures and animals move about as a whole. Fungi and plants may make movements with parts of their bodies (see Chapter 14).
Respiration describes the chemical reactions in cells that break down nutrient molecules and release energy for metabolism. Most organisms need oxygen for this (see Chapter 12).
Sensitivity is the ability to detect or sense stimuli in the internal or external environment and to make appropriate responses (see Chapter 14).
Growth is a permanent increase in size and dry mass by an increase in cell number or cell size or both (see Chapter 16). Even bacteria and single-celled creatures show an increase in size. Multicellular organisms increase the numbers of cells in their bodies, become more complicated and change their shape as well as increasing in size (see 'Sexual reproduction in humans' in Chapter 16).
Excretion is the removal from organisms of the waste products of metabolism (chemical reactions in cells including respiration), toxic materials and substances in excess of requirements (see Chapter 13).
Respiration and other chemical changes in the cells produce waste products such as carbon dioxide. Living organisms expel these substances from their bodies in various ways (see Chapter 13).
Nutrition is the taking in of materials for energy, growth and development. Plants require light, carbon dioxide, water and ions. Animals need organic compounds and ions and usually need water (see Chapters 6 and 7).
Organisms can take in the materials they need as solid food, as animals do, or they can digest them first and then absorb them, like fungi do, or they can build them up for themselves, like plants do. Animals, using ready-made organic molecules as their food source, are called heterotrophs and form the consumer levels of food chains. Photosynthetic plants are called autotrophs and are usually the first organisms in food chains (see Chapters 6 and 19).

Concept and use of a classification system

Key definitions

A **species** is a group of organisms that can reproduce to produce fertile offspring.

The **binomial system** is an internationally agreed system in which the scientific name of an organism is made up of two parts showing the genus and the species.

You do not need to be a biologist to realise that there are millions of different organisms living on the Earth, but it takes a biologist to sort them into a meaningful order, i.e. to **classify** them.

There are many possible ways of classifying organisms. You could group all aquatic organisms together or put all black and white creatures into the same group. However, these do not make very meaningful groups; a seaweed and a porpoise are both aquatic organisms, a magpie and a zebra are both black and white; but neither of these pairs has much in common apart from being living organisms and the latter two being animals. These would be **artificial systems** of classification.

A biologist looks for a **natural system** of classification using important features which are shared by as large a group as possible. In some cases it is easy. Birds all have wings, beaks and feathers; there is rarely any doubt about whether a creature is a bird or not. In other cases it is not so easy. As a result, biologists change their ideas from time to time about how living things should be grouped. New groupings are suggested and old ones abandoned.

Species

The smallest natural group of organisms is the **species**. A species can be defined as a group of organisms that can reproduce to produce fertile offspring.

Members of a species also often resemble each other very closely in appearance, unless humans have taken a hand in the breeding programmes. All cats belong to the same species but there are wide variations in the appearance of different breeds (see 'Variation' in Chapter 18). An American Longhair and a Siamese may look very different but they have few problems in breeding together. Robins, blackbirds and sparrows are three different species of bird. Apart from small variations, members of a species are almost identical in their anatomy, physiology and behaviour.

Closely related species are grouped into a **genus** (plural: **genera**). For example, stoats, weasels and polecats are grouped into the genus *Mustela*.

Binomial nomenclature

Species must be named in such a way that the name is recognised all over the world.

'Cuckoo flower' and 'Lady's smock' are two common names for the same wild plant. If you are not aware that these are alternative names this could lead to confusion. If the botanical name, *Cardamine pratensis*, is used, however, there is no chance of error. The Latin form of the name allows it to be used in all the countries of the world irrespective of language barriers.

People living in Britain are familiar with the appearance of a blackbird – a very common garden visitor. The male has jet black plumage, while the female is brown. Its scientific name is *Turdus merula* and the adult is about 24 cm long (see Figure 1.1). However, someone living in North America would describe a blackbird very differently. For example, the male of one species, *Agelaius phoeniceus*, has black plumage with red shoulder patches and yellow flashes, while the female is speckled brown. It is about the size of a sparrow – only about 20 cm long (see Figure 1.2). A British scientist could get very confused talking to an American scientist about a blackbird! Again, the use of the scientific name avoids any confusion.

The **binomial system** of naming species is an internationally agreed system in which the scientific name of an organism is made up of two parts showing the genus and the species. Binomial means 'two names'; the first name gives the genus and the second gives the species. For example, the stoat and weasel are both in the genus *Mustela* but they are different species; the stoat is *Mustela erminea* and the weasel is *Mustela nivalis*.

The name of the genus (the generic name) is always given a capital letter and the name of the species (the specific name) always starts with a small letter.

Frequently, the specific name is descriptive, for example *edulis* means 'edible', *aquatilis* means 'living in water', *bulbosus* means 'having a bulb', *serratus* means 'having a jagged (serrated) edge'.

Figure 1.1 *Turdus merula* ♂

Figure 1.2 *Agelaius phoeniceus* ♂

If you are studying the extended syllabus you need to be able to explain why it is important to classify organisms. By classifying organisms it is possible to identify those most at risk of extinction. Strategies can then be put in place to conserve the threatened species. Apart from the fact that we have no right to wipe out species forever, the chances are that we will deprive ourselves not only of the beauty and diversity of species, but also of potential sources of valuable products such as drugs. Many of our present-day drugs are derived from plants (e.g. quinine and aspirin) and there may be many more sources as yet undiscovered. We are also likely to deprive the world of genetic resources (see 'Conservation' in Chapter 21).

By classifying organisms it is also possible to understand evolutionary relationships. Vertebrates all have the presence of a vertebral column, along with a skull protecting a brain, and a pair of jaws (usually with teeth). By studying the anatomy of different groups of vertebrates it is possible to gain an insight into their evolution.

The skeletons of the front limb of five types of vertebrate are shown in Figure 1.3. Although the limbs have different functions, such as grasping, flying, running and swimming, the arrangement and number of the bones is almost the same in all five. There is a single top bone (the humerus), with a ball and socket joint at one end and a hinge joint at the other. It makes a joint with two other bones (the radius and ulna) which join to a group of small wrist bones. The limb skeleton ends with five groups of bones (the hand and fingers), although some of these groups are missing in the bird.

The argument for evolution says that, if these animals are not related, it seems very odd that such a similar limb skeleton should be used to do such different things as flying, running and swimming. If, on the other hand, all the animals came from the same ancestor, the ancestral skeleton could have changed by small stages in different ways in each group. So we would expect to find that the basic pattern of bones was the same in all these animals. There are many other examples of this kind of evidence among the vertebrate animals.

Classification is traditionally based on studies of **morphology** (the study of the form, or outward appearance, of organisms) and **anatomy** (the study of their internal structure, as revealed by dissection). Aristotle was the first known person to attempt to devise a system of classification based on morphology and anatomy. He placed organisms in a hierarchy according to the complexity of their structure and function. Indeed, some of his ideas still existed just 200 years ago. He separated animals into two groups: those with blood and those without, placing invertebrates into the second group and vertebrates into the first. However, he was

not aware that some invertebrates do have a form of haemoglobin. Using blood as a common feature would put earthworms and humans in the same group! Earthworm blood is red: it contains haemoglobin, although it is not contained in red blood cells.

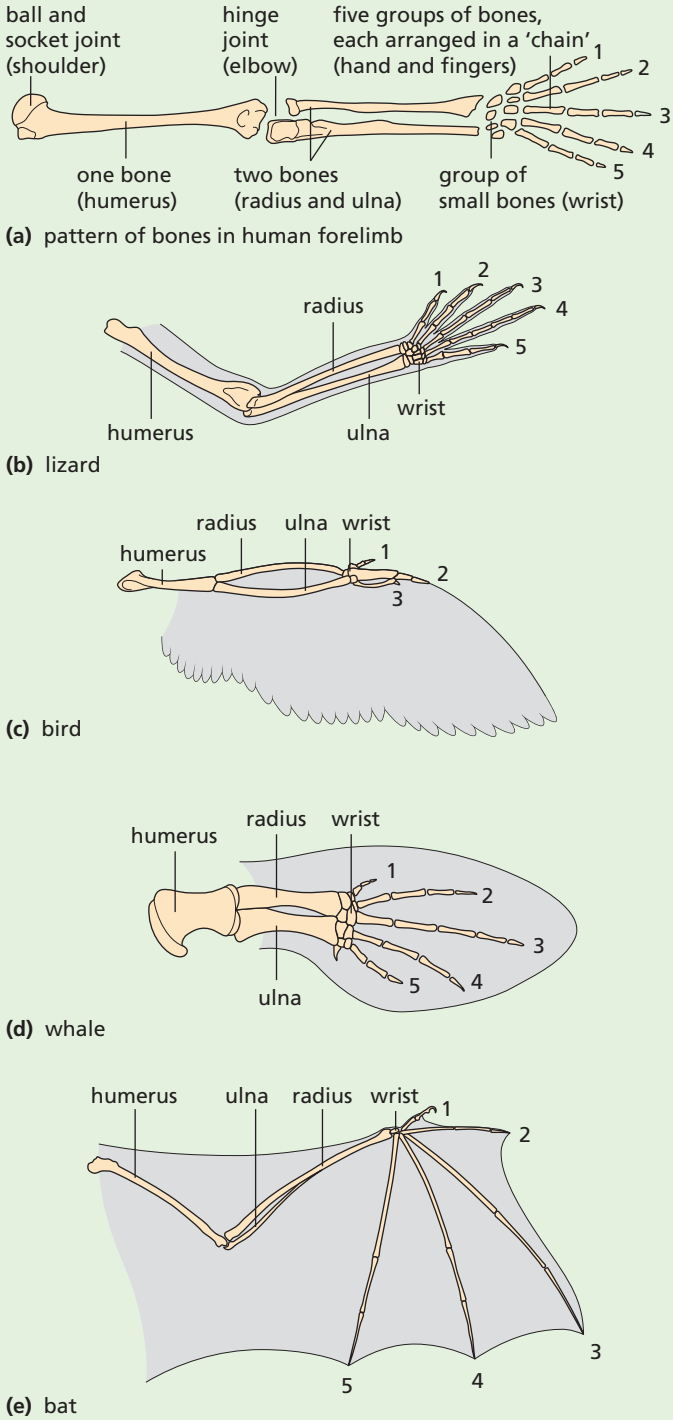


Figure 1.3 Skeletons of five vertebrate limbs

Plants have been classified according to their morphology, but appearances can be deceptive. The London Plane tree and the British Sycamore were considered to be closely related because of the similarity in their leaf shape, as shown in Figure 1.4.

Figure 1.4 Leaves of the British Sycamore (left) and London Plane (right)

However, a closer study of the two species exposes major differences: leaf insertion (how they are arranged on a branch) in London Plane is alternate, while it is opposite in the Sycamore. Also, their fruits are very different, as shown in Figure 1.5.

Figure 1.5 Fruits of the British Sycamore (left) and London Plane (right)

The scientific name of the London Plane is *Platanus acerifolia* (meaning 'leaves like an Acer'); that of the British Sycamore is *Acer pseudoplatanus* ('pseudo' means 'false'). They do not even belong in the same genus.

The use of **DNA** has revolutionised the process of classification. Eukaryotic organisms contain chromosomes made up of strings of genes. The chemical which forms these genes is called DNA

(which is short for deoxyribonucleic acid). The DNA is made up of a sequence of bases, coding for amino acids and, therefore, proteins (see Chapters 4 and 17). Each species has a distinct number of chromosomes and a unique sequence of bases in its DNA, making it identifiable and distinguishable from other species. This helps particularly when different species are very similar morphologically (in appearance) and anatomically (in internal structure).

The process of biological classification called **cladistics** involves organisms being grouped together according to whether or not they have one or more shared unique characteristics derived from the group's last common ancestor, which are not present in more distant ancestors. Organisms which share a more recent ancestor (and are, therefore, more closely related) have DNA base sequences that are more similar than those that share only a distant ancestor.

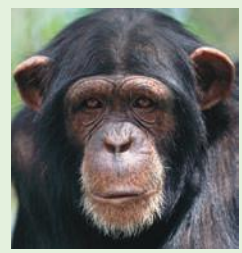
Human and primate evolution is a good example of how DNA has been used to clarify a process of evolution. Traditional classification of primates (into monkeys, apes and humans) was based on their anatomy, particularly their bones and teeth. This put humans on a separate branch, while grouping the other apes together into one family called Pongidae.

However, genetic evidence using DNA provides a different insight – humans are more closely related to chimpanzees (1.2% difference in the genome – the complete set of genetic material of the organism) and gorillas (1.6% different) than to orang-utans (3.1% different). Also, chimpanzees are closer to humans than to gorillas (see Figure 1.6).

Bonobos and chimps are found in Zaire and were only identified as different species in 1929. The two species share the same percentage difference in the genome from humans.

Orang-utan
48 chromosomes

Gorilla
48 chromosomes



Chimpanzee
48 chromosomes

Bonobo
48 chromosomes

Human
46 chromosomes

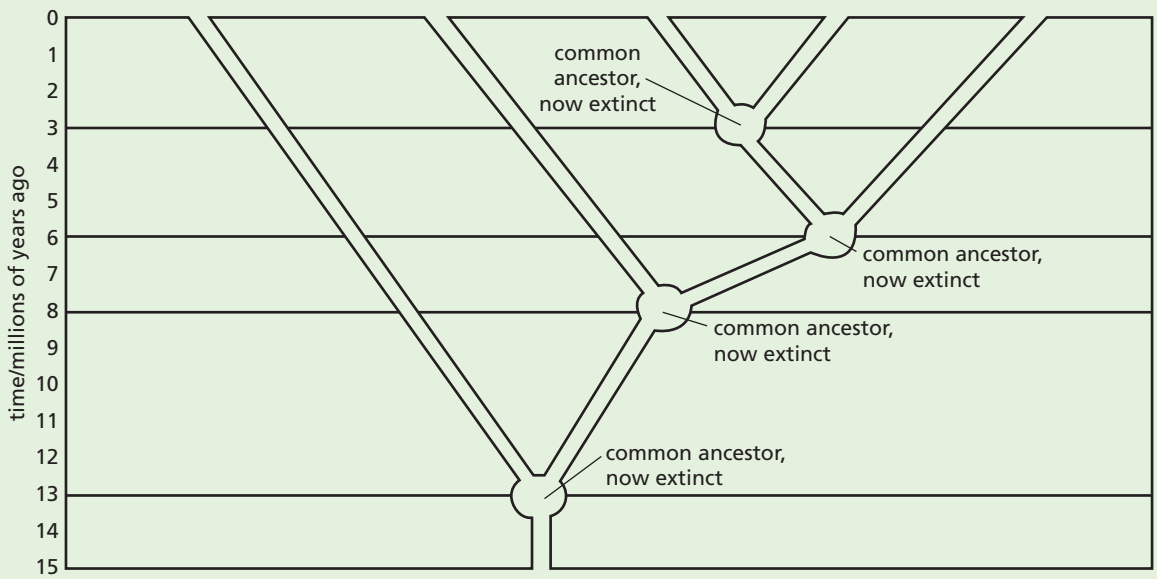


Figure 1.6 Classification of primates, based on DNA evidence

Features of organisms

All living organisms have certain features in common, including the presence of cytoplasm and cell membranes, and DNA as genetic material.

All living organisms also contain **ribosomes** in the cytoplasm, floating freely or attached to membranes called **rough endoplasmic reticulum** (ER). Ribosomes are responsible for protein synthesis.

The Whittaker five-kingdom scheme

The largest group of organisms recognised by biologists is the kingdom. But how many kingdoms should there be? Most biologists used to favour the adoption of two kingdoms, namely **Plants** and **Animals**. This, however, caused problems in trying to classify fungi, bacteria and single-celled organisms which do not fit obviously into either kingdom. A scheme now favoured by many biologists is the Whittaker five-kingdom scheme consisting of **Animal**, **Plant**, **Fungus**, **Prokaryote** and **Protoctist**.

It is still not easy to fit all organisms into the five-kingdom scheme. For example, many protoctista with chlorophyll (the protophyta) show important resemblances to some members of the algae, but the algae are classified into the plant kingdom.

Viruses are not included in any kingdom – they are not considered to be living organisms because they lack cell membranes (made of protein and lipid), cytoplasm and ribosomes and do not demonstrate the characteristics of living things: they do not feed, respire, excrete or grow. Although viruses do reproduce, this only happens inside the cells of living organisms, using materials provided by the host cell.

This kind of problem will always occur when we try to devise rigid classification schemes with distinct boundaries between groups. The process of evolution would hardly be expected to result in a tidy scheme of classification for biologists to use.

Extension work

As scientists learn more about organisms, classification schemes change. Genetic sequencing has provided scientists with a different way of studying relationships between organisms. The **three-domain scheme** was introduced by Carl Woese in 1978 and involves grouping organisms using differences in ribosomal RNA structure. Under this scheme, organisms are classified into three domains and six kingdoms, rather than five. The sixth kingdom is created by splitting the Prokaryote kingdom into two. The domains are:

1. **Archaea**: containing ancient prokaryotic organisms which do not have a nucleus surrounded by a membrane. They have an independent evolutionary history to other bacteria and their biochemistry is very different to other forms of life.
2. **Eubacteria**: prokaryotic organisms which do not have a nucleus surrounded by a membrane.
3. **Eukarya**: organisms that have a membrane-bound nucleus. This domain is further subdivided into the kingdoms Protoctist, Fungus, Plant and Animal.

A summary of the classification schemes proposed by scientists is shown in Figure 1.7.

A two-kingdom scheme: Linnaeus

Animal	Plant

A five-kingdom scheme: Whittaker

Animal	Plant	Fungus	Prokaryote	Protoctist

A six-kingdom system: Woese

Animal	Plant	Fungus	Eubacteria	Archaebacteria	Protoctist

A three-domain system: Woese

Eubacteria	Archaea	Eukarya

Figure 1.7 A summary of the classification schemes proposed by scientists

An outline classification of plants and animals follows and is illustrated in Figures 1.8–1.11.

The plant kingdom

These are made up of many cells – they are multicellular. Plant cells have an outside wall made of cellulose. Many of the cells in plant leaves and stems contain chloroplasts with photosynthetic pigments, e.g. chlorophyll. Plants make their food by photosynthesis.

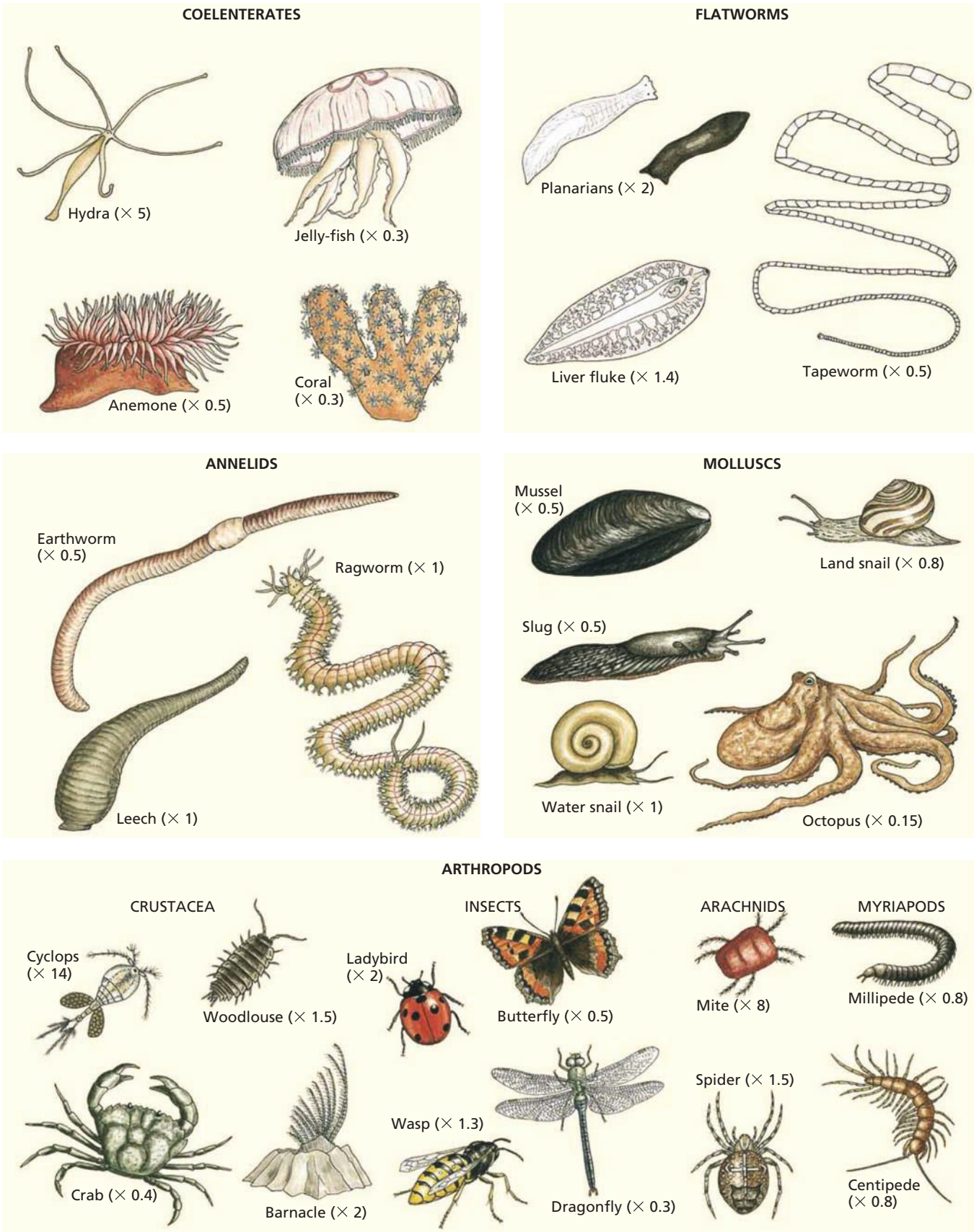


Figure 1.8 The animal kingdom; examples of five invertebrate groups (phyla)

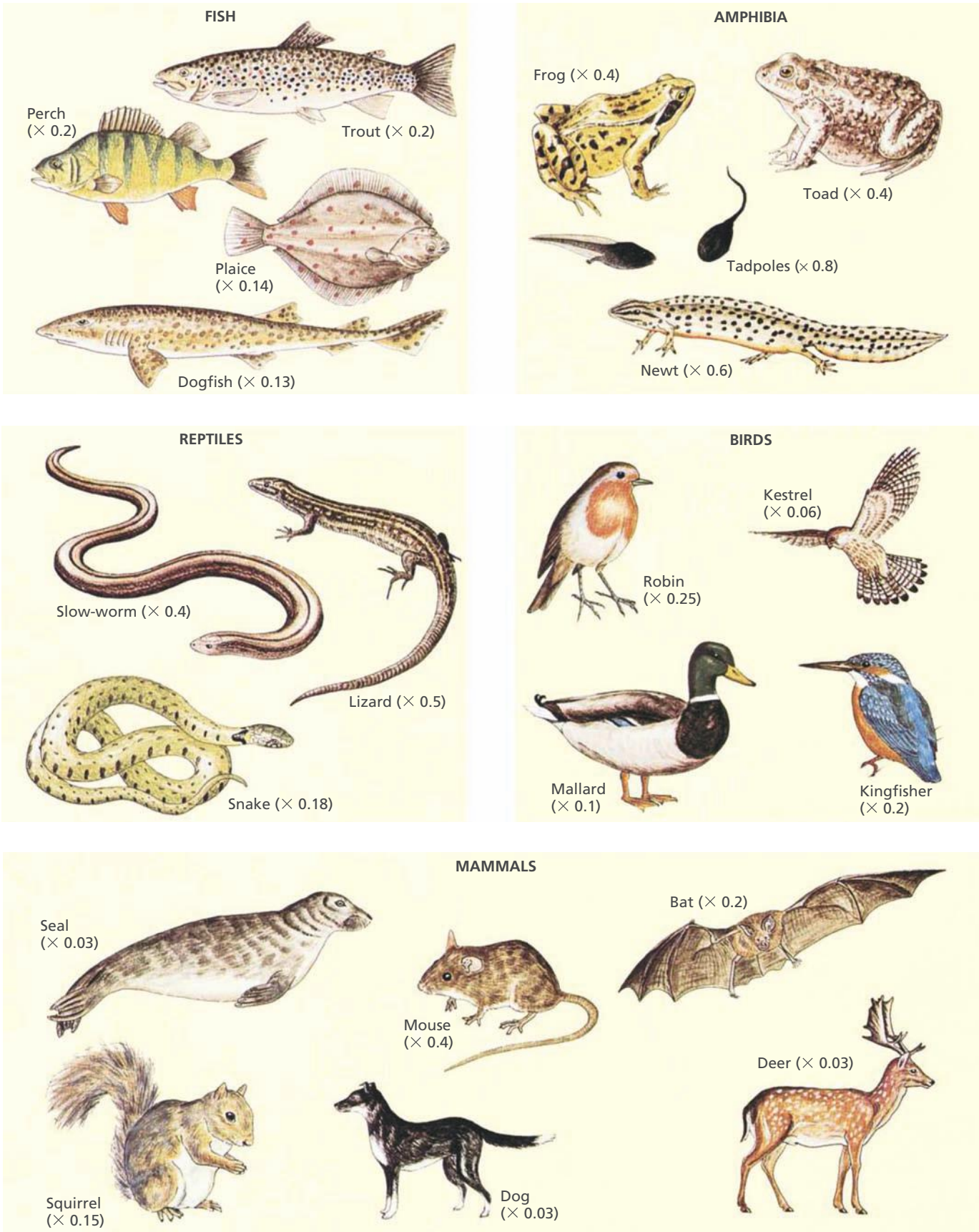


Figure 1.9 The animal kingdom; the vertebrate classes

Figure 1.10 The plant kingdom; plants that do not bear seeds

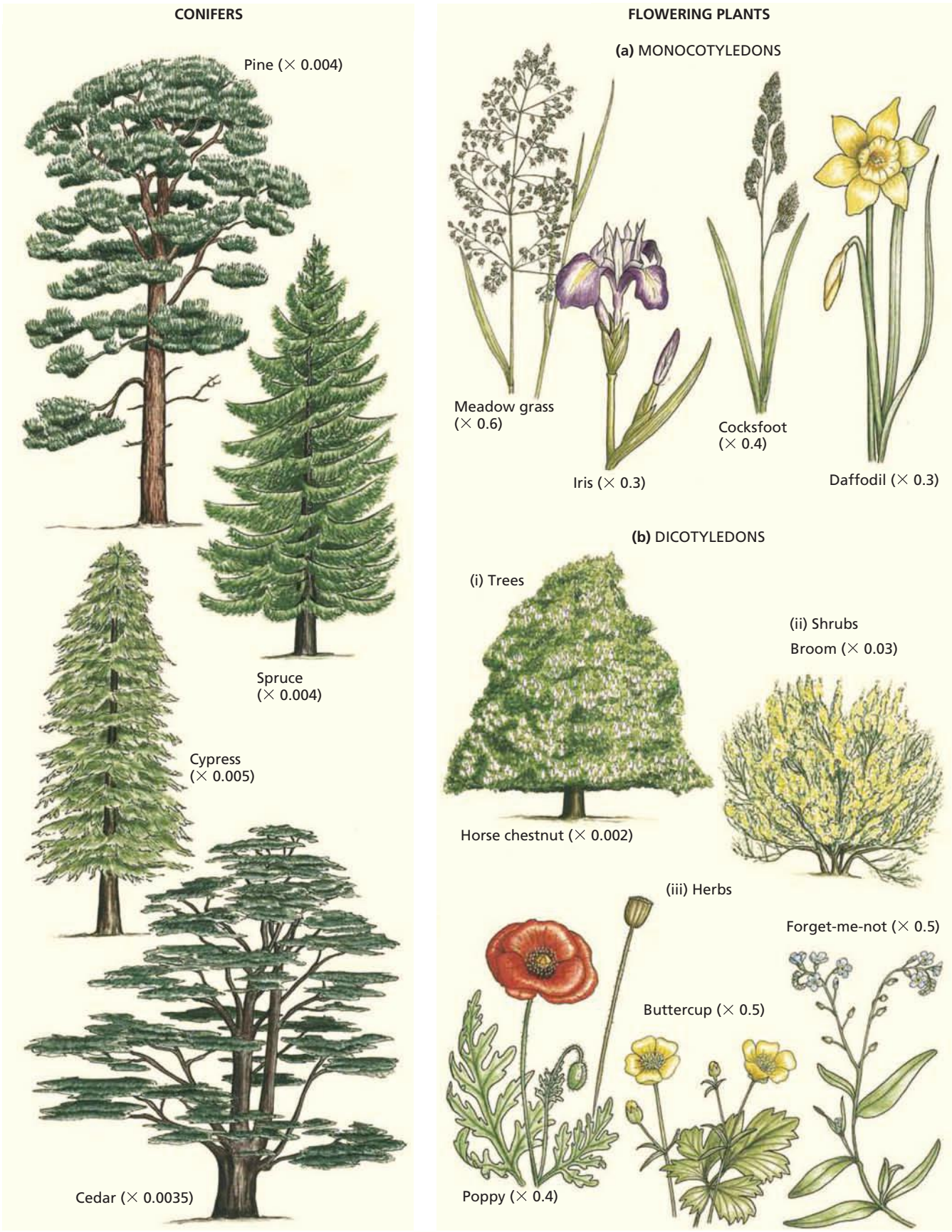


Figure 1.11 The plant kingdom; seed-bearing plants

The animal kingdom

Animals are multicellular organisms whose cells have no cell walls or chloroplasts. Most animals ingest solid food and digest it internally.

Animal kingdom

(Only eight groups out of 23 are listed here.) Each group is called a phylum (plural = phyla).

- **Coelenterates** (sea anemones, jellyfish)
- **Flatworms**
- **Nematode worms**
- **Annelids** (segmented worms)
- **Arthropods***
  - CLASS
  - Crustacea (crabs, shrimps, water fleas)
  - Insects
  - Arachnids (spiders and mites)
  - Myriapods (centipedes and millipedes)
- **Molluscs** (snails, slugs, mussels, octopuses)
- **Echinoderms** (starfish, sea urchins)

- **Vertebrates**
  - CLASS
  - Fish
  - Amphibia (frogs, toads, newts)
  - Reptiles (lizards, snakes, turtles)
  - Birds
  - Mammals
  - (Only four subgroups out of about 26 are listed.)
    - Insectivores
    - Carnivores
    - Rodents
    - Primates

*All the organisms which do not have a vertebral column are often referred to as invertebrates. Invertebrates are not a natural group, but the term is convenient to use.

Arthropods

The arthropods include the crustacea, insects, centipedes and spiders (see Figure 1.8 on page 7). The name arthropod means 'jointed limbs', and this is a feature common to them all. They also have a hard, firm external skeleton, called a **cuticle**, which encloses their bodies. Their bodies are segmented and, between the segments, there are flexible joints which permit movement. In most arthropods, the segments are grouped together to form distinct regions, the head, thorax and abdomen. Table 1.1 outlines the key features of the four classes of arthropod.

Crustacea

Marine crustacea are crabs, prawns, lobsters, shrimps and barnacles. Freshwater crustacea are water fleas, *Cyclops*, the freshwater shrimp (*Gammarus*) and the water louse (*Asellus*). Woodlice are land-dwelling crustacea. Some of these crustacea are illustrated in Figure 1.8 on page 7.

Like all arthropods, crustacea have an exoskeleton and jointed legs. They also have two pairs of antennae which are sensitive to touch and to chemicals, and they have **compound eyes**. Compound eyes are made up of tens or hundreds of separate lenses with light-sensitive cells beneath. They are able to form a crude image and are very sensitive to movement.

Typically, crustacea have a pair of jointed limbs on each segment of the body, but those on the head segments are modified to form antennae or specialised mouth parts for feeding (see Figure 1.12).

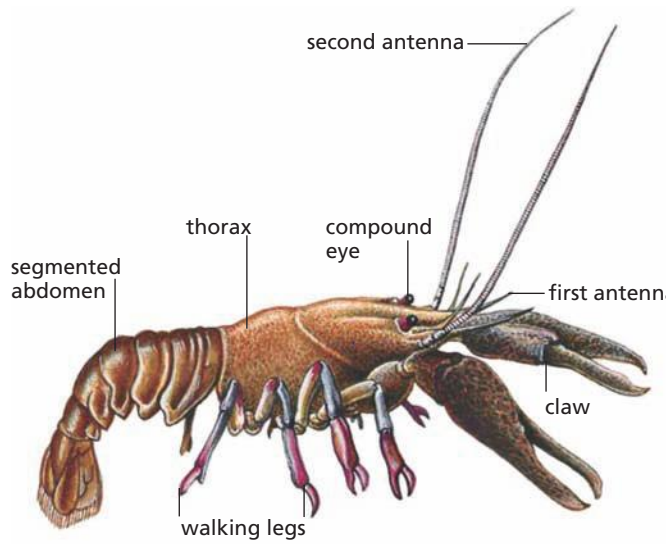


Figure 1.12 External features of a crustacean (lobster ×0.2)

Insects

The insects form a very large class of arthropods. Bees, butterflies, mosquitoes, houseflies, earwigs, greenfly and beetles are just a few of the subgroups in this class.

Insects have segmented bodies with a firm exoskeleton, three pairs of jointed legs, compound eyes and, typically, two pairs of wings. The segments are grouped into distinct head, thorax and abdomen regions (see Figure 1.13).

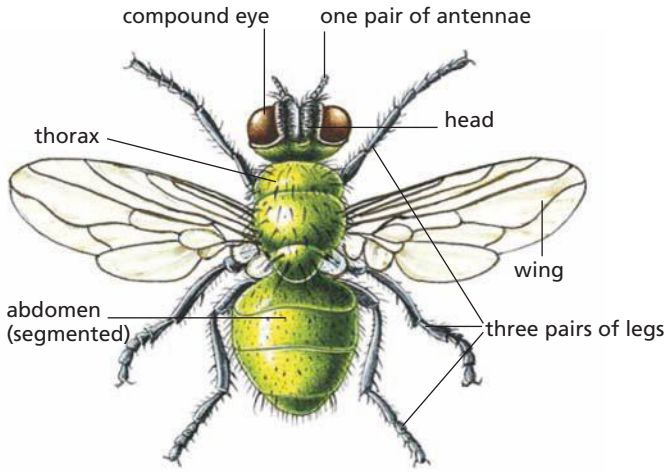


Figure 1.13 External features of an insect (greenbottle, ×5). Flies, midges and mosquitoes have only one pair of wings.

Insects differ from crustacea in having wings, only one pair of antennae and only three pairs of legs. There are no limbs on the abdominal segments.

The insects have very successfully colonised the land. One reason for their success is the relative impermeability of their cuticles, which prevents desiccation even in very hot, dry climates.

Arachnids

These are the spiders, scorpions, mites and ticks. Their bodies are divided into two regions, the cephalothorax and the abdomen (see Figure 1.14). They have four pairs of limbs on the cephalothorax, two pedipalps and two chelicerae. The pedipalps are used in reproduction; the chelicerae are used to pierce their prey and paralyse it with a poison secreted by a gland at the base. There are usually several pairs of simple eyes.

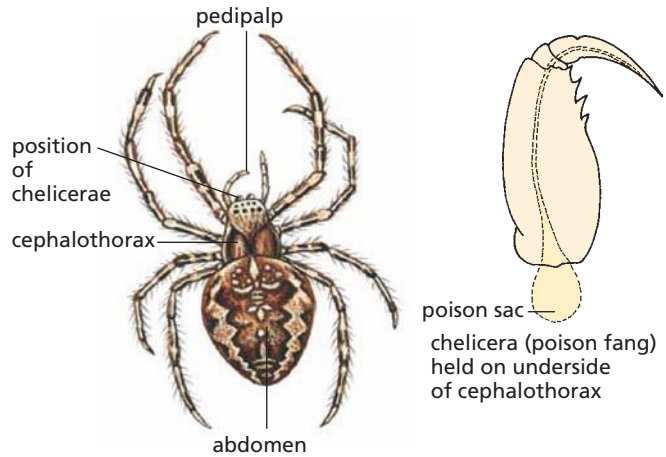


Figure 1.14 External features of an arachnid (×2.5)

Myriapods

These are millipedes and centipedes. They have a head and a segmented body which is not obviously divided into thorax and abdomen. There is a pair of legs on each body segment but in the millipede the abdominal segments are fused in pairs and it looks as if it has two pairs of legs per segment (see Figure 1.15).

As the myriapod grows, additional segments are formed. The myriapods have one pair of antennae and simple eyes. Centipedes are carnivorous; millipedes feed on vegetable matter.

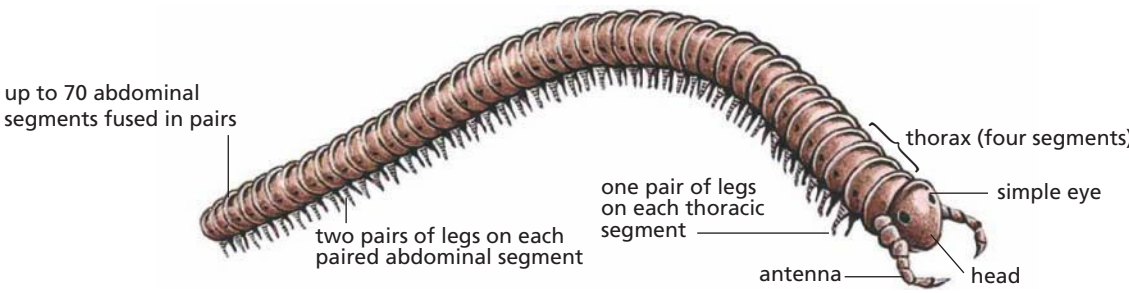


Figure 1.15 External features of a myriapod (×2.5)

Table 1.1 Key features of the four classes of arthropods

Insects	Arachnids	Crustacea	Myriapods
e.g. dragonfly, wasp	e.g. spider, mite	e.g. crab, woodlouse	e.g. centipede, millipede
• three pairs of legs	• four pairs of legs	• five or more pairs of legs	• ten or more pairs of legs (usually one pair per segment)
• body divided into head, thorax and abdomen	• body divided into cephalothorax and abdomen	• body divided into cephalothorax and abdomen	• body not obviously divided into thorax and abdomen
• one pair of antennae		• two pairs of antennae	• one pair of antennae
• one pair of compound eyes	• several pairs of simple eyes	• one pair of compound eyes	• simple eyes
• usually have two pairs of wings	• chelicerae for biting and poisoning prey	• exoskeleton often calcified to form a carapace (hard)	

Vertebrates

Vertebrates are animals which have a vertebral column. The vertebral column is sometimes called the spinal column or just the spine and consists of a chain of cylindrical bones (vertebrae) joined end to end.

Each vertebra carries an arch of bone on its dorsal (upper) surface. This arch protects the spinal cord (see Chapter 14), which runs most of the length of the vertebral column. The front end of the spinal cord is expanded to form a brain which is enclosed and protected by the skull.

The skull carries a pair of jaws which, in most vertebrates, have rows of teeth.

The five classes of vertebrates are fish, amphibia, reptiles, birds and mammals. Table 1.2 summarises the key features of these classes.

Body temperature

Fish, amphibia and reptiles are often referred to as 'cold-blooded'. This is a misleading term. A fish in a tropical lagoon or a lizard basking in the sun will have warm blood. The point is that these animals have a variable body temperature which, to some extent, depends on the temperature of their surroundings. Reptiles, for example, may control their temperature by moving into sunlight or retreating into shade but there is no internal regulatory mechanism.

So-called 'warm-blooded' animals, for the most part, have a body temperature higher than that of their surroundings. The main difference, however, is that these temperatures are kept more or less constant despite any variation in external temperature. There are internal regulatory mechanisms (see Chapter 14) which keep the body temperature within narrow limits.

It is better to use the terms **poikilothermic** (variable temperature) and **homoiothermic** (constant temperature). However, to simplify the terms, 'cold blooded' and 'warm blooded' will be referred to in this section.

The advantage of homoiothermy is that an animal's activity is not dependent on the surrounding temperature. A lizard may become sluggish if the surrounding temperature falls. This could be a disadvantage if the lizard is being pursued by a homoiothermic predator whose speed and reactions are not affected by low temperatures.

Fish

Fish are poikilothermic (cold blooded) vertebrates. Many of them have a smooth, streamlined shape which offers minimal resistance to the water through which they move (see Figure 1.16). Their bodies are covered with overlapping scales and they have fins which play a part in movement.

Fish breathe by means of filamentous gills which are protected by a bony plate, the operculum.

Fish reproduce sexually but fertilisation usually takes place externally; the female lays eggs and the male sheds sperms on them after they have been laid.

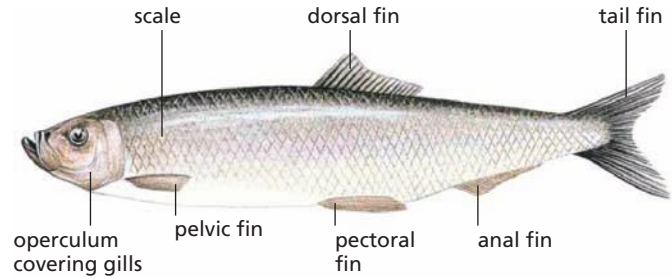


Figure 1.16 Herring (*Clupea*, ×0.3)

Amphibia

Amphibia are poikilothermic (cold blooded) vertebrates with four limbs and no scales. The class includes frogs, toads and newts. The name, amphibian, means 'double life' and refers to the fact that the organism spends part of its life in water and part on the land. In fact, most frogs, toads and newts spend much of their time on the land, in moist situations, and return to ponds or other water only to lay eggs.

The external features of the common frog are shown in Figure 1.17. Figure 1.9 on page 8 shows the toad and the newt.

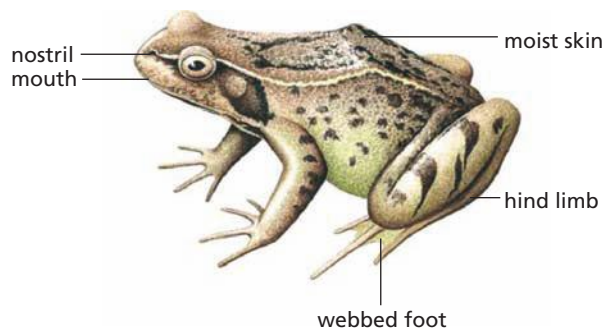


Figure 1.17 *Rana* (×0.75)

The toad's skin is drier than that of the frog and it has glands which can exude an unpleasant-tasting chemical which discourages predators. Newts differ

from frogs and toads in having a tail. All three groups are carnivorous.

Amphibia have four limbs. In frogs and toads, the hind feet have a web of skin between the toes. This offers a large surface area to thrust against the water when the animal is swimming. Newts swim by a wriggling, fish-like movement of their bodies and make less use of their limbs for swimming.

Amphibia have moist skins with a good supply of capillaries which can exchange oxygen and carbon dioxide with the air or water. They also have lungs which can be inflated by a kind of swallowing action. They do not have a diaphragm or ribs.

Frogs and toads migrate to ponds where the males and females pair up. The male climbs on the female's back and grips firmly with his front legs (see Figure 1.18). When the female lays eggs, the male simultaneously releases sperms over them. Fertilisation, therefore, is external even though the frogs are in close contact for the event.

Figure 1.18 Frogs pairing. The male clings to the female's back and releases his sperm as she lays the eggs.

Reptiles

Reptiles are land-living vertebrates. Their skins are dry and the outer layer of epidermis forms a pattern of scales. This dry, scaly skin resists water loss. Also the eggs of most species have a tough, parchment-like shell. Reptiles, therefore, are not restricted to damp habitats, nor do they need water in which to breed.

Reptiles are poikilothermic (cold blooded) but they can regulate their temperature to some extent. They do this by basking in the sun until their bodies warm up. When reptiles warm up, they can move about rapidly in pursuit of insects and other prey.

The reptiles include lizards, snakes, turtles, tortoises and crocodiles (see Figure 1.19 and Figure 1.9 on page 8).

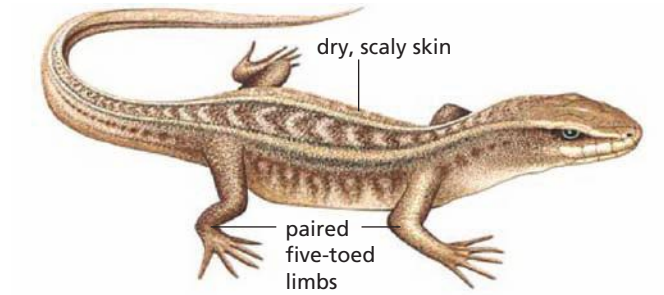


Figure 1.19 *Lacerta* (×1.5)

Apart from the snakes, reptiles have four limbs, each with five toes. Some species of snake still retain the vestiges of limbs and girdles.

Male and female reptiles mate, and sperms are passed into the female's body. The eggs are, therefore, fertilised internally before being laid. In some species, the female retains the eggs in the body until they are ready to hatch.

Birds

Birds are homoiothermic (warm blooded) vertebrates.

The vertebral column in the neck is flexible but the rest of the vertebrae are fused to form a rigid structure. This is probably an adaptation to flight, as the powerful wing muscles need a rigid frame to work against.

The epidermis over most of the body produces a covering of feathers but, on the legs and toes, the epidermis forms scales. The feathers are of several kinds. The fluffy down feathers form an insulating layer close to the skin; the contour feathers cover the body and give the bird its shape and colouration; the large quill feathers on the wing are essential for flight.

Birds have four limbs, but the forelimbs are modified to form wings. The feet have four toes with claws which help the bird to perch, scratch for seeds or capture prey, according to the species.

The upper and lower jaws are extended to form a beak which is used for feeding in various ways.

Figure 1.20 shows the main features of a bird.

In birds, fertilisation is internal and the female lays hard-shelled eggs in a nest where she incubates them.

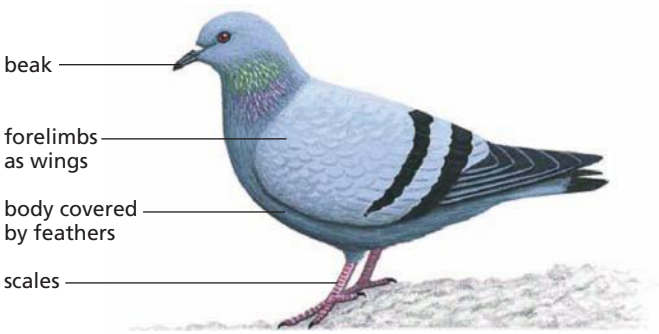


Figure 1.20 The main features of a pigeon (×0.14)

Mammals

Mammals are homoiothermic (warm blooded) vertebrates with four limbs. They differ from birds in having hair rather than feathers. Unlike the other vertebrates they have a diaphragm which plays a part in breathing (see Chapter 11). They also have mammary glands and suckle their young on milk.

A sample of mammals is shown in Figure 1.9 on page 8 and Figure 1.21 illustrates some of the mammalian features.

Humans are mammals. All mammals give birth to fully formed young instead of laying eggs. The eggs are fertilised internally and undergo a period of development in the uterus (see 'Sexual reproduction in humans' in Chapter 16).

Figure 1.21 Mammalian features. The furry coat, the external ear pinnae and the facial whiskers (vibrissae) are visible mammalian features in this gerbil.

The young may be blind and helpless at first, e.g. cats, or they may be able to stand up and move about soon after birth, e.g. sheep and cows. In either case, the youngster's first food is the milk which it sucks from the mother's teats. The milk is made in the mammary glands and contains all the nutrients that the offspring need for the first few weeks or months, depending on the species.

As the youngsters get older, they start to feed on the same food as the parents. In the case of carnivores, the parents bring the food to the young until they are able to fend for themselves.

Table 1.2 Key features of the five classes of vertebrates

Vertebrate class	Fish	Amphibia	Reptiles	Birds	Mammals
Examples	herring, perch, also sharks	frog, toad, newt	lizard, snake	robin, pigeon	mouse
Body covering	scales	moist skin	dry skin, with scales	feathers, with scales on legs	fur
Movement	fins (also used for balance)	four limbs, back feet are often webbed to make swimming more efficient	four legs (apart from snakes)	two wings and two legs	four limbs
Reproduction	produce jelly-covered eggs in water	produce jelly-covered eggs in water	produce eggs with a rubbery, waterproof shell; laid on land	produce eggs with a hard shell; laid on land	produce live young
Sense organs	eyes; no ears; lateral line along body for detecting vibrations in water	eyes; ears	eyes; ears	eyes; ears	eyes; ears with a pinna (external flap)
Other details	cold blooded; gills for breathing	cold blooded; lungs and skin for breathing	cold blooded; lungs for breathing	warm blooded; lungs for breathing; beak	warm blooded; lungs for breathing; females have mammary glands to produce milk to feed young; four types of teeth

The plant kingdom

It is useful to have an overview of the classification of the plant kingdom, although only two groups (ferns and flowering plants) will be tested in the examination.

Plant kingdom

DIVISION

Red algae, **Brown algae**, **Green algae** } seaweeds and filamentous forms; mostly aquatic

Bryophytes (no specialised conducting tissue)

CLASS
Liverworts
Mosses

Vascular plants (well-developed xylem and phloem)

CLASS
Ferns

{Conifers (seeds not enclosed in fruits), Flowering plants (seeds enclosed in fruits)} Sometimes called, collectively, 'seed-bearing plants'

SUBCLASS
Monocotyledons (grasses, lilies)
Dicotyledons (trees, shrubs, herbaceous plants)

FAMILY
e.g. Ranunculaceae (one of about 70 families)

GENUS
e.g. *Ranunculus*

SPECIES
e.g. *Ranunculus bulbosus* (bulbous buttercup)

Ferns

Ferns are land plants with quite highly developed structures. Their stems, leaves and roots are very similar to those of the flowering plants.

The stem is usually entirely below ground and takes the form of a structure called a **rhizome**. In bracken, the rhizome grows horizontally below ground, sending up leaves at intervals. The roots which grow from the rhizome are called adventitious roots (see 'Transport in plants' in Chapter 8). This is the name given to any roots which grow directly from the stem rather than from other roots.

The stem and leaves have sieve tubes and water-conducting cells similar to those in the xylem and phloem of a flowering plant (see Chapter 8). For this reason, the ferns and seed-bearing plants are sometimes referred to as vascular plants, because they all have vascular bundles or vascular tissue. Ferns also have multicellular roots with vascular tissue.

The leaves of ferns vary from one species to another (see Figure 1.22, and Figure 1.10 on page 9), but they are all several cells thick. Most of them have an upper and lower epidermis, a layer of palisade cells and a spongy mesophyll similar to the leaves of a flowering plant.

Figure 1.22 Young fern leaves. Ferns do not form buds like those of the flowering plants. The midrib and leaflets of the young leaf are tightly coiled and unwind as it grows.

Ferns produce gametes but no seeds. The zygote gives rise to the fern plant, which then produces single-celled spores from numerous **sporangia** (spore capsules) on its leaves. The sporangia are formed on the lower side of the leaf but their position depends on the species of fern. The sporangia are usually arranged in compact groups (see Figure 1.23).

Figure 1.23 Polypody fern. Each brown patch on the underside of the leaf is made up of many sporangia.

Flowering plants

Flowering plants reproduce by seeds which are formed in flowers. The seeds are enclosed in an ovary. The general structure of flowering plants is described in Chapter 8. Examples are shown in Figure 1.11 on page 10. Flowering plants are divided into two subclasses: monocotyledons and dicotyledons. Monocotyledons (monocots for short), are flowering plants which have only one cotyledon in their seeds. Most, but not all, monocots also have long, narrow leaves (e.g. grasses, daffodils, bluebells) with parallel leaf veins (see Figure 1.24(a)).

The dicotyledons (dicots for short), have two cotyledons in their seeds. Their leaves are usually broad and the leaf veins form a branching network (see Figure 1.24(b)).

The key features of monocots and dicots are summarised in Table 1.3.

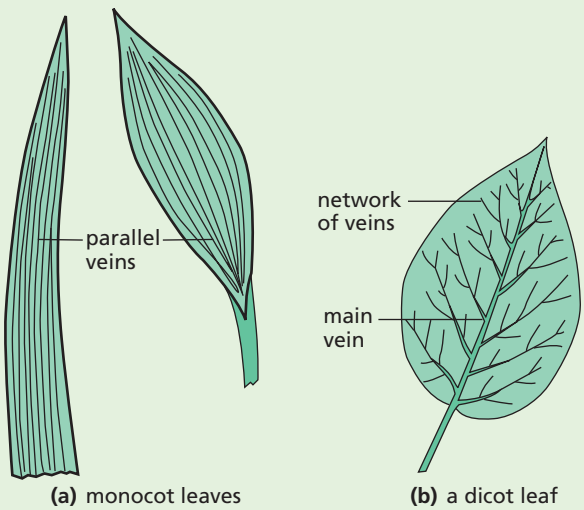


Figure 1.24 Leaf types in flowering plants

Table 1.3 Summary of the key features of monocots and dicots

Feature	Monocotyledon	Dicotyledon
leaf shape	long and narrow	broad
leaf veins	parallel	branching
cotyledons	one	two
grouping of flower parts (petals, sepals and carpels)	threes	fives

In addition to knowing the features used to place animals and plants into the appropriate kingdoms, you also need to know the main features of the following kingdoms: Fungus, Prokaryote and Protoctist.

The fungi kingdom

Most fungi are made up of thread-like hyphae (see Figure 1.25), rather than cells, and there are many nuclei distributed throughout the cytoplasm in their hyphae (see Figure 1.26).

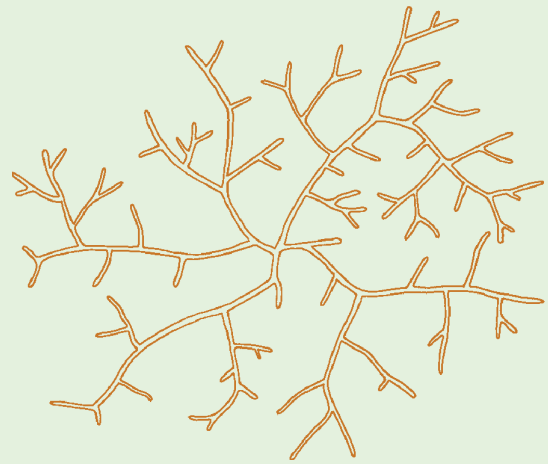


Figure 1.25 The branching hyphae form a mycelium.

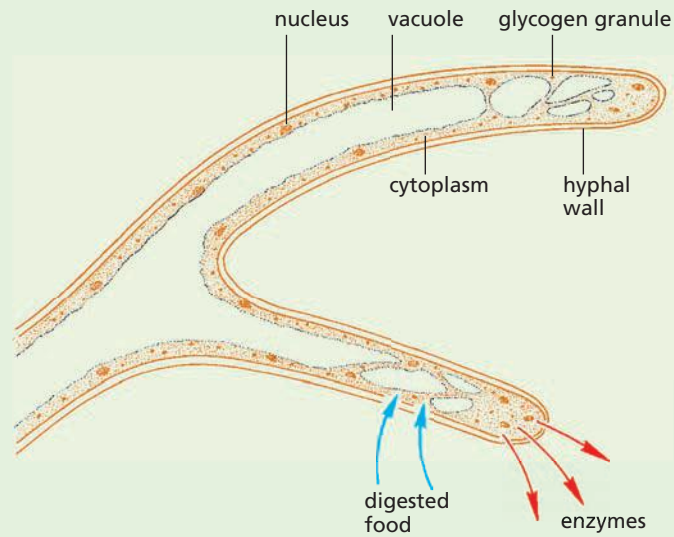


Figure 1.26 The structure of fungal hyphae

The fungi include fairly familiar organisms such as mushrooms, toadstools, puffballs and the bracket fungi that grow on tree trunks (Figure 1.27). There are also the less obvious, but very important, mould fungi which grow on stale bread, cheese, fruit or other food. Many of the mould fungi live in the soil or in dead wood. The yeasts are single-celled fungi similar to the moulds in some respects.

Some fungal species are parasites, as is the bracket fungus shown in Figure 1.27. They live in other organisms, particularly plants, where they cause diseases which can affect crop plants, such as the mildew shown in Figure 1.28. (See also Chapter 10.)

Figure 1.27 A parasitic fungus. The 'brackets' are the reproductive structures. The mycelium in the trunk will eventually kill the tree.

Figure 1.28 Mildew on wheat. Most of the hyphae are inside the leaves, digesting the cells, but some grow out and produce the powdery spores seen here.

The Prokaryote kingdom

These are the bacteria and the blue-green algae. They consist of single cells but differ from other single-celled organisms because their chromosomes are not organised into a nucleus.

Bacterial structure

Bacteria (singular: bacterium) are very small organisms consisting of single cells rarely more than 0.01 mm in length. They can be seen only with the higher powers of the microscope.

Their cell walls are made, not of cellulose, but of a complex mixture of proteins, sugars and lipids. Some bacteria have a **slime capsule** outside their cell wall. Inside the cell wall is the cytoplasm, which may contain granules of glycogen, lipid and other food reserves (see Figure 1.29).

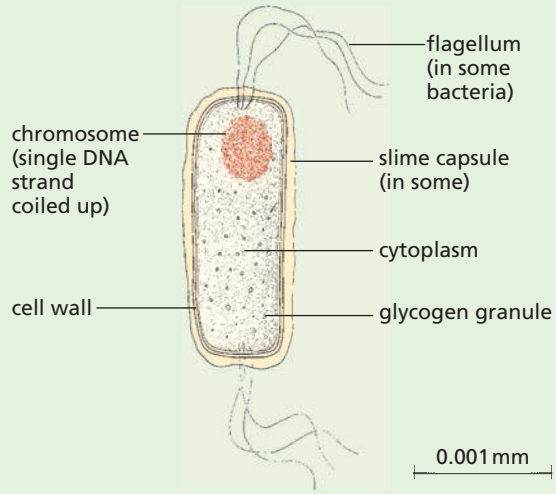


Figure 1.29 Generalised diagram of a bacterium

Each bacterial cell contains a single chromosome, consisting of a circular strand of DNA (see Chapter 4 and 'Chromosomes, genes and proteins' in Chapter 17). The chromosome is not enclosed in a nuclear membrane but is coiled up to occupy part of the cell, as shown in Figure 1.30.

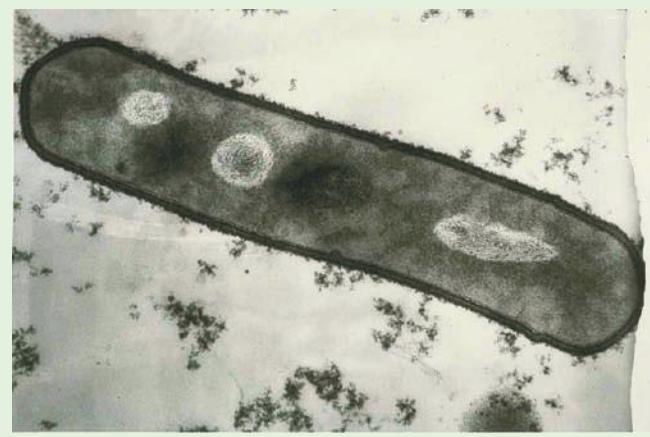


Figure 1.30 Longitudinal section through a bacterium (×27 000). The light areas are coiled DNA strands. There are three of them because the bacterium is about to divide twice (see Figure 1.31).

Individual bacteria may be spherical, rod-shaped or spiral and some have filaments, called **flagella**, projecting from them. The flagella can flick and so move the bacterial cell about.

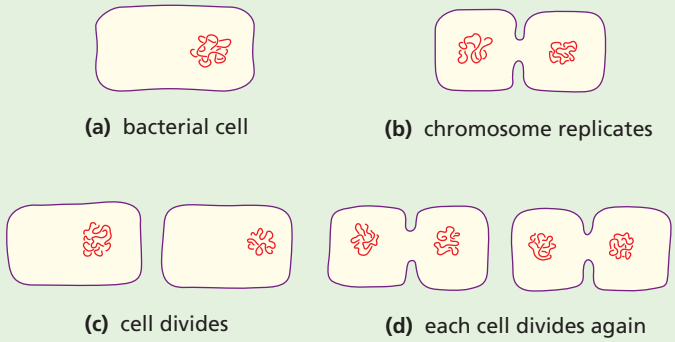


Figure 1.31 Bacterium reproducing. This is asexual reproduction by cell division (see 'Asexual reproduction' in Chapter 16 and 'Mitosis' in Chapter 17).

The Protoctist kingdom

These are single-celled (unicellular) organisms which have their chromosomes enclosed in a nuclear membrane to form a nucleus. Some examples are shown in Figure 1.32.

Some of the protoctista, e.g. *Euglena*, possess chloroplasts and make their food by photosynthesis. These protoctista are often referred to as unicellular 'plants' or **protophyta**. Organisms such as *Amoeba* and *Paramecium* take in and digest solid food and thus resemble animals in their feeding. They may be called unicellular 'animals' or **protozoa**.

Amoeba is a protozoan which moves by a flowing movement of its cytoplasm. It feeds by picking up bacteria and other microscopic organisms as it goes. *Vorticella* has a contractile stalk and feeds by creating a current of water with its cilia. The current brings particles of food to the cell. *Euglena* and *Chlamydomonas* have chloroplasts in their cells and feed, like plants, by photosynthesis.

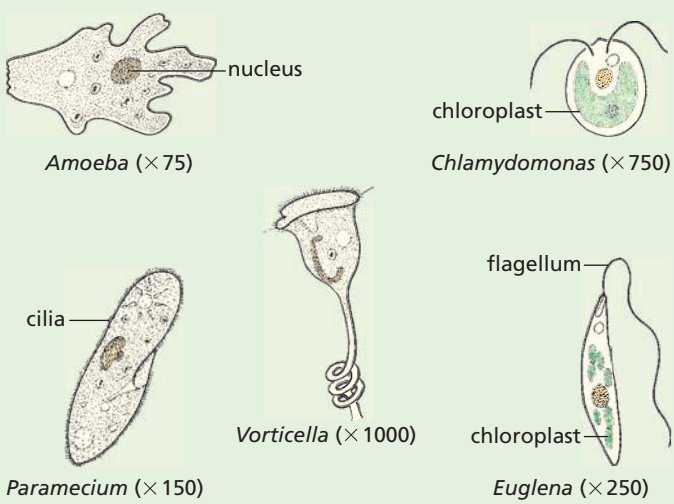


Figure 1.32 Protoctista. *Chlamydomonas* and *Euglena* have chloroplasts and can photosynthesise. The others are protozoa and ingest solid food.

Viruses

There are many different types of virus and they vary in their shape and structure. All viruses, however, have a central core of RNA or DNA (see Chapter 4) surrounded by a protein coat. Viruses have no nucleus, cytoplasm, cell organelles or cell membrane, though some forms have a membrane outside their protein coats.

Virus particles, therefore, are not cells. They do not feed, respire, excrete or grow and it is debatable whether they can be classed as living organisms. Viruses do reproduce, but only inside the cells of living organisms, using materials provided by the host cell.

A generalised virus particle is shown in Figure 1.33. The nucleic acid core is a coiled single strand of RNA. The coat is made up of regularly packed protein units called **capsomeres** each containing many protein molecules. The protein coat is called a **capsid**.

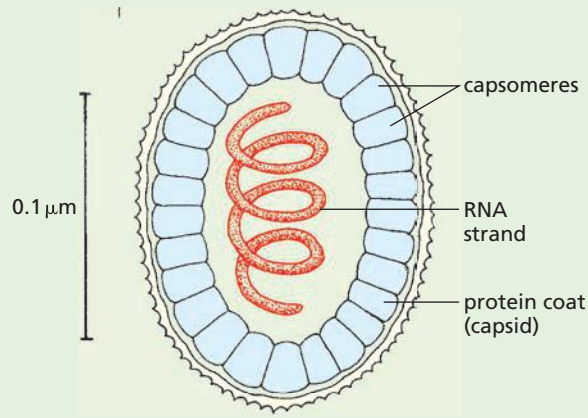


Figure 1.33 Generalised structure of a virus

Extension work

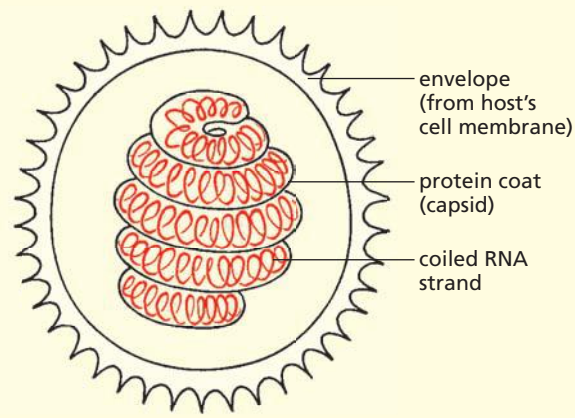


Figure 1.34 Structure of the influenza virus

Outside the capsid, in the influenza virus and some other viruses, is an envelope which is probably derived from the cell membrane of the host cell (Figure 1.34).

Ideas about classification

From the earliest days, humans must have given names to the plants and animals they observed, particularly those that were useful as food or medicine. Over the years, there have been many attempts to sort plants and animals into related groups. Aristotle's 'Ladder of Nature' (Figure 1.35) organised about 500 animal species into broad categories.

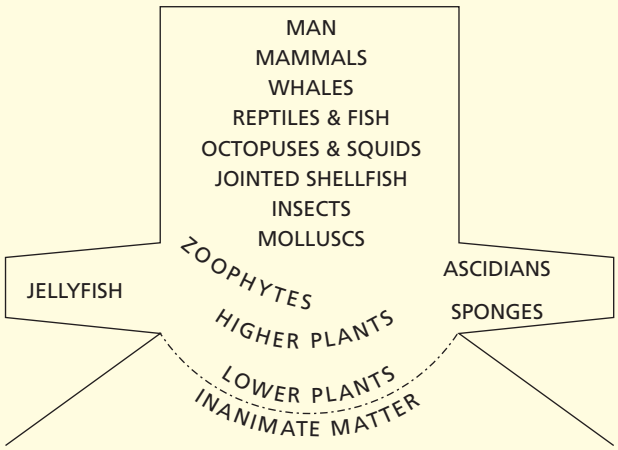


Figure 1.35 Aristotle's 'Ladder of Nature'

The 16th-century herbalists, such as John Gerard, divided the plant world into 'kindes' such as grasses, rushes, grains, irises and bulbs. Categories such as 'medicinal plants' and 'sweet-smelling plants', however, did not constitute a 'natural' classification based on structural features. The herbalists also gave the plants descriptive Latin names, e.g. *Anemone tenuifoliaflorecoccinea* ('the small-leaved scarlet anemone'). The first name shows a recognition of relationship to *Anemone nemorumfloreplenoalbo* ('the double white wood anemone'), for example. This method of naming was refined and popularised by Carl Linnaeus (see below).

John Ray (1625–1705)

Ray was the son of a blacksmith who eventually became a Fellow of the Royal Society. He travelled widely in Britain and Europe making collections of plants, animals and rocks.

In 1667 and 1682 he published a catalogue of British plants based on the structure of their flowers, seeds, fruits and roots. He was the first person to make a distinction between monocots and dicots. Ray also published a classification of animals, based on hooves, toes and teeth. Ultimately he devised classificatory systems for plants, birds, mammals, fish and insects. In doing this, he brought order out of a chaos of names and systems.

At the same time he studied functions, adaptations and behaviour of organisms.

In 1691 he claimed that fossils were the mineralised remains of extinct creatures, possibly from a time when the Earth was supposedly covered by water. This was quite contrary to established (but varied) views on the significance of fossils. Some thought that the fossils grew and developed in the rocks, others supposed that God had put them there 'for his pleasure' and still others claimed that the Devil put them in the rocks to 'tempt, frighten or confuse'. A more plausible theory was that a huge flood had washed marine creatures on to the land.

Despite Ray's declaration, the modern idea of the significance of fossils was not generally accepted until Darwin's day (see 'Selection' in Chapter 18).

Carl Linnaeus (1707–1778)

Linnaeus was a Swedish naturalist who initially graduated in medicine but became interested in plants. He travelled in Scandinavia, England and Eastern Europe, discovering and naming new plant species.

In 1735 he published his *Systema Naturae*, which accurately described about 7700 plant species and classified them, largely on the basis of their reproductive structures (stamens, ovaries, etc., see 'Sexual reproduction in plants' in Chapter 16). He further grouped species into genera, genera into classes, and classes into orders. ('Phyla' came later.) He also classified over 4000 animals, but rather less successfully, into mammals, birds, insects and worms.

Linnaeus refined and popularised the binomial system of naming organisms, in which the first name represents the genus and the second name the species. (See 'Concept and use of a classification system' earlier in this chapter.) This system is still the official starting point for naming or revising the names of organisms.

Although the classificatory system must have suggested some idea of evolution, Linnaeus steadfastly rejected the theory and insisted that no species created by God had ever become extinct.

Dichotomous keys

Dichotomous keys are used to identify unfamiliar organisms. They simplify the process of identification. Each key is made up of pairs of contrasting features (dichotomous means two branches), starting with quite general characteristics and progressing to more specific ones. By following the key and making appropriate choices it is possible to identify the organism correctly.

Figure 1.36 shows an example of a dichotomous key that could be used to place an unknown vertebrate in the correct class. Item 1 gives you a choice between two alternatives. If the animal is poikilothermic (cold blooded), you move to item 2 and make a further choice. If it is homoiothermic (warm blooded), you move to item 4 for your next choice.

The same technique may be used for assigning an organism to its class, genus or species. However, the important features may not always be easy to see and you have to make use of less fundamental characteristics.

VERTEBRATE CLASSES

1	Poikilothermic	2
	Homoiothermic	4
2	Has fins but no limbs	**Fish**
	Has four limbs	3
3	Has no scales on body	**Amphibian**
	Has scales	**Reptile**
4	Has feathers	**Bird**
	Has fur	**Mammal**

Figure 1.36 A dichotomous key for vertebrate classes

Figure 1.37 is a key for identifying some of the possible invertebrates to be found in a compost heap. Of course, you do not need a key to identify these familiar animals but it does show you how a key can be constructed.

You need to be able to develop the skills to construct simple dichotomous keys, based on easily identifiable features. If you know the main characteristics of a group, it is possible to draw up a systematic plan for identifying an unfamiliar organism. One such plan is shown in Figure 1.38 (on the next page).

INHABITANTS OF A COMPOST HEAP

1	Has legs	2
	No legs	5
2	More than six legs	3
	Six legs	4
3	Short, flattened grey body	**Woodlouse**
	Long brown/yellow body	**Centipede**
4	Pincers on last segment	**Earwig**
	Hard wing covers	**Beetle**
5	Body segmented	**Earthworm**
	Body not segmented	6
6	Has a shell	**Snail**
	No shell	**Slug**

Figure 1.37 A dichotomous key for some invertebrates in a compost heap

Figure 1.39 (overleaf) shows five different items of laboratory glassware. If you were unfamiliar with the resources in a science lab you may not be able to name them. We are going to create a dichotomous key to help with identification. All the items have one thing in common – they are made of glass. However, each has features which make it unique and we can devise questions based on these features. The first task is to study the items, to work out what some of them have in common and what makes them different from others. For example, some have a pouring spout, others have graduations marked on the glass for measuring, some have a neck (where the glass narrows to form a thinner structure), some can stand without support because they have a flat base, and so on.

The first question should be based on a feature which will split the group into two. The question is going to generate a 'yes' or 'no' answer. For each of the two sub-groups formed, a further question based on the features of some of that sub-group should then be formulated. Figure 1.40 (overleaf) shows one possible solution.

This is not the only way that a dichotomous key could be devised for the laboratory glassware shown. Construct your own key and test it for each object.

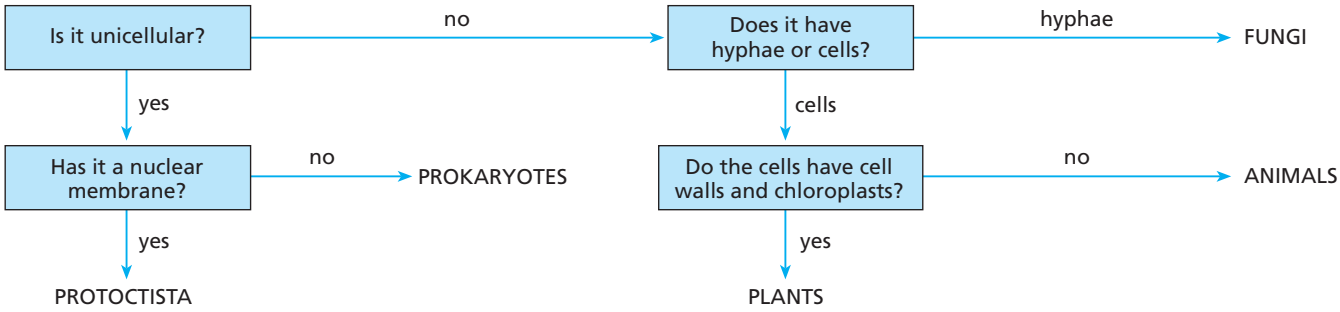


Figure 1.38 Identification plan

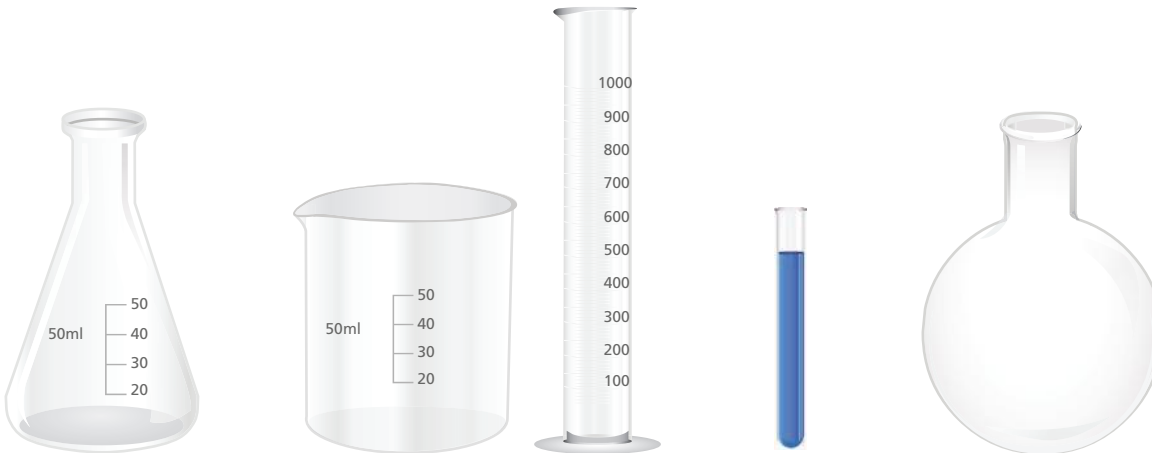


Figure 1.39 Items of laboratory glassware

1 Has it got a pouring spout?

Yes 2

No 3

2 Has it got a broad base?

Yes ..... **Beaker**

No ..... **Measuring cylinder**

3 Has it got straight sides for the whole of its length?

Yes ..... **Boiling tube**

No **4**

4 Has it got sloping sides?

Yes ..... **Conical flask**

No ..... **Round-bottomed flask**

Figure 1.40 Dichotomous key for identifying laboratory glassware

Questions

Core

1 Why do you think poikilothermic (cold blooded) animals are slowed down by low temperatures? (See Chapter 5.)
2 Which vertebrate classes:
   a are warm-blooded
   b have four legs
   c lay eggs
   d have internal fertilisation
   e have some degree of parental care?
3 Figure 1.32 on page 19 shows some protoctista. Using only the features shown in the drawings, construct a dichotomous key that could be used to identify these organisms.
4 Construct a dichotomous key that would lead an observer to distinguish between the following plants: daffodil, poppy, buttercup, meadow grass, iris (see Figure 1.11, page 10). (There is more than one way.)
   Why this is an 'artificial' key rather than a 'natural' key?

Extended

5 Classify the following organisms: beetle, sparrow, weasel, gorilla, bracken, buttercup.
   For example, butterfly: Kingdom, animal; Group, arthropod; Class, insect.
6 The white deadnettle is *Lamium album*; the red deadnettle is *Lamium purpureum*. Would you expect these two plants to cross-pollinate successfully?
7 If a fire destroys all the above-ground vegetation, the bracken (a type of fern) will still grow well in the next season. Suggest why this should be so.
8 Which kingdoms contain organisms with:
   a many cells
   b nuclei in their cells
   c cell walls
   d hyphae
   e chloroplasts?

Checklist

After studying Chapter 1 you should know and understand the following:

- The seven characteristics of living things are movement, respiration, sensitivity, growth, reproduction, excretion and nutrition.
- A species is a group of organisms that can reproduce to produce fertile offspring.
- The binomial system is an internationally agreed system in which the scientific name of an organism is made up of two parts showing the genus and the species.
- Classification is a way of sorting organisms into a meaningful order, traditionally using morphology and anatomy, but recently also using DNA.
- All living organisms have certain features in common, including the presence of cytoplasm and cell membranes, and DNA as genetic material.
- Animals get their food by eating plants or other animals.
- Arthropods have a hard exoskeleton and jointed legs.
- Crustacea mostly live in water and have more than three pairs of legs.
- Insects mostly live on land and have wings and three pairs of legs.
- Arachnids have four pairs of legs and poisonous mouth parts.
- Myriapods have many pairs of legs.
- Vertebrates have a spinal column and skull.
- Fish have gills, fins and scales.
- Amphibia can breathe in air or in water.
- Reptiles are land animals; they lay eggs with leathery shells.
- Birds have feathers, beaks and wings; they are homoiothermic (warm-blooded).
- Mammals have fur, they suckle their young and the young develop inside the mother.
- Keys are used to identify unfamiliar organisms.
- Dichotomous means two branches, so the user is given a choice of two possibilities at each stage.

- Prokaryotes are microscopic organisms; they have no proper nucleus.
- Protoctists are single-celled organisms containing a nucleus.
- Fungi are made up of thread-like hyphae. They reproduce by spores.
- Plants make their food by photosynthesis.
- Ferns have well-developed stems, leaves and roots. They reproduce by spores.
- Seed-bearing plants reproduce by seeds.
- Flowering plants have flowers; their seeds are in an ovary which forms a fruit.
- Monocots have one cotyledon in the seed; dicots have two cotyledons in the seed.
- Viruses do not possess the features of a living organism.

2 Organisation and maintenance of the organism

Cell structure and organisation
Plant and animal cell structures
Functions of structures

Ribosomes, rough ER and mitochondria
Mitochondria and respiration

Levels of organisation
Specialised cells and their functions
Definitions and examples of tissues, organs and systems

Size of specimens
Calculations of magnification and size, using millimetres

Calculations of magnification using micrometres

Cell structure and organisation

Cell structure

If a very thin slice of a plant stem is cut and studied under a microscope, it can be seen that the stem consists of thousands of tiny, box-like structures. These structures are called **cells**. Figure 2.1 is a thin slice taken from the tip of a plant shoot and photographed through a microscope. Photographs like this are called **photomicrographs**. The one in Figure 2.1 is 60 times larger than life, so a cell which appears to be 2 mm long in the picture is only 0.03 mm long in life.

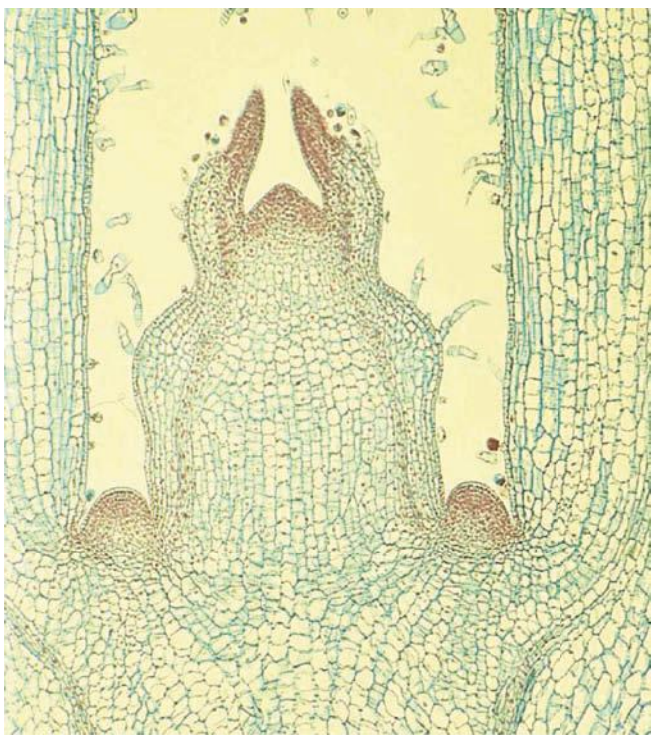
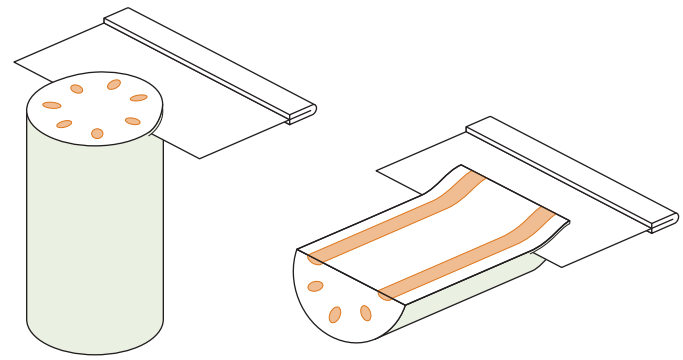


Figure 2.1 Longitudinal section through the tip of a plant shoot (×60). The slice is only one cell thick, so light can pass through it and allow the cells to be seen clearly.

Thin slices of this kind are called **sections**. If you cut *along the length* of the structure, you are taking a **longitudinal section** (Figure 2.2(b)). Figure 2.1 shows a longitudinal section, which passes through two small developing leaves near the tip of the shoot, and two larger leaves below them. The leaves, buds and stem are all made up of cells. If you cut *across* the structure, you make a **transverse section** (Figure 2.2(a)).



(a) transverse section **(b)** longitudinal section

Figure 2.2 Cutting sections of a plant stem

It is fairly easy to cut sections through plant structures just by using a razor blade. To cut sections of animal structures is more difficult because they are mostly soft and flexible. Pieces of skin, muscle or liver, for example, first have to be soaked in melted wax. When the wax goes solid it is then possible to cut thin sections. The wax is dissolved away after making the section.

When sections of animal structures are examined under the microscope, they, too, are seen to be made up of cells but they are much smaller than plant cells and need to be magnified more. The photomicrograph of kidney tissue in Figure 2.3 has been magnified 700 times to show the cells clearly. The sections are often treated with dyes, called **stains**, in order to make the structures inside the cells show up more clearly.

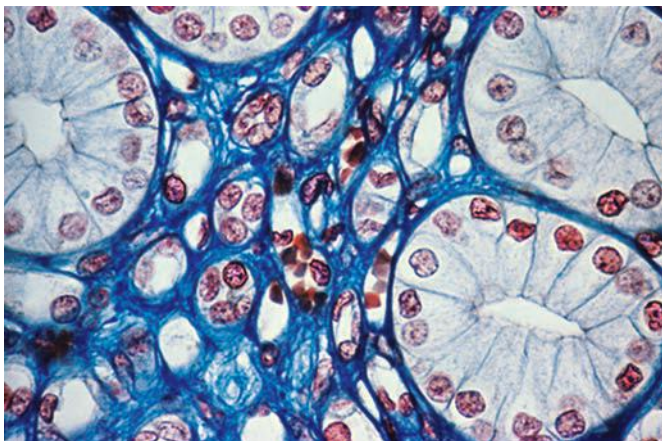


Figure 2.3 Transverse section through a kidney tubule (×700). A section through a tube will look like a ring (see Figure 2.14(b)). In this case, each 'ring' consists of about 12 cells.

Making sections is not the only way to study cells. Thin strips of plant tissue, only one cell thick, can be pulled off stems or leaves (Experiment 1, page 28). Plant or animal tissue can be squashed or smeared on a microscope slide (Experiment 2, page 29) or treated with chemicals to separate the cells before studying them.

There is no such thing as a typical plant or animal cell because cells vary a great deal in their size and shape depending on their function. Nevertheless, it is possible to make a drawing like Figure 2.4 to show features which are present in most cells. *All cells* have a **cell membrane**, which is a thin boundary enclosing the **cytoplasm**. Most cells have a **nucleus**.

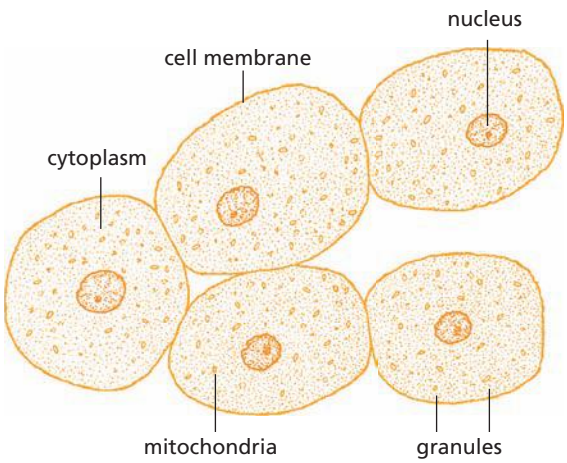


Figure 2.4 A group of liver cells. These cells have all the characteristics of animal cells.

Cytoplasm

Under the ordinary microscope (light microscope), cytoplasm looks like a thick liquid with particles in it. In plant cells it may be seen to be flowing about. The particles may be food reserves such as oil droplets or granules of starch. Other particles are structures known as **organelles**, which have particular functions in the cytoplasm. In the cytoplasm, a great many chemical reactions are taking place which keep the cell alive by providing energy and making substances that the cell needs.

The liquid part of cytoplasm is about 90% water with molecules of salts and sugars dissolved in it. Suspended in this solution there are larger molecules of fats (lipids) and proteins (see Chapter 4). Lipids and proteins may be used to build up the cell structures, such as the membranes. Some of the proteins are **enzymes** (see Chapter 5). Enzymes control the rate and type of chemical reactions which take place in the cells. Some enzymes are attached to the membrane systems of the cell, whereas others float freely in the liquid part of the cytoplasm.

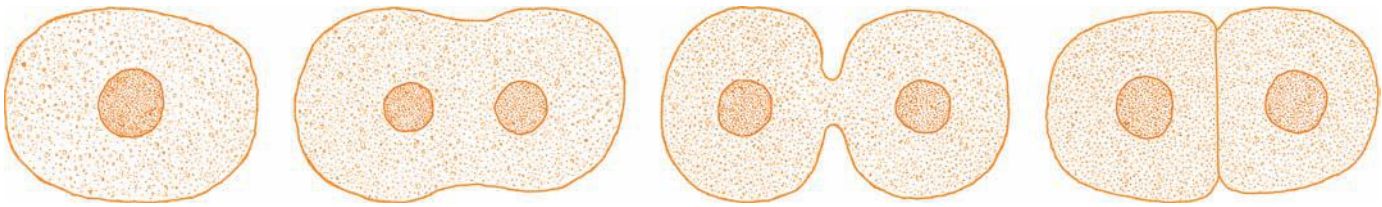
Cell membrane

This is a thin layer of cytoplasm around the outside of the cell. It stops the cell contents from escaping and also controls the substances which are allowed to enter and leave the cell. In general, oxygen, food and water are allowed to enter; waste products are allowed to leave and harmful substances are kept out. In this way the cell membrane maintains the structure and chemical reactions of the cytoplasm.

Nucleus (plural: nuclei)

Most cells contain one nucleus, which is usually seen as a rounded structure enclosed in a membrane and embedded in the cytoplasm. In drawings of cells, the nucleus may be shown darker than the cytoplasm because, in prepared sections, it takes up certain stains more strongly than the cytoplasm. The function of the nucleus is to control the type and quantity of enzymes produced by the cytoplasm. In this way it regulates the chemical changes which take place in the cell. As a result, the nucleus determines what the cell will be, for example, a blood cell, a liver cell, a muscle cell or a nerve cell.

The nucleus also controls cell division, as shown in Figure 2.5. A cell without a nucleus cannot reproduce. Inside the nucleus are thread-like structures called **chromosomes**, which can be seen most easily at the time when the cell is dividing (see Chapter 17 for a fuller account of chromosomes).



(a) Animal cell about to divide.

(b) The nucleus divides first.

(c) The daughter nuclei separate and the cytoplasm pinches off between the nuclei.

(d) Two cells are formed – one may keep the ability to divide, and the other may become specialised.

Figure 2.5 Cell division in an animal cell

Plant cells

A few generalised animal cells are represented by Figure 2.4, while Figure 2.6 is a drawing of two palisade cells from a plant leaf. (See 'Leaf structure' in Chapter 6.)

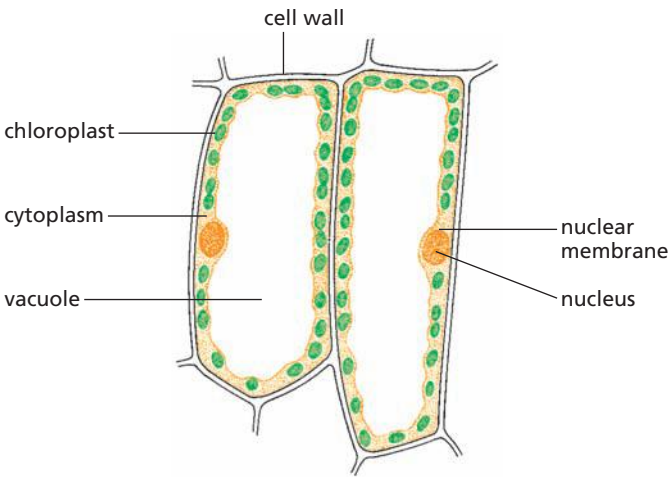


Figure 2.6 Palisade cells from a leaf

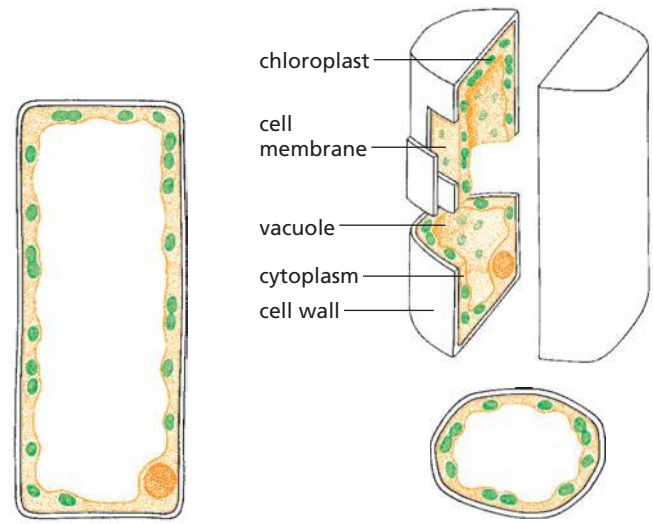
Plant cells differ from animal cells in several ways.

1 Outside the cell membrane they all have a **cell wall** which contains cellulose and other compounds. It is non-living and allows water and dissolved substances to pass through. The cell wall is not selective like the cell membrane. (Note that plant cells *do* have a cell membrane but it is not easy to see or draw because it is pressed against the inside of the cell wall (see Figure 2.7).)

Under the microscope, plant cells are quite distinct and easy to see because of their cell walls. In Figure 2.1 it is only the cell walls (and in some cases the nuclei) which can be seen. Each plant cell has its own cell wall but the boundary between two cells side by side does not usually show up clearly. Cells next to each other therefore appear to be sharing the same cell wall.

2 Most mature plant cells have a large, fluid-filled space called a **vacuole**. The vacuole contains **cell sap**, a watery solution of sugars, salts and sometimes pigments. This large, central vacuole pushes the cytoplasm aside so that it forms just a thin lining inside the cell wall. It is the outward pressure of the vacuole on the cytoplasm and cell wall which makes plant cells and their tissues firm (see 'Osmosis' in Chapter 3). Animal cells may sometimes have small vacuoles in their cytoplasm but they are usually produced to do a particular job and are not permanent.

3 In the cytoplasm of plant cells are many organelles called **plastids**. These are not present in animal cells. If they contain the green substance **chlorophyll**, the organelles are called **chloroplasts** (see Chapter 6). Colourless plastids usually contain starch, which is used as a food store. (Note: the term *plastid* is **not** a syllabus requirement.)



(a) longitudinal section

(b) transverse section

Figure 2.7 Structure of a palisade mesophyll cell. It is important to remember that, although cells look flat in sections or in thin strips of tissue, they are in fact three-dimensional and may seem to have different shapes according to the direction in which the section is cut. If the cell is cut across it will look like (b); if cut longitudinally it will look like (a).

The shape of a cell when seen in a transverse section may be quite different from when the same cell is seen in a longitudinal section and Figure 2.7 shows why this is so. Figures 8.4(b) and 8.4(c) on page 112 show the appearance of cells in a stem vein as seen in transverse and longitudinal section.

Table 2.1 Summary: the parts of a cell

	Name of part	Description	Where found	Function (supplement only)
Animal and plant cells	cytoplasm	jelly-like, with particles and organelles in	enclosed by the cell membrane	contains the cell organelles, e.g. mitochondria, nucleus site of chemical reactions
	cell membrane	a partially permeable layer that forms a boundary around the cytoplasm	around the cytoplasm	prevents cell contents from escaping controls what substances enter and leave the cell
	nucleus	a circular or oval structure containing DNA in the form of chromosomes	inside the cytoplasm	controls cell division controls cell development controls cell activities
Plant cells only	cell wall	a tough, non-living layer made of cellulose surrounding the cell membrane	around the outside of plant cells	prevents plant cells from bursting allows water and salts to pass through (freely permeable)
	vacuole	a fluid-filled space surrounded by a membrane	inside the cytoplasm of plant cells	contains salts and sugars helps to keep plant cells firm
	chloroplast	an organelle containing chlorophyll	inside the cytoplasm of some plant cells	traps light energy for photosynthesis

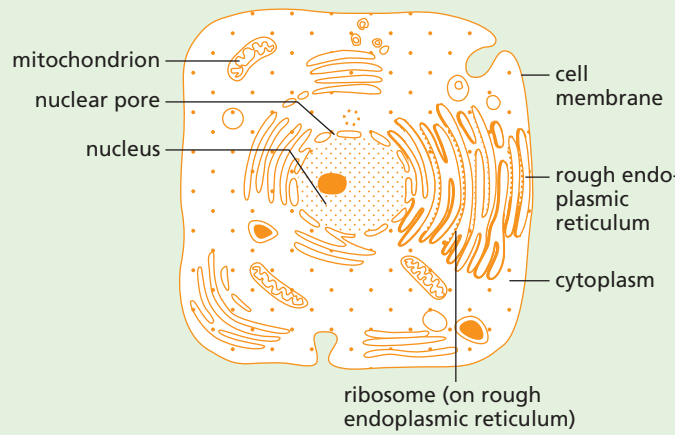
When studied at much higher magnifications with the **electron microscope**, the cytoplasm of animal and plant cells no longer looks like a structureless jelly but appears to be organised into a complex system of membranes and vacuoles. Organelles present include the **rough endoplasmic reticulum**, a network of flattened cavities surrounded by a membrane, which links with the nuclear membrane. The membrane holds **ribosomes**, giving its surface a rough appearance. Rough endoplasmic reticulum has the function of producing, transporting and storing proteins. Ribosomes can also be found free in the cytoplasm. They build up the cell's proteins (see Chapter 4).

Mitochondria are tiny organelles, which may appear slipper-shaped, circular or oval when viewed in section. In three dimensions, they may be spherical, rod-like or elongated. They have an outer membrane and an inner membrane with many inward-pointing folds. Mitochondria are most numerous in regions of rapid chemical activity and are responsible for producing energy from food substances through the process of aerobic respiration (see Chapter 12).

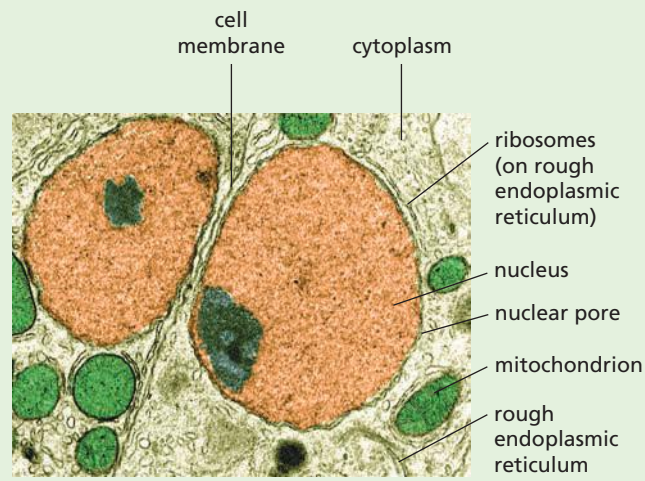
Note that prokaryotes do not possess mitochondria or rough endoplasmic reticulum in their cytoplasm.

Figure 2.8(a) is a diagram of an animal cell magnified 10 000 times. Figure 2.8(b) is an electron micrograph of a liver cell. Organelles in the cytoplasm can be seen clearly. They have recognisable shapes and features.

Figure 2.8(c) is an electron micrograph of a plant cell. In addition to the organelles already named and described, other organelles are also present such as chloroplasts and a cell wall.

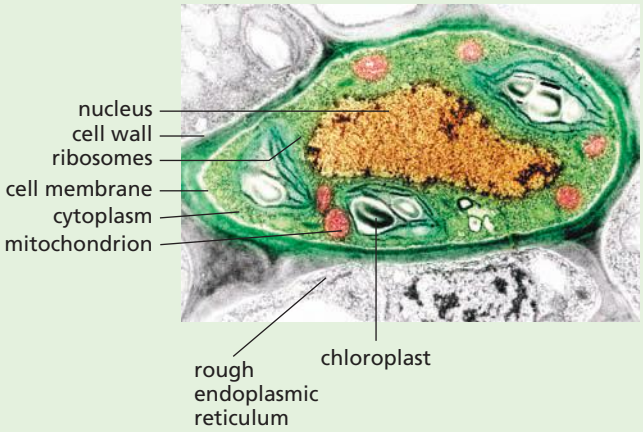


(a) diagram of a liver cell (×10 000)



(b) electron micrograph of two liver cells (×10 000)

Figure 2.8 Cells at high magnification



(c) electron micrograph of a plant cell (×6 000)

Figure 2.8 Cells at high magnification (continued)

Practical work

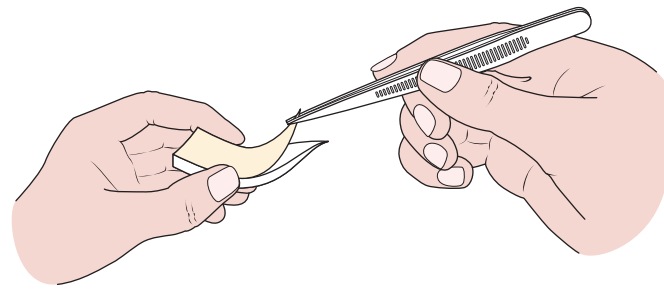
Looking at cells

1 Plant cells – preparing a slide of onion epidermis cells

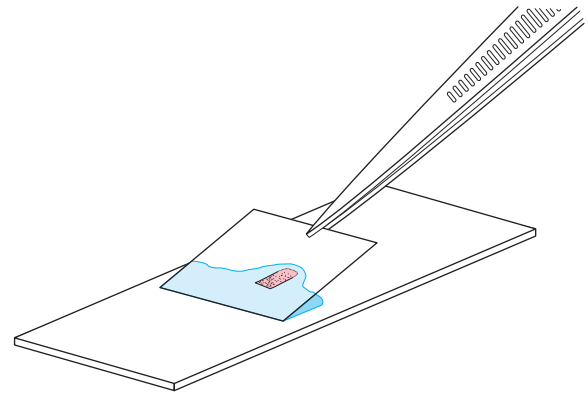
The onion provides a very useful source of epidermal plant tissue which is one cell thick, making it relatively easy to set up as a temporary slide. The onion is made up of fleshy leaves. On the incurve of each leaf there is an epidermal layer which can be peeled off (Figure 2.9(a)).

- Using forceps, peel a piece of epidermal tissue from the incurve of an onion bulb leaf.
- Place the epidermal tissue on a glass microscope slide.
- Using a scalpel, cut out a 1 cm square of tissue (discarding the rest) and arrange it in the centre of the slide.
- Add two to three drops of iodine solution. (This will stain any starch in the cells and provides a contrast between different components of the cells.)
- Using forceps, a mounted needle or a wooden splint, support a coverslip with one edge resting near to the onion tissue, at an angle of about 45° (Figure 2.9(b)).
- Gently lower the coverslip over the onion tissue, trying to avoid trapping any air bubbles. (Air bubbles will reflect light when viewing under the light microscope, obscuring the features you are trying to observe.)
- Leave the slide for about 5 minutes to allow the iodine stain to react with the specimen. The iodine will stain the cell nuclei pale yellow and the starch grains blue.
- Place the slide on to the microscope stage, select the lowest power objective lens and focus on the specimen. Increase the magnification using the other objective lenses. Under high power, the cells should look similar to those shown in Figure 2.10.
- Make a large drawing of **one** cell and label the following parts: cell wall, cell membrane, cytoplasm, nucleus.

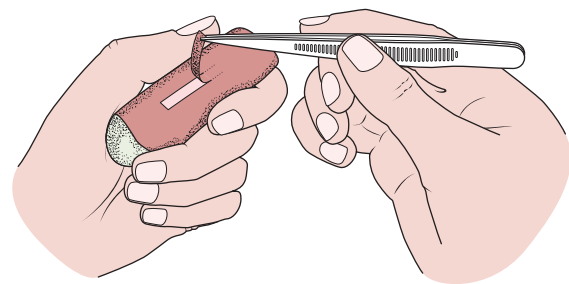
An alternative tissue is rhubarb epidermis (Figure 2.9(c)). This can be stripped off from the surface of a stalk and treated in the same way as the onion tissue. If red epidermis from rhubarb stalk is used, you will see the red cell sap in the vacuoles.



(a) peel the epidermis from the inside of an onion bulb leaf



(b) place the epidermis on to the slide, adding 2–3 drops of iodine solution and carefully lowering a coverslip on to it



(c) alternatively, peel a strip of red epidermis from a piece of rhubarb skin

Figure 2.9 Looking at plant cells

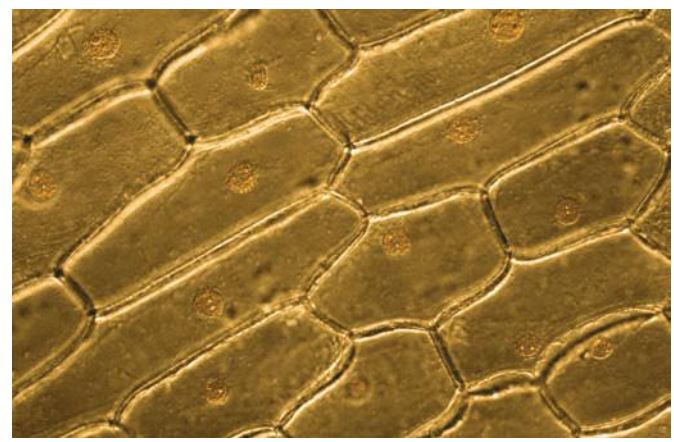


Figure 2.10 Onion epidermis cells

2 Plant cells – preparing cells with chloroplasts

- Using forceps, remove a leaf from a moss plant.
- Place the leaf in the centre of a microscope slide and add one or two drops of water.
- Place a coverslip over the leaf.
- Examine the leaf cells with the high power objective of a microscope. The cells should look similar to those shown in Figure 2.11.

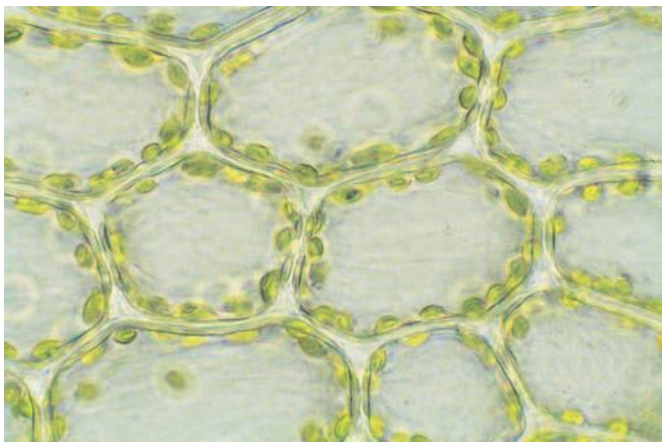


Figure 2.11 Cells in a moss leaf (×500). The vacuole occupies most of the space in each cell. The chloroplasts are confined to the layer of cytoplasm lining the cell wall.

3 Animal cells – preparing human cheek cells

Human cheek cells are constantly being rubbed off inside the mouth as they come in contact with the tongue and food. They can therefore be collected easily for use in a temporary slide.

Note: The Department of Education and Science and, subsequently, Local Authorities, used to recommend that schools should not use the technique which involves studying the epithelial cells which appear in a smear taken from the inside of the cheek. This was because of the very small risk of transmitting the AIDS virus. However, this guidance has now changed. A document, *Safety in Science Education* (1996) by the DfEE in Britain states that official government guidance on cheek cells has been effectively reversed, indicating that the use of cotton buds is now 'permitted' together with appropriate precautions to treat contaminated items with disinfectant or by autoclaving.

- Rinse your mouth with water to remove any fragments of food.
- Take a cotton bud from a freshly opened pack. Rub the cotton bud lightly on the inside of your cheek and gums to collect some cheek cells in saliva.
- Rub the cotton bud on to the centre of a clean microscope slide, to leave a sample of saliva. Repeat if the sample is too small. Then drop the cotton bud into a container of absolute alcohol or disinfectant.
- Add two to three drops of methylene blue dye. (This will stain parts of the cheek cells to make nuclei more visible.)
- Using forceps, a mounted needle or wooden splint, support a coverslip with one edge resting near to the cheek cell sample, at an angle of about 45°. Gently lower the coverslip over the tissue, trying to avoid trapping any air bubbles. (Air bubbles will reflect light when viewing under the light microscope, obscuring the features you are trying to observe.)
- Leave the slide for a few minutes to allow the methylene blue stain to react with the specimen.
- Place the slide on to the microscope stage, select the lowest power objective lens and focus on the specimen. Increase the magnification using the other objective lenses. Under high power, the cells should look similar to those shown in Figure 2.12, but less magnified.
- Make a large drawing of **one** cell and label the following parts: cell membrane, cytoplasm, nucleus.
- Place your used slide in laboratory disinfectant before washing.

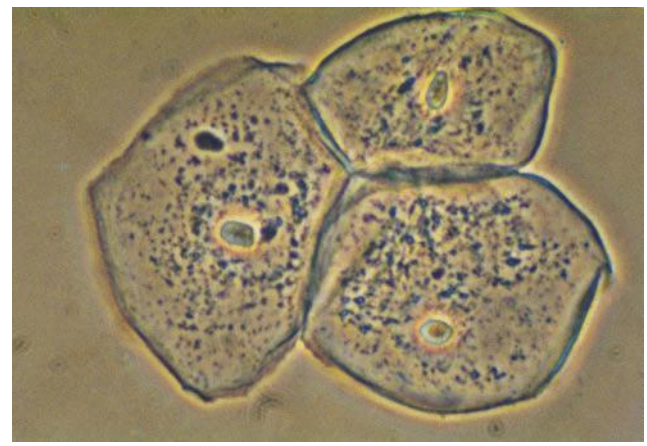


Figure 2.12 Cells from the lining epithelium of the cheek (×1500)

An alternative method of obtaining cells is to press some transparent sticky tape on to a well-washed wrist. When the tape is removed and studied under the microscope, cells with nuclei can be seen. A few drops of methylene blue solution will stain the cells and make the nuclei more distinct.

Levels of organisation

Specialisation of cells

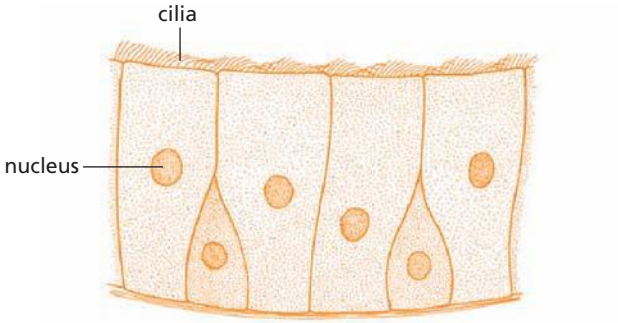
Most cells, when they have finished dividing and growing, become specialised. When cells are specialised:

- they do one particular job
- they develop a distinct shape
- special kinds of chemical change take place in their cytoplasm.

The changes in shape and the chemical reactions enable the cell to carry out its special function. Red blood cells and root hair cells are just two examples of specialised cells. Figure 2.13 shows a variety of specialised cells.

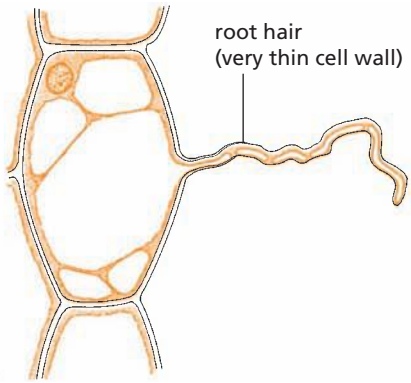
The specialisation of cells to carry out particular functions in an organism is sometimes referred to as '**division of labour**' within the organism. Similarly,

the special functions of mitochondria, ribosomes and other cell organelles may be termed division of labour within the cell.



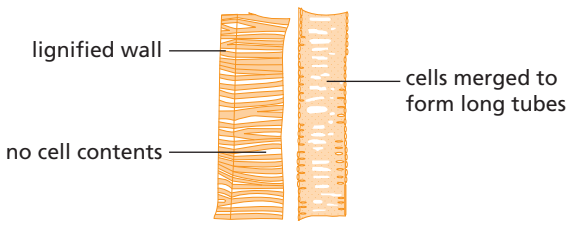
(a) ciliated cells

These cells form the lining of the nose and windpipe, and the tiny cytoplasmic 'hairs', called cilia, are in a continual flicking movement which creates a stream of fluid (mucus) that carries dust and bacteria through the bronchi and trachea, away from the lungs.



(b) root hair cell

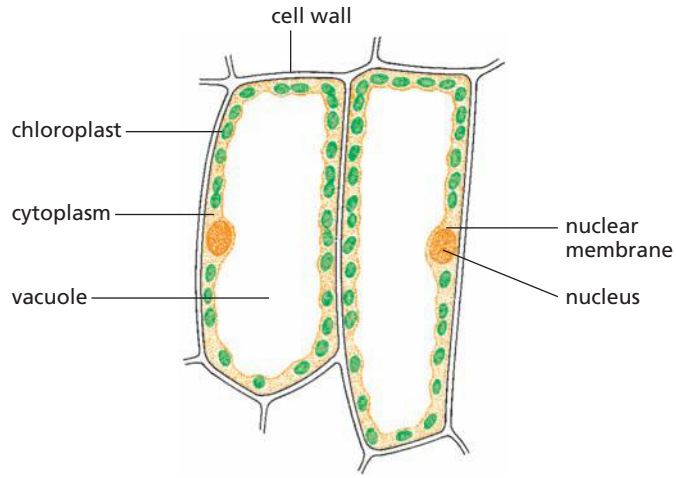
These cells absorb water and mineral salts from the soil. The hair-like projection on each cell penetrates between the soil particles and offers a large absorbing surface. The cell membrane is able to control which dissolved substances enter the cell.



(c) xylem vessels

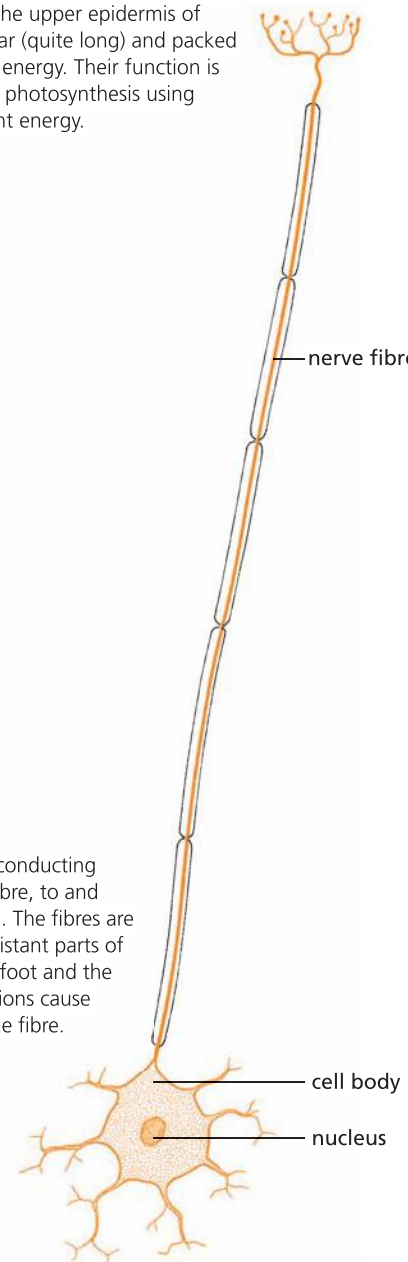
These cells transport mineral ions from the roots to the leaves. A substance called lignin impregnates and thickens the cell walls making the cells very strong and impermeable. This gives the stem strength. The lignin forms distinctive patterns in the vessels – spirals, ladder shapes, reticulate (net-like) and pitted. Xylem vessels are made up of a series of long xylem cells joined end-to-end (Figure 8.4(a)). Once a region of the plant has stopped growing, the end walls of the cells are digested away to form a continuous, fine tube (Figure 8.4(c)). The lignin thickening prevents the free passage of water and nutrients, so the cytoplasm in the cells dies. Effectively, the cells form long, thin, strong straws.

Figure 2.13 Specialised cells (not to scale)



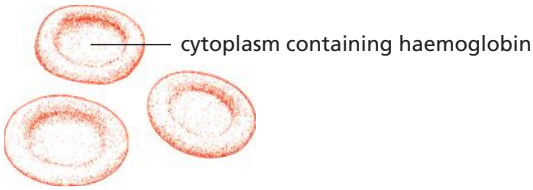
(d) palisade mesophyll cells

These are found underneath the upper epidermis of plant leaves. They are columnar (quite long) and packed with chloroplasts to trap light energy. Their function is to make food for the plant by photosynthesis using carbon dioxide, water and light energy.



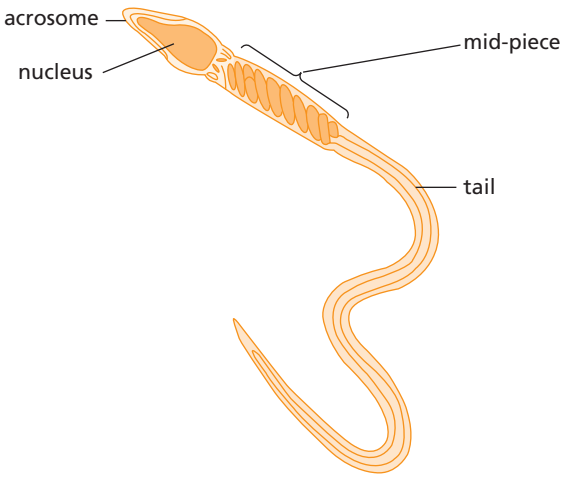
(e) nerve cells

These cells are specialised for conducting electrical impulses along the fibre, to and from the brain and spinal cord. The fibres are often very long and connect distant parts of the body to the CNS, e.g. the foot and the spinal column. Chemical reactions cause the impulses to travel along the fibre.



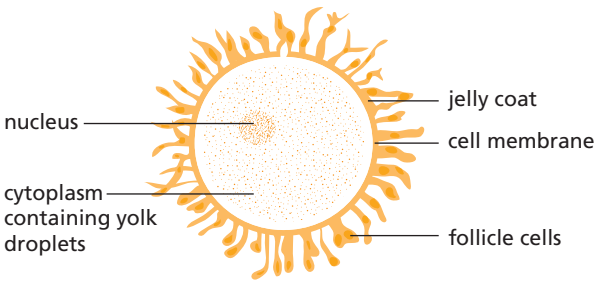
(f) red blood cells

These cells are distinctive because they have no nucleus when mature. They are tiny disc-like cells which contain a red pigment called haemoglobin. This readily combines with oxygen and their function is the transport of oxygen around the body.



(g) sperm cell

Sperm cells are male sex cells. The front of the cell is oval shaped and contains a nucleus which carries genetic information. There is a tip, called an acrosome, which secretes enzymes to digest the cells around an egg and the egg membrane. Behind this is a mid-piece which is packed with mitochondria to provide energy for movement. The tail moves with a whip-like action enabling the sperm to swim. Their function is reproduction, achieved by fertilising an egg cell.



(h) egg cell

Egg cells (ova, singular: ovum) are larger than sperm cells and are spherical. They have a large amount of cytoplasm, containing yolk droplets made up of protein and fat. The nucleus carries genetic information. The function of the egg cell is reproduction.

Figure 2.13 Specialised cells (not to scale) (continued)

Tissues and organs

There are some microscopic organisms that consist of one cell only (see 'Features of organisms' in Chapter 1). These can carry out all the processes necessary for their survival. The cells of the larger plants and animals cannot survive on their own. A muscle cell could not obtain its own food and oxygen. Other specialised cells have to provide the food and oxygen needed for the muscle cell to live. Unless these cells are grouped together in large numbers and made to work together, they cannot exist for long.

Tissues

A **tissue**, such as bone, nerve or muscle in animals, and epidermis, xylem or pith in plants, is made up of many hundreds of cells often of a single type. The cells of each type have a similar structure and function so that the tissue itself can be said to have a particular function; for example, muscles contract to cause movement, xylem carries water in plants. Figure 2.14 shows how some cells are arranged to form simple tissues.

Key definition
A **tissue** is a group of cells with similar structures, working together to perform a shared function.

Organs

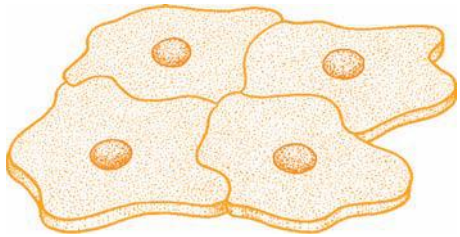
Organs consist of several tissues grouped together to make a structure with a special function. For example, the stomach is an organ which contains tissues made from epithelial cells, gland cells and muscle cells. These cells are supplied with food and oxygen brought by blood vessels. The stomach also has a nerve supply. The heart, lungs, intestines, brain and eyes are further examples of organs in animals. In flowering plants, the root, stem and leaves are the organs. The tissues of the leaf include epidermis, palisade tissue, spongy tissue, xylem and phloem (see Chapter 8).

Key definition
An **organ** is a structure made up of a group of tissues, working together to perform a specific function.

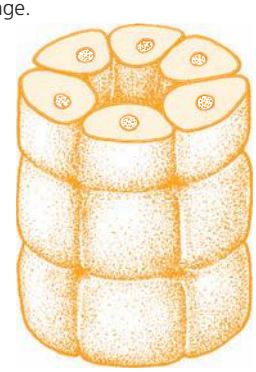
Organ systems

An **organ system** usually refers to a group of organs whose functions are closely related. For example, the heart and blood vessels make up the **circulatory system**; the brain, spinal cord and nerves make up the **nervous system** (Figure 2.15). In a flowering plant, the stem, leaves and buds make up a system called the **shoot** (Figure 8.1 on page 110).

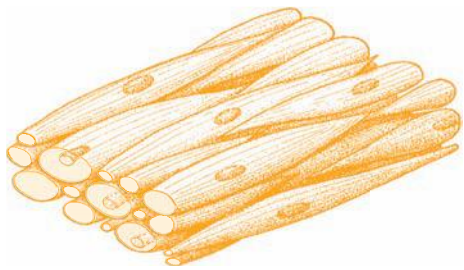
Key definition
A **system** is a group of organs with related functions, working together to perform a body function.



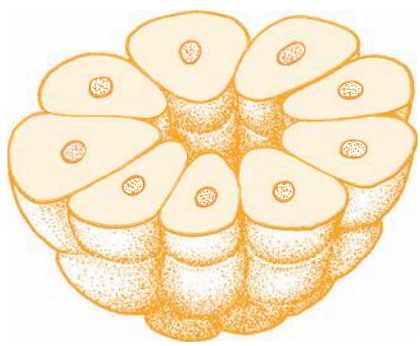
(a) cells forming an epithelium
A thin layer of tissue, e.g. the lining of the mouth cavity. Different types of epithelium form the internal lining of the windpipe, air passages food canal, etc., and protect these organs from physical or chemical damage.



(b) cells forming a small tube
e.g. a kidney tubule (see p. 177). Tubules such as this carry liquids from one part of an organ to another.

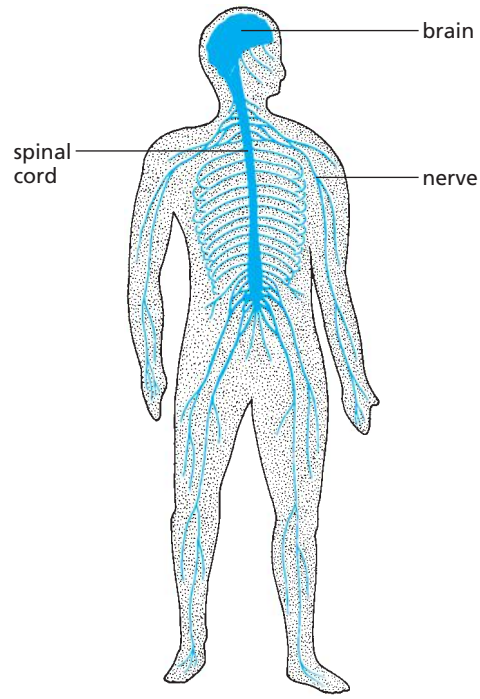


(c) one kind of muscle cell
Forms a sheet of muscle tissue. Blood vessels, nerve fibres and connective tissues will also be present. Contractions of this kind of muscle help to move food along the food canal or close down small blood vessels.

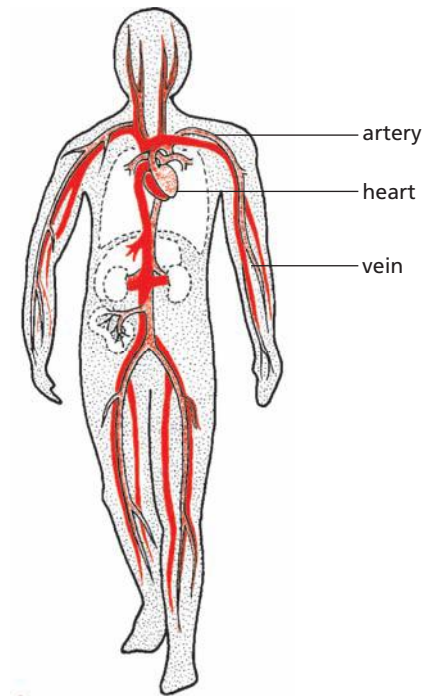


(d) cells forming part of a gland
The cells make chemicals which are released into the central space an carried away by a tubule such as shown in **(b)**. Hundreds of cell groups like this would form a gland like the salivary gland.

Figure 2.14 How cells form tissues



(a) nervous system



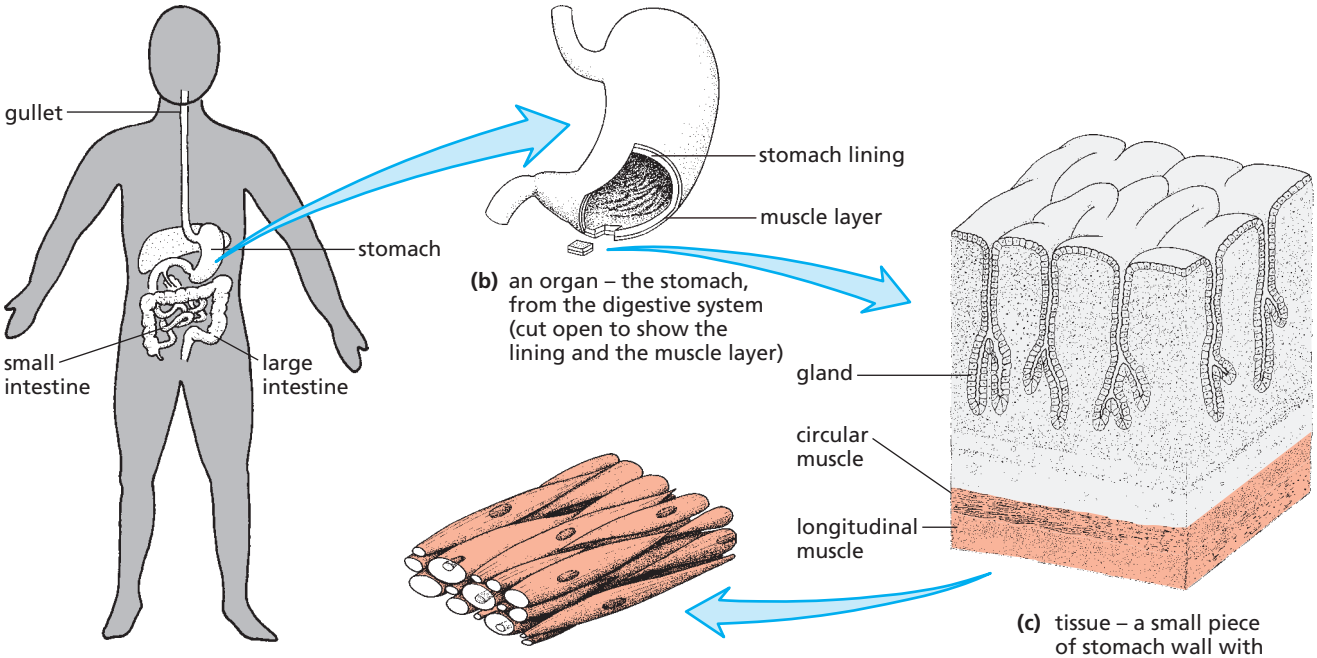
(b) circulatory system

Figure 2.15 Two examples of systems in the human body

Organisms

An **organism** is formed by the organs and systems working together to produce an independent plant or animal.

An example in the human body of how cells, tissues and organs are related is shown in Figure 2.16.



(a) a system – the digestive system of the human organism

(b) an organ – the stomach, from the digestive system (cut open to show the lining and the muscle layer)

(c) tissue – a small piece of stomach wall with muscle tissue and gland tissue

(d) cells – some muscle cells from the muscle tissue

Figure 2.16 An example of how cells, tissues and organs are related

Size of specimens

The light microscope

Most cells cannot be seen with the naked eye. A **hand lens** has a magnification of up to ×20, but this is not sufficient to observe the detail in cells. The **light microscope** (Figure 2.17) has two convex lenses, providing magnifications of up to ×1500, although most found in school laboratories will only magnify to ×400. The eyepiece lens is usually ×10 and there is a choice of objective lenses (typically ×4, ×10 and ×40), set in a nosepiece which can be rotated. Light, provided by a mirror or a bulb, is projected through the specimen mounted on a microscope slide. It passes through the objective and eyepieces lenses and the image is magnified so that detail of the specimen can be seen. Coarse and fine focus knobs are used to sharpen the image. Specimens are mounted on microscope slides, which may be temporary or permanent preparations. Temporary slides are quick to prepare, but the specimens dry out quite rapidly, so they cannot be stored successfully. A coverslip (a thin piece of glass) is carefully laid over the specimen. This helps to keep it in place, slows down dehydration and protects the objective lens from moisture or stains. A permanent preparation usually involves dehydrating the specimen and fixing it in a special resin such as Canada Balsam. These types of slides can be kept for many years.

Calculating magnification

A lens is usually marked with its magnifying power. This indicates how much larger the image will be, compared to the specimen's actual size. So, if the lens is marked ×10, the image will be ten times greater than the specimen's real size. Since a light microscope has two lenses, the magnification of both of these lenses needs to be taken into account. For example, if the specimen is viewed using a ×10 eyepiece lens and ×40 objective lens, the total magnification will be $10 \times 40 = 400$.

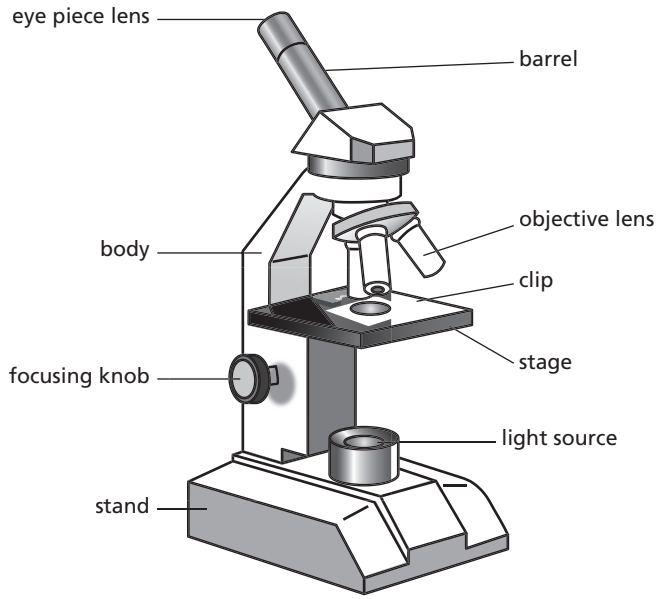


Figure 2.17 A light microscope

When the image is drawn, the drawing is usually much larger than the image, so the overall magnification of the specimen is greater still.

$$\text{Magnification} = \frac{\text{observed size of the image (or drawing)}}{\text{actual size of the specimen}}$$

When performing this type of calculation, make sure that the units of both sizes are the same. If they are different, convert one to make them the same. For example, if the actual size is in millimetres and the observed size is in centimetres, convert the centimetres to millimetres. (There are 10 millimetres in a centimetre.)

You may be required to calculate the actual size of a specimen, given a drawing or photomicrograph and a magnification.

$$\text{Actual size of the specimen} = \frac{\text{observed size of the image (or drawing)}}{\text{magnification}}$$

When you state the answer, make sure you quote the units (which will be the same as those used for measuring the observed size).

Organelles in cells are too small to be measured in millimetres. A smaller unit, called the **micrometre** (micron or μm) is used. Figure 2.18 shows a comparison of the sizes of a range of objects. The scale is in **nanometres** because of the tiny size of some of the objects. There are 1000 nanometres in 1 micrometre. (Note: the term nanometre is **not** a syllabus requirement.)

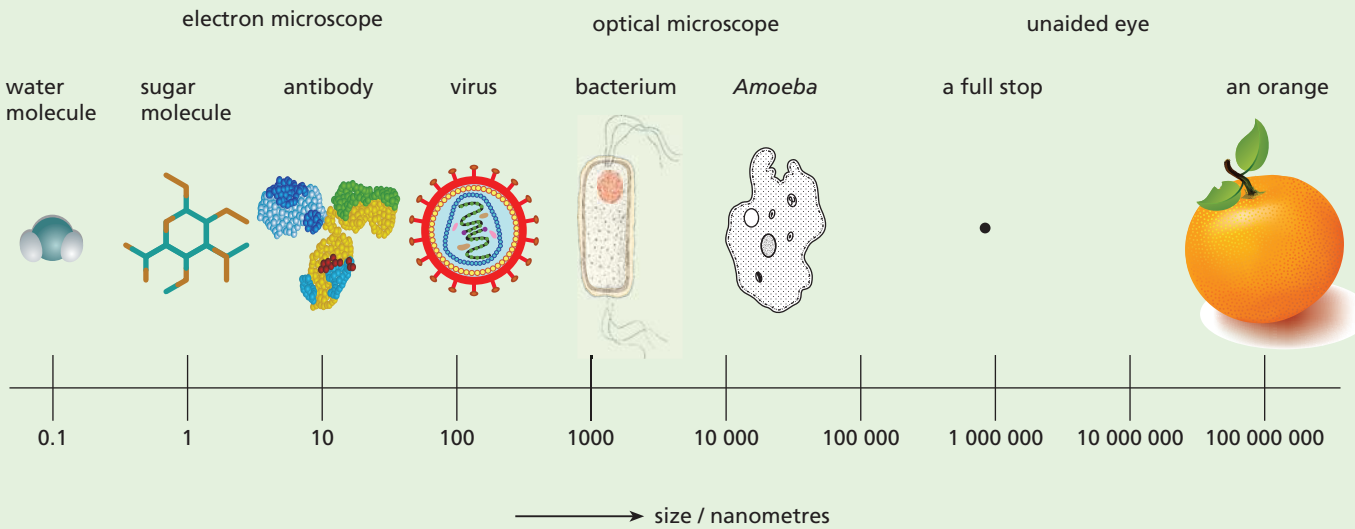


Figure 2.18 Comparing the sizes of a range of objects

There are

1 000 000 micrometres in a metre

10 000 micrometres in a centimetre

1000 micrometres in a millimetre.

Remember to make sure that the units of both sizes used in a calculation involving magnification are the same. So, if the actual size is in micrometres and the observed size is in millimetres, convert the millimetres to micrometres.

Questions

Core

1 a What structures are usually present in both animal and plant cells?
  b What structures are present in plant cells but not in animal cells?
2 What cell structure is largely responsible for controlling the entry and exit of substances into or out of the cell?
3 In what way does the red blood cell shown in Figure 2.13(f) differ from most other animal cells?
4 How does a cell membrane differ from a cell wall?
5 Why does the cell shown in Figure 2.7(b) appear to have no nucleus?
6 a In order to see cells clearly in a section of plant tissue, which magnification would you have to use?
    A ×5
    B ×10
    C ×100
    D ×1000
  b What is the approximate width (in millimetres) of one of the largest cells in Figure 2.3?
7 In Figure 2.3, the cell membranes are not always clear. Why is it still possible to decide roughly how many cells there are in each tubule section?
8 a Study Figure 8.7 on page 113 and identify examples of tissues and an organ.
  b Study Figure 7.13 on page 97 and identify examples of tissues and an organ.

Checklist

After studying Chapter 2 you should know and understand the following:

- Nearly all plants and animals are made up of thousands or millions of microscopic cells.
- All cells contain cytoplasm enclosed in a cell membrane.
- Most cells have a nucleus.
- Many chemical reactions take place in the cytoplasm to keep the cell alive.
- The nucleus directs the chemical reactions in the cell and also controls cell division.
- Plant cells have a cellulose cell wall and a large central vacuole.
- Cells are often specialised in their shape and activity to carry out particular jobs.
- Large numbers of similar cells packed together form a tissue.
- Different tissues arranged together form organs.
- A group of related organs makes up a system.
- The magnification of a specimen can be calculated if the actual size and the size of the image are known.

- Cytoplasm contains organelles such as mitochondria, chloroplasts and ribosomes.
- The magnification and size of biological specimens can be calculated using millimetres or micrometres.

3 Movement in and out of cells

Diffusion
Definition
Importance of diffusion of gases and solutes
Movement of substances in and out of cells

Kinetic energy of molecules and ions
Factors that influence diffusion

Osmosis
Movement of water through the cell membrane
Plant support

Definition of osmosis and other terms associated with the process
The effect of different solutions on tissues

Water potential
The uptake of water by plants
The importance of turgor pressure to plant support

Active transport
Definition of active transport
Movement of molecules and ions against a concentration gradient, using energy from respiration

The importance of active transport to the uptake of glucose

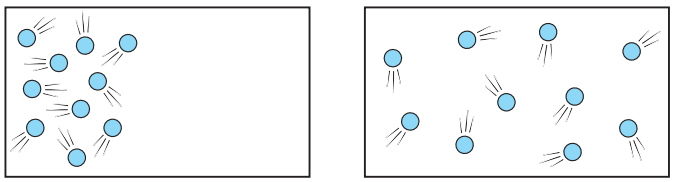
Cells need food materials which they can oxidise for energy or use to build up their cell structures. They also need salts and water, which play a part in chemical reactions in the cell. Finally, they need to get rid of substances such as carbon dioxide, which, if they accumulated in the cell, would upset some of the chemical reactions or even poison the cell.

Substances may pass through the cell membrane either passively by diffusion or actively by some form of active transport.

Diffusion

Key definition
Diffusion is the net movement of molecules and ions from a region of their higher concentration to a region of their lower concentration down a concentration gradient, as a result of their random movement.

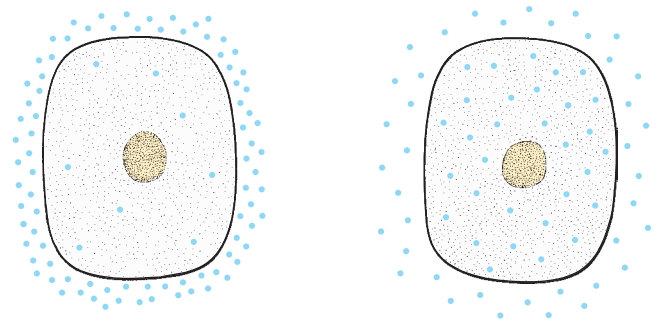
The molecules of a gas such as oxygen are moving about all the time. So are the molecules of a liquid or a substance such as sugar dissolved in water. As a result of this movement, the molecules spread themselves out evenly to fill all the available space (Figure 3.1).



molecules moving about — become evenly distributed

Figure 3.1 Diffusion

This process is called **diffusion**. One effect of diffusion is that the molecules of a gas, a liquid or a dissolved substance will move from a region where there are a lot of them (i.e. concentrated) to regions where there are few of them (i.e. less concentrated) until the concentration everywhere is the same. Figure 3.2(a) is a diagram of a cell with a high concentration of molecules (e.g. oxygen) outside and a low concentration inside. The effect of this difference in concentration is to make the molecules diffuse into the cell until the concentration inside and outside is the same, as shown in Figure 3.2(b).



(a) greater concentration outside cell — **(b)** concentrations equal on both sides of the cell membrane

Figure 3.2 Molecules entering a cell by diffusion

Whether this will happen or not depends on whether the cell membrane will let the molecules through. Small molecules such as water (H_2O), carbon dioxide (CO_2) and oxygen (O_2) can pass through the cell membrane fairly easily. So diffusion tends to equalise the concentration of these molecules inside and outside the cell all the time.

When a cell uses oxygen for its aerobic respiration, the concentration of oxygen inside the cell falls and so oxygen molecules diffuse into the cell until the concentration is raised again. During tissue respiration, carbon dioxide is produced and so its concentration inside the cell increases. Once again diffusion takes place, but this time the molecules move out of the cell. In this way, diffusion can explain how a cell takes in its oxygen and gets rid of its carbon dioxide.

The importance of diffusion of gases and solutes

Gases

Most living things require a reliable source of oxygen for respiration. This moves into the organism by diffusion down a concentration gradient. Small animals with a large surface area to volume ratio may obtain oxygen through their body surface. Larger animals rely on gas exchange organs such as lungs or gills, which provide a large surface area for gas exchange, and a circulatory system to transport the oxygen to all their cells. Carbon dioxide, produced during aerobic respiration, is potentially toxic if it builds up. It is removed using the same mechanisms, again by diffusion.

Photosynthetic plants need carbon dioxide for making their food. This diffuses through the stomata in the leaves (see Chapter 8) into the air spaces in the mesophyll, eventually reaching the palisade cells. Oxygen, produced during photosynthesis, along with water vapour from the transpiration stream, diffuses out of the leaf through the stomata. The rate of diffusion of water vapour depends on the temperature, humidity and wind speed (see 'Water uptake' in Chapter 8). Any oxygen needed for respiration (some is generated by photosynthesis) and carbon dioxide produced (some is used up by photosynthesis) also diffuses through the stomata of the leaves.

Nitrogen is the commonest gas in the atmosphere. (78% of the air is nitrogen.) Nitrogen gas also enters the bloodstream by diffusion, but it is not used by the body. It is an inert (unreactive) gas so, under normal circumstances, it causes no problems. However, divers are at risk. As a diver swims deeper, the surrounding water pressure increases and this in turns raises the pressure in the diver's air tank. An increase in nitrogen pressure in the air tank results in more nitrogen diffusing into the diver's tissues, the amount going up the longer the diver stays at depth. Nitrogen is not used by the body tissues, so it builds up. When the diver begins to return to the surface of the water, the pressure decreases and the nitrogen can come out of solution, forming bubbles in the blood if the diver ascends too quickly. These bubbles can block blood flow and become lodged in joints resulting in a condition called **decompression sickness**, or '**the bends**'. Unless the diver rises slowly in planned stages, the effect of the nitrogen bubbles is potentially lethal and can only be overcome by rapid recompression.

Solutes

Mineral ions in solution, such as nitrates and magnesium, are thought to diffuse across the tissues of plant roots, but most are absorbed into the roots by active transport.

In the ileum, water-soluble vitamins such as vitamin B and vitamin C are absorbed into the bloodstream by diffusion.

In the kidneys, some solutes in the renal capsule, such as urea and salts, pass back into the bloodstream by diffusion. Initially, glucose is reabsorbed by diffusion, but active transport is also involved. Dialysis machines (see Chapter 13) use diffusion to remove small solutes (urea, uric acid and excess salts) from the blood.

Rates of diffusion

Molecules and ions in liquids and gases move around randomly using **kinetic energy** (energy from movement). The speed with which a substance diffuses through a cell wall or cell membrane will depend on temperature and many other conditions including the distance it has to diffuse, the difference between its concentration inside and outside the cell, the size of its molecules or ions and the surface area across which the diffusion is occurring.

Surface area

If 100 molecules diffuse through 1 mm^2 of a membrane in 1 minute, it is reasonable to suppose that an area of 2 mm^2 will allow twice as many through in the same time. Thus the rate of diffusion into a cell will depend on the cell's surface area. The greater the surface area, the faster is the total diffusion. Cells which are involved in rapid absorption, such as those in the kidney or the intestine, often have their 'free' surface membrane

formed into hundreds of tiny projections called **microvilli** (see Figure 3.3) which increase the absorbing surface.

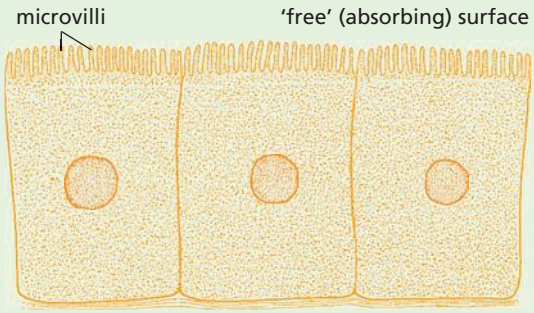


Figure 3.3 Microvilli

The shape of a cell will also affect the surface area. For example, the cell in Figure 3.4(a) has a greater surface area than that in Figure 3.4(b), even though they each have the same volume.

Figure 3.4 Surface area. The cells both have the same volume but the cell in (a) has a much greater surface area.

Temperature

An increase in temperature causes an increase in the kinetic energy which molecules and ions possess. This enables them to move faster, so the process of diffusion speeds up.

Concentration gradient

The bigger the difference in the concentration of a substance on either side of a membrane, the faster it will tend to diffuse. The difference is called a **concentration gradient** or **diffusion gradient** (Figure 3.5). If a substance on one side of a membrane is steadily removed, the diffusion gradient is maintained. When oxygen molecules enter a red blood cell they combine with a chemical (haemoglobin) which takes them out of solution. Thus the concentration of free oxygen molecules inside the cell is kept very low and the diffusion gradient for oxygen is maintained.

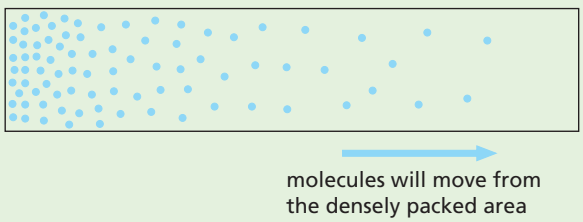


Figure 3.5 Concentration gradient

Distance

Cell membranes are all about the same thickness (approximately 0.007 µm) but plant cell walls vary in their thickness and permeability. Generally speaking, the thicker the wall, the slower the rate of diffusion. When oxygen diffuses from the alveoli of the lungs into red blood cells, it has to travel through the cell membranes of the alveoli, the blood capillaries and the red blood cells in addition to the cytoplasm of each cell. This increased distance slows down the diffusion rate.

Size of molecules or ions

In general, the larger the molecules or ions, the slower they diffuse. However, many ions and molecules in solution attract water molecules around them (see p. 43) and so their effective size is greatly increased. It may not be possible to predict the rate of diffusion from the molecular size alone.

Controlled diffusion

Although for any one substance, the rate of diffusion through a cell membrane depends partly on the concentration gradient, the rate is often faster or slower than expected. Water diffuses more slowly and amino acids diffuse more rapidly through a membrane than might be expected. In some cases this is thought to happen because the ions or molecules can pass through the membrane only by means of special pores. These pores may be few in number or they may be open or closed in different conditions.

In other cases, the movement of a substance may be speeded up by an enzyme working in the cell membrane. So it seems that 'simple passive' diffusion, even of water molecules, may not be so simple or so passive after all where cell membranes are concerned.

When a molecule gets inside a cell there are a great many structures and processes which may move it from where it enters to where it is needed. Simple diffusion is unlikely to play a very significant part in this movement.

Practical work

Experiments on diffusion

1 Diffusion and surface area

- Use a block of starch agar or gelatine at least 3 cm thick. Using a ruler and a sharp knife, measure and cut four cubes

from the jelly with sides of 3.0 cm, 2.0 cm, 1.0 cm and 0.5 cm.
- Place the cubes into a beaker of methylene blue dye or potassium permanganate solution.
- After 15 minutes, remove the cubes with forceps and place them on to a white tile.
- Cut each of the cubes in half and measure the depth to which the dye has diffused.
- Calculate the surface area and volume of each cube and construct a table of your data. Remember to state the units in the heading for each column.

Question
Imagine that these cubes were animals, with the jelly representing living cells and the dye representing oxygen. Which of the 'animals' would be able to survive by relying on diffusion through their surface to provide them with oxygen?

Taking it further
Try cutting different shapes, for example cutting a block 3.0 cm long, 1.0 cm wide and 0.5 cm deep. What type of animal would this represent? (Refer to Figure 1.7 on page 6.) Research how this type of animal obtains its oxygen.

2 Diffusion and temperature

- Set up two beakers with equal volumes of hot water and iced water.
- Add a few grains of potassium permanganate to each beaker and observe how rapidly the dissolved dye spreads through each column of water. An alternative is to use tea bags.

Question
Give an explanation for the results you observed.

3 Diffusion and concentration gradients and distance

- Push squares of wetted red litmus paper with a glass rod or wire into a wide glass tube which is at least 30 cm long and corked at one end, so that they stick to the side and are evenly spaced out, as shown in Figure 3.6. (It is a good strategy to mark 2 cm intervals along the outside of the tube, starting at 10 cm from one end, with a permanent marker or white correction fluid before inserting the litmus paper.)
- Close the open end of the tube with a cork carrying a plug of cotton wool saturated with a strong solution of ammonia. Start a stop watch.
- Observe and record the time when each square of litmus starts to turn blue in order to determine the rate at which the alkaline ammonia vapour diffuses along the tube.
- Repeat the experiment using a dilute solution of ammonia.
- Plot both sets of results on a graph, labelling each plot line.

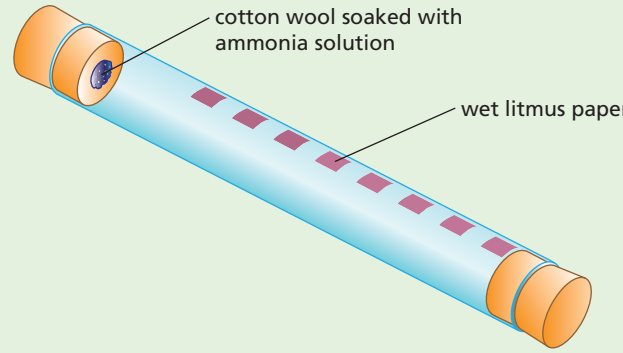


Figure 3.6 Experiment to measure the rate of diffusion of ammonia in air

Questions
1 Which ammonia solution diffused faster? Can you explain why?
2 Study your graph. What happened to the rate of diffusion as the ammonia travelled further along the tube? Can you explain why?

4 Diffusion and particle size

- Take a 15 cm length of dialysis tubing which has been soaked in water and tie a knot tightly at one end.
- Use a dropping pipette to partly fill the tubing with a mixture of 1% starch solution and 1% glucose solution.
- Rinse the tubing and test-tube under the tap to remove all traces of starch and glucose solution from the outside of the dialysis tubing.
- Put the tubing in a boiling tube and hold it in place with an elastic band as shown in Figure 3.7.
- Fill the boiling tube with water and leave for 30 minutes.
- Use separate teat pipettes to remove samples of liquid from the dialysis tubing and the boiling tube. Test both samples with iodine solution and Benedict's reagent.

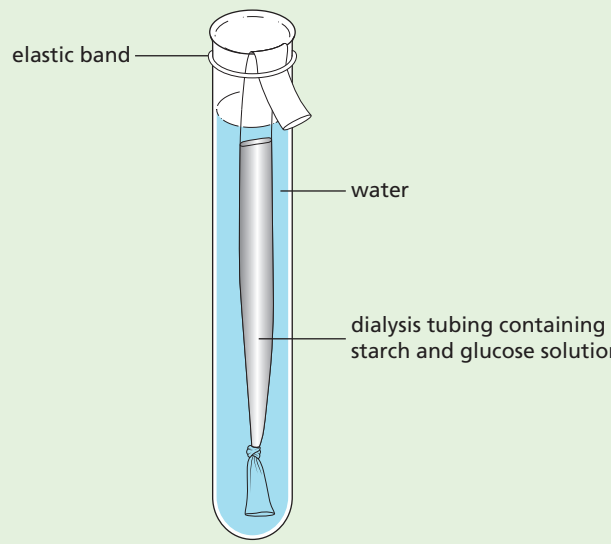


Figure 3.7 Demonstrating the partial permeability of dialysis tubing

Result
The liquid inside the dialysis tubing goes blue with iodine solution and may give a positive Benedict's test, but the sample from the boiling tube only gives a positive Benedict's test.

Interpretation
The blue colour is characteristic of the reaction which takes place between starch and iodine, and is used as a test for starch. A positive Benedict's test gives a colour change from blue to cloudy green, yellow or brick red (see Chapter 4). The results show that glucose molecules have passed through the dialysis tubing into the water but the starch molecules have not moved out of the dialysis tubing. This is what we would expect if the dialysis tubing was partially permeable on the basis of its pore size. Starch molecules are very large (see Chapter 4) and probably cannot get through the pores. Glucose molecules are much smaller and can, therefore, get through.

Osmosis

If a dilute solution is separated from a concentrated solution by a **partially permeable** membrane, water diffuses across the membrane from the dilute to the concentrated solution. This is known as **osmosis** and is shown in Figure 3.8.

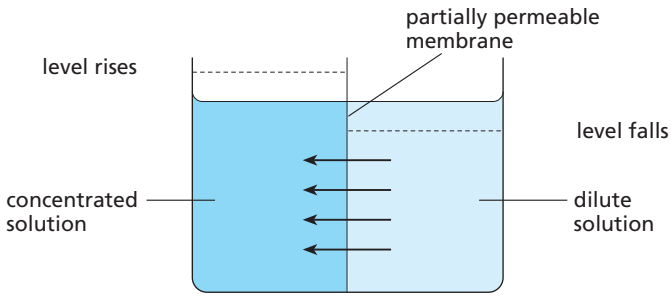


Figure 3.8 Osmosis. Water will diffuse from the dilute solution to the concentrated solution through the partially permeable membrane. As a result, the liquid level will rise on the left and fall on the right.

A partially permeable membrane is porous but allows water to pass through more rapidly than dissolved substances.

Since a dilute solution contains, in effect, more water molecules than a concentrated solution, there is a diffusion gradient which favours the passage of water from the dilute solution to the concentrated solution.

In living cells, the cell membrane is partially permeable and the cytoplasm and vacuole (in plant cells) contain dissolved substances. As a consequence, water tends to diffuse into cells by osmosis if they are surrounded by a weak solution, e.g. fresh water. If the cells are surrounded by a stronger solution, e.g. sea water, the cells may lose water by osmosis. These effects are described more fully later.

Animal cells

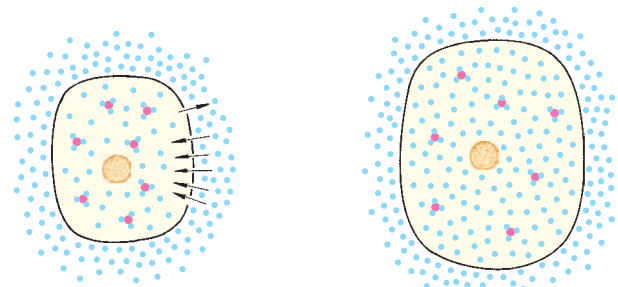
In Figure 3.9 an animal cell is shown very simply. The coloured circles represent molecules in the cytoplasm. They may be sugar, salt or protein molecules. The blue circles represent water molecules.

The cell is shown surrounded by pure water. Nothing is dissolved in the water; it has 100% concentration of water molecules. So the concentration of free water molecules outside the cell is greater than that inside and, therefore, water will diffuse into the cell by osmosis.

The membrane allows water to go through either way. So in our example, water can move into or out of the cell.

The cell membrane is partially permeable to most of the substances dissolved in the cytoplasm. So although the concentration of these substances inside may be high, they cannot diffuse freely out of the cell.

The water molecules move into and out of the cell, but because there are more of them on the outside, they will move in faster than they move out. The liquid outside the cell does not have to be 100% pure water. As long as the concentration of water outside is higher than that inside, water will diffuse in by osmosis.



(a) There is a higher concentration of free water molecules outside the cell than inside, so water diffuses into the cell.

(b) The extra water makes the cell swell up.

Figure 3.9 Osmosis in an animal cell

Water entering the cell will make it swell up and, unless the extra water is expelled in some way, the cell will burst.

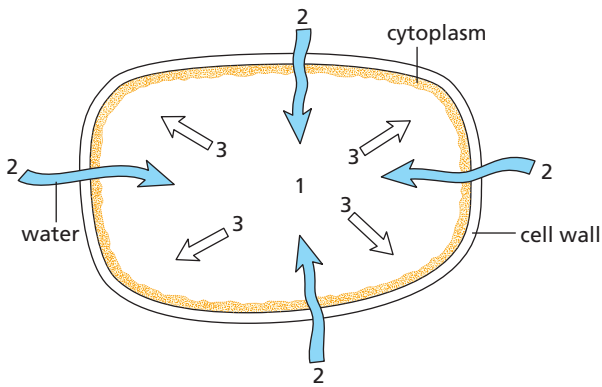
Conversely, if the cells are surrounded by a solution which is more concentrated than the cytoplasm, water will pass out of the cell by osmosis and the cell will shrink. Excessive uptake or loss of water by osmosis may damage cells.

For this reason, it is very important that the cells in an animal's body are surrounded by a liquid which has the same concentration as the liquid inside the cells. The liquid outside the cells is called **tissue fluid** (see 'Blood and lymphatic vessels' in Chapter 9) and its concentration depends on the concentration of the blood. In vertebrates, the concentration of the blood is monitored by the brain and adjusted by the kidneys, as described in Chapter 13.

By keeping the blood concentration within narrow limits, the concentration of the tissue fluid remains more or less constant (see 'Homeostasis' in Chapter 14) and the cells are not bloated by taking in too much water or dehydrated by losing too much.

Plant cells

The cytoplasm of a plant cell and the cell sap in its vacuole contain salts, sugars and proteins which effectively reduce the concentration of free water molecules inside the cell. The cell wall is freely permeable to water and dissolved substances but the cell membrane of the cytoplasm is partially permeable. If a plant cell is surrounded by water or a solution more dilute than its contents, water will pass into the vacuole by osmosis. The vacuole will expand and press outwards on the cytoplasm and cell wall. The cell wall of a mature plant cell cannot be stretched, so there comes a time when the inflow of water is resisted by the inelastic cell wall, as shown in Figure 3.10.



1 since there is effectively a lower concentration of water in the cell sap
2 water diffuses into the vacuole
3 and makes it push out against the cell wall

Figure 3.10 Osmosis in a plant cell

This has a similar effect to inflating a soft bicycle tyre. The tyre represents the firm cell wall, the floppy inner tube is like the cytoplasm and the air inside corresponds to the vacuole. If enough air is pumped in, it pushes the inner tube against the tyre and makes the tyre hard.

When plant cells have absorbed a maximum amount of water by osmosis, they become very rigid, due to the pressure of water pressing outwards on the cell wall. The end result is that the stems and leaves are supported. If the cells lose water there is no longer any water pressure pressing outwards against the cell walls and the stems and leaves are no longer supported. At this point, the plant becomes limp and wilts (see Figure 3.11).

(a) plant wilting

(b) plant recovered after watering

Figure 3.11 Wilting

Practical work

Experiments on osmosis

Some of the experiments use 'Visking' dialysis tubing. It is made from cellulose and is partially permeable, allowing water molecules to diffuse through freely, but restricting the passage of dissolved substances to varying extents. It is used in kidney dialysis machines because it lets the small molecules of harmful waste products, such as urea, out of the blood but retains the blood cells and large protein molecules (Chapter 13).

1 Osmosis and water flow

- Take a 20 cm length of dialysis tubing which has been soaked in water and tie a knot tightly at one end.
- Place 3 cm^3 of a strong sugar solution in the tubing using a plastic syringe and add a little coloured dye.
- Fit the tubing over the end of a length of capillary tubing and hold it in place with an elastic band. Push the capillary tubing into the dialysis tubing until the sugar solution enters the capillary.
- Now clamp the capillary tubing so that the dialysis tubing is totally immersed in a beaker of water, as shown in Figure 3.12.
- Watch the level of liquid in the capillary tubing over the next 10–15 minutes.

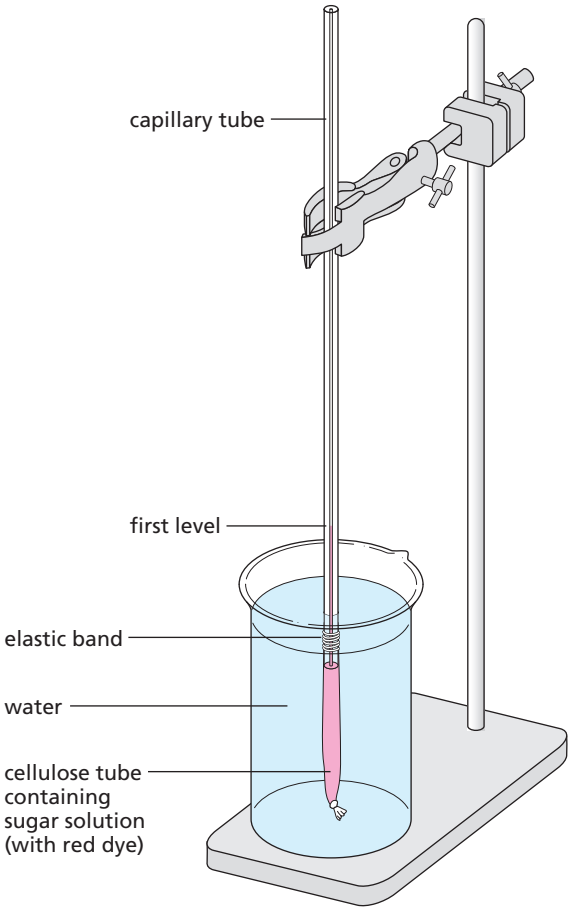


Figure 3.12 Demonstration of osmosis

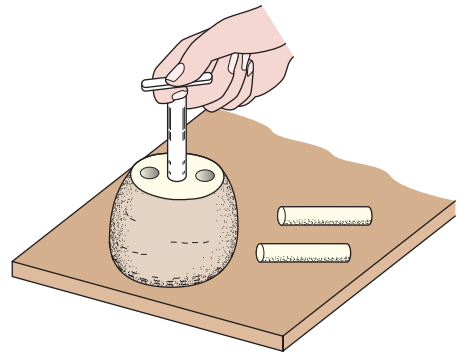
Result
The level of liquid in the capillary tube rises.

Interpretation
Water must be passing into the sugar solution from the beaker. This is what you would expect when a concentrated solution is separated from water by a partially permeable membrane.

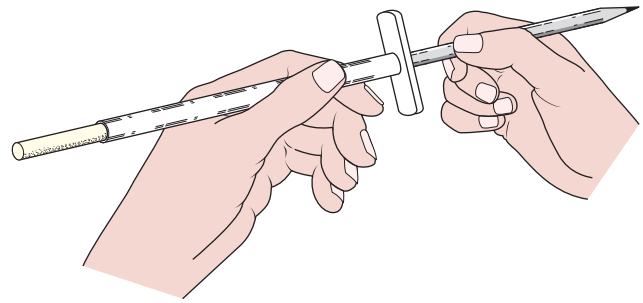
A process similar to this might be partially responsible for moving water from the roots to the stem of a plant.

2 The effects of water and sugar solution on potato tissue

- Push a No.4 or No.5 cork borer into a large potato. **Caution:** Do not hold the potato in your hand but use a board as in Figure 3.13(a).
- Push the potato tissue out of the cork borer using a pencil as in Figure 3.13(b). Prepare a number of potato cylinders in this way and choose the two longest. (They should be at least 50 mm long.) Cut these two accurately to the same length, e.g. 50, 60 or 70 mm. Measure carefully.
- Label two test-tubes A and B and place a potato cylinder in each. Cover the potato tissue in tube A with water; cover the tissue in B with a 20% sugar solution.
- Leave the tubes for 24 hours.
- After this time, remove the cylinder from tube A and measure its length. Notice also whether it is firm or flabby. Repeat this for the potato in tube B, but rinse it in water before measuring it.



(a) place the potato on a board



(b) push the potato cylinder out with a pencil

Figure 3.13 Obtaining cylinders of potato tissue

Result
The cylinder from tube A should have gained a millimetre or two and feel firm. The cylinder from tube B should be a millimetre or two shorter and feel flabby.

Interpretation
The cells of the potato in tube A have absorbed water by osmosis, causing an increase in the length of the potato cylinder.

In tube B, the sugar solution is stronger than the cell sap of the potato cells, so these cells have lost water by osmosis, resulting in the potato cylinder becoming flabby and shorter.

An alternative to measuring the potato cores is to weigh them before and after the 24 hours' immersion in water or sugar solution. The core in tube A should gain weight and that in tube B should lose weight. It is important to blot the cores dry with a paper towel before weighing them.

Whichever method is used, it is a good idea to pool the results of the whole class since the changes may be quite small. A gain in length of 1 or 2 mm might be due to an error in measurement, but if most of the class record an increase in length, then experimental error is unlikely to be the cause.

Key definition

Osmosis is the net movement of water molecules from a region of higher water potential (a dilute solution) to a region of lower water potential (a concentrated solution) through a partially permeable membrane.

How osmosis works

When a substance such as sugar dissolves in water, the sugar molecules attract some of the water molecules and stop them moving freely. This, in effect, reduces the concentration of water molecules. In Figure 3.14 the sugar molecules on the right have 'captured' half the water molecules. There are more free water molecules on the left of the membrane than on the right, so water will diffuse more rapidly from left to right across the membrane than from right to left.

The partially permeable membrane does not act like a sieve in this case. The sugar molecules can diffuse from right to left but, because they are bigger and surrounded by a cloud of water molecules, they diffuse more slowly than the water, as shown in Figure 3.15.

Artificial partially permeable membranes are made from cellulose acetate in sheets or tubes and used for **dialysis**. The pore size can be adjusted during manufacture so that large molecules cannot get through at all.

The **cell membrane** behaves like a partially permeable membrane. The partial permeability may depend on pores in the cell membrane but the processes involved are far more complicated than in an artificial membrane and depend on the structure of the membrane and on living processes in the cytoplasm. The cell membrane contains lipids and proteins. Anything which denatures proteins, for example, heat, also destroys the structure and the partially permeable properties of a cell membrane. If this happens, the cell will die as essential substances diffuse out of the cell and harmful chemicals diffuse in.

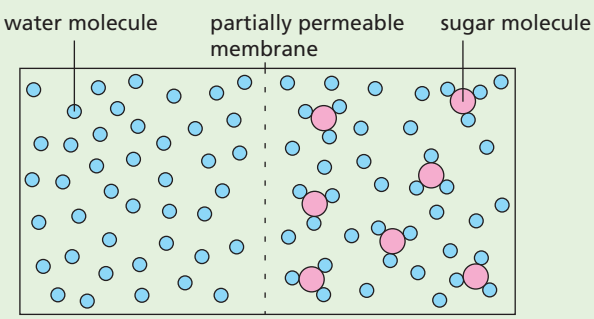


Figure 3.14 The diffusion gradient for water. There are more free water molecules on the left, so more will diffuse from left to right than in the other direction. Sugar molecules will diffuse more slowly from right to left.

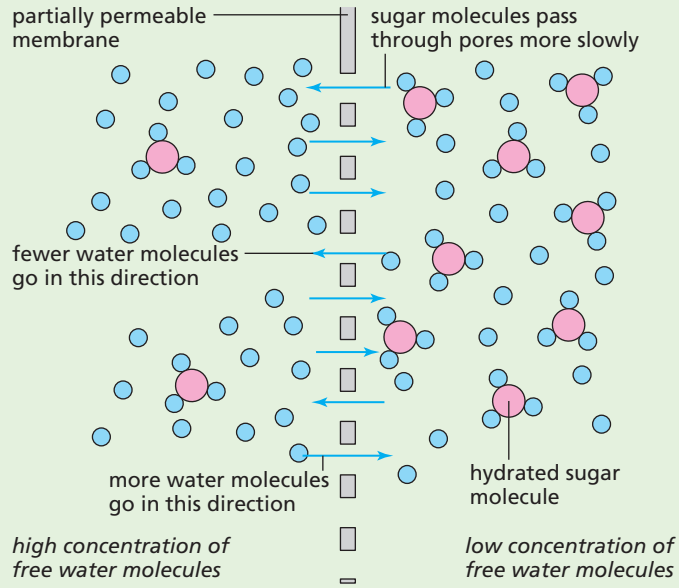


Figure 3.15 The diffusion theory of osmosis

Water potential

The **water potential** of a solution is a measure of whether it is likely to lose or gain water molecules from another solution. A dilute solution, with its high proportion of free water molecules, is said to have a higher water potential than a concentrated solution, because water will flow from the dilute to the concentrated solution (from a high potential to a low potential). Pure water has the highest possible water potential because water molecules will flow from it to any other aqueous solution, no matter how dilute. When adjacent cells contain sap with different water potentials, a water potential gradient is created. Water will move from a cell with a higher water potential (a more dilute solution) to a cell with a lower water potential (a more concentrated solution). This is thought to be one way in which water moves from root hair cells through to the xylem of a plant root (see Figure 8.11 on page 115).

The importance of water potential and osmosis in the uptake of water by plants

A plant cell with the vacuole pushing out on the cell wall is said to be **turgid** and the vacuole is exerting **turgor pressure** on the inelastic cell wall.

If all the cells in a leaf and stem are turgid, the stem will be firm and upright and the leaves held out straight. If the vacuoles lose water for any reason, the

cells will lose their turgor and become **flaccid**. (See Experiment 4 'Plasmolysis' on page 46.) If a plant has flaccid cells, the leaves will be limp and the stem will droop. A plant which loses water to this extent is said to be 'wilting' (see Figure 3.11).

Root hair cells are in contact with water trapped between soil particles. When the water potential of the cell sap is lower than that of the soil water, the water will enter the cells by osmosis providing the plant with the water it needs. (This process is described in more detail in 'Water uptake' in Chapter 8.)

When a farmer applies chemical fertilisers to the soil, the fertilisers dissolve in the soil water. Too much fertiliser can lower the osmotic potential of the soil water. This can draw water out of the plant root hair cells by osmosis, leading to wilting and death of crop plants.

Irrigation of crops can have a similar effect. Irrigation which provides just enough water for the plant can lead to a build-up of salts in the soil. The salts will eventually cause the soil water to have a lower water potential than the plant root cells. Crops can then no longer be grown on the land, because they wilt and die because of water loss by osmosis. Much agricultural land in hot countries has become unusable due to the side-effects of irrigation (Figure 3.16).

Figure 3.16 An irrigation furrow

Some countries apply salt to roads in the winter to prevent the formation of ice (Figure 3.17). However, vehicle wheels splash the salt on to plants at the side of the road. The build-up of salts in the roadside soil can kill plants living there, due to water loss from the roots by osmosis.

Figure 3.17 Salt gritter at work to prevent ice formation on a road

The importance of water potential and osmosis in animal cells and tissues

It is vital that the fluid which bathes cells in animals, such as tissue fluid or blood plasma, has the same water potential as the cell contents. This prevents any net flow of water into or out of the cells. If the bathing fluid has a higher water potential (a weaker concentration) than the cells, water will move into the cells by osmosis causing them to swell up. As animal cells have no cell wall and the membrane has little strength, water would continue to enter and the cells will eventually burst (a process called **haemolysis** in red blood cells). Single-celled animals such as *Amoeba* (see Figure 1.32 on page 19) living in fresh water obviously have a problem. They avoid bursting by possessing a **contractile vacuole**. This collects the water as it enters the cell and periodically releases it through the cell membrane, effectively baling the cell out. When surgeons carry out operations on a patient's internal organs, they sometimes need to rinse a wound. Pure water cannot be used as this would enter any cells it came into contact with and cause them to burst. A saline solution, with the same water potential as tissue fluid, has to be used.

In England in 1995, a teenager called Leah Betts (Figure 3.18) collapsed after taking an Ecstasy tablet. One of the side-effects of taking Ecstasy is that the brain thinks the body is dehydrating so the person becomes very thirsty. Leah drank far too much water: over 7 litres (12 pints) in 90 minutes. Her kidneys could not cope and the extra water in her system

diluted her blood. Her brain cells took in water by osmosis, causing them to swell up and burst. She died hours later.

Figure 3.18 Poster campaign featuring Leah Betts to raise awareness of the dangers of taking the drug ecstasy.

Diarrhoea is the loss of watery faeces. It is caused when water cannot be absorbed from the contents of the large intestine, or when extra water is secreted into the large intestine due to a viral or bacterial infection. For example, the cholera bacterium produces a toxin (poison) that causes the secretion of chloride ions into the small intestine. This lowers the water potential of the gut contents, so water is drawn into the intestine by osmosis. The result is the production of watery faeces. Unless the condition is treated, dehydration and loss of salts occur, which can be fatal. Patients need rehydration therapy. This involves the provision of frequent sips of water and the use of rehydration drinks. These usually come in sachets available from pharmacists and supermarkets. The contents are dissolved in water and drunk to replace the salts and glucose that are lost through dehydration.

During physical activity, the body may sweat in order to maintain a steady temperature. If liquids are not drunk to compensate for water loss through sweating, the body can become dehydrated. Loss of water from the blood results in the plasma becoming more concentrated (its water potential decreases). Water is then drawn out of the red blood cells by osmosis. The cells become **plasmolysed**. Their surface area is reduced, causing them to be less effective in carrying oxygen. The shape of the cells is known as being **crenated** (see Figure 3.19).

People doing sport sometimes use sports drinks (Figure 3.20) which are **isotonic** (they have the same water potential as body fluids). The drinks contain water, salts and glucose and are designed to replace lost water and salts, as well as providing energy, without creating osmotic problems to body cells. However, use of such drinks when not exercising vigorously can lead to weight gain in the same way as the prolonged use of any sugar-rich drink.

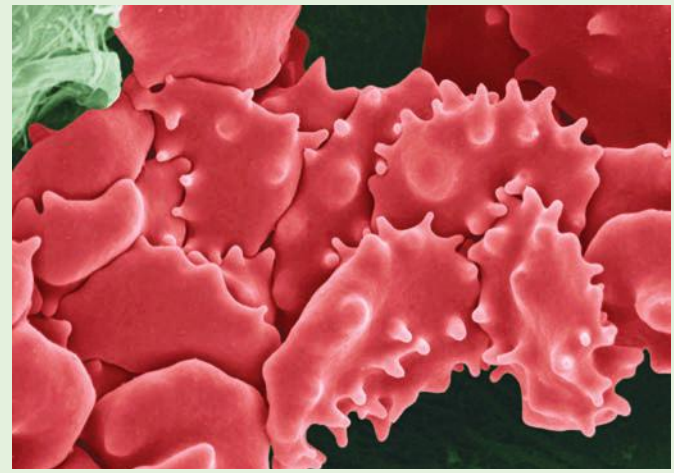


Figure 3.19 Plasmolysed red blood cells

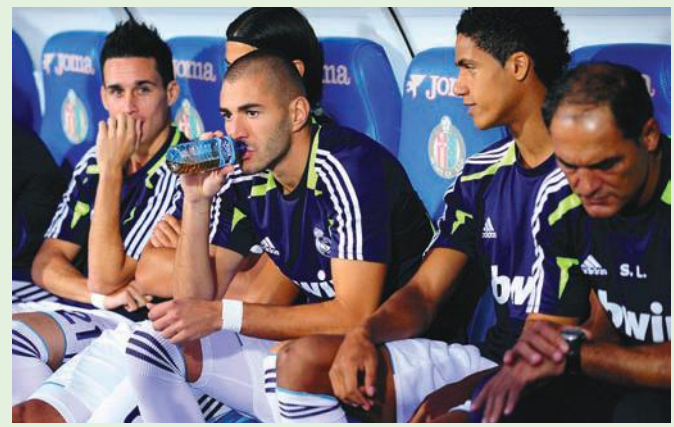


Figure 3.20 People may use isotonic sports drinks.

Practical work

Further experiments on osmosis

3 Osmosis and turgor

- Take a 20 cm length of dialysis tubing which has been soaked in water and tie a knot tightly at one end.
- Place 3 cm^3 of a strong sugar solution in the tubing using a plastic syringe (Figure 3.21(a)) and then knot the open end of the tube (Figure 3.21(b)). The partly-filled tube should be quite floppy (Figure 3.21(c)).

- Place the tubing in a test-tube of water for 30–45 minutes.
- After this time, remove the dialysis tubing from the water and note any changes in how it looks or feels.

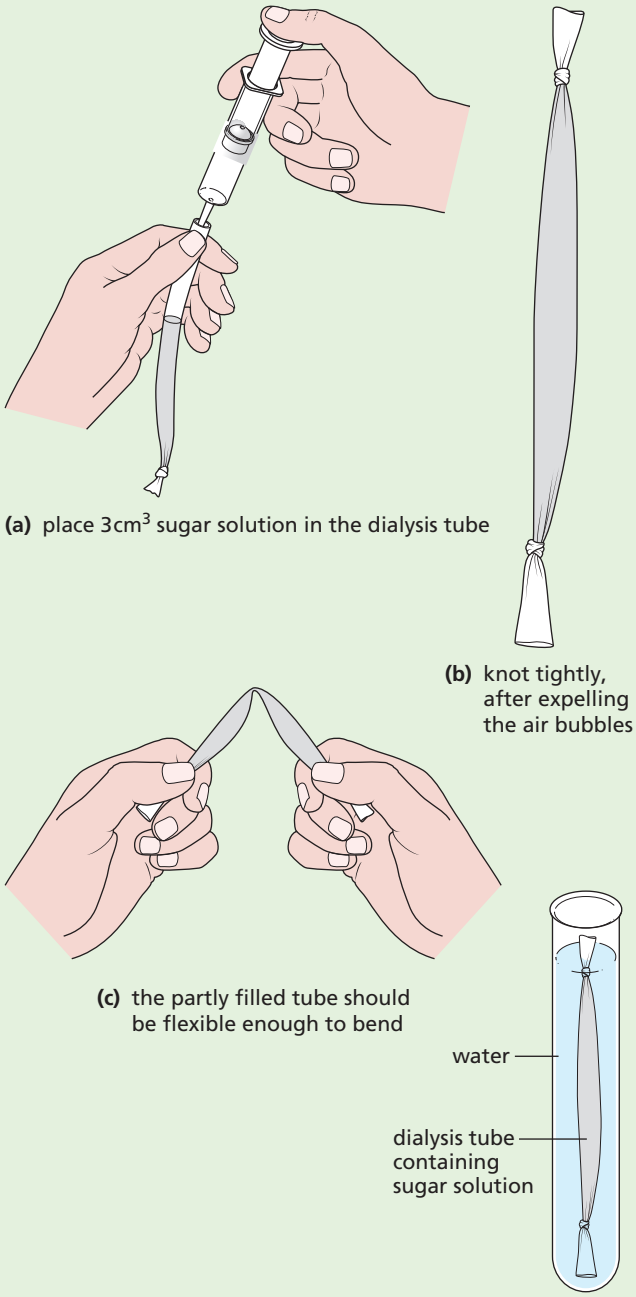


Figure 3.21 Experiment to illustrate turgor in a plant cell

Result
The tubing will become firm, distended by the solution inside.

Interpretation
The dialysis tubing is partially permeable and the solution inside has fewer free water molecules than outside. Water has, therefore, diffused in and increased the volume and the pressure of the solution inside.

This is a crude model of what is thought to happen to a plant cell when it becomes turgid. The sugar solution represents the cell sap and the dialysis tubing represents the cell membrane and cell wall combined.

4 Plasmolysis

- Peel a small piece of epidermis (the outer layer of cells) from a red area of a rhubarb stalk (see Figure 2.9(c) on page 28).
- Place the epidermis on a slide with a drop of water and cover with a coverslip (see Figure 2.9(b)).
- Put the slide on a microscope stage and find a small group of cells.
- Place a 30% solution of sugar at one edge of the coverslip with a pipette and then draw the solution under the coverslip by placing a piece of blotting paper on the opposite side, as shown in Figure 3.22.
- Study the cells you identified under the microscope and watch for any changes in their appearance.

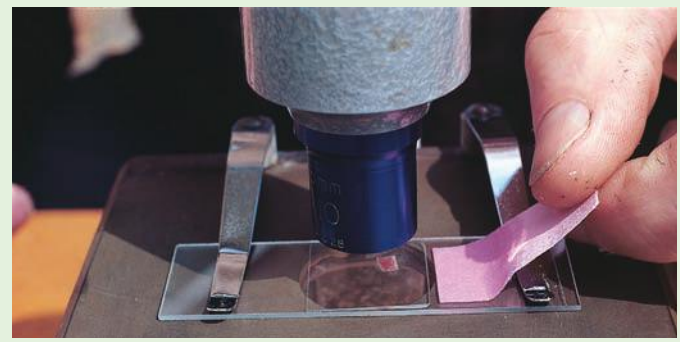
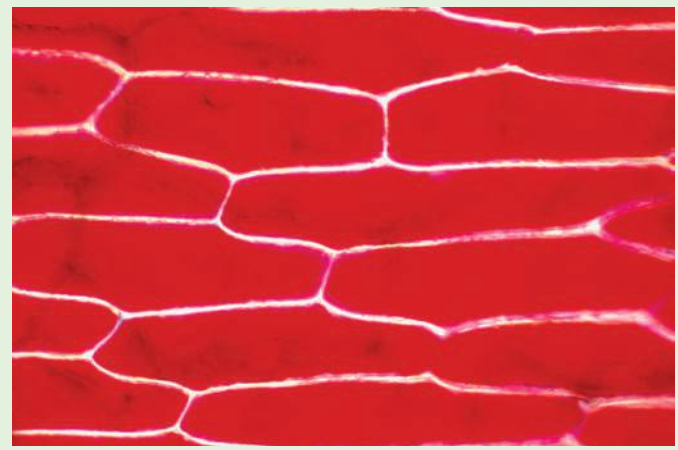


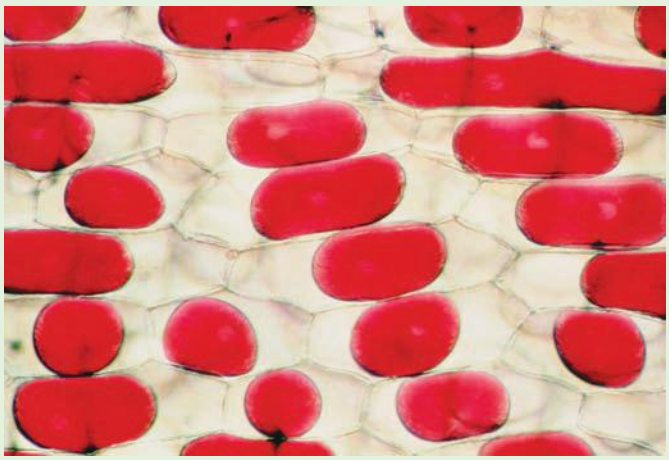
Figure 3.22 Changing the water for sugar solution

Result
The red cell sap will appear to shrink and get darker and pull the cytoplasm away from the cell wall leaving clear spaces. (It is not possible to see the cytoplasm but its presence can be inferred from the fact that the red cell sap seems to have a distinct outer boundary in those places where it has separated from the cell wall.) Figure 3.23 shows the turgid and plasmolysed cells.



(a) Turgid cells (×100). The cells are in a strip of epidermis from a rhubarb stalk. The cytoplasm is pressed against the inside of the cell wall by the vacuole.

Figure 3.23 Demonstration of plasmolysis in rhubarb cells

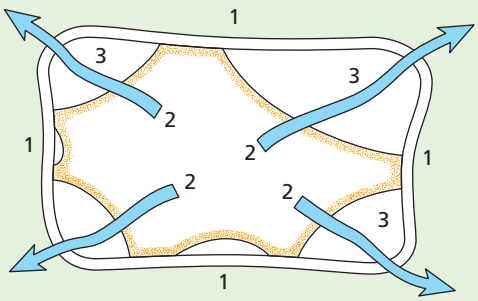


(b) Plasmolysed cells (×100). The same cells as they appear after treatment with sugar solution. The vacuole has lost water by osmosis, shrunk and pulled the cytoplasm away from the cell wall.

Figure 3.23 Demonstration of plasmolysis in rhubarb cells (continued)

Interpretation

The interpretation in terms of osmosis is outlined in Figure 3.24. The cells are said to be **plasmolysed**.



1 the solution outside the cell is more concentrated than the cell sap
2 water diffuses out of the vacuole
3 the vacuole shrinks, pulling the cytoplasm away from the cell wall, leaving the cell flaccid

Figure 3.24 Plasmolysis

The plasmolysis can be reversed by drawing water under the coverslip in the same way that you drew the sugar solution under. It may need two or three lots of water to flush out all the sugar. If you watch a group of cells, you should see their vacuoles expanding to fill the cells once again.

Rhubarb is used for this experiment because the coloured cell sap shows up. If rhubarb is not available, the epidermis from a red onion scale can be used.

5 The effects of varying the concentration of sucrose solution on potato tissue

- Push a No.4 or No.5 cork borer into a large potato. **Caution:** Do not hold the potato in your hand, but use a board as in Figure 3.13(a) on page 42.
- Push the potato tissue out of the cork borer using a pencil as in Figure 3.13(b). Prepare six potato cylinders in this way and cut them all to the same length. (They should be at least 50 mm long.) Measure them carefully.
- Label six test-tubes with the concentration of sucrose solution in them (e.g. 0.0 mol dm^{-3}, 0.2 mol dm^{-3}, 0.4 mol dm^{-3}, 0.6 mol dm^{-3}, 0.8 mol dm^{-3} and 1.0 mol dm^{-3}) and place them in a test-tube rack.
- Add the same volume of the correct sucrose solution to each test-tube.
- Weigh a cylinder of potato, record its mass and place it in the first test-tube. Repeat until all the test-tubes have been set up.
- Leave the tubes for at least 30 minutes.
- After this time, remove the potato cylinder from the first tube, surface dry the potato and re-weigh it. Notice also whether it is firm or flabby. Repeat this for the other potato cylinders.
- Calculate the change in mass and the percentage change in mass for each cylinder.

$$\text{Percentage change in mass} = \frac{\text{change in mass}}{\text{mass at start}} \times 100$$

- Plot the results on a graph with sucrose concentration on the horizontal axis and percentage change in mass on the vertical axis.
  Note: there will be negative as well as positive percentage changes in mass, so your graph axes will have to allow for this.

Result

The cylinders in the weaker sucrose solutions will have gained mass and feel firm. One of the cylinders may have shown no change in mass. The cylinders in the more concentrated sucrose solutions will have lost mass and feel limp.

Interpretation

If the cells of the potato have absorbed water by osmosis, there will be an increase in the mass of the potato cylinder. This happens when the external solution has a higher water potential than that inside the potato cells. (The sucrose solution is less concentrated than the contents of the potato cells.) Water molecules move into each cell through the cell membrane. The water molecules move from a higher water potential to a lower water potential. The cells become turgid, so the cylinder feels firm.

If the cells of the potato have lost water by osmosis, there will be a decrease in mass of the potato cylinder. This happens when the external solution has a lower water potential than that inside the potato cells. (The sucrose solution is more concentrated than the contents of the potato cells.) Water molecules move out of each cell through the cell membrane. The water molecules move from a higher water potential to a lower water potential. The cells become plasmolysed or flaccid, so the cylinder feels flabby.

Question
Study your graph. Can you predict the sucrose concentration which would be equivalent to the concentration of the cell sap in the potato cells?

6 Partial permeability

- Take a 15 cm length of dialysis tubing which has been soaked in water and tie a knot tightly at one end.
- Use a dropping pipette to partly fill the tubing with 1% starch solution.
- Put the tubing in a test-tube and hold it in place with an elastic band as shown in Figure 3.25.
- Rinse the tubing and test-tube under the tap to remove all traces of starch solution from the outside of the dialysis tube.
- Fill the test-tube with water and add a few drops of iodine solution to colour the water yellow.
- Leave for 10–15 minutes.
- After this time, observe any changes in the solution in the test-tube.

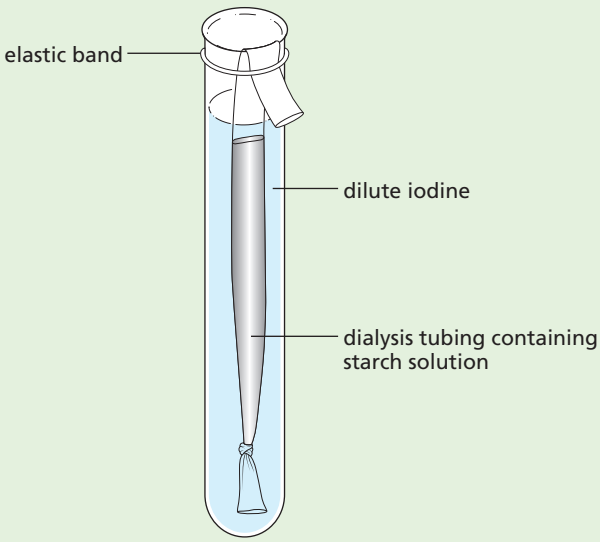


Figure 3.25 Experiment to demonstrate the effect of a partially permeable membrane

Result
The starch inside the dialysis tubing goes blue but the iodine outside stays yellow or brown.

Interpretation
The blue colour is characteristic of the reaction which takes place between starch and iodine, and is used as a test for starch (see Chapter 4). The results show that iodine molecules have passed through the dialysis tubing into the starch but the starch molecules have not moved out into the iodine. This is what we would expect if the dialysis tubing were partially permeable on the basis of its pore size. Starch molecules are very large and probably cannot get through the pores. Iodine molecules are much smaller and can, therefore, get through.

Note: This experiment illustrates that movement of water is not necessarily involved and the pore size of the membrane makes it genuinely partially permeable with respect to iodine and starch.

Active transport

Key definition
Active transport is the movement of particles through a cell membrane from a region of lower concentration to a region of higher concentration using the energy from respiration.

The importance of active transport

If diffusion were the only method by which a cell could take in substances, it would have no control over what went in or out. Anything that was more concentrated outside would diffuse into the cell whether it was harmful or not. Substances which the cell needed would diffuse out as soon as their concentration inside the cell rose above that outside it. The cell membrane, however, has a great deal of control over the substances which enter and leave the cell.

In some cases, substances are taken into or expelled from the cell against the concentration gradient. For example, sodium ions may continue to pass out of a cell even though the concentration outside is greater than inside. The cells lining the small intestine take up glucose against a concentration gradient. The processes by which substances are moved against a concentration gradient are not fully understood and may be quite different for different substances but they are all generally described as **active transport**.

Anything which interferes with respiration, such as a lack of oxygen or glucose, prevents active transport taking place. This indicates that active transport needs a supply of energy from respiration. Figure 3.26 shows a possible model to explain active transport.

The carrier molecules shown in Figure 3.26 are protein molecules. As shown in (b), they are responsible for transporting substances across the membrane during active transport.

In some cases, a combination of active transport and controlled diffusion seems to occur. For example, sodium ions are thought to get into a cell by diffusion through special pores in the membrane and are expelled by a form of active transport. The reversed diffusion gradient for sodium ions created in this way is very important in the conduction of nerve impulses in nerve cells.

Epithelial cells in the villi of the small intestine have the role of absorbing glucose against a concentration gradient. The cells contain numerous mitochondria in which respiration takes place. The chemical energy produced is converted into kinetic energy for the movement of the glucose molecules. The same type of process occurs in the cells of the kidney tubules for the reabsorption of glucose molecules into the bloodstream against their concentration gradient.

Plants need to absorb mineral salts from the soil, but these salts are in very dilute solution. Active transport enables the cells of plant roots to take up salts from this dilute solution against the concentration gradient. Again, chemical energy from respiration is converted into kinetic energy for movement of the salts.

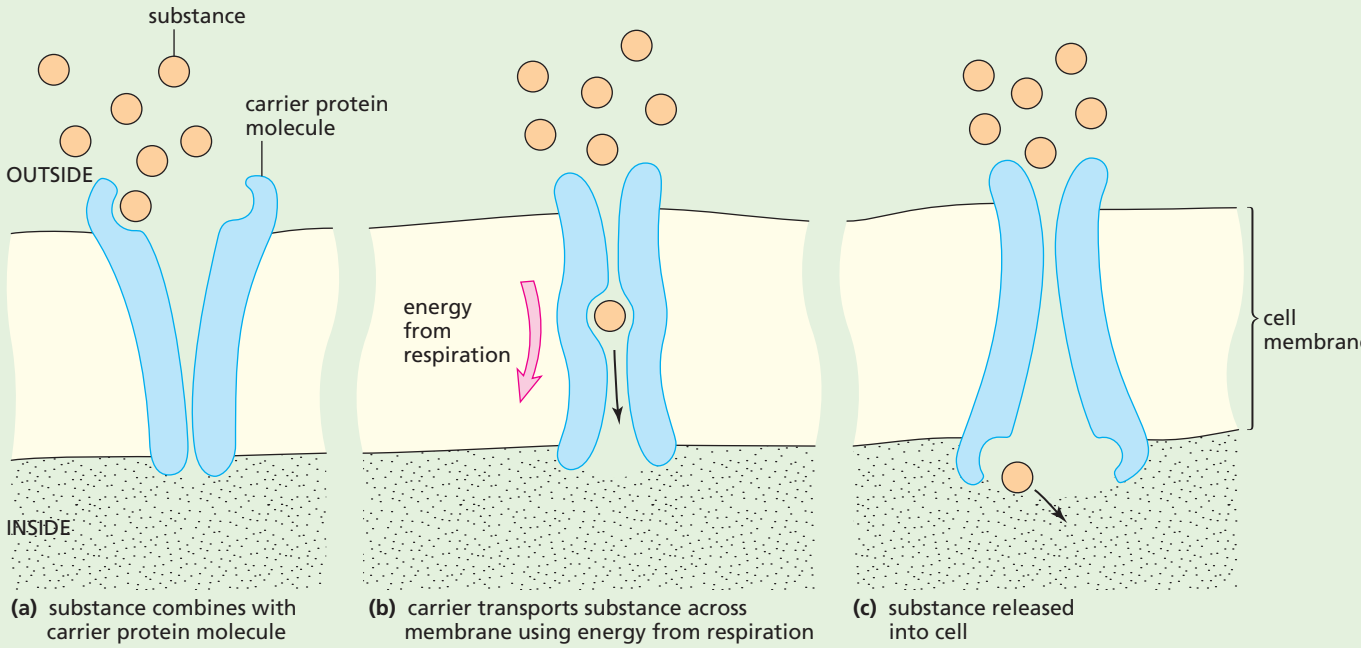


Figure 3.26 A theoretical model to explain active transport

Questions

Core

1 A 10% solution of copper sulfate is separated by a partially permeable membrane from a 5% solution of copper sulfate.
Will water diffuse from the 10% solution to the 5% solution or from the 5% solution to the 10% solution? Explain your answer.

2 If a fresh beetroot is cut up, the pieces washed in water and then left for an hour in a beaker of water, little or no red pigment escapes from the cells into the water. If the beetroot is boiled first, the pigment does escape into the water.
Bearing in mind the properties of a living cell membrane, offer an explanation for this difference.

3 In Experiment 1 (Figure 3.12), what do you think would happen in these cases?
   a A much stronger sugar solution was placed in the cellulose tube.
   b The beaker contained a weak sugar solution instead of water.
   c The sugar solution was in the beaker and the water was in the cellulose tube?

4 In Experiment 1, the column of liquid accumulating in the capillary tube exerts an ever-increasing pressure on the solution in the dialysis tubing. Bearing this in mind and assuming a very long capillary, at what stage would you expect the net flow of water from the beaker into the dialysis tubing to cease?

Extended

5 When doing experiments with animal tissues they are usually bathed in Ringer's solution, which has a concentration similar to that of blood or tissue fluid.
Why do you think this is necessary?

6 Why does a dissolved substance reduce the number of 'free' water molecules in a solution?

7 When a plant leaf is in daylight, its cells make sugar from carbon dioxide and water. The sugar is at once turned into starch and deposited in plastids.
What is the osmotic advantage of doing this? (Sugar is soluble in water; starch is not.)

8 In Experiment 3 (Figure 3.21), what might happen if the cellulose tube filled with sugar solution was left in the water for several hours?

9 In Experiment 4, Figure 3.24 explains why the vacuole shrinks. Give a brief explanation of why it swells up again when the cell is surrounded by water.

10 An alternative interpretation of the results of Experiment 6 might be that the dialysis tubing allowed molecules (of any size) to pass in but not out. Describe an experiment to test this possibility and say what results you would expect:
   a if it were correct
   b if it were false.

11 Look at Figure 9.25 on page 136. The symbol O_2 represents an oxygen molecule.
Explain why oxygen is entering the cells drawn on the left but leaving the cells on the right.

12 Look at Figure 11.5 on page 158. It represents one of the small air pockets (an alveolus) which form the lung.
   a Suggest a reason why the oxygen and carbon dioxide are diffusing in opposite directions.
   b What might happen to the rate of diffusion if the blood flow were to speed up?

13 List the ways in which a cell membrane might regulate the flow of substances into the cell.

14 What is your interpretation of the results shown by the graph in Figure 3.27?

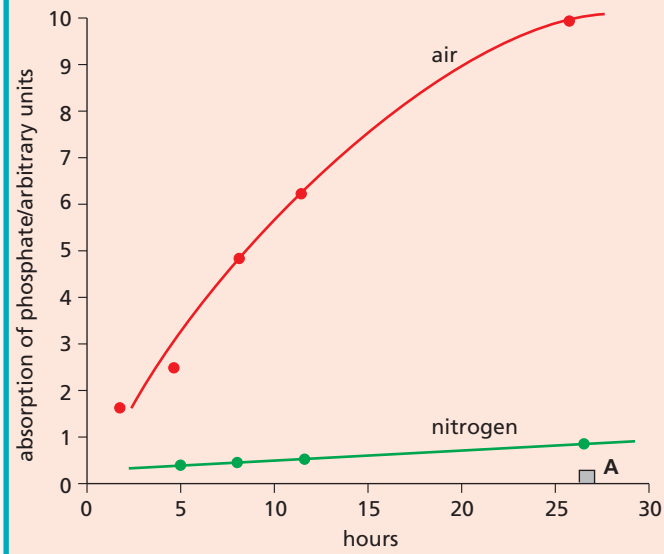


Figure 3.27 The absorption of phosphate ions in air and in nitrogen by roots of beech. **A** represents the concentration of phosphate in external solution

Checklist

After studying Chapter 3 you should know and understand the following:

- Diffusion is the result of molecules of liquid, gas or dissolved solid moving about.
- The molecules of a substance diffuse from a region where they are very concentrated to a region where they are less concentrated.
- Substances may enter cells by simple diffusion, controlled diffusion or active transport.
- Osmosis is the diffusion of water through a partially permeable membrane, from a dilute solution of salt or sugar to a concentrated solution because the concentrated solution contains fewer free water molecules.
- Cell membranes are partially permeable and cytoplasm and cell sap contain many substances in solution.
- Cells take up water from dilute solutions but lose water to concentrated solutions because of osmosis.
- Osmosis maintains turgor in plant cells.
- Active transport involves the movement of substances against their concentration gradient.
- Active transport requires energy.

- Kinetic energy of molecules and ions results in their diffusion.
- Osmosis involves the diffusion of water from a region of higher water potential to a region of lower water potential through a partially permeable membrane.
- The meanings of the terms *turgid*, *turgor pressure*, *plasmolysis* and *flaccid*.
- The importance of water potential and osmosis to animal and plant cells.
- Turgor pressure in cells provides support in plants.
- Active transport is important as it allows movement of substances across membranes against a concentration gradient.

4 Biological molecules

Biological molecules
The chemical elements that make up carbohydrates, fats and proteins
The sub-units that make up biological molecules
Food tests for starch, reducing sugars, proteins, fats and oils, vitamin C
The role of water as a solvent

The shape of proteins and their functions
The structure of DNA
Roles of water as a solvent in organisms

Biological molecules

Carbon is an element present in all biological molecules. Carbon atoms can join together to form chains or ring structures, so biological molecules can be very large (macromolecules), often constructed of repeating sub-units (monomers). Other elements always present are oxygen and hydrogen. Nitrogen is sometimes present. When macromolecules are made of long chains of monomers held together by chemical bonds, they are known as **polymers** (poly means 'many'). Examples are polysaccharides (chains of single sugar units such as glucose), proteins (chains of amino acids) and nucleic acids (chains of nucleotides). Molecules constructed of lots of small units often have different properties from their sub-units, making them suitable for specific functions in living things. For example, glucose is very soluble and has no strength, but cellulose (a macromolecule made of glucose units) is insoluble and very tough – ideal for the formation of cell walls around plant cells.

Cells need chemical substances to make new cytoplasm and to produce energy. Therefore the organism must take in food to supply the cells with these substances. Of course, it is not quite as simple as this; most cells have specialised functions (Chapter 2) and so have differing needs. However, all cells need water, oxygen, salts and food substances and all cells consist of water, proteins, lipids, carbohydrates, salts and vitamins or their derivatives.

Carbohydrates

These may be simple, soluble sugars or complex materials like starch and cellulose, but all carbohydrates contain carbon, hydrogen and oxygen only. A commonly occurring simple sugar is **glucose**, which has the chemical formula $C_6H_{12}O_6$.

The glucose molecule is often in the form of a ring, represented as

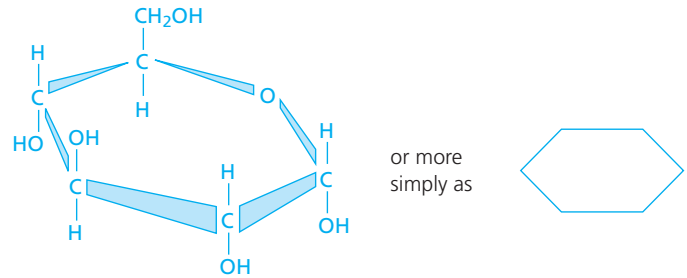


Figure 4.1 Glucose molecule showing ring structure

Two molecules of glucose can be combined to form a molecule of maltose $C_{12}H_{22}O_{11}$ (Figure 4.2).

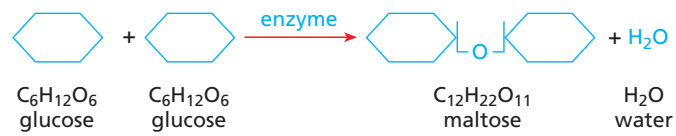


Figure 4.2 Formation of maltose

Sugars with a single carbon ring are called **monosaccharides**, e.g. glucose and fructose. Those sugars with two carbon rings in their molecules are called **disaccharides**, e.g. maltose and sucrose. Mono- and disaccharides are readily soluble in water.

When many glucose molecules are joined together, the carbohydrate is called a **polysaccharide**. **Glycogen** (Figure 4.3) is a polysaccharide that forms a food storage substance in many animal cells. The **starch** molecule is made up of hundreds of glucose molecules joined together to form long chains. Starch is an important storage substance in the plastids of plant cells. Plastids are important organelles in plant cells. They are the sites where molecules like starch are made and stored. One familiar example of a plastid is the chloroplast. **Cellulose** consists of even longer chains of glucose molecules. The chain molecules are grouped together to form microscopic fibres, which are laid down in layers to form the cell wall in plant cells (Figures 4.4 and 4.5).

Polysaccharides are not readily soluble in water.

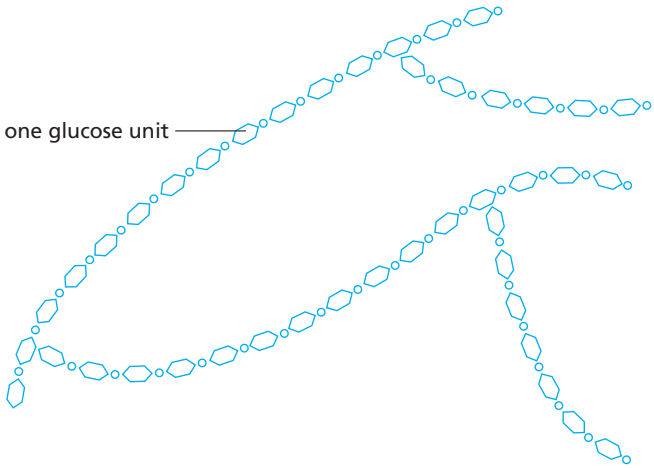


Figure 4.3 Part of a glycogen molecule

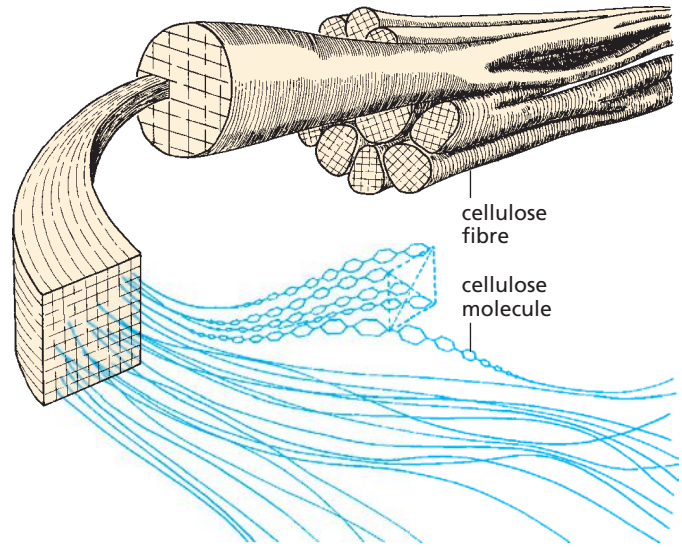


Figure 4.4 Cellulose. Plant cell walls are composed of long, interwoven and interconnected cellulose fibres, which are large enough to be seen with the electron microscope. Each fibre is made up of many long-chain cellulose molecules.

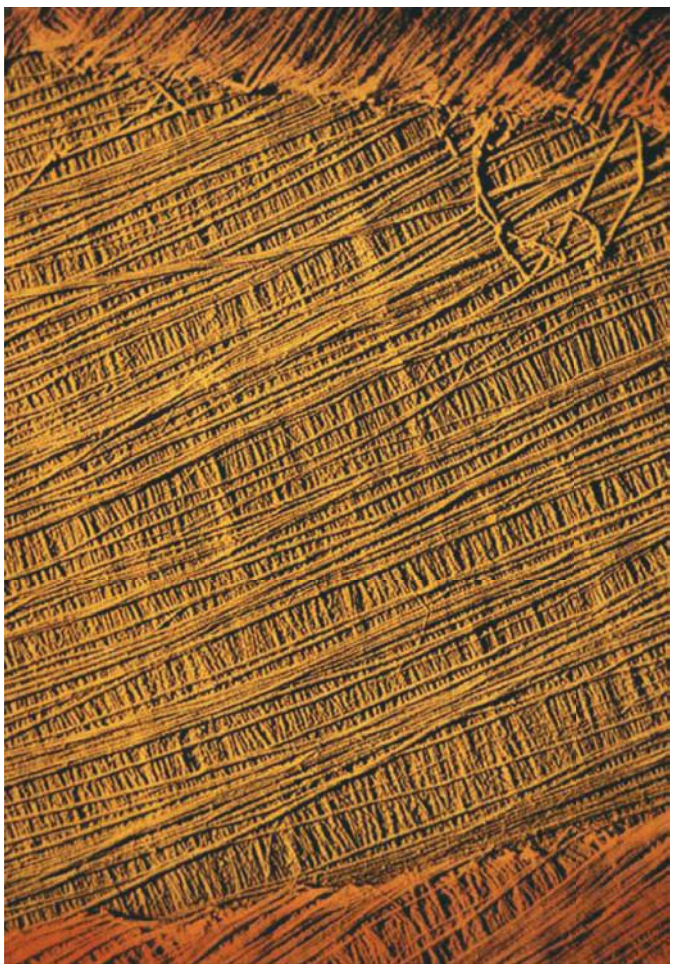
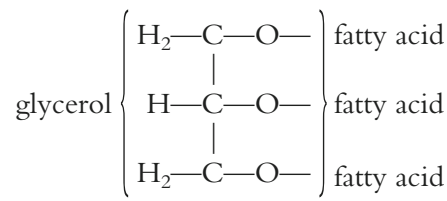


Figure 4.5 Scanning electron micrograph of a plant cell wall (×20 000) showing the cellulose fibres

Fats

Fats are a solid form of a group of molecules called **lipids**. When lipids are liquid they are known as oils. Fats and oils are formed from carbon, hydrogen and oxygen only. A molecule of fat (or oil) is made up of three molecules of an organic acid, called a **fatty acid**, combined with one molecule of **glycerol**.



Drawn simply, fat molecules can be represented as in Figure 4.6.

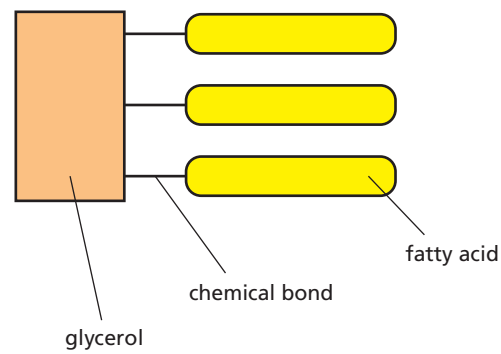


Figure 4.6 Fat molecule

Lipids form part of the cell membrane and the internal membranes of the cell such as the nuclear membrane. Droplets of fat or oil form a source of energy when stored in the cytoplasm.

Proteins

Some proteins contribute to the structures of the cell, e.g. to the cell membranes, the mitochondria, ribosomes and chromosomes. These proteins are called **structural proteins**.

There is another group of proteins called **enzymes**. Enzymes are present in the membrane systems, in the mitochondria, in special vacuoles and in the fluid part of the cytoplasm. Enzymes control the chemical reactions that keep the cell alive (see Chapter 5).

Although there are many different types of protein, all contain carbon, hydrogen, oxygen and nitrogen, and many contain sulfur. Their molecules are made up of long chains of simpler chemicals called **amino acids** (Figure 4.7).

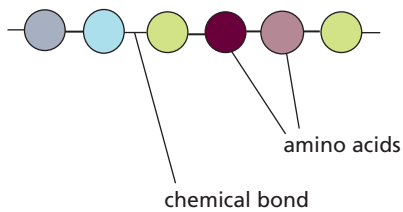


Figure 4.7 Protein molecule (part of)

Vitamins

This is a category of substances which, in their chemical structure at least, have little in common. Plants can make their own vitamins. Animals have to obtain many of their vitamins ready-made. Vitamins, or substances derived from them, play a part in chemical reactions in cells – for example those which involve a transfer of energy from one compound to another. If cells are not supplied with vitamins or the substances needed to make them, the cell physiology is thrown out of order and the whole organism suffers. One example of a vitamin is ascorbic acid (vitamin C) (see 'Diet' in Chapter 7).

Water

Most cells contain about 75% water and will die if their water content falls much below this. Water is a good solvent and many substances move about the cells in a watery solution.

Synthesis and conversion in cells

Cells are able to build up (synthesise) or break down their proteins, lipids and carbohydrates, or change one to another. For example, animal cells synthesise glycogen from glucose by joining glucose molecules together (Figure 4.3); plant cells synthesise starch and cellulose from glucose. All cells can make proteins from amino acids and they can build up fats from glycerol and fatty acids. Animal cells can change carbohydrates to lipids, and lipids to carbohydrates; they can also change proteins to carbohydrates but they cannot make proteins unless they are supplied with amino acids. Plant cells, on the other hand, can make their own amino acids starting from sugars and salts. The cells in the green parts of plants can even make glucose starting from only carbon dioxide and water (see 'Photosynthesis' in Chapter 6).

Proteins

There are about 20 different amino acids in animal proteins, including alanine, leucine, valine, glutamine, cysteine, glycine and lysine. A small protein molecule might be made up from a chain consisting of a hundred or so amino acids, e.g. glycine–valine–valine–cysteine–leucine–glutamine–, etc. Each type of protein has its amino acids arranged in a particular sequence.

The chain of amino acids in a protein takes up a particular shape as a result of cross-linkages. Cross-linkages form between amino acids that are not neighbours, as shown in Figure 4.8. The shape of a protein molecule has a very important effect on its reactions with substances, as explained in 'Enzymes' in Chapter 5.

For example, the shape of an enzyme molecule creates an **active site**, which has a complementary shape to the substrate molecule on which it acts. This makes enzymes very specific in their action (they usually only work on one substrate).

Antibodies are proteins produced by white blood cells called lymphocytes. Each antibody has a binding site, which can lock onto pathogens such as bacteria. This destroys the pathogen directly, or marks it so that it can be detected by other white blood cells called phagocytes. Each pathogen has **antigens** on its surface that are a particular shape, so specific antibodies with complementary shapes to the antigen are needed (see Chapter 10, page 149).

When a protein is heated to temperatures over 50 °C, the cross-linkages in its molecules break down; the protein molecules lose their shape and will not usually regain it even when cooled. The protein is said to have been **denatured**. Because the shape of the molecules has been altered, the protein will have lost its original properties.

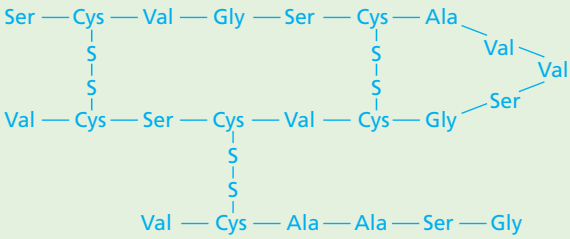


Figure 4.8 A small imaginary protein made from only five different kinds of amino acid. Note that cross-linkage occurs between cysteine molecules with the aid of sulfur atoms.

Egg-white is a protein. When it is heated, its molecules change shape and the egg-white goes from a clear, runny liquid to a white solid and cannot be changed back again. The egg-white protein, albumen, has been denatured by heat.

Proteins form enzymes and many of the structures in the cell, so if they are denatured the enzymes and the cell structures will stop working and the cell will die. Whole organisms may survive for a time above 50 °C depending on the temperature, the period of exposure and the proportion of the cells that are damaged.

Structure of DNA

A DNA molecule is made up of long chains of nucleotides, formed into two strands. A **nucleotide** is a 5-carbon sugar molecule joined to a phosphate group ($-PO_3$) and an organic base (Figure 4.9). In DNA the sugar is deoxyribose and the organic base is either **adenine** (A), **thymine** (T), **cytosine** (C) or **guanine** (G).

Note: for exam purposes, it is only necessary to be able state the letters, *not* the names of these bases.

The nucleotides are joined by their phosphate groups to form a long chain, often thousands of nucleotides long. The phosphate and sugar molecules are the same all the way down the chain but the bases may be any one of the four listed above (Figure 4.10).

The DNA in a chromosome consists of two strands (chains of nucleotides) held together by chemical bonds between the bases. The size of the molecules ensures that A (adenine) always pairs with T (thymine) and C (cytosine) pairs with G (guanine). The double strand is twisted to form a helix (like a twisted rope ladder with the base pairs representing the rungs) (Figures 4.11 and 4.12).

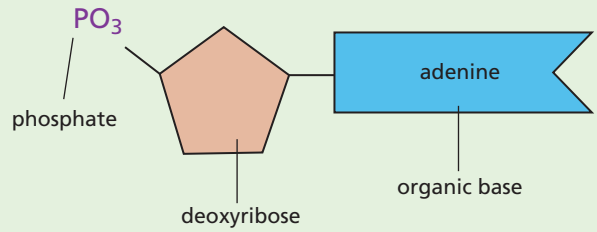


Figure 4.9 A nucleotide (adenosine monophosphate)

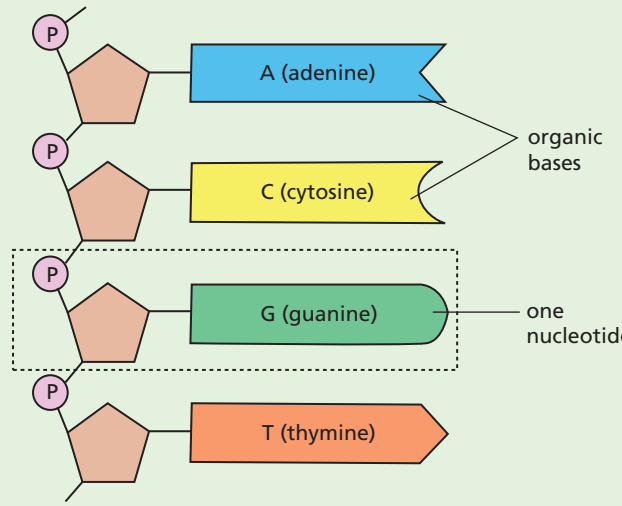


Figure 4.10 Part of a DNA molecule with four nucleotides

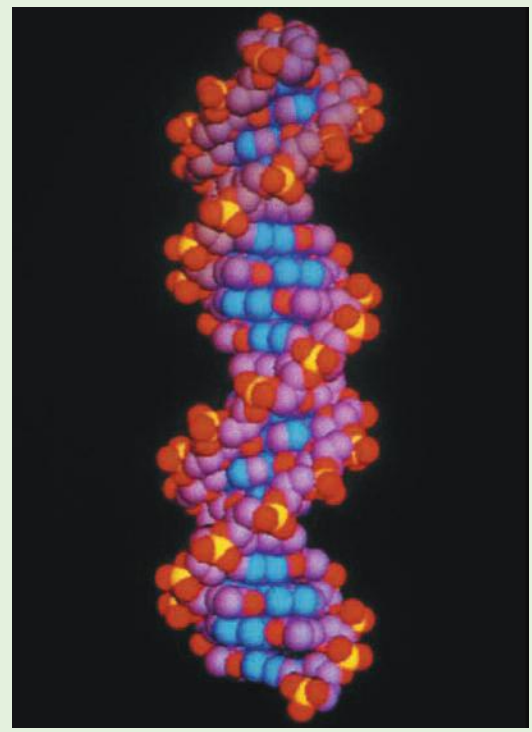


Figure 4.11 Model of the structure of DNA

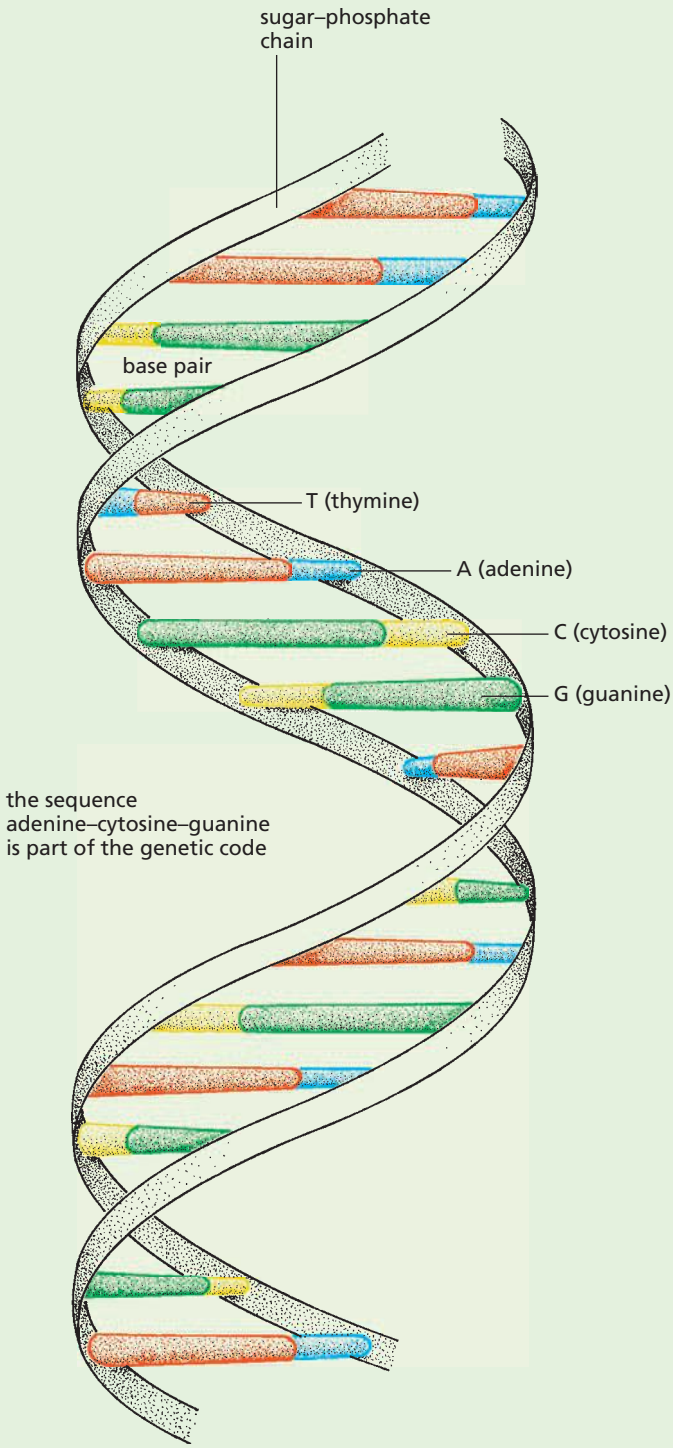


Figure 4.12 The drawing shows part of a DNA molecule schematically

Water

Water molecules take part in a great many vital chemical reactions. For example, in green plants, water combines with carbon dioxide to form sugar (see Chapter 6). In animals, water helps to break down and dissolve food molecules (see 'Chemical digestion' in Chapter 7). Blood is made up of cells and a liquid called **plasma**. This plasma is 92% water and acts as a transport medium for many dissolved substances, such as carbon dioxide, urea, digested food and hormones. Blood cells are carried around the body in the plasma.

Water also acts as a transport medium in plants. Water passes up the plant from the roots to the leaves in xylem vessels and carries with it dissolved mineral ions. Phloem vessels transport sugars and amino acids in solution from the leaves to their places of use or storage (see Chapter 8).

Water plays an important role in excretion in animals. It acts as a powerful solvent for excretory materials, such as nitrogenous molecules like urea, as well as salts, spent hormones and drugs. The water has a diluting effect, reducing the toxicity of the excretory materials.

The physical and chemical properties of water differ from those of most other liquids but make it uniquely effective in supporting living activities. For example, water has a high capacity for heat (high thermal capacity). This means that it can absorb a lot of heat without its temperature rising to levels that damage the proteins in the cytoplasm. However, because water freezes at 0 °C most cells are damaged if their temperature falls below this and ice crystals form in the cytoplasm. (Oddly enough, rapid freezing of cells in liquid nitrogen at below –196 °C does not harm them).

Table 4.1 Summary of the main nutrients

Nutrient	Elements present	Examples	Sub-units
carbohydrate	carbon, hydrogen, oxygen	starch, glycogen, cellulose, sucrose	glucose
fat/oil (oils are liquid at room temperature, but fats are solid)	carbon, hydrogen, oxygen (but lower oxygen content than carbohydrates)	vegetable oils, e.g. olive oil; animal fats, e.g. cod liver oil, waxes	fatty acids and glycerol
protein	carbon, hydrogen, oxygen, nitrogen, sometimes sulfur or phosphorus	enzymes, muscle, haemoglobin, cell membranes	amino acids (about 20 different forms)

Extension work

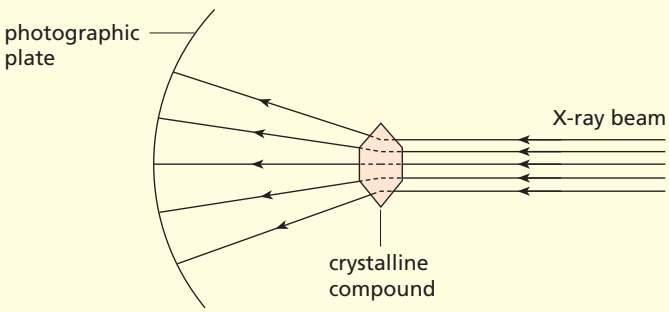
DNA

In 1869, a chemist working on cell chemistry discovered a compound that contained nitrogen and phosphorus (as well as carbon). This was an unusual combination. The substance seemed to originate from nuclei and was at first called 'nuclein' and then 'nucleic acid'. Subsequent analysis revealed the bases adenine, thymine, cytosine and guanine in nucleic acid, together with a carbohydrate later identified as deoxyribose. In the early 1900s, the structure of nucleotides (base–sugar–phosphate, Figure 4.9) was determined and also how they linked up to form deoxyribonucleic acid (DNA).

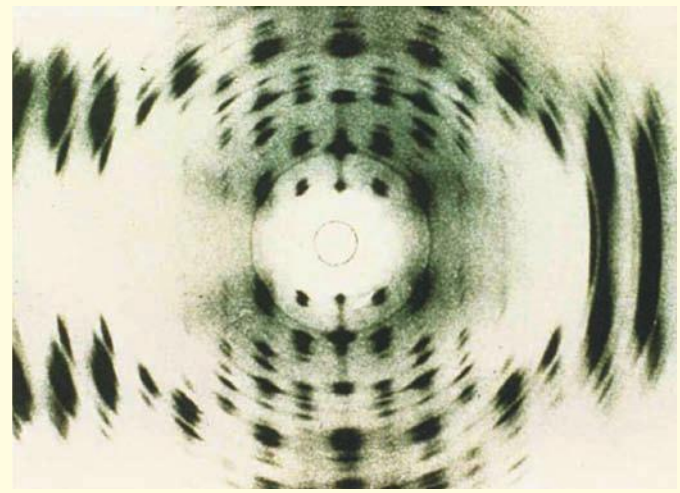
In the 1940s, a chemist, Chargaff, showed that, in a sample of DNA, the number of adenines (A) was always the same as the number of thymines (T). Similarly, the amounts of cytosine (C) and guanine (G) were always equal. This information was to prove crucial to the work of Crick and Watson in determining the structure of DNA.

Francis Crick was a physicist and **James Watson** (from the USA) a biologist. They worked together in the Cavendish Laboratory at Cambridge in the 1950s. They did not do chemical analyses or experiments, but used the data that was available from X-ray crystallography and the chemistry of nucleotides to try out different models for the structure of DNA.

The regular pattern of atoms in a crystal causes a beam of X-rays to be scattered in such a way that the structure of the molecules in the crystal can be determined (Figure 4.13(a)). The scattered X-rays are directed on to a photographic plate which, when developed, reveals images similar to the one in Figure 4.13(b).



(a) simplified representation of the scattering of X-rays by crystalline structures



(b) one of the X-ray images produced by X-rays scattered by DNA. The number and positions of the dark areas allows the molecular structure to be calculated.

Figure 4.13 X-ray crystallography

By precise measurements of the spots on the photograph and some very complex mathematics, the molecular structure of many compounds could be discovered.

It proved possible to obtain DNA in a crystalline form and subject it to X-ray analysis. Most of the necessary X-ray crystallography was carried out by **Maurice Wilkins** and **Rosalind Franklin** at King's College, London.

Crick and Watson assembled models on a trial-and-error basis. The suitability of the model was judged by how well it conformed to the X-ray measurements and the chemical properties of the components.

The evidence all pointed to a **helical** structure (like a spiral staircase). At first they tried models with a core of three or four nucleotide chains twisted around each other and with the bases attached to the outside.

These models did not really fit the X-ray data or the chemical structures of the nucleotides. Watson tried a two-chain helical model with the bases pointing inwards. Initially he paired adenine (A) with adenine (A), cytosine (C) with cytosine (C), etc. But thymine (T) and cytosine (C) were smaller molecules than adenine (A) and guanine (G) and this pairing would distort the double helix.

This is where Chargaff's work came to the rescue. If there were equal numbers of adenine (A) and thymine (T), and equal numbers of cytosine (C) and guanine (G), it was likely that this pairing of bases, large plus small, would fit inside the sugar–phosphate double helix without distortion.

The X-ray data confirmed that the diameter of the helix would allow this pairing and the chemistry of the bases would allow them to hold together. The outcome is the model of DNA shown in Figures 4.10, 4.11 and 4.12.

Crick, Watson and Wilkins were awarded the Nobel Prize for medicine and physiology in 1962. Rosalind Franklin died in 1958, so her vital contribution was not formally rewarded.

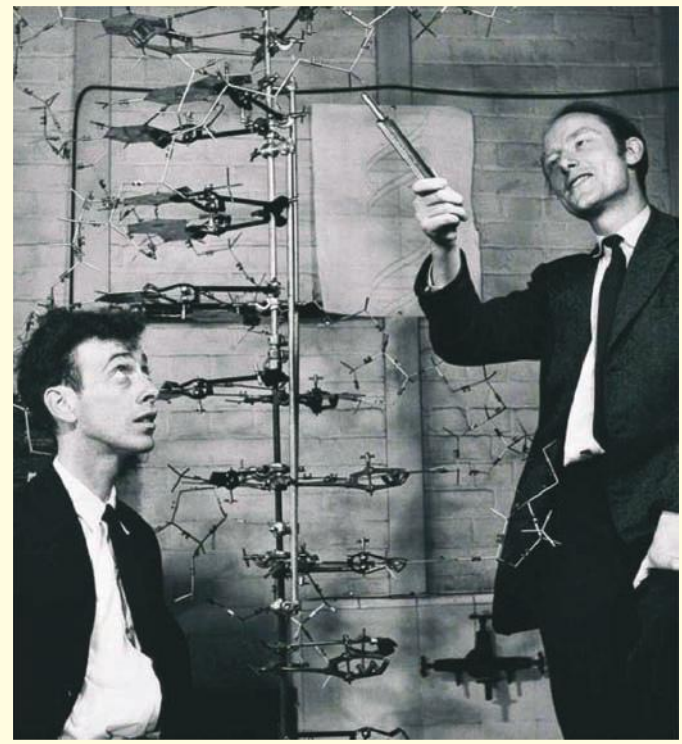


Figure 4.14 Crick (right) and Watson with their model of the DNA molecule

Practical work

Food tests

1 Test for starch

- Shake a little starch powder in a test-tube with some warm water to make a suspension.
- Add 3 or 4 drops of **iodine solution**. A dark blue colour should be produced.

Note: it is also possible to use iodine solution to test for starch in leaves, but a different procedure is used (see Chapter 6).

2 Test for reducing sugar

- Heat a little glucose solution with an equal volume of **Benedict's solution** in a test-tube. The heating is done by placing the test-tube in a beaker of boiling water (see Figure 4.15), or warming it gently over a blue Bunsen flame. However, if this second technique is used, the test-tube should be moved constantly in and out of the Bunsen flame to prevent the liquid boiling and shooting out of the tube. The solution will change from clear blue to cloudy green, then yellow and finally to a red precipitate (deposit) of copper(I) oxide.

3 Test for protein (Biuret test)

- To a 1% solution of albumen (the protein of egg-white) add 5 cm^3 dilute sodium hydroxide (**CARE**: this solution is caustic), followed by 5 cm^3 1% copper sulfate solution. A purple colour indicates protein. If the copper sulfate is run into the food solution without mixing, a violet halo appears where the two liquids come into contact.

4 Test for fat

- Shake two drops of cooking oil with about 5 cm^3 ethanol in a dry test-tube until the fat dissolves.
- Pour this solution into a test-tube containing a few cm^3 water. A milky white emulsion will form. This shows that the solution contained some fat or oil.

5 Test for vitamin C

- Draw up 2 cm^3 fresh lemon juice into a plastic syringe.
- Add this juice drop by drop to 2 cm^3 of a 0.1% solution of DCPIP (a blue dye) in a test-tube. The DCPIP will become colourless quite suddenly as the juice is added. The amount of juice added from the syringe should be noted down.
- Repeat the experiment but with orange juice in the syringe. If it takes more orange juice than lemon juice to decolourise the DCPIP, the orange juice must contain less vitamin C.

Application of the food tests

The tests can be used on samples of food such as milk, potato, raisins, onion, beans, egg-yolk or peanuts to find out what food materials are present. The solid samples are crushed in a mortar and shaken with warm water to extract the soluble products. Separate samples of the watery mixture of crushed food are tested for starch, glucose or protein as described above. To test for fats, the food must first be crushed in ethanol, not water, and then filtered. The clear filtrate is poured into water to see if it goes cloudy, indicating the presence of fats.

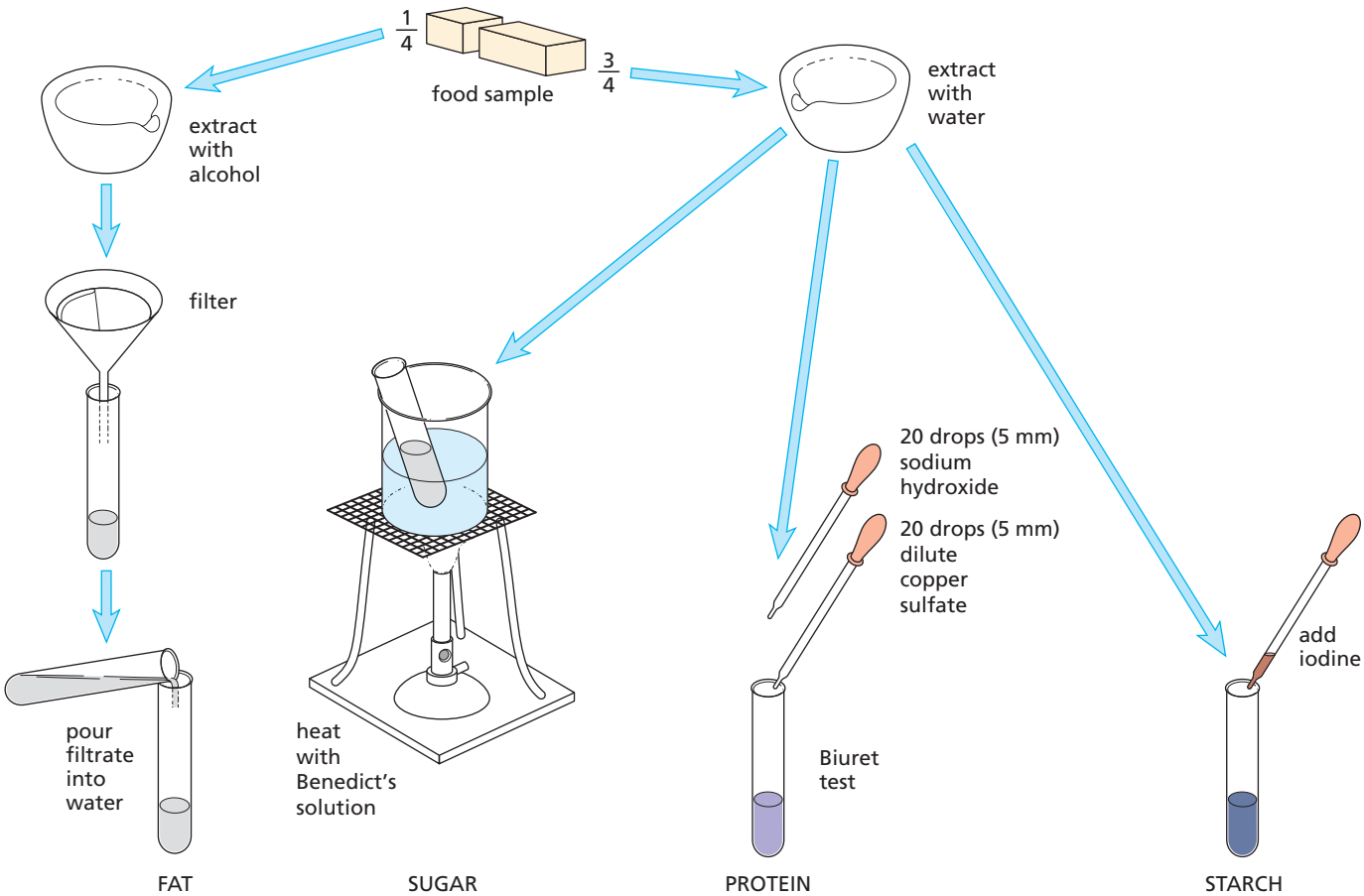


Figure 4.15 Experiment to test foods for different nutrients

Question

Core

1 a What do the chemical structures of carbohydrates and fats have in common?
b How do their chemical structures differ?
c Suggest why there are many more different proteins than there are carbohydrates.

Checklist

After studying Chapter 4 you should know and understand the following:

- Living matter is made up of a number of important types of molecules, including proteins, lipids and carbohydrates.
- All three types of molecule contain carbon, hydrogen and oxygen atoms; proteins also contain nitrogen and sometimes phosphorus or sulfur.
- Carbohydrates are made from monosaccharide units, often glucose.
- Carbohydrates are used as an energy source; glycogen and starch make good storage molecules. Cellulose gives plant cell walls their strength.
- Proteins are built up from amino acids joined together by chemical bonds.
- Lipids include fats, fatty acids and oils.
- Fats are made from fatty acids and glycerol.
- Proteins and lipids form the membranes outside and inside the cell.
- Food tests are used to identify the main biological molecules.
- Water is important in living things as a solvent.

- In different proteins the 20 or so amino acids are in different proportions and arranged in different sequences.
- The structure of a protein molecule enables it to carry out specific roles as enzymes and antibodies.
- DNA is another important biological molecule. It has a very distinctive shape, made up of nucleotides containing bases.
- Water has an important role as a solvent in organisms.

5 Enzymes

Enzyme action
Definitions of catalyst and enzyme
The importance of enzymes in living organisms
The specific nature of enzymes
The effects of pH and temperature on enzyme activity
Complementary shape of enzyme and substrate

Description of enzyme action
Active site
Explanation of the effect of temperature and pH on enzyme molecules
Specificity

Key definitions
A **catalyst** is a substance that increases the rate of a chemical reaction and is not changed by the reaction.
An **enzyme** is a protein that functions as a biological catalyst.

Enzymes are proteins that act as **catalysts**. They are made in all living cells. Enzymes, like catalysts, can be used over and over again because they are not used up during the reaction and only a small amount is needed to speed the reaction up (Figure 5.1).

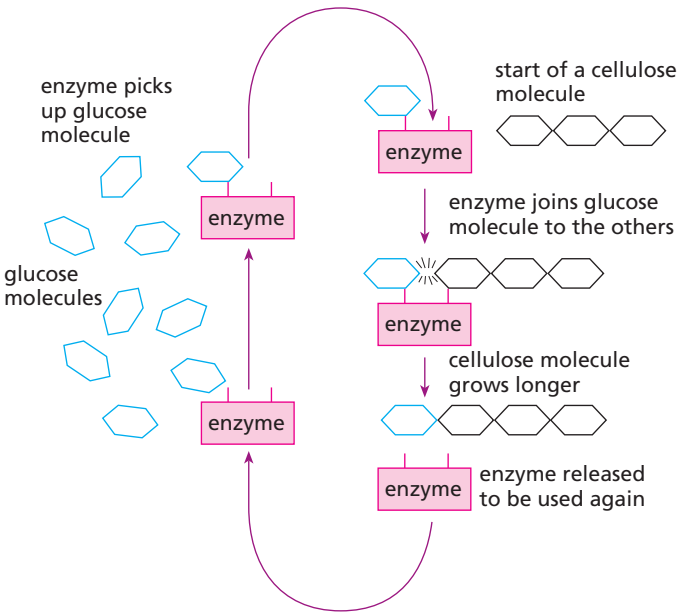


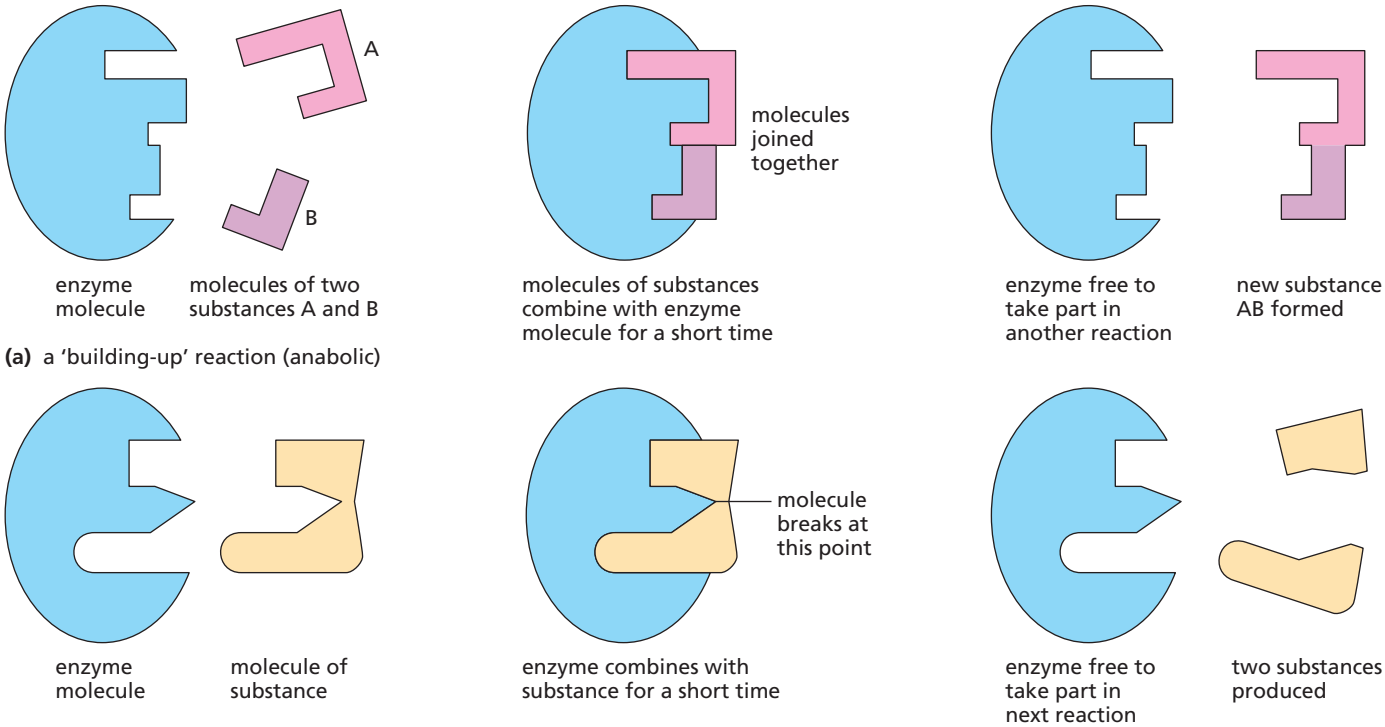
Figure 5.1 Building up a cellulose molecule

Enzyme action

How an enzyme molecule might work to join two other molecules together and so form a more complicated substance (the product) is shown in Figure 5.2.

An example of an enzyme-controlled reaction such as this is the joining up of two glucose molecules to form a molecule of maltose. You can see that the enzyme and substrate molecules have **complementary** shapes (like adjacent pieces of a jigsaw) so they fit together. Other substrate molecules would not fit into this enzyme as they would have the 'wrong' shape. For example, the substrate molecule in Figure 5.2(b) would not fit the enzyme molecule in Figure 5.2(a). The product (substance AB in Figure 5.2(a)) is released by the enzyme molecule and the enzyme is then free to repeat the reaction with more substrate molecules. Molecules of the two substances might have combined without the enzyme being present, but they would have done so very slowly (it could take hours or days to happen without the enzyme). By bringing the substances close together, the enzyme molecule makes the reaction take place much more rapidly. The process can be extremely fast: it has been found that catalase, a very common enzyme found in most cells, can break down 40 000 molecules of hydrogen peroxide every second! A complete chemical reaction takes only a few seconds when the right enzyme is present.

As well as enzymes being responsible for joining two substrate molecules together, such as two glucose molecules to form maltose, they can also create long chains. For example, hundreds of glucose molecules can be joined together, end to end, to form a long molecule of starch to be stored in the plastid of a plant cell. The glucose molecules can also be built up into a molecule of cellulose to be added to the cell wall. Protein molecules are built up by enzymes, which join together tens or hundreds of amino acid molecules. These proteins are added to the cell membrane, to the cytoplasm or to the nucleus of the cell. They may also become the proteins that act as enzymes.



(a) a 'building-up' reaction (anabolic)

(b) a 'breaking-down' reaction (catabolic)

Figure 5.2 Possible explanation of enzyme action

Enzymes and temperature

A rise in temperature increases the rate of most chemical reactions; a fall in temperature slows them down. However, above 50 °C the enzymes, being proteins, are denatured and stop working.

Figure 5.2 shows how the shape of an enzyme molecule could be very important if it has to fit the substances on which it acts. Above 50 °C the shapes of enzymes are permanently changed and the enzymes can no longer combine with the substances.

This is one of the reasons why organisms may be killed by prolonged exposure to high temperatures. The enzymes in their cells are denatured and the chemical reactions proceed too slowly to maintain life.

One way to test whether a substance is an enzyme is to heat it to boiling point. If it can still carry out its reactions after this, it cannot be an enzyme. This technique is used as a 'control' (see 'Aerobic respiration' in Chapter 12) in enzyme experiments.

Enzymes and pH

Acid or alkaline conditions alter the chemical properties of proteins, including enzymes. Most enzymes work best at a particular level of acidity or alkalinity (pH), as shown in Figure 5.3.

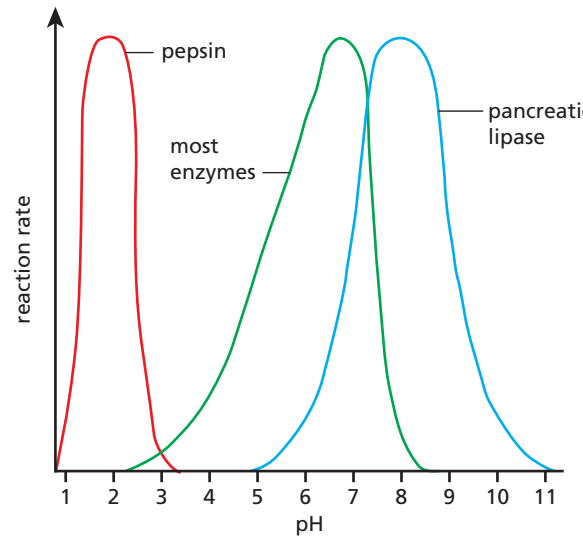


Figure 5.3 The effect of pH on digestive enzymes

The protein-digesting enzyme in your stomach, for example, works well at an acidity of pH 2. At this pH, the enzyme amylase, from your saliva, cannot work at all. Inside the cells, most enzymes will work best in neutral conditions (pH 7). The pH or temperature at which an enzyme works best is often called its **optimum** pH or temperature. Conditions in the duodenum are slightly alkaline: the optimum pH for pancreatic lipase is pH 8.

Although changes in pH affect the activity of enzymes, these effects are usually reversible, i.e. an enzyme that is inactivated by a low pH will resume its normal activity when its optimum pH is restored.

Rates of enzyme reactions

As explained above, the rate of an enzyme-controlled reaction depends on the temperature and pH. It also depends on the concentrations of the enzyme and its substrate. The more enzyme molecules produced by a cell, the faster the reaction will proceed, provided there are enough substrate molecules available. Similarly, an increase in the substrate concentration will speed up the reaction if there are enough enzyme molecules to cope with the additional substrate.

Intra- and extracellular enzymes

All enzymes are made inside cells. Most of them remain inside the cell to speed up reactions in the cytoplasm and nucleus. These are called **intracellular enzymes** ('intra' means 'inside'). In a few cases, the enzymes made in the cells are let out of the cell to do their work outside. These are **extracellular enzymes** ('extra' means 'outside'). Fungi and bacteria (see 'Features of organisms' in Chapter 1) release extracellular enzymes in order to digest their food. A mould growing on a piece of bread releases starch-digesting enzymes into the bread and absorbs the soluble sugars that the enzyme produces from the bread. In the digestive systems of animals ('Alimentary canal' in Chapter 7), extracellular enzymes are released into the stomach and intestines in order to digest the food.

An enzyme-controlled reaction involves three groups of molecules, although the product may be two or more different molecules:

$$\text{substrate} \xrightarrow{\text{enzyme}} \text{product}$$

The substance on which an enzyme acts is called its **substrate** and the molecules produced are called the **products**. Thus, the enzyme sucrase acts on the substrate sucrose to produce the monosaccharide products glucose and fructose.

Reactions in which large molecules are built up from smaller molecules are called **anabolic** reactions (Figure 5.2(a)). When the enzyme combines with the substrate, an **enzyme-substrate complex** is formed temporarily.

Figure 5.2(b) shows an enzyme speeding up a chemical change, but this time it is a reaction in which the molecule of a substance is split into smaller molecules. Again, when the enzyme combines with the substrate, an **enzyme-substrate complex** is formed temporarily. Try chewing a piece of bread, but keep it in your mouth without swallowing it. Eventually you should detect the food tasting sweeter, as maltose sugar is formed. If starch is mixed with water it will break down very slowly to sugar, taking several years. In your saliva there is an enzyme called **amylase** that can break down starch to sugar in minutes or seconds. In cells, many of the 'breaking-down' enzymes are helping to break down glucose to carbon dioxide and water in order to produce energy (Chapter 12).

Reactions that split large molecules into smaller ones are called **catabolic** reactions.

Enzymes are specific

This means simply that an enzyme which normally acts on one substance will not act on a different one. Figure 5.2(a) shows how the shape of an enzyme can control what substances it combines with. The enzyme in Figure 5.2(a) has a shape called the **active site**, which exactly fits the substances on which it acts, but will not fit the substance in Figure 5.2(b). So, the shape of the active site of the enzyme molecule and the substrate molecule are **complementary**. Thus, an enzyme which breaks down starch to maltose will not also break down proteins to amino acids. Also, if a reaction takes place in stages, e.g.

$$\text{starch} \longrightarrow \text{maltose (stage 1)}$$

$$\text{maltose} \longrightarrow \text{glucose (stage 2)}$$

a different enzyme is needed for each stage.

The names of enzymes usually end with **-ase** and they are named according to the substance on which they act, or the reaction which they speed up. For example, an enzyme that acts on proteins may be called a **protease**; one that removes hydrogen from a substance is a **dehydrogenase**.

Enzymes and temperature

Figure 5.4 shows the effect of temperature on an enzyme-controlled reaction.

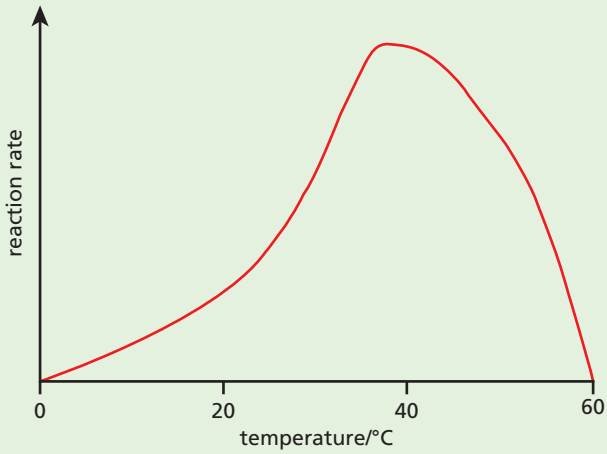


Figure 5.4 Graph showing the effect of temperature on the rate of an enzyme-controlled reaction

Generally, a rise of 10 °C will double the rate of an enzyme-controlled reaction in a cell, up to an optimum temperature of around 37 °C (body temperature). This is because the enzyme and substrate molecules are constantly moving, using kinetic energy. The reaction only occurs when the enzyme and substrate molecules come into contact with each other. As the temperature is increased, the molecules gain more kinetic energy, so they move faster and there is a greater chance of collisions happening. Therefore the rate of reaction increases. Above the optimum temperature the reaction will slow down. This is because enzyme molecules are proteins. Protein molecules start to lose their shape at higher temperatures, so the active site becomes deformed. Substrate molecules cannot fit together with the enzyme, stopping the reaction. Not all the enzyme molecules are affected straight away, so the reaction does not suddenly stop – it is a gradual process as the temperature increases above 37 °C. Denaturation is a permanent change in the shape of the enzyme molecule. Once it has happened the enzyme will not work any more, even if the temperature is reduced below 37 °C. An example of a protein denaturing is the cooking of egg-white (made of the protein albumin). Raw egg-white is liquid, transparent and colourless. As it is heated, it turns solid and becomes opaque and white. It cannot be changed back to its original state or appearance.

Enzymes and pH

Extremes of pH may denature some enzymes irreversibly. This is because the active site of the enzyme molecule can become deformed (as it does when exposed to high temperatures). As a result, the enzyme and substrate molecules no longer have complementary shapes and so will not fit together.

Practical work

Tests for proteins, fats and carbohydrates are described in Chapter 4. Experiments on the digestive enzymes amylase and pepsin are described in Chapter 7.

1 Extracting and testing an enzyme from living cells

In this experiment, the enzyme to be extracted and tested is **catalase** and the substrate is hydrogen peroxide (H_2O_2). Certain reactions in the cell produce hydrogen peroxide, which is poisonous. Catalase makes the hydrogen peroxide harmless by breaking it down to water and oxygen.

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

- Grind a small piece of liver with about 20 cm^3 water and a little sand in a mortar. This will break open the liver cells and release their contents.
- Filter the mixture and share it between two test-tubes, A and B. The filtrate will contain a great variety of substances dissolved out from the cytoplasm of the liver cells, including many enzymes. Because enzymes are specific, however, only one of these, catalase, will act on hydrogen peroxide.
- Add some drops of the filtrate from test-tube A to a few cm^3 of hydrogen peroxide in a test-tube. You will see a vigorous reaction as the hydrogen peroxide breaks down to produce oxygen. (The oxygen can be tested with a glowing splint.)
- Now boil the filtrate in tube B for about 30 seconds. Add a few drops of the boiled filtrate to a fresh sample of hydrogen peroxide. There will be no reaction because boiling has denatured the catalase.
- Next, shake a little manganese(IV) oxide powder in a test-tube with some water and pour this into some hydrogen peroxide. There will be a vigorous reaction similar to the one with the liver extract. If you now boil some manganese(IV) oxide with water and add this to hydrogen peroxide, the reaction will still occur. Manganese(IV) oxide is a catalyst but it is not an enzyme because heating has not altered its catalytic properties.
- The experiment can be repeated with a piece of potato to compare its catalase content with that of the liver. The piece of potato should be about the same size as the liver sample.

Extension work

Investigate a range of plant tissues to find out which is the best source of catalase. Decide how to make quantitative comparisons (observations which involve measurements). Possible plant tissues include potato, celery, apple and carrot.

2 The effect of temperature on an enzyme reaction

Amylase is an enzyme that breaks down starch to a sugar (maltose).

- Draw up 5 cm^3 of 5% amylase solution in a plastic syringe (or graduated pipette) and place 1 cm^3 in each of three test-tubes labelled A, B and C.
- Rinse the syringe thoroughly and use it to place 5 cm^3 of a 1% starch solution in each of three test-tubes labelled 1, 2 and 3.
- To each of tubes 1 to 3, add six drops only of dilute iodine solution using a dropping pipette.

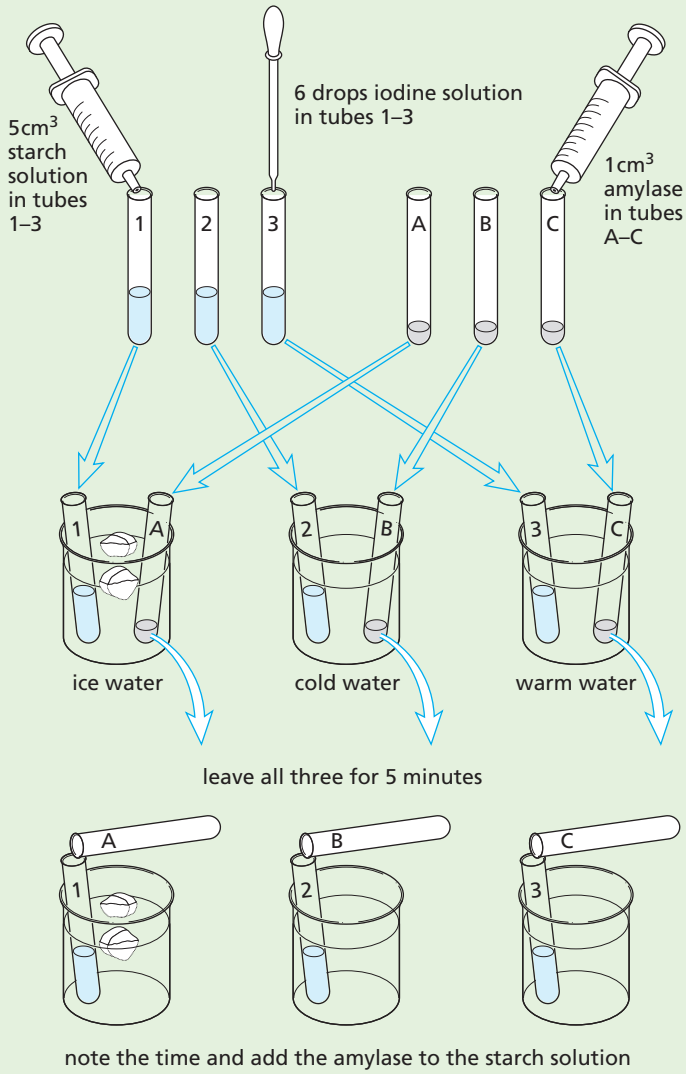


Figure 5.5 Experiment to investigate the effect of temperature on an enzyme reaction

- Prepare three water baths by half filling beakers or jars with:
  - **a** ice and water, adding ice during the experiment to keep the temperature at about 10 °C
  - **b** water from the cold tap at about 20 °C
  - **c** warm water at about 35 °C by mixing hot and cold water.
- Place tubes 1 and A in the cold water bath, tubes 2 and B in the water at room temperature, and tubes 3 and C in the warm water.
- Leave them for 5 minutes to reach the temperature of the water (Figure 5.5).
- After 5 minutes, take the temperature of each water bath, then pour the amylase from tube A into the starch solution in tube 1 and return tube 1 to the water bath.
- Repeat this with tubes 2 and B, and 3 and C.
- As the amylase breaks down the starch, it will cause the blue colour to disappear. Make a note of how long this takes in each case.

Questions

1 At what temperature did the amylase break down starch most rapidly?

2 What do you think would have been the result if a fourth water bath at 90 °C had been used?

3 The effect of pH on an enzyme reaction

- Label five test-tubes 1 to 5 and use a plastic syringe (or graduated pipette) to place 5 cm^3 of a 1% starch solution in each tube.
- Add acid or alkali to each tube as indicated in the table below. Rinse the syringe when changing from sodium carbonate to acid.

Tube	Chemical	Approximate pH	
1	1 cm^3 sodium carbonate solution (0.05 mol dm^{-3})	9	(alkaline)
2	0.5 cm^3 sodium carbonate solution (0.05 mol dm^{-3})	7–8	(slightly alkaline)
3	nothing	6–7	(neutral)
4	2 cm^3 ethanoic (acetic) acid (0.1 mol dm^{-3})	6	(slightly acid)
5	4 cm^3 ethanoic (acetic) acid (0.1 mol dm^{-3})	3	(acid)

- Place several rows of iodine solution drops in a cavity tile.
- Draw up 5 cm^3 of 5% amylase solution in a clean syringe and place 1 cm^3 in each tube. Shake the tubes and note the time (Figure 5.6).
- Use a clean dropping pipette to remove a small sample from each tube in turn and let one drop fall on to one of the iodine drops in the cavity tile. Rinse the pipette in a beaker of water between each sample. Keep on sampling in this way.
- When any of the samples fails to give a blue colour, this means that the starch in that tube has been completely broken down to sugar by the amylase. Note the time when this happens for each tube and stop taking samples from

that tube. Do not continue sampling for more than about 15 minutes, but put a drop from each tube on to a piece of pH paper and compare the colour produced with a colour chart of pH values.

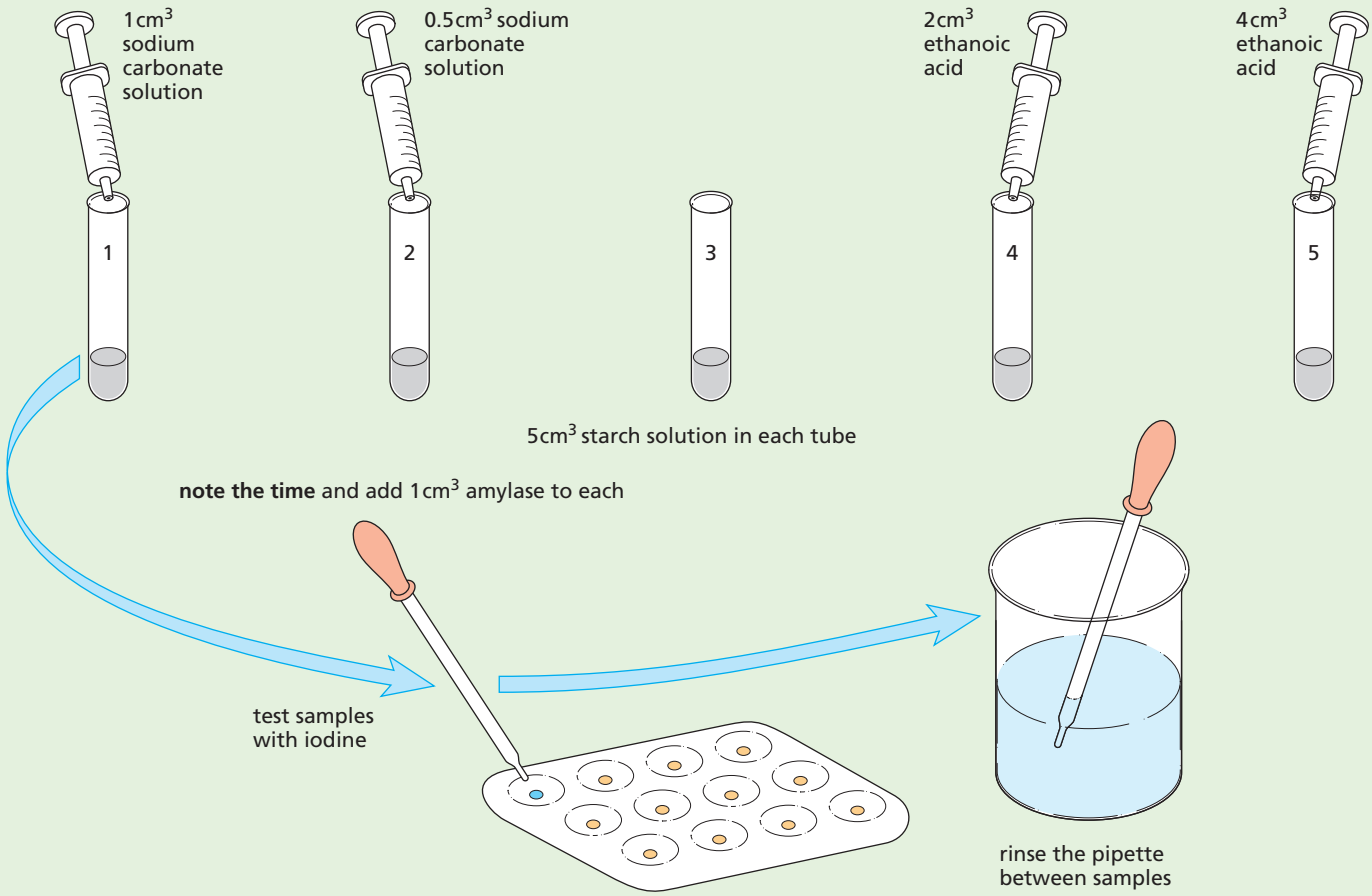


Figure 5.6 Experiment to investigate the effect of pH on an enzyme reaction

Questions

1 At what pH did the enzyme, amylase, work most rapidly?
2 Is this its optimum pH?
3 Explain why you might have expected the result that you got.
4 Your stomach pH is about 2. Would you expect starch digestion to take place in the stomach?

Questions

Extended

1 Which of the following statements apply both to enzymes and to any other catalysts?
   a Their activity is stopped by high temperature.
   b They speed up chemical reactions.
   c They are proteins.
   d They are not used up during the reaction.
2 How would you expect the rate of an enzyme-controlled reaction to change if the temperature was raised:
   a from 20 °C to 30 °C
   b from 35 °C to 55 °C?
   Explain your answers.
3 There are cells in your salivary glands that can make an extracellular enzyme, amylase. Would you expect these cells to make intracellular enzymes as well? Explain your answer.

4 Apple cells contain an enzyme that turns the tissues brown when an apple is peeled and left for a time. Boiled apple does not go brown (Figure 5.7). Explain why the boiled apple behaves differently.

Figure 5.7 Experiment to investigate enzyme activity in an apple. Slice A has been freshly cut. B and C were cut 2 days earlier but C was dipped immediately in boiling water for 1 minute.

Checklist

After studying Chapter 5 you should know and understand the following:

- Catalysts are substances that increase the rate of chemical reactions and are not changed in the process.
- Enzymes are proteins that function as biological catalysts.
- Enzymes are important in all organisms because they maintain a reaction speed needed to sustain life.
- The substance on which an enzyme acts is called the substrate. After the reaction, a product is formed.
- An enzyme and its substrate have complementary shapes.
- Enzymes are affected by pH and temperature and are denatured above 50 °C.

- Different enzymes may accelerate reactions which build up or break down molecules.
- Each enzyme acts on only one substance (breaking down) or a pair of substances (building up).
- Enzymes tend to be very specific in the reactions they catalyse, due to the complementary shape of the enzyme and its substrate.
- Changes in temperature affect the kinetic energy of enzyme molecules and their shape.
- Enzymes can be denatured by changes in temperature and pH.

6 Plant nutrition

Photosynthesis
Definition of photosynthesis
Word equation
Investigations into the necessity for chlorophyll, light and carbon dioxide for photosynthesis, using appropriate controls
Investigations into the effects of varying light intensity, carbon dioxide concentration and temperature on the rate of photosynthesis

Balanced chemical equation
Use and storage of the products of photosynthesis
Definition of limiting factors
Role of glasshouses in creating optimal conditions for photosynthesis

Leaf structure
Identify the main tissues in a leaf

Adaptations of leaves for photosynthesis

Mineral requirements
The importance of nitrate ions and magnesium ions

Explaining the effects of mineral deficiencies on plant growth

Photosynthesis

Key definition
Photosynthesis is the process by which plants manufacture carbohydrates from raw materials using energy from light.

All living organisms need food. They need it as a source of raw materials to build new cells and tissues as they grow. They also need food as a source of energy. Food is a kind of 'fuel' that drives essential living processes and brings about chemical changes (see 'Diet' in Chapter 7 and 'Aerobic respiration' in Chapter 12). Animals take in food, digest it and use the digested products to build their tissues or to produce energy.

Plants also need energy and raw materials but, apart from a few insect-eating species, plants do not appear to take in food. The most likely source of their raw materials would appear to be the soil. However, experiments show that the weight gained by a growing plant is far greater than the weight lost by the soil it is growing in. So there must be additional sources of raw materials.

Jean-Baptiste van Helmont was a Dutch scientist working in the 17th century. At that time very little was known about the process of photosynthesis. He carried out an experiment using a willow shoot. He planted the shoot in a container with 90.8 kg of dry soil and placed a metal grill over the soil to prevent any accidental gain or loss of mass. He left the shoot for 5 years in an open yard, providing it with only rainwater and distilled water for growth. After 5 years he reweighed the tree and the soil (see Figure 6.1) and came to the conclusion that the increase in mass of the tree (74.7 kg) was due entirely to the water it had received. However, he was unaware that plants also take in mineral salts and carbon dioxide, or that they use light as a source of energy.

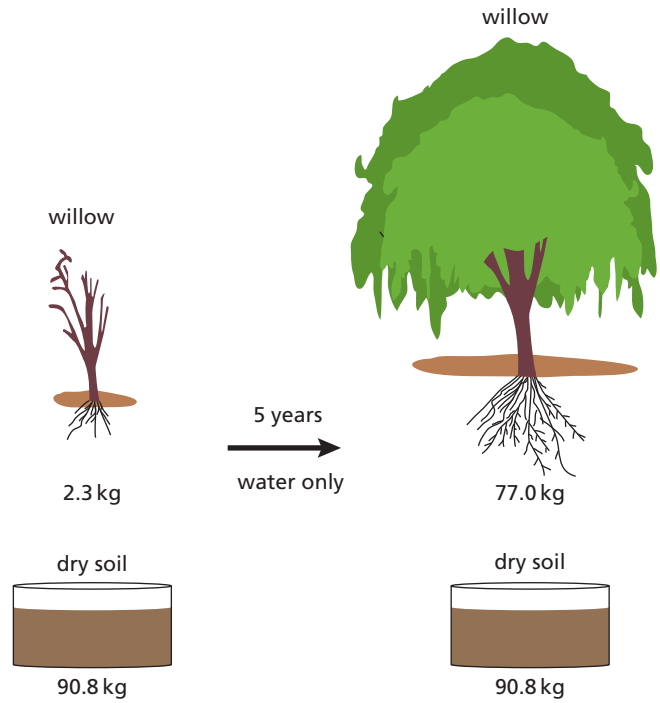


Figure 6.1 Van Helmont's experiment

A **hypothesis** to explain the source of food in a plant is that it *makes it* from air, water and soil salts. Carbohydrates (Chapter 4) contain the elements carbon, hydrogen and oxygen, as in glucose ($C_6H_{12}O_6$). The carbon and oxygen could be supplied by carbon dioxide (CO_2) from the air, and the hydrogen could come from the water (H_2O) in the soil. The nitrogen and sulfur needed for making proteins (Chapter 4) could come from nitrates and sulfates in the soil.

This building-up of complex food molecules from simpler substances is called **synthesis** and it needs enzymes and energy to make it happen. The enzymes are present in the plant's cells and the energy for the first stages in the synthesis comes from sunlight. The process is, therefore, called **photosynthesis** ('photo'

means 'light'). There is evidence to suggest that the green substance, **chlorophyll**, in the chloroplasts of plant cells, plays a part in photosynthesis. Chlorophyll absorbs sunlight and makes the energy from sunlight available for chemical reactions. Thus, in effect, the function of chlorophyll is to convert light energy to chemical energy.

A chemical equation for photosynthesis would be

$$\text{carbon dioxide} + \text{water} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{glucose} + \text{oxygen}$$

In order to keep the equation simple, glucose is shown as the food compound produced. In reality, the glucose is rapidly converted to sucrose for transport around the plant, then stored as starch or converted into other molecules.

Practical work

Experiments to investigate photosynthesis

The design of biological experiments is discussed in Chapter 12 'Aerobic respiration', and this should be revised before studying the next section.

A hypothesis is an attempt to explain certain observations. In this case the hypothesis is that plants make their food by photosynthesis. The equation shown above is one way of stating the hypothesis and is used here to show how it might be tested.

$$\underset{\text{uptake of carbon dioxide}}{6CO_2} + \underset{\text{uptake of water}}{6H_2O} \xrightarrow[\text{chlorophyll}]{\text{sunlight}} \underset{\text{production of sugar (or starch)}}{C_6H_{12}O_6} + \underset{\text{release of oxygen}}{6O_2}$$

If photosynthesis is occurring in a plant, then the leaves should be producing sugars. In many leaves, as fast as sugar is produced it is turned into starch. Since it is easier to test for starch than for sugar, we regard the production of starch in a leaf as evidence that photosynthesis has taken place.

The first three experiments described below are designed to see if the leaf can make starch without chlorophyll, sunlight or carbon dioxide, in turn. If the photosynthesis hypothesis is sound, then the lack of any one of these three conditions should stop photosynthesis, and so stop the production of starch. But, if starch production continues, then the hypothesis is no good and must be altered or rejected.

In designing the experiments, it is very important to make sure that only *one* variable is altered. If, for example, the method of keeping light from a leaf also cuts off its carbon dioxide supply, it would be impossible to decide whether it was the lack of light or lack of carbon dioxide that stopped the production of starch. To make sure that the experimental design has not altered more than one variable, a **control** is set up in each case. This is an identical situation, except that the condition missing from the experiment, e.g. light, carbon dioxide or chlorophyll, is present in the control (see 'Aerobic respiration' in Chapter 12).

Destarching a plant

If the production of starch is your evidence that photosynthesis is taking place, then you must make sure that the leaf does not contain any starch at the beginning of the experiment. This is done by **destarching** the leaves. It is not possible to remove the starch chemically, without damaging the leaves, so a plant is destarched simply by leaving it in darkness for 2 or 3 days. Potted plants are destarched by leaving them in a dark cupboard for a few days. In the darkness, any starch in the leaves will be changed to sugar and carried away from the leaves to other parts of the plant. For plants in the open, the experiment is set up on the day before the test. During the night, most of the starch will be removed from the leaves. Better still, wrap the leaves in aluminium foil for 2 days while they are still on the plant. Then test one of the leaves to see that no starch is present.

Testing a leaf for starch

Iodine solution (yellow/brown) and starch (white) form a deep blue colour when they mix. The test for starch, therefore, is to add iodine solution to a leaf to see if it goes blue. However, a living leaf is impermeable to iodine and the chlorophyll in the leaf masks any colour change. So, the leaf has to be treated as follows:

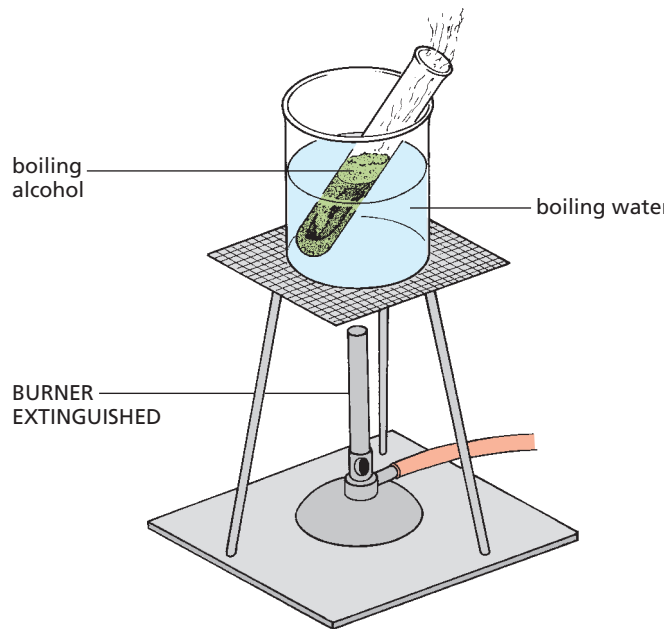


Figure 6.2 Experiment to remove chlorophyll from a leaf

- Heat some water to boiling point in a beaker and then **turn off the Bunsen flame**.
- Use forceps to dip a leaf in the hot water for about 30 seconds. This kills the cytoplasm, denatures the enzymes and makes the leaf more permeable to iodine solution.
- **Note**: make sure the Bunsen flame is extinguished before starting the next part of the procedure, as ethanol is flammable.

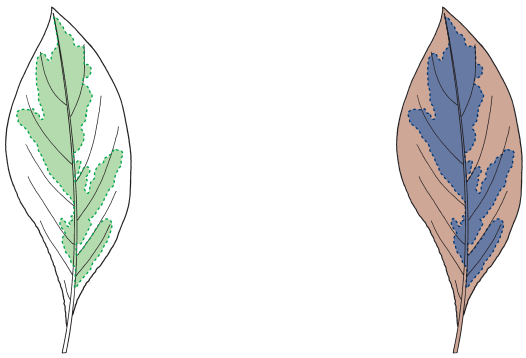
- Push the leaf to the bottom of a test-tube and cover it with ethanol (alcohol). Place the tube in the hot water (Figure 6.2). The alcohol will boil and dissolve out most of the chlorophyll. This makes colour changes with iodine easier to see.
- Pour the green alcohol into a spare beaker, remove the leaf and dip it once more into the hot water to soften it.
- Spread the decolourised leaf flat on a white tile and drop iodine solution on to it. The parts containing starch will turn blue; parts without starch will stain brown or yellow with iodine.

1 Is chlorophyll necessary for photosynthesis?

It is not possible to remove chlorophyll from a leaf without killing it, and so a variegated leaf, which has chlorophyll only in patches, is used. A leaf of this kind is shown in Figure 6.3(a). The white part of the leaf serves as the experiment, because it lacks chlorophyll, while the green part with chlorophyll is the control. After being destarched, the leaf – still on the plant – is exposed to daylight for a few hours. Remove a leaf from the plant; draw it carefully to show where the chlorophyll is (i.e. the green parts) and test it for starch as described above.

Result

Only the parts that were previously green turn blue with iodine. The parts that were white stain brown (Figure 6.3(b)).



(a) variegated leaf **(b)** after testing for starch

Figure 6.3 Experiment to show that chlorophyll is necessary

Interpretation

Since starch is present only in the parts that originally contained chlorophyll, it seems reasonable to suppose that chlorophyll is needed for photosynthesis.

It must be remembered, however, that there are other possible interpretations that this experiment has not ruled out; for example, starch could be made in the green parts and sugar in the white parts. Such alternative explanations could be tested by further experiments.

2 Is light necessary for photosynthesis?

- Cut a simple shape from a piece of aluminium foil to make a stencil and attach it to a destarched leaf (Figure 6.4(a)).
- After 4 to 6 hours of daylight, remove the leaf and test it for starch.

Result

Only the areas which had received light go blue with iodine (Figure 6.4(b)).

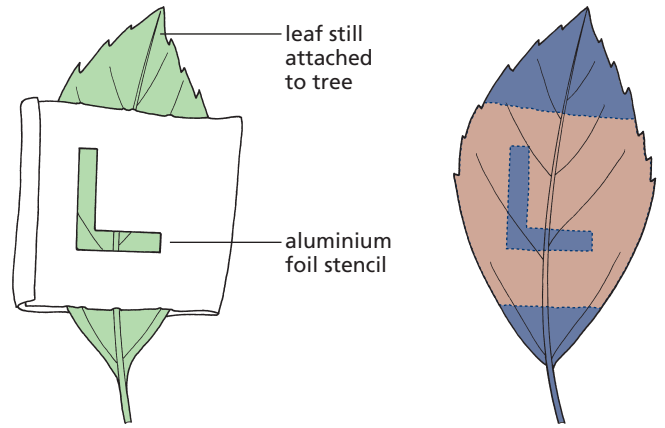


Figure 6.4 Experiment to show that light is necessary

Interpretation

As starch has not formed in the areas that received no light, it seems that light is needed for starch formation and thus for photosynthesis.

You could argue that the aluminium foil had stopped carbon dioxide from entering the leaf and that it was shortage of carbon dioxide rather than absence of light which prevented photosynthesis taking place. A further control could be designed, using transparent material instead of aluminium foil for the stencil.

3 Is carbon dioxide needed for photosynthesis?

- Water two destarched potted plants and enclose their shoots in polythene bags.
- In one pot place a dish of soda-lime to absorb the carbon dioxide from the air (the experiment). In the other place a dish of sodium hydrogencarbonate solution to produce carbon dioxide (the control), as shown in Figure 6.5.
- Place both plants in the light for several hours and then test a leaf from each for starch.

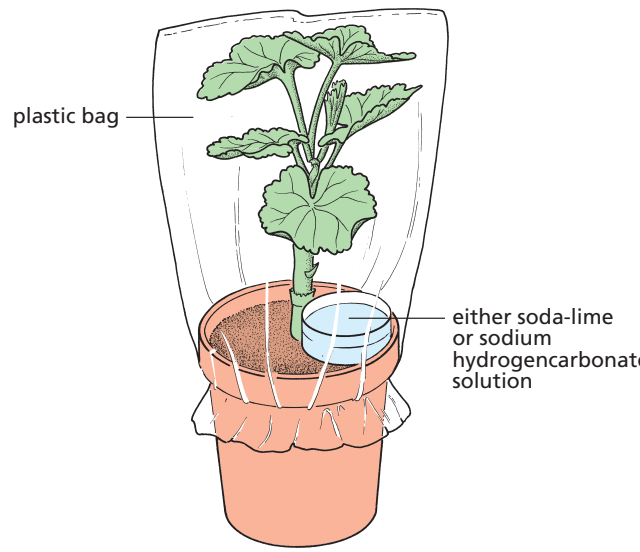


Figure 6.5 Experiment to show that carbon dioxide is necessary

Result
The leaf that had no carbon dioxide does not turn blue. The one from the polythene bag containing carbon dioxide does turn blue.

Interpretation
The fact that starch was made in the leaves that had carbon dioxide, but not in the leaves that had no carbon dioxide, suggests that this gas must be necessary for photosynthesis. The control rules out the possibility that high humidity or high temperature in the plastic bag prevents normal photosynthesis.

4 Is oxygen produced during photosynthesis?

- Place a short-stemmed funnel over some Canadian pondweed in a beaker of water.
- Fill a test-tube with water and place it upside-down over the funnel stem (Figure 6.6). (The funnel is raised above the bottom of the beaker to allow the water to circulate.)
- Place the apparatus in sunlight. Bubbles of gas should appear from the cut stems and collect in the test-tube.
- Set up a control in a similar way but place it in a dark cupboard.
- When sufficient gas has collected from the plant in the light, remove the test-tube and insert a glowing splint.

Result
The glowing splint bursts into flames.

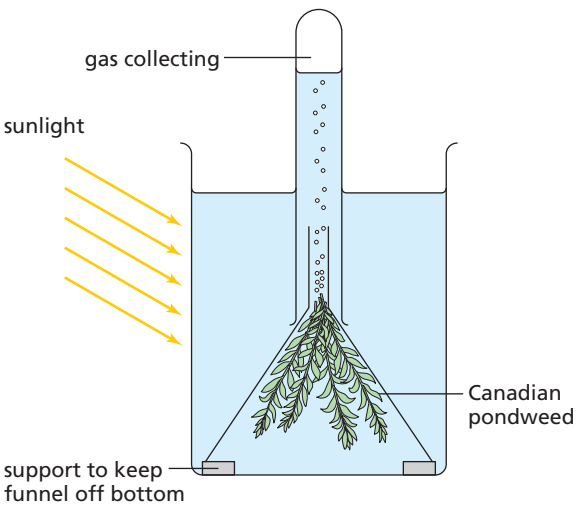


Figure 6.6 Experiment to show that oxygen is produced

Interpretation
The relighting of a glowing splint does not prove that the gas collected in the test-tube is *pure* oxygen, but it does show that it contains extra oxygen and this must have come from the plant. The oxygen is given off only in the light.

Note that water contains dissolved oxygen, carbon dioxide and nitrogen. These gases may diffuse in or out of the bubbles as they pass through the water and collect in the test-tube. The composition of the gas in the test-tube may not be the same as that in the bubbles leaving the plant.

Controls

When setting up an experiment and a control, which of the two procedures constitutes the 'control' depends on the way the prediction is worded. For example, if the prediction is that 'in the absence of light, the pondweed will not produce oxygen', then the 'control' is the plant in the light. If the prediction is that 'the pondweed in the light will produce oxygen', then the 'control' is the plant in darkness. As far as the results and interpretation are concerned, it does not matter which is the 'control' and which is the 'experiment'.

The results of the four experiments support the hypothesis of photosynthesis as stated at the beginning of this chapter and as represented by the equation. Starch formation (our evidence for photosynthesis) does not take place in the absence of light, chlorophyll or carbon dioxide, and oxygen production occurs only in the light.

If starch or oxygen production had occurred in the absence of any one of these conditions, we should have to change our hypothesis about the way plants obtain their food. Bear in mind, however, that although our results support the photosynthesis theory, they do not prove it. For example, it is now known that many stages in the production of sugar and starch from carbon dioxide do not need light (the 'light-independent' reaction).

5 What is the effect of changing light intensity on the rate of photosynthesis? (Method 1)

In this investigation, the rate of production of bubbles by a pond plant is used to calculate the rate of photosynthesis.

- Prepare a beaker of water or a boiling tube, into which a spatula end of sodium hydrogencarbonate has been stirred (this dissolves rapidly and saturates the water with carbon dioxide, so CO_2 is not a limiting factor).
- Collect a fresh piece of Canadian pondweed and cut one end of the stem, using a scalpel blade.
- Attach a piece of modelling clay or paperclip to the stem and put it into the beaker (or boiling tube).
- Set up a light source 10 cm away from the beaker and switch on the lamp (Figure 6.7). Bubbles should start appearing from the cut end of the plant stem. Count the number of bubbles over a fixed time e.g. 1 minute and record the result. Repeat the count.

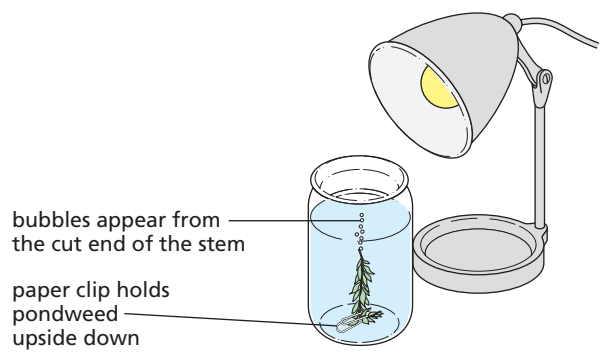


Figure 6.7 Experiment to investigate light intensity and oxygen production

- Now move the light source so that it is 20 cm from the beaker. Switch on the lamp and leave it for a few minutes, to allow the plant to adjust to the new light intensity. Count the bubbles as before and record the results.
- Repeat the procedure so that the numbers of bubbles for at least five different distances have been recorded. Also, try switching off the bench lamp and observe any change in the production of bubbles.
- There is a relationship between the distance of the lamp from the plant and the light intensity received by the plant. Light intensity = $\frac{1}{D^2}$ where D = distance.
- Convert the distances to light intensity, then plot a graph of light intensity/arbitrary units (*x*-axis) against rate of photosynthesis/bubbles per minute (*y*-axis).

Note: in this investigation another variable, which could affect the rate of photosynthesis, is the heat given off from the bulb. To improve the method, another beaker of water could be placed between the bulb and the plant to act as a heat filter while allowing the plant to receive the light.

- If the bubbles appear too rapidly to count, try tapping a pen or pencil on a sheet of paper at the same rate as the bubbles appear and get your partner to slide the paper slowly along for 15 seconds. Then count the dots (Figure 6.8).

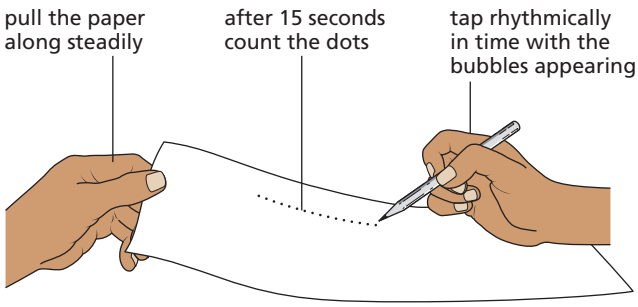


Figure 6.8 Estimating the rate of bubble production

Result

The rate of bubbling should decrease as the lamp is moved further away from the plant. When the light is switched off, the bubbling should stop.

Interpretation

Assuming that the bubbles contain oxygen produced by photosynthesis, as the light intensity is increased the rate of photosynthesis (as indicated by the rate of oxygen bubble production) increases. This is because the plant uses the light energy to photosynthesise and oxygen is produced as a waste product. The oxygen escapes from the plant through the cut stem. We are assuming also that the bubbles do not change in size during the experiment. A fast stream of small bubbles might represent the same volume of gas as a slow stream of large bubbles.

6 What is the effect of changing light intensity on the rate of photosynthesis? (Method 2)

This alternative investigation uses leaf discs from land plants (Figure 6.9).

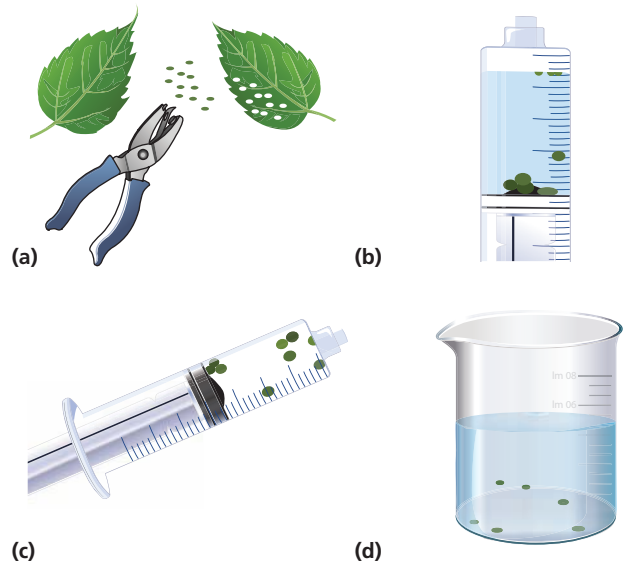


Figure 6.9 Using leaf discs to investigate the effect of light intensity on photosynthesis

- Use a cork borer or paper hole punch to cut out discs from a fresh, healthy leaf such as spinach, avoiding any veins (Figure 6.9(a)). The leaves contain air spaces. These cause the leaf discs to float when they are placed in water.
- At the start of the experiment, the air needs to be removed from the discs. To do this place about 10 discs into a large (10 cm^3) syringe and tap it so the discs fall to the bottom (opposite the plunger end).
- Place one finger over the hole at the end of the syringe barrel. Fill the barrel with water, then replace the plunger.
- Turn the syringe so the needle end is facing up and release your finger.
- Gently push the plunger into the barrel of the syringe to force out any air from above the water (Figure 6.9(b)).
- Now replace your finger over the syringe hole and withdraw the plunger to create a vacuum.
- Keep the plunger withdrawn for about 10 seconds. This sucks out all the air from the leaf discs. They should then sink to the bottom (Figure 6.9(c)). Release the plunger.
- Repeat the procedure if the discs do not all sink.
- Remove the discs from the syringe and place them in a beaker, containing water, with a spatula of sodium hydrogencarbonate dissolved in it (Figure 6.9(d)).
- Start a stopwatch and record the time taken for each of the discs to float to the surface. Ignore those that did not sink. Calculate an average time for the discs to float.
- Repeat the method, varying the light intensity the discs are exposed to in the beaker (see Experiment 5 for varying the light intensity produced by a bench lamp).

Result

The greater the light intensity, the quicker the leaf discs float to the surface.

Interpretation

As the leaf discs photosynthesise they produce oxygen, which is released into the air spaces in the disc. The oxygen makes the

discs more buoyant, so as the oxygen accumulates, they float to the surface of the water. As light intensity increases, the rate of photosynthesis increases.

7 What is the effect of changing carbon dioxide concentration on the rate of photosynthesis?

Sodium hydrogencarbonate releases carbon dioxide when dissolved in water. Use the apparatus shown in Figure 6.10.

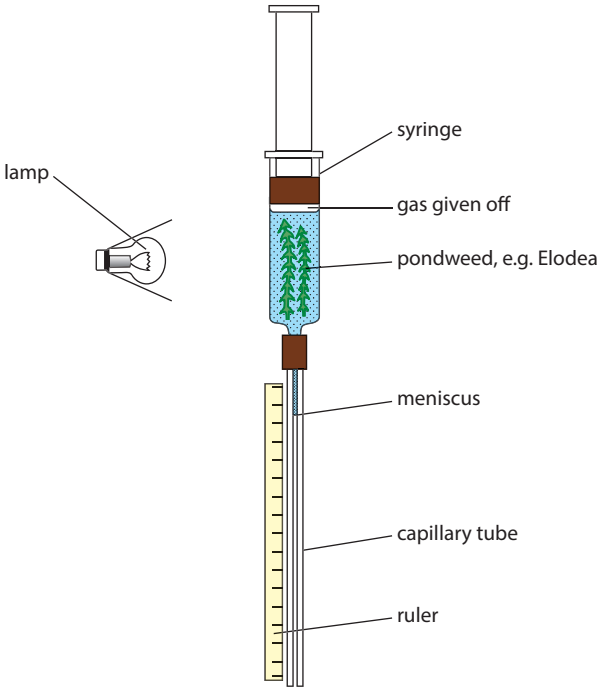


Figure 6.10 Apparatus for investigating the effect of changing carbon dioxide concentration on the rate of photosynthesis

- To set this up, remove the plunger from the 20 cm^3 syringe and place two or three pieces of pondweed, with freshly cut stems facing upwards, into the syringe barrel. Hold a finger over the end of the capillary tube and fill the syringe with distilled water.
- Replace the plunger, turn the apparatus upside down and push the plunger to the 20 cm^3 mark, making sure that no air is trapped.
- Arrange the apparatus as shown in Figure 6.10 and move the syringe barrel until the meniscus is near the top of the graduations on the ruler. The bulb should be a fixed distance from the syringe, e.g. 10 cm.
- Switch on the lamp and measure the distance the meniscus moves over 3 minutes. Repeat this several times, then calculate an average.
- Repeat the procedure using the following concentrations of sodium hydrogencarbonate solution: 0.010, 0.0125, 0.0250, 0.0500 and 0.1000 mol dm^{-3}.
- Plot a graph of the concentration of sodium hydrogencarbonate solution (*x*-axis) against the mean distance travelled by the meniscus (*y*-axis).

Result

The higher the concentration of sodium hydrogencarbonate solution, the greater the distance moved by the meniscus.

Interpretation

As the concentration of available carbon dioxide is increased, the distance travelled by the meniscus also increases. The movement of the meniscus is caused by oxygen production by the pondweed due to photosynthesis. So an increase in carbon dioxide increases the rate of photosynthesis.

8 What is the effect of changing temperature on the rate of photosynthesis?

Use the methods described in Experiments 5 or 6, but vary the temperature of the water instead of the light intensity.

Questions

1 Which of the following are needed for starch production in a leaf?
carbon dioxide, oxygen, nitrates, water, chlorophyll, soil, light
2 In Experiment 1 (concerning the need for chlorophyll), why was it not necessary to set up a separate control experiment?
3 What is meant by 'destarching' a leaf? Why is it necessary to destarch leaves before setting up some of the photosynthesis experiments?
4 In Experiment 3 (concerning the need for carbon dioxide), what were the functions of:
   a the soda-lime
   b the sodium hydrogencarbonate
   c the polythene bag?
5 a Why do you think pondweed, rather than a land plant, is used for Experiment 4 (concerning production of oxygen)?
   b In what way might this choice make the results less useful?
6 A green plant makes sugar from carbon dioxide and water. Why is it not suitable to carry out an experiment to see if depriving a plant of water stops photosynthesis?
7 Does the method of destarching a plant take for granted the results of Experiment 2? Explain your answer.

You need to be able to state the balanced chemical equation for photosynthesis.

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

The process of photosynthesis

Although the details of photosynthesis vary in different plants, the hypothesis as stated in this chapter has stood up to many years of experimental testing and is universally accepted. The next section describes how photosynthesis takes place in a plant.

The process takes place mainly in the cells of the leaves (Figure 6.11) and is summarised in

Figure 6.12. In land plants water is absorbed from the soil by the roots and carried in the water vessels of the veins, up the stem to the leaf. Carbon dioxide is absorbed from the air through the stomata (pores in the leaf, see 'Leaf structure' later in this chapter). In the leaf cells, the carbon dioxide and water are combined to make sugar. The energy for this reaction comes from sunlight that has been absorbed by the green pigment **chlorophyll**. The chlorophyll is present in the chloroplasts of the leaf cells and it is inside the **chloroplasts** that the reaction takes place. Chloroplasts (Figure 6.12(d)) are small, green structures present in the cytoplasm of the leaf cells. Chlorophyll is the substance that gives leaves and stems their green colour. It is able to absorb energy from light and use it to split water molecules into hydrogen and oxygen (the 'light' or 'light-dependent' reaction). The oxygen escapes from the leaf and the hydrogen molecules are added to carbon dioxide molecules to form sugar (the 'dark' or 'light-independent' reaction). In this way the light energy has been transferred into the chemical energy of carbohydrates as they are synthesised.

Figure 6.11 All the reactions involved in producing food take place in the leaves. Notice how little the leaves overlap

There are four types of chlorophyll that may be present in various proportions in different species. There are also a number of photosynthetic pigments, other than chlorophyll, which may mask the colour of chlorophyll even when it is present, e.g. the brown and red pigments that occur in certain seaweeds.

The plant's use of photosynthetic products

The glucose molecules produced by photosynthesis are quickly built up into starch molecules and added to the growing starch granules in the chloroplast. If the glucose concentration was allowed to increase in the mesophyll cells of the leaf, it could disturb the osmotic balance between the cells (see 'Osmosis' in Chapter 3). Starch is a relatively insoluble compound and so does not alter the osmotic potential of the cell contents.

The starch, however, is steadily broken down to sucrose (Chapter 4) and this soluble sugar is transported out of the cell into the food-carrying cells (see Chapter 8) of the leaf veins. These veins will distribute the sucrose to all parts of the plant that do not photosynthesise, e.g. the growing buds, the ripening fruits, the roots and the underground storage organs.

The cells in these regions will use the sucrose in a variety of ways (Figure 6.13).

Respiration

The sugar can be used to provide energy. It is oxidised by respiration (Chapter 12) to carbon dioxide and water, and the energy released is used to drive other chemical reactions such as the building-up of proteins described below.

Storage

Sugar that is not needed for respiration is turned into starch and stored. Some plants store it as starch grains in the cells of their stems or roots. Other plants, such as the potato or parsnip, have special storage organs (tubers) for holding the reserves of starch (see 'Asexual reproduction' in Chapter 16). Sugar may be stored in the fruits of some plants; grapes, for example, contain a large amount of glucose.

Synthesis of other substances

As well as sugars for energy and starch for storage, the plant needs cellulose for its cell walls, lipids for its cell membranes, proteins for its cytoplasm and pigments for its flower petals, etc. All these substances are built up (synthesised) from the sugar molecules and other molecules produced in photosynthesis.

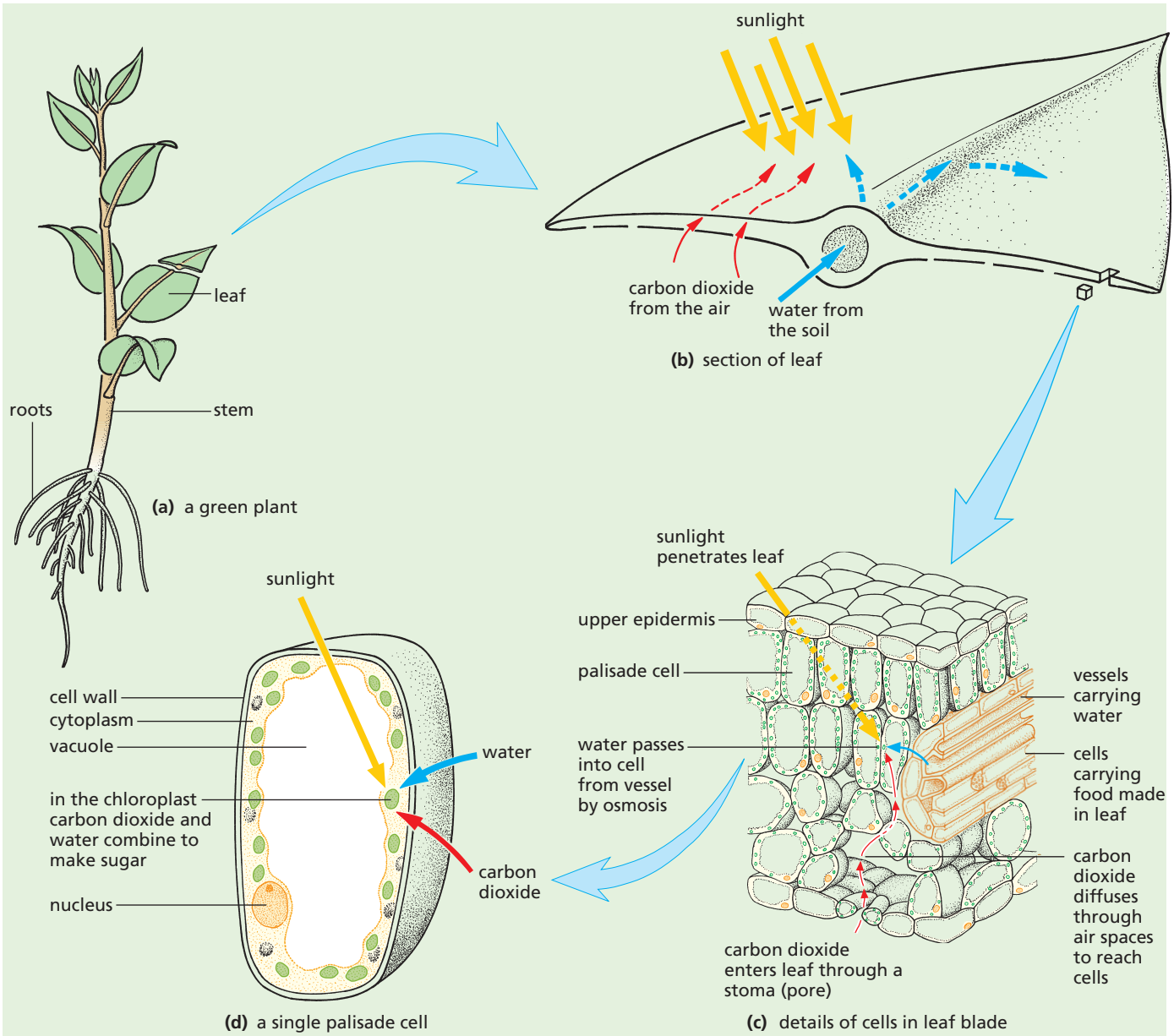


Figure 6.12 Photosynthesis in a leaf

By joining hundreds of glucose molecules together, the long-chain molecules of cellulose (Chapter 4, Figure 4.4) are built up and added to the cell walls.

Amino acids (see Chapter 4) are made by combining **nitrogen** with sugar molecules or smaller carbohydrate molecules. These amino acids are then joined together to make the proteins that form the enzymes and the cytoplasm of the cell. The nitrogen for this synthesis comes from **nitrates** which are absorbed from the soil by the roots.

Some proteins also need **sulfur** molecules and these are absorbed from the soil in the form of **sulfates** (SO_4). **Phosphorus** is needed for DNA (Chapter 4) and for reactions involving energy release. It is taken up as phosphates (PO_4).

The chlorophyll molecule needs magnesium (Mg). This metallic element is also obtained from salts in the soil.

Many other elements, e.g. iron, manganese, boron, are also needed in very small quantities for healthy growth. These are often referred to as **trace elements**.

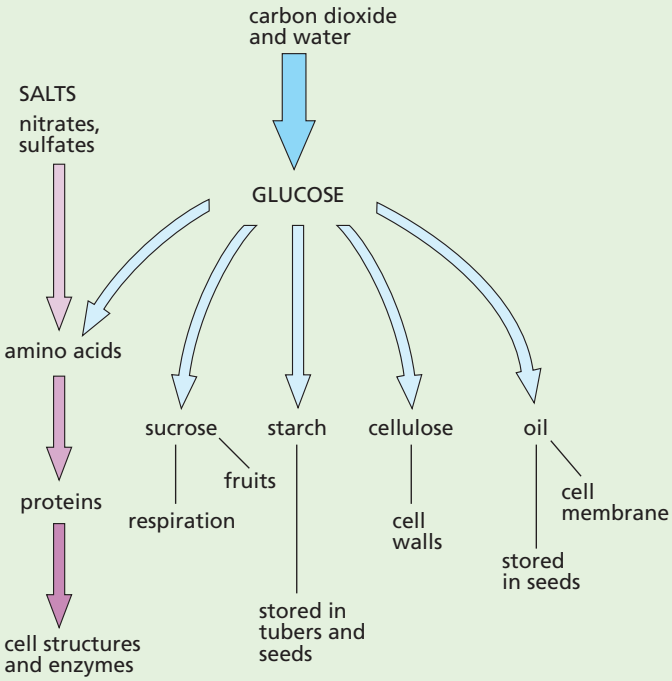


Figure 6.13 Green plants can make all the materials they need from carbon dioxide, water and salts.

The metallic and non-metallic elements are all taken up in the form of their ions by the plant roots.

All these chemical processes, such as the uptake of salts and the building-up of proteins, need energy from respiration to make them happen.

Gaseous exchange in plants

Air contains the gases nitrogen, oxygen, carbon dioxide and water vapour. Plants and animals take in or give out these last three gases and this process is called **gaseous exchange**.

You can see from the equation for photosynthesis that one of its products is oxygen. Therefore, in daylight, when photosynthesis is going on in green plants, they will be taking in carbon dioxide and giving out oxygen. This exchange of gases is the opposite of that resulting from respiration (Chapter 12) but it must not be thought that green plants do not respire. The energy they need for all their living processes – apart from photosynthesis – comes from respiration, and this is going on all the time, using up oxygen and producing carbon dioxide.

During the daylight hours, plants are photosynthesising as well as respiring, so that all the carbon dioxide produced by respiration is used up by photosynthesis. At the same time, all the oxygen needed by respiration is provided by photosynthesis. Only when the rate of photosynthesis is faster than the rate of respiration will carbon dioxide be taken in and the excess oxygen given out (Figure 6.14).

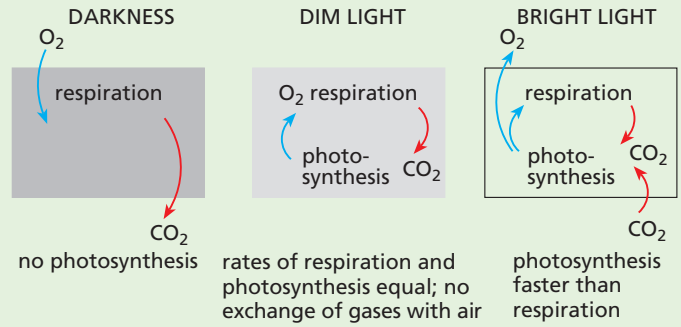


Figure 6.14 Respiration and photosynthesis

Compensation point

As the light intensity increases during the morning and fades during the evening, there will be a time when the rate of photosynthesis exactly matches the rate of respiration. At this point, there will be no net intake or output of carbon dioxide or oxygen. This is the **compensation point**. The sugar produced by photosynthesis exactly compensates for the sugar broken down by respiration.

Practical work

How will the gas exchange of a plant be affected by being kept in the dark and in the light?

This investigation makes use of hydrogencarbonate indicator, which is a test for the presence of carbon dioxide. A build-up of carbon dioxide turns it from pink/red to yellow. A decrease in carbon dioxide levels causes the indicator to turn purple.

- Wash three boiling tubes first with tap water, then with distilled water and finally with hydrogencarbonate indicator (the indicator will change colour if the boiling tube is not clean).
- Then fill the three boiling tubes to about two thirds full with hydrogencarbonate indicator solution.
- Add equal-sized pieces of Canadian pondweed to tubes 1 and 2 and seal all the tubes with stoppers.
- Expose tubes 1 and 3 to light using a bench lamp and place tube 2 in a black box, or a dark cupboard, or wrap it in aluminium foil (Figure 6.15). After 24 hours note the colour of the hydrogencarbonate indicator in each tube.

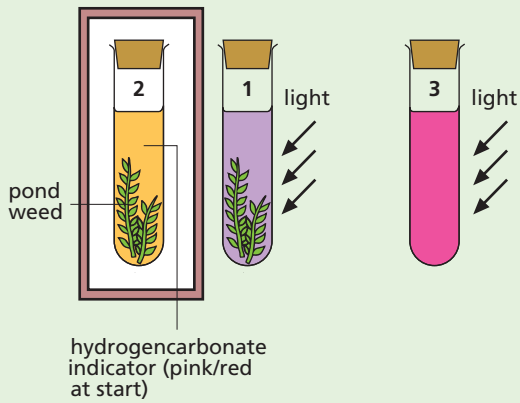


Figure 6.15 Experiment to compare gas exchange in plants kept in the dark and in the light

Result

The indicator in tube 3 (the control) which was originally pink/red should not change colour; that in tube 2 (plant in the dark) should turn yellow; and in tube 1 (plant in the light) the indicator should be purple.

Interpretation

Hydrogencarbonate indicator is a mixture of dilute sodium hydrogencarbonate solution with the dyes cresol red and thymol blue. It is a pH indicator in equilibrium with the carbon dioxide, i.e. its original colour represents the acidity produced by the carbon dioxide in the air. An increase in carbon dioxide makes it more acidic and it changes colour from orange/red to yellow. A decrease in carbon dioxide makes it less acid and causes a colour change to purple.

The results, therefore, provide evidence that in the light (tube 1) aquatic plants use up more carbon dioxide in photosynthesis than they produce in respiration. In darkness (tube 2) the plant produces carbon dioxide (from respiration). Tube 3 is the control, showing that it is the presence of the plant that causes a change in the solution in the boiling tube.

The experiment can be criticised on the grounds that the hydrogencarbonate indicator is not a specific test for carbon dioxide but will respond to any change in acidity or alkalinity. In tube 1 there would be the same change in colour if the leaf produced an alkaline gas such as ammonia, and in tube 2 any acid gas produced by the leaf would turn the indicator yellow. However, knowledge of the metabolism of the leaf suggests that these are less likely events than changes in the carbon dioxide concentration.

Effects of external factors on rate of photosynthesis

The rate of the light reaction will depend on the light intensity. The brighter the light, the faster will water molecules be split in the chloroplasts. The 'dark' reaction will be affected by temperature. A rise in temperature will increase the rate at which carbon dioxide is combined with hydrogen to make carbohydrate.

Limiting factors

Key definition

A **limiting factor** is something present in the environment in such short supply that it restricts life processes.

If you look at Figure 6.16(a), you will see that an increase in light intensity does indeed speed up photosynthesis, but only up to a point. Beyond that point, any further increase in light intensity has only a small effect. This limit on the rate of increase could be because all available chloroplasts are fully occupied in light absorption. So, no matter how much the light intensity increases, no more light can be absorbed and used. Alternatively, the limit could be imposed by the fact that there is not enough carbon dioxide in the air to cope with the increased supply of hydrogen atoms produced by the light reaction. Or, it may be that low temperature is restricting the rate of the 'dark' reaction.

Figure 6.16(b) shows that, if the temperature of a plant is raised, then the effect of increased illumination is not limited so much. Thus, in Figure 6.16(a), it seems likely that the increase in the rate of photosynthesis could have been limited by the temperature. Any one of the external factors – temperature, light intensity or carbon dioxide concentration – may limit the effects of the other two. A temperature rise may cause photosynthesis to speed up, but only to the point where the light intensity limits further increase. In such conditions, the external factor that restricts the effect of the others is called the **limiting factor**.

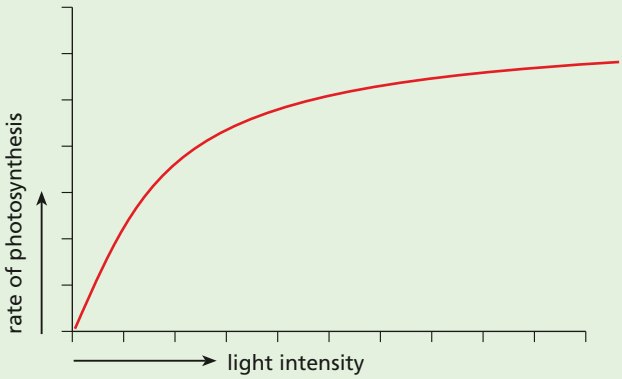
Since there is only 0.03% of carbon dioxide in the air, it might seem that a shortage of carbon dioxide could be an important limiting factor. Indeed, experiments do show that an increase in carbon dioxide concentration does allow a faster rate of photosynthesis. However, recent work in plant physiology has shown that the extra carbon dioxide affects reactions other than photosynthesis.

The main effect of extra carbon dioxide is to slow down the rate of oxidation of sugar by a process called **photorespiration** and this produces the same effect as an increase in photosynthesis.

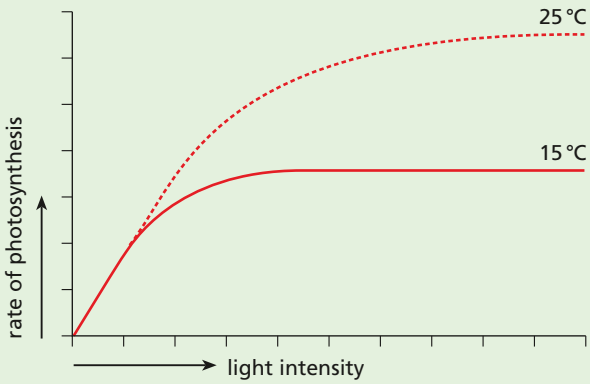
Although carbon dioxide concentration limits photosynthesis only indirectly, artificially high levels of carbon dioxide in greenhouses do effectively increase yields of crops (Figure 6.17).

Greenhouses also maintain a higher temperature and so reduce the effect of low temperature as a limiting factor, and they clearly optimise the light reaching the plants.

Parts of the world such as tropical countries often benefit from optimum temperatures and rainfall for crop production. However, greenhouses are still often used because they allow the growers to control how much water and nutrients the plants receive and they can also reduce crop damage by insect pests and disease. Sometimes rainfall is too great to benefit the plants. In an experiment in the Seychelles in the wet season of 1997, tomato crops in an open field yielded 2.9 kg m^{-2}. In a greenhouse, they yielded 6.5 kg m^{-2}.



(a) increasing light intensity



(b) increasing light intensity and temperature

Figure 6.16 Limiting factors in photosynthesis

The concept of limiting factors does not apply only to photosynthesis. Adding fertiliser to the soil, for example, may increase crop yields, but only up to the point where the roots can take up all the nutrients and the plant can build them into proteins, etc. The uptake of mineral ions is limited by the absorbing area of the roots, rates of respiration, aeration of the soil and availability of carbohydrates from photosynthesis.

Figure 6.17 Carrot plants grown in increasing concentrations of carbon dioxide from left to right

Currently there is debate about whether athletic performance is limited by the ability of the heart and lungs to supply oxygenated blood to muscles, or by the ability of the muscles to take up and use the oxygen.

The role of the stomata

The **stomata** (Figure 6.20) in a leaf may affect the rate of photosynthesis according to whether they are open or closed. When photosynthesis is taking place, carbon dioxide in the leaf is being used up and its concentration falls. At low concentrations of carbon dioxide, the stomata will open. Thus, when photosynthesis is most rapid, the stomata are likely to be open, allowing carbon dioxide to diffuse into the leaf. When the light intensity falls, photosynthesis will slow down and the build-up of carbon dioxide from respiration will make the stomata close. In this way, the stomata are normally regulated by the rate of photosynthesis rather than photosynthesis being limited by the stomata. However, if the stomata close during the daytime as a result of excessive water loss from the leaf, their closure will restrict photosynthesis by preventing the inward diffusion of atmospheric carbon dioxide.

Normally the stomata are open in the daytime and closed at night. Their closure at night, when intake of carbon dioxide is not necessary, reduces the loss of water vapour from the leaf (see 'Transpiration' in Chapter 8).

Leaf structure

The relationship between a leaf and the rest of the plant is described in Chapter 8.

A typical leaf of a broad-leaved plant is shown in Figure 6.18(a). (Figure 6.18(b) shows a transverse section through the leaf.) It is attached to the stem by a **leaf stalk**, which continues into the leaf as a **midrib**. Branching from the midrib is a network of veins that deliver water and salts to the leaf cells and carry away the food made by them.

As well as carrying food and water, the network of veins forms a kind of skeleton that supports the softer tissues of the leaf blade.

The **leaf blade** (or **lamina**) is broad. A vertical section through a small part of a leaf blade is shown in Figure 6.18(c) and Figure 6.19 is a photograph of a leaf section under the microscope.

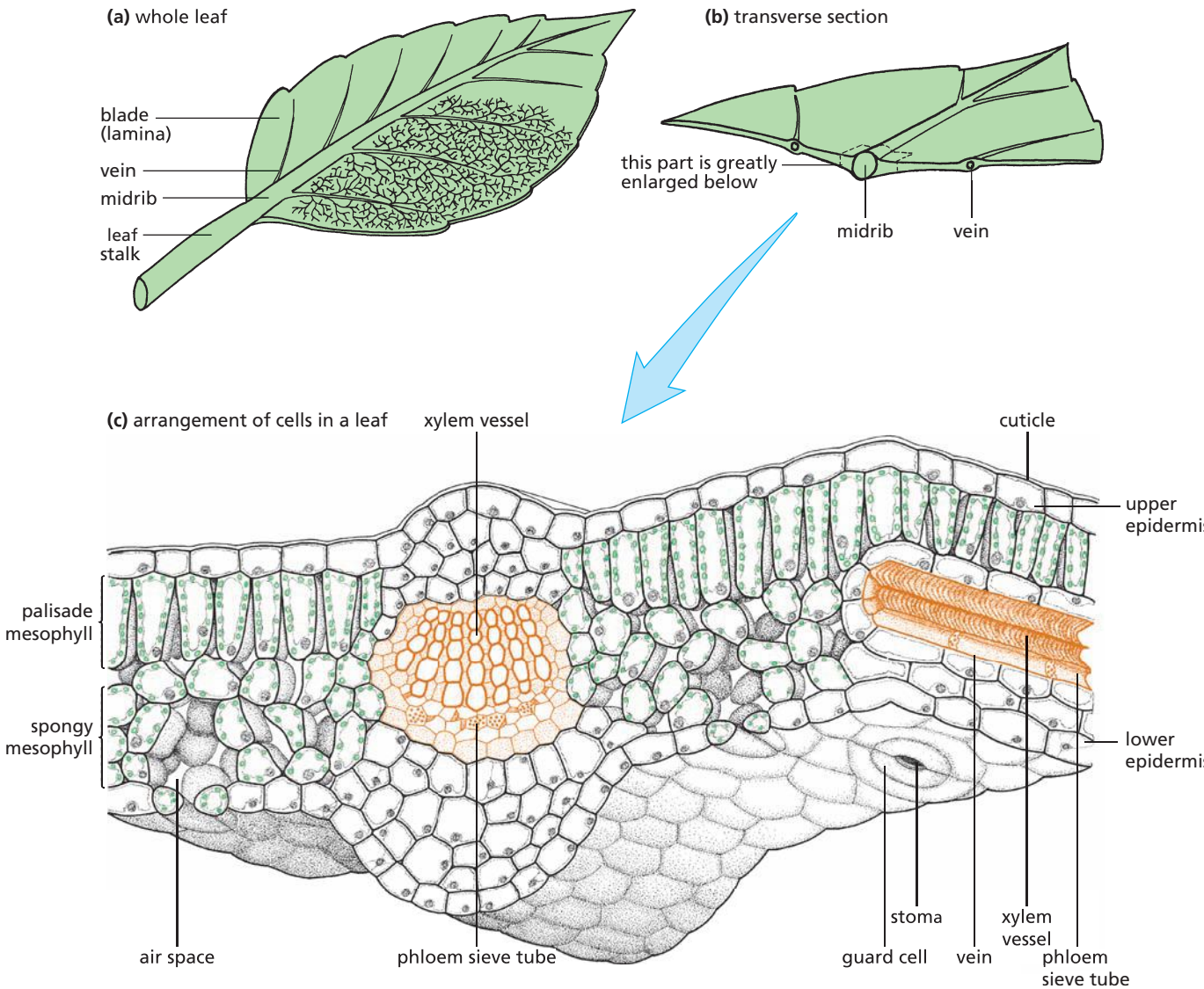


Figure 6.18 Leaf structure

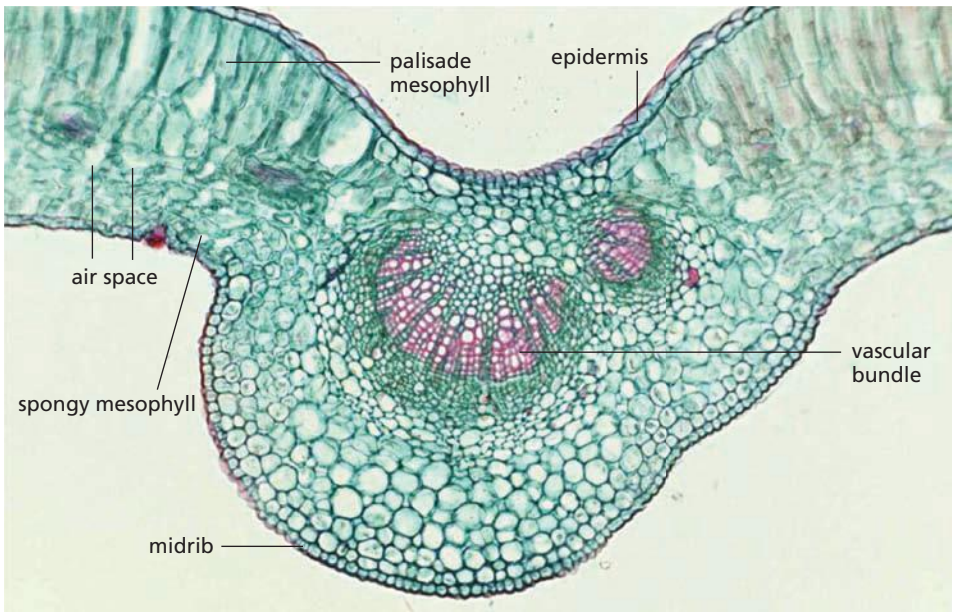


Figure 6.19 Transverse section through a leaf (×30)

Epidermis

The epidermis is a single layer of cells on the upper and lower surfaces of the leaf. There is a thin waxy layer called the **cuticle** over the epidermis.

Stomata

In the leaf epidermis there are structures called **stomata** (singular = stoma). A stoma consists of a pair of **guard cells** (Figure 6.20) surrounding an opening or stomatal pore. In most dicotyledons (i.e. the broad-leaved plants; see 'Features of organisms' in Chapter 1), the stomata occur only in the lower epidermis. In monocotyledons (i.e. narrow-leaved plants such as grasses) the stomata are equally distributed on both sides of the leaf.

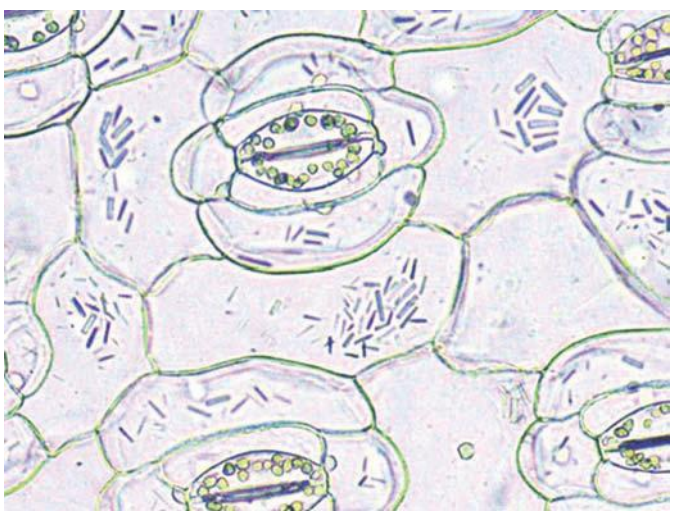


Figure 6.20 Stomata in the lower epidermis of a leaf (×350)

Mesophyll

The tissue between the upper and lower epidermis is called **mesophyll** (Figure 6.18(c)). It consists of two zones: the upper **palisade mesophyll** and the lower **spongy mesophyll** (Figure 6.23). The palisade cells are usually long and contain many **chloroplasts**. Chloroplasts are green organelles, due to the presence of the pigment chlorophyll, found in the cytoplasm of the photosynthesising cells. The spongy mesophyll cells vary in shape and fit loosely together, leaving many air spaces between them. They also contain chloroplasts.

Veins (vascular bundles)

The main **vein** of the leaf is called the midrib. Other veins branch off from this and form a network throughout the leaf. Vascular bundles consist of two different types of tissues, called **xylem** and **phloem**. The xylem vessels are long thin tubes with no cell contents when mature. They have thickened cell walls, impregnated with a material called **lignin**, which can form distinct patterns in the vessel walls, e.g. spirals (see Chapter 8). Xylem carries water and salts to cells in the leaf. The phloem is in the form of sieve tubes. The ends of each elongated cell are perforated to form sieve plates and the cells retain their contents. Phloem transports food substances such as sugars away from the leaf to other parts of the plant.

Table 6.1 Summary of parts of a leaf

Part of leaf	Details
cuticle	Made of wax, waterproofing the leaf. It is secreted by cells of the upper epidermis.
upper epidermis	These cells are thin and transparent to allow light to pass through. No chloroplasts are present. They act as a barrier to disease organisms.
palisade mesophyll	The main region for photosynthesis. Cells are columnar (quite long) and packed with chloroplasts to trap light energy. They receive carbon dioxide by diffusion from air spaces in the spongy mesophyll.
spongy mesophyll	These cells are more spherical and loosely packed. They contain chloroplasts, but not as many as in palisade cells. Air spaces between cells allow gaseous exchange – carbon dioxide to the cells, oxygen from the cells during photosynthesis.
vascular bundle	This is a leaf vein, made up of xylem and phloem. Xylem vessels bring water and minerals to the leaf. Phloem vessels transport sugars and amino acids away (this is called translocation).
lower epidermis	This acts as a protective layer. Stomata are present to regulate the loss of water vapour (this is called transpiration). It is the site of gaseous exchange into and out of the leaf.
stomata	Each stoma is surrounded by a pair of guard cells. These can control whether the stoma is open or closed. Water vapour passes out during transpiration. Carbon dioxide diffuses in and oxygen diffuses out during photosynthesis.

Functions of parts of the leaf

Epidermis

The epidermis helps to keep the leaf's shape. The closely fitting cells (Figure 6.18(c)) reduce evaporation from the leaf and prevent bacteria and fungi from getting in. The cuticle is a waxy layer lying over the epidermis, which helps to reduce water loss. It is produced by the epidermal cells.

Stomata

Changes in the turgor (see 'Osmosis' in Chapter 3) and shape of the guard cells can open or close the stomatal pore. In very general terms, stomata are open during the hours of daylight but closed during the evening and most of the night (Figure 6.21). This pattern, however, varies greatly with the plant species. A satisfactory explanation of stomatal rhythm has not been worked out, but when the stomata are open (i.e. mostly during daylight), they allow carbon dioxide to diffuse into the leaf where it is used for photosynthesis.

If the stomata close, the carbon dioxide supply to the leaf cells is virtually cut off and photosynthesis stops. However, in many species, the stomata are closed during the hours of darkness, when photosynthesis is not taking place anyway.

It seems, therefore, that stomata allow carbon dioxide into the leaf when photosynthesis is taking place and prevent excessive loss of water vapour (see 'Transpiration' in Chapter 8) when photosynthesis stops, but the story is likely to be more complicated than this.

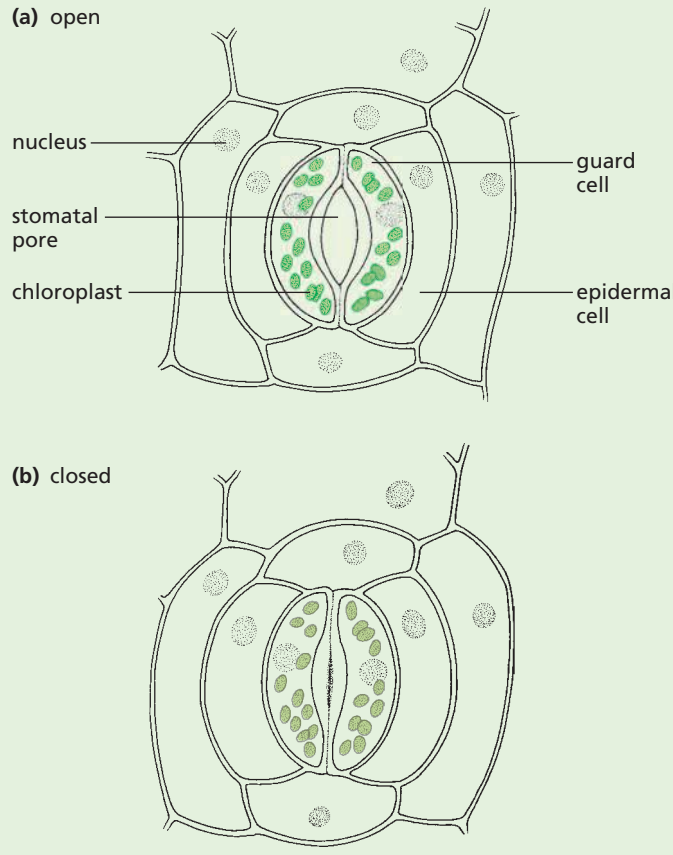


Figure 6.21 Stoma

The detailed mechanism by which stomata open and close is not fully understood, but it is known that in the light, the potassium concentration in the guard cell vacuoles increases. This lowers the water potential (see 'Osmosis' in Chapter 3) of the cell sap and water enters the guard cells by osmosis from their neighbouring epidermal cells. This

inflow of water raises the turgor pressure inside the guard cells.

The cell wall next to the stomatal pore is thicker than elsewhere in the cell and is less able to stretch (Figure 6.22). So, although the increased turgor tends to expand the whole guard cell, the thick inner wall cannot expand. This causes the guard cells to curve in such a way that the stomatal pore between them is opened.

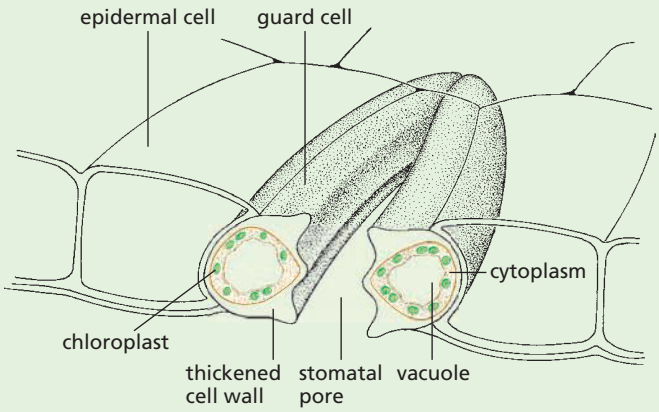


Figure 6.22 Structure of guard cells

When potassium ions leave the guard cell, the water potential rises, water passes out of the cells by osmosis, the turgor pressure falls and the guard cells straighten up and close the stoma.

Where the potassium ions come from and what triggers their movement into or out of the guard cells is still under active investigation.

You will notice from Figures 6.21 and 6.22 that the guard cells are the only epidermal cells containing chloroplasts. At one time it was thought that the chloroplasts built up sugar by photosynthesis during daylight, that the sugars made the cell sap more concentrated and so caused the increase in turgor. In fact, little or no photosynthesis takes place in these chloroplasts and their function has not been explained, though it is known that starch accumulates in them during the hours of darkness. In some species of plants, the guard cells have no chloroplasts.

Mesophyll

The function of the palisade cells and – to a lesser extent – of the spongy mesophyll cells is to make food by photosynthesis. Their chloroplasts absorb sunlight and use its energy to join carbon dioxide and water molecules to make sugar molecules as described earlier in this chapter.

In daylight, when photosynthesis is rapid, the mesophyll cells are using up carbon dioxide. As a result, the concentration of carbon dioxide in the air spaces falls to a low level and more carbon dioxide diffuses in (Chapter 3) from the outside air, through the stomata (Figure 6.23). This diffusion continues through the air spaces, up to the cells which are using carbon dioxide. These cells are also producing oxygen as a by-product of photosynthesis. When the concentration of oxygen in the air spaces rises, it diffuses out through the stomata.

Vascular bundles

The water needed for making sugar by photosynthesis is brought to the mesophyll cells by the veins. The mesophyll cells take in the water by osmosis (Chapter 3) because the concentration of free water molecules in a leaf cell, which contains sugars, will be less than the concentration of water in the water vessels of a vein. The branching network of leaf veins means that no cell is very far from a water supply.

The sugars made in the mesophyll cells are passed to the phloem cells (Chapter 8) of the veins, and these cells carry the sugars away from the leaf into the stem.

The ways in which a leaf is thought to be well adapted to its function of photosynthesis are listed in the next paragraph.

Adaptation of leaves for photosynthesis

When biologists say that something is **adapted**, they mean that its structure is well suited to its function. The detailed structure of the leaf is described in the first section of this chapter and although there are wide variations in leaf shape, the following general statements apply to a great many leaves, and are illustrated in Figures 6.18(b) and (c).

- Their broad, flat shape offers a large surface area for absorption of sunlight and carbon dioxide.
- Most leaves are thin and the carbon dioxide only has to diffuse across short distances to reach the inner cells.

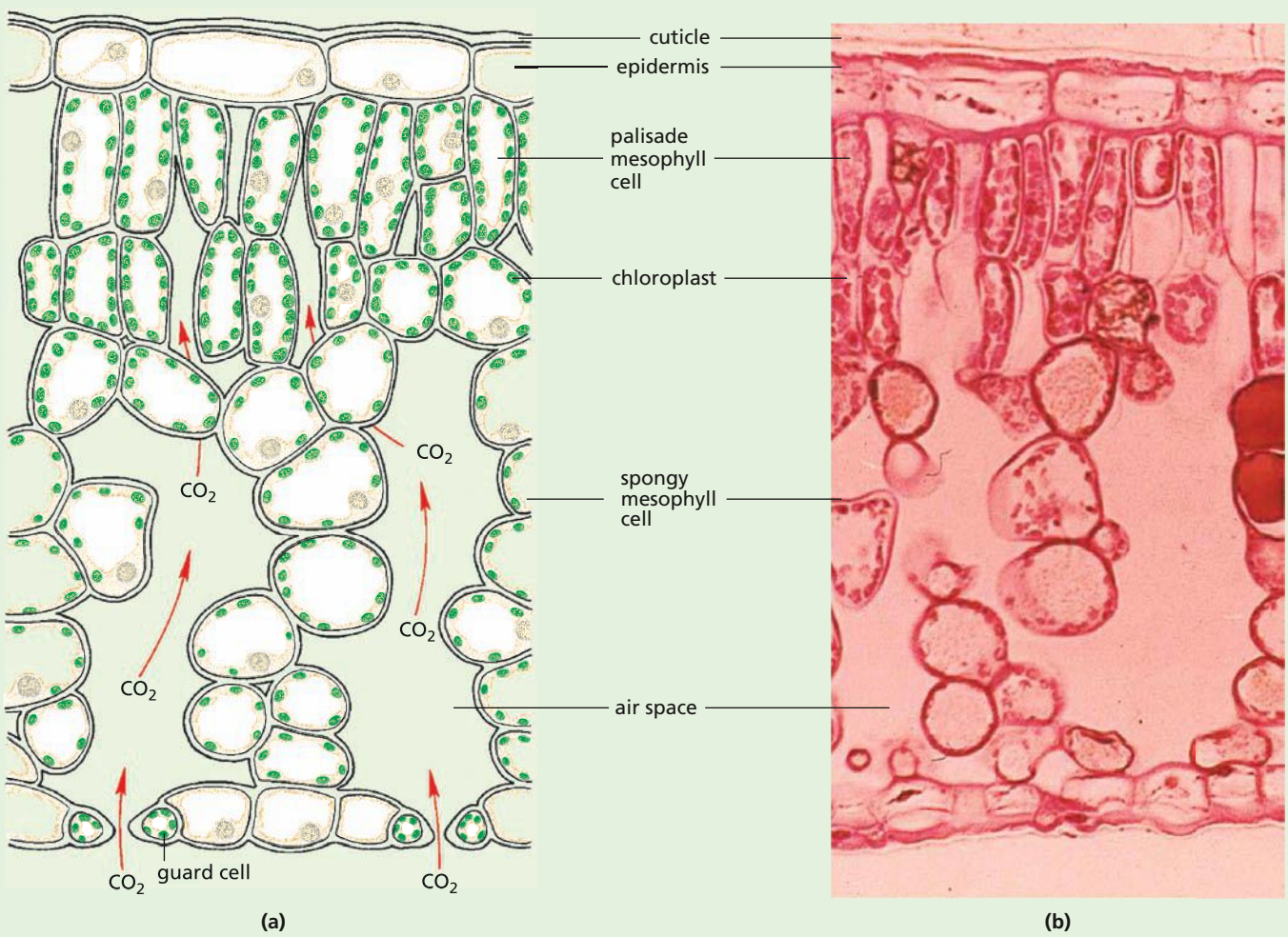


Figure 6.23 Vertical section through a leaf blade (×300)

- The large spaces between cells inside the leaf provide an easy passage through which carbon dioxide can diffuse.
- There are many stomata (pores) in the lower surface of the leaf. These allow the exchange of carbon dioxide and oxygen with the air outside.
- There are more chloroplasts in the upper (palisade) cells than in the lower (spongy mesophyll) cells. The palisade cells, being on the upper surface, will receive most sunlight and this will reach the chloroplasts without being absorbed by too many cell walls.
- The branching network of veins provides a good water supply to the photosynthesising cells. No cell is very far from a water-conducting vessel in one of these veins.

Although photosynthesis takes place mainly in the leaves, any part of the plant that contains chlorophyll will photosynthesise. Many plants have green stems in which photosynthesis takes place.

Mineral requirements

Plants need a source of nitrate ions (NO_3^-) for making amino acids (Chapter 4). Amino acids are important because they are joined together to make proteins, needed to form the enzymes and cytoplasm of the cell. Nitrates are absorbed from the soil by the roots.

Magnesium ions (Mg^{2+}) are needed to form chlorophyll, the photosynthetic pigment in chloroplasts. This metallic element is also obtained in salts from the soil (see the salts listed under 'Water cultures' on page 82).

Sources of mineral elements and effects of their deficiency

The substances mentioned previously (nitrates, magnesium) are often referred to as 'mineral salts' or 'mineral elements'. If any mineral element is lacking, or deficient, in the soil then the plants may show visible deficiency symptoms.

Many slow-growing wild plants will show no deficiency symptoms even on poor soils. Fast-growing crop plants, on the other hand, will show distinct deficiency symptoms though these will vary according to the species of plant. If nitrate ions are in short supply, the plant will show stunted growth. The stem becomes weak. The lower leaves become yellow and die, while the upper leaves turn pale green. If the plant is deficient in magnesium, it will not be able to make magnesium. The leaves turn yellow from the bottom of the stem upwards (a process called **chlorosis**). Farmers and gardeners can recognise these symptoms and take steps to replace the missing minerals.

The mineral elements needed by plants are absorbed from the soil in the form of salts. For example, a plant's needs for potassium (K) and nitrogen (N) might be met by absorbing the ions of the salt **potassium nitrate** (KNO_3). Salts like this come originally from rocks, which have been broken down to form the soil. They are continually being taken up from the soil by plants or washed out of the soil by rain. They are replaced partly from the dead remains of plants and animals. When these organisms die and their bodies decay, the salts they contain are released back into the soil. This process is explained in some detail, for nitrates, in Chapter 19 'Nutrient cycles'.

In arable farming, the ground is ploughed and whatever is grown is removed. There are no dead plants left to decay and replace the mineral salts. The farmer must replace them by spreading animal manure, sewage sludge or artificial fertilisers in measured quantities over the land.

Three manufactured fertilisers in common use are ammonium nitrate, superphosphate and compound NPK.

Ammonium nitrate (NH_4NO_3)
The formula shows that ammonium nitrate is a rich source of nitrogen but no other plant nutrients. It is sometimes mixed with calcium carbonate to form a compound fertiliser such as 'Nitro-chalk'.

Superphosphates
These fertilisers are mixtures of minerals. They all contain calcium and phosphate and some have sulfate as well.

Compound NPK fertiliser
'N' is the chemical symbol for nitrogen, 'P' for phosphorus and 'K' for potassium. NPK fertilisers are made by mixing ammonium sulfate, ammonium phosphate and potassium chloride in varying proportions. They provide the ions of nitrate, phosphate and potassium, which are the ones most likely to be below the optimum level in an agricultural soil.

Water cultures

It is possible to demonstrate the importance of the various mineral elements by growing plants in **water cultures**. A full water culture is a solution containing the salts that provide all the necessary elements for healthy growth, such as

- potassium nitrate for potassium and nitrogen
- magnesium sulfate for magnesium and sulfur
- potassium phosphate for potassium and phosphorus
- calcium nitrate for calcium and nitrogen.

From these elements, plus the carbon dioxide, water and sunlight needed for photosynthesis, a green plant can make all the substances it needs for a healthy existence.

Some branches of horticulture, e.g. growing of glasshouse crops, make use of water cultures on a large scale. Sage plants may be grown with their roots in flat polythene tubes. The appropriate water culture solution is pumped along these tubes (Figure 6.24). This method has the advantage that the yield is increased and the need to sterilise the soil each year, to destroy pests, is eliminated. This kind of technique is sometimes described as **hydroponics** or soil-less culture.

Figure 6.24 Soil-less culture. The sage plants are growing in a nutrient solution circulated through troughs of polythene.

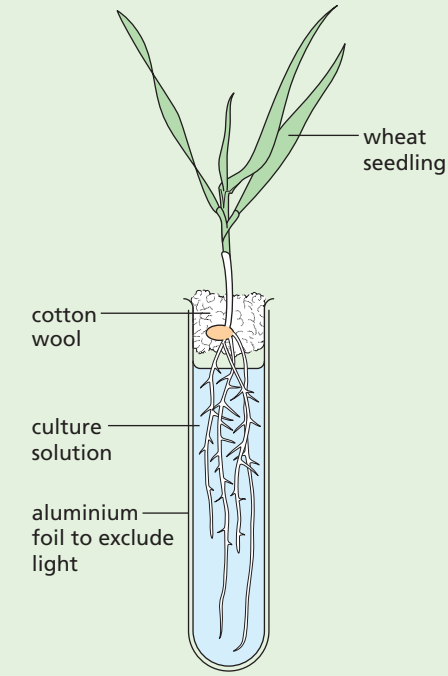


Figure 6.25 Apparatus for a water culture to investigate plant mineral requirements

Practical work

The importance of different mineral elements

- Place wheat seedlings in test-tubes containing water cultures as shown in Figure 6.25.
- Cover the tubes with aluminium foil to keep out light and so stop green algae from growing in the solution.
- Some of the solutions have one of the elements missing. For example, magnesium chloride is used instead of magnesium sulfate and so the solution will lack sulfur. In a similar way, solutions lacking nitrogen, potassium and phosphorus can be prepared.
- Leave the seedlings to grow in these solutions for a few weeks, keeping the tubes topped up with distilled water.

Result

The kind of result that might be expected from wheat seedlings is shown in Figure 6.26. Generally, the plants in a complete culture will be tall and sturdy, with large, dark green leaves. The plants lacking nitrogen will usually be stunted and have small, pale leaves. In the absence of magnesium, chlorophyll cannot be made, and these plants will be small with yellow leaves.

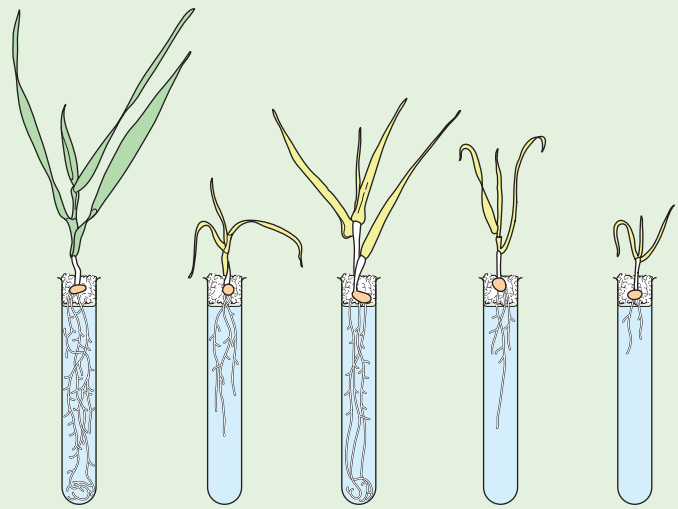


Figure 6.26 Result of water culture experiment

Interpretation

The healthy plant in the full culture is the control and shows that this method of raising plants does not affect them. The other, less healthy plants show that a full range of mineral elements is necessary for normal growth.

Quantitative results

Although the effects of mineral deficiency can usually be seen simply by looking at the wheat seedlings, it is better if actual measurements are made.

The height of the shoot, or the total length of all the leaves on one plant, can be measured. The total root length can also be measured, though this is difficult if root growth is profuse.

Alternatively, the **dry weight** of the shoots and roots can be measured. In this case, it is best to pool the results of several experiments. All the shoots from the complete culture are placed in a labelled container; all those from the 'no nitrate' culture solution are placed in another container; and so on for all the plants from the different solutions. The shoots are then dried at 110 °C for 24 hours and weighed. The same procedure can be carried out for the roots.

You would expect the roots and shoots from the complete culture to weigh more than those from the nutrient-deficient cultures.

Questions

Core

1 a What substances must a plant take in, in order to carry on photosynthesis?
  b Where does it get each of these substances from?
2 Look at Figure 6.23(a). Identify the palisade cells, the spongy mesophyll cells and the cells of the epidermis. In which of these would you expect photosynthesis to occur:
  a most rapidly
  b least rapidly
  c not at all?
  Explain your answers.
3 a What provides a plant with energy for photosynthesis?
  b What chemical process provides a plant with energy to carry on all other living activities?
4 Look at Figure 6.23. Why do you think that photosynthesis does not take place in the cells of the epidermis?
5 During bright sunlight, what gases are:
  a passing out of the leaf through the stomata
  b entering the leaf through the stomata?

Extended

6 a What substances does a green plant need to take in, to make:
  i sugar
  ii proteins?
  b What must be present in the cells to make reactions i and ii work?
7 A molecule of carbon dioxide enters a leaf cell at 4 p.m. and leaves the same cell at 6 p.m. What is likely to have happened to the carbon dioxide molecule during the 2 hours it was in the leaf cell?
8 In a partially controlled environment such as a greenhouse:
  a how could you alter the external factors to obtain maximum photosynthesis
  b which of these alterations might not be cost effective?
9 Figure 6.27 is a graph showing the average daily change in the carbon dioxide concentration, 1 metre above an agricultural crop in July. From what you have learned about photosynthesis and respiration, try to explain the changes in the carbon dioxide concentration.

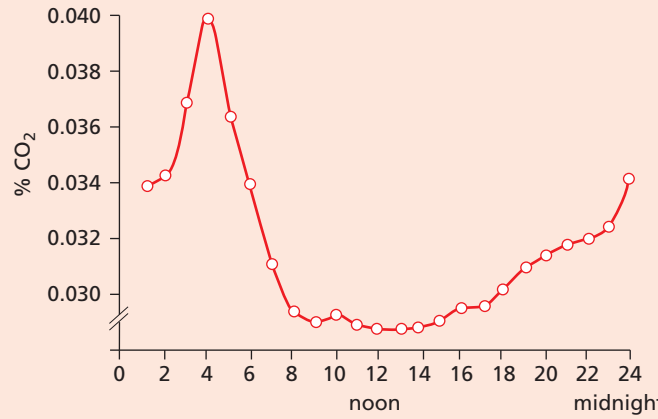


Figure 6.27 Daily changes in concentration of carbon dioxide 1 metre above a plant crop

10 What gases would you expect a leaf to be (i) taking in and (ii) giving out:
  a in bright sunlight
  b in darkness?
11 Measurements on a leaf show that it is giving out carbon dioxide and taking in oxygen. Does this prove that photosynthesis is *not* going on in the leaf? Explain your answer.
12 How could you adapt the experiment with hydrogencarbonate indicator on page 74 to find the light intensity that corresponded to the compensation point?
13 How would you expect the compensation points to differ between plants growing in a wood and those growing in a field?
14 What are the functions of:
  a the epidermis
  b the mesophyll of a leaf?
15 In some plants, the stomata close for a period at about midday. Suggest some possible advantages and disadvantages of this to the plant.
16 What salts would you put in a water culture which is to contain *no* nitrogen?
17 How can a floating pond plant, such as duckweed, survive without having its roots in soil?
18 In the water culture experiment, why should a lack of nitrate cause reduced growth?

19 Figure 6.28 shows the increased yield of winter wheat in response to adding more nitrogenous fertiliser.
   a If the applied nitrogen is doubled from 50 to 100 kg per hectare, how much extra wheat does the farmer get?
   b If the applied nitrogen is doubled from 100 to 200 kg per hectare, how much extra wheat is obtained?
   c What sort of calculations will a farmer need to make before deciding to increase the applied nitrogen from 150 to 200 kg per hectare?

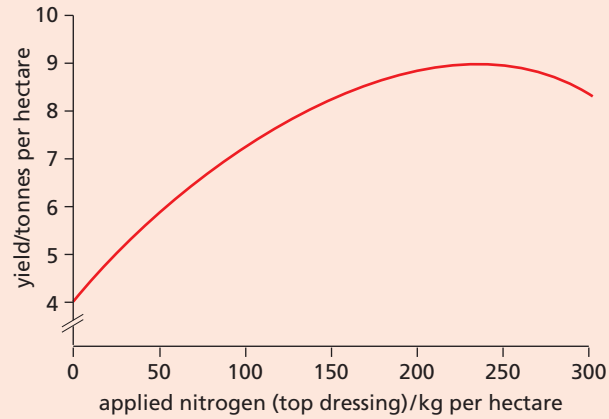


Figure 6.28

Checklist

After studying Chapter 6 you should know and understand the following:

- Photosynthesis is the way plants make their food.
- They combine carbon dioxide and water to make sugar.
- To do this, they need energy from sunlight, which is absorbed by chlorophyll.
- Chlorophyll converts light energy to chemical energy.
- The word equation to represent photosynthesis is

$$\text{carbon dioxide + water} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{glucose + oxygen}$$

- Plant leaves are adapted for the process of photosynthesis by being broad and thin, with many chloroplasts in their cells.
- From the sugar made by photosynthesis, a plant can make all the other substances it needs, provided it has a supply of mineral salts like nitrates.
- In daylight, respiration and photosynthesis will be taking place in a leaf; in darkness, only respiration will be taking place.
- In daylight, a plant will be taking in carbon dioxide and giving out oxygen.
- In darkness, a plant will be taking in oxygen and giving out carbon dioxide.
- Experiments to test photosynthesis are designed to exclude light, or carbon dioxide, or chlorophyll, to see if the plant can still produce starch.
- A starch test can be carried out to test if photosynthesis has occurred in a leaf.
- Leaves have a structure which adapts them for photosynthesis.
- Plants need a supply of nitrate ions to make protein and magnesium ions to make chlorophyll.

- The balanced chemical equation for photosynthesis is

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

- The rate of photosynthesis may be restricted by light intensity and temperature. These are 'limiting factors'.
- Glasshouses can be used to create optimal conditions for photosynthesis.
- Nitrate ions are needed to make proteins; magnesium ions are needed to make chlorophyll.

7 Human nutrition

Diet
Balanced diet
Sources and importance of food groups
Malnutrition

Kwashiorkor and marasmus

Alimentary canal
Definitions of digestion, absorption, assimilation, egestion
Regions of the alimentary canal and their functions
Diarrhoea
Cholera

How cholera affects osmosis in the gut

Mechanical digestion
Teeth
Dental decay
Tooth care

Chemical digestion
Importance
Sites of enzyme secretion
Functions of enzymes and hydrochloric acid

Roles of bile and enzymes

Absorption
Role of small intestine
Absorption of water

Significance of villi

The need for food

All living organisms need food. An important difference between plants and animals is that green plants can make food in their leaves but animals have to take it in 'ready-made' by eating plants or the bodies of other animals. In all plants and animals, food is used as follows:

For growth

It provides the substances needed for making new cells and tissues.

As a source of energy

Energy is required for the chemical reactions that take place in living organisms to keep them alive. When food is broken down during respiration (see Chapter 12), the energy from the food is used for chemical reactions such as building complex molecules (Chapter 4). In animals the energy is also used for activities such as movement, the heart beat and nerve impulses. Mammals and birds use energy to maintain their body temperature.

For replacement of worn and damaged tissues

The substances provided by food are needed to replace the millions of our red blood cells that break down each day, to replace the skin that is worn away and to repair wounds.

Diet

Balanced diets

A **balanced diet** must contain enough carbohydrates and fats to meet our energy needs. It must also contain enough protein of the right kind to provide the essential amino acids to make new cells and tissues for growth or repair. The diet must also contain vitamins and mineral salts, plant fibre and water. The composition of four food samples is shown in Figure 7.1.

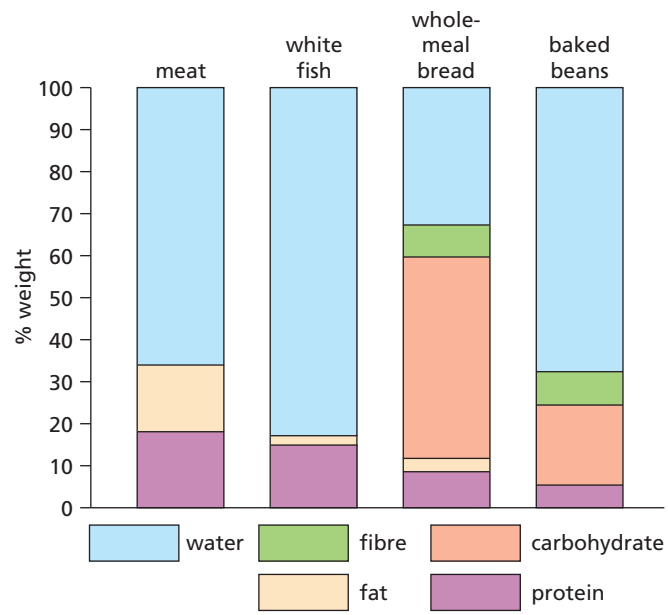


Figure 7.1 An analysis of four food samples
Note: The percentage of water includes any salts and vitamins. There are wide variations in the composition of any given food sample according to its source and the method of preservation and cooking. 'White fish' (e.g. cod, haddock, plaice) contains only 0.5% fat whereas herring and mackerel contain up to 14%. White bread contains only 2–3% fibre. Frying the food greatly adds to its fat content.

Energy requirements

Energy can be obtained from carbohydrates, fats and proteins. The cheapest energy-giving food is usually carbohydrate; the greatest amount of energy is available in fats; proteins give about the same energy as carbohydrates but are expensive. Whatever mixture of carbohydrate, fat and protein makes up the diet, the total energy must be sufficient:

- to keep our internal body processes working (e.g. heart beating, breathing action)
- to keep up our body temperature, and
- to meet the needs of work and other activities.

The amount of energy that can be obtained from food is measured in calories or joules. One gram of carbohydrate or protein can provide us with 16 or 17 kJ (kilojoules). A gram of fat can give 37 kJ. We need to obtain about 12 000 kJ of energy each day from our food. Table 7.1 shows how this figure is obtained. However, the figure will vary greatly according to our age, occupation and activity (Figure 7.2). It is fairly obvious that a person who does hard manual work, such as digging, will use more energy than someone who sits in an office. Similarly, someone who takes part in a lot of sport will need more energy input than someone who doesn't do much physical exercise.

Females tend to have lower energy requirements than males. Two reasons for this are that females have, on average, a lower body mass than males, which has a lower demand on energy intake, and there are also different physical demands made on boys and girls. However, an active female may well have a higher energy requirement than an inactive male of the same age.

As children grow, the energy requirement increases because of the energy demands of the growth process and the extra energy associated with maintaining their body temperature. However, metabolism, and therefore energy demands, tends to slow down with age once we become adults due to a progressive loss of muscle tissue.

Table 7.1 Energy requirements in kJ

8 hours asleep	2 400
8 hours awake; relatively inactive physically	3 000
8 hours physically active	6 600
Total	12 000

The 2400 kJ used during 8 hours' sleep represents the energy needed for **basal metabolism**, which maintains the circulation, breathing, body temperature, brain function and essential chemical processes in the liver and other organs.

If the diet includes more food than is needed to supply the energy demands of the body, the surplus food is stored either as glycogen in the liver or as fat below the skin and in the abdomen.

In 2006, the Food Standards Agency in Britain recommended that, for a balanced diet, 50% of our energy intake should be made up of carbohydrate, 35% of fat (with not more than 11% saturated fat) and the remaining percentage made up of fibre.

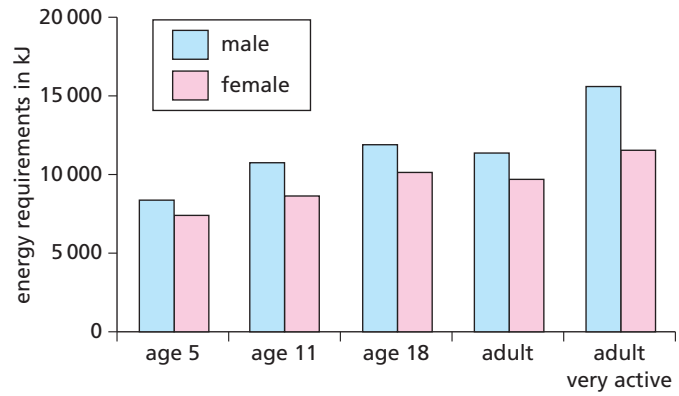


Figure 7.2 The changing energy requirements with age and activity

Protein requirements

Proteins are an essential part of the diet because they supply the amino acids needed to build up our own body structures. Estimates of how much protein we need have changed over the last few years. A recent WHO/FAO/UNU report recommended that an average person needs 0.57 g protein for every kilogram of body weight. That is, a 70 kg person would need 70 × 0.57 = 39.9, i.e. about 40 g protein per day.

This could be supplied by about 200 g (7 ounces) lean meat or 500 g bread but 2 kg potatoes would be needed to supply this much protein and even this will not contain all the essential amino acids.

Vegetarian and vegan diets

There is relatively less protein in food derived from plants than there is in animal products. **Vegetarians** and semi-vegetarians, who include dairy products, eggs and possibly fish in their diets, will obtain sufficient protein to meet their needs (Table 7.2). However, some vegetarian foods now contain relatively high proportions of protein: *Quorn* products (made from mycoprotein – derived from

fungi) typically contain 14.5 g protein per 100 g, compared with 18.0 g protein per 100 g for beef sausage, and they do not contain animal fats. **Vegans**, who eat no animal products, need to ensure that their diets include a good variety of cereals, peas, beans and nuts in order to obtain all the essential amino acids to build their body proteins.

Special needs

Pregnancy

A pregnant woman who is already receiving an adequate diet needs no extra food. Her body's metabolism will adapt to the demands of the growing baby although the demand for energy and protein does increase. If, however, her diet is deficient in protein, calcium, iron, vitamin D or folic acid, she will need to increase her intake of these substances to meet the needs of the baby. The baby needs protein for making its tissues, calcium and vitamin D are needed for bone development, and iron is used to make the haemoglobin in its blood.

Lactation

'Lactation' means the production of breast milk for feeding the baby. The production of milk, rich in proteins and minerals, makes a large demand on the mother's resources. If her diet is already adequate, her metabolism will adjust to these demands. Otherwise, she may need to increase her intake of proteins, vitamins and calcium to produce milk of adequate quality and quantity.

Growing children

Most children up to the age of about 12 years need less food than adults, but they need more in proportion to their body weight. For example, an adult may need 0.57 g protein per kg body weight, but a 6–11-month baby needs 1.85 g per kg and a 10-year-old child needs 1.0 g per kg for growth. In addition, children need extra calcium for growing bones, iron for their red blood cells, vitamin D to help calcify their bones and vitamin A for disease resistance.

Malnutrition

Malnutrition is often taken to mean simply not getting enough food, but it has a much wider meaning than this, including getting too much food or the wrong sort of food.

If the total intake of food is not sufficient to meet the body's need for energy, the body tissues themselves are broken down to provide the energy to stay alive. This leads to loss of weight, muscle wastage, weakness and ultimately **starvation**. Extreme slimming diets, such as those that avoid carbohydrate foods, can result in the disease anorexia nervosa.

Coronary heart disease can occur when the diet contains too much fat (see 'Heart' in Chapter 9). Deposits of a fatty substance build up in the arteries, reducing the diameter of these blood vessels, including the coronary artery. Blood clots are then more likely to form. Blood supply to the heart can be reduced resulting in **angina** (chest pains when exercising or climbing stairs, for example) and eventually a coronary **heart attack**.

If food intake is drastically inadequate, it is likely that the diet will also be deficient in proteins, minerals and vitamins so that deficiency diseases such as anaemia, rickets and scurvy also make an appearance. **Scurvy** is caused by a lack of vitamin C (ascorbic acid) in the diet. Vitamin C is present in citrus fruit such as lemons, blackcurrants, tomatoes, fresh green vegetables and potatoes. It is not unusual for people in developed countries who rely on processed food such as tinned products, rather than eating fresh produce, to suffer from scurvy. Symptoms of scurvy include bleeding under the skin, swollen and bleeding gums and poor healing of wounds. The victims of malnutrition due to food deficiencies such as those mentioned above will also have reduced resistance to infectious diseases such as malaria or measles. Thus, the symptoms of malnutrition are usually the outcome of a variety of causes, but all resulting from an inadequate diet.

The **causes of malnutrition** can be famine due to drought or flood, soil erosion, wars, too little land for too many people, ignorance of proper dietary needs but, above all, poverty. Malnourished populations are often poor and cannot afford to buy enough nutritious food.

World food

The world population doubled in the last 30 years but food production, globally, rose even faster. The 'Green Revolution' of the 1960s greatly increased global food production by introducing high-yielding varieties of crops. However, these varieties needed a high input of fertiliser and the use of pesticides, so only the wealthy farmers could afford to use them. Moreover, since 1984, the yields are no longer rising

fast enough to feed the growing population or keep pace with the loss of farmland due to erosion and urbanisation.

It is estimated that, despite the global increase in food production, 15% of the world population is undernourished and 180 million children are underweight (Figure 7.4).

There are no obvious, easy or universal solutions to this situation. Genetically modified crops (see 'Genetic engineering' in Chapter 20) may hold out some hope but they are some way off. There is resistance to their introduction in some countries because of concerns about their safety, gene transfer to wild plants or animals, the creation of allergies, the cost of seed and, with some GM seed, the necessity to buy particular pesticides to support them. Redistribution of food from the wealthy to the poorer countries is not a practical proposition except in emergencies, and the process can undermine local economies.

The strategies adopted need to be tailored to the needs and climate of individual countries. Crops suited to the region should be grown. Millet and sorghum grow far better in dry regions than do rice or wheat and need little or no irrigation. Cash crops such as coffee, tea or cotton can earn foreign currency but have no food value and do not feed the local population. There has been a surge in the production of palm oil (Figure 7.3) due to world demand for the product as a biofuel as well as for food manufacture. This has resulted in deforestation to provide land to grow the crop and is putting endangered species at risk of extinction. Countries such as Indonesia and Malaysia have been particularly affected. Where cash crops are grown, it might be better to use the land, where suitable, to cultivate food crops.

Figure 7.3 A new palm oil plantation, replacing a rainforest

The agricultural practices need to be sustainable and not result in erosion. Nearly one-third of the world's crop-growing land has had to be abandoned in the last 40 years because erosion has made it unproductive. Over-irrigation can also cause a build-up in soil salinity, making the land effectively sterile due to the osmotic problems the salt creates (see 'Osmosis' in Chapter 3). Conservation of land, water and energy is essential for sustainable agriculture. A reduction in the growth of the world's population, if it could be achieved, would have a profound effect in reducing malnutrition.

Apart from the measures outlined above, lives could be saved by such simple and inexpensive steps as provision of regular vitamin and mineral supplements. It is estimated that about 30 million children are deficient in vitamin A. This deficiency leads to blindness and death if untreated.

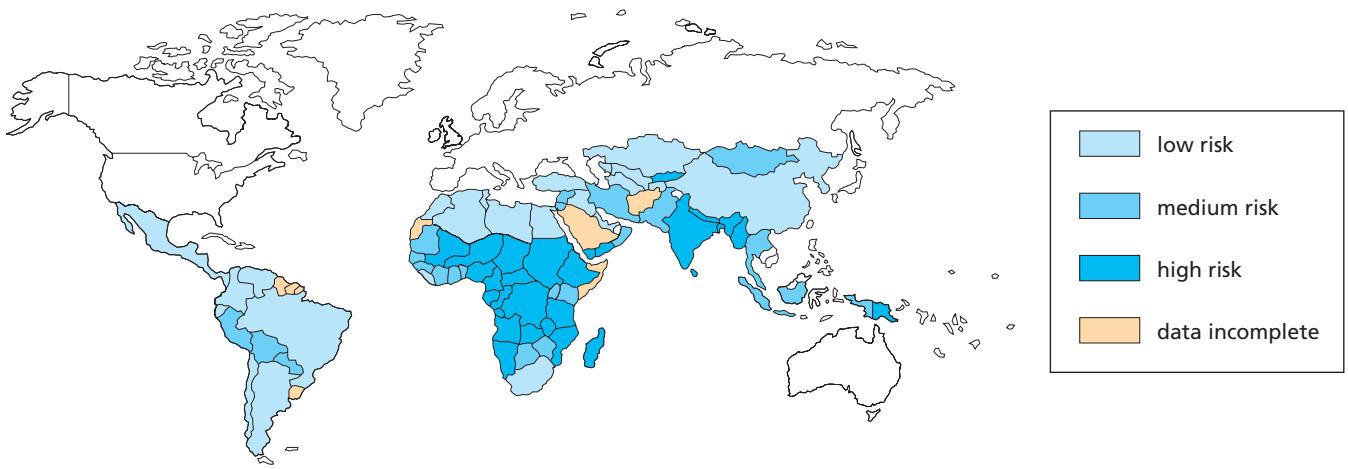


Figure 7.4 Countries with populations at risk of inadequate nutrition

Western diets

In the affluent societies, e.g. USA and Europe, there is no general shortage of food and most people can afford a diet with an adequate energy and protein content. So, few people are undernourished. Eating too much food or food of the 'wrong' sort, however, leads to malnutrition of a different kind.

Refined sugar (sucrose)

This is a very concentrated source of energy. You can absorb a lot of sugar from biscuits, ice-cream, sweets, soft drinks, tinned fruits and sweet tea without ever feeling 'full up'. So you tend to take in more sugar than your body needs, which may lead to you becoming overweight or obese. The food industry has been urged to reduce the sugar content of its products to help curb the increase in obesity in countries like Great Britain and America.

Sugar is also a major cause of tooth decay (see 'Mechanical digestion').

Fats

Fatty deposits, called 'plaques', in the arteries can lead to coronary heart disease and strokes (see 'Heart' in Chapter 9). These plaques are formed from lipids and **cholesterol** combined with proteins (**low density lipoproteins** or **LDLs**). Although the liver makes LDLs, there is evidence to suggest that a high intake of fats, particularly animal fats, helps raise the level of LDLs in the blood and increase the risk of plaque formation.

Most animal fats are formed from **saturated fatty acids**, so called because of their molecular structure. Plant oils are formed from **unsaturated fatty acids** (polyunsaturates) and are thought less likely to cause fatty plaques in the arteries. For this reason, vegetable fats and certain margarines are considered, by some nutritionists, to be healthier than butter and cream. However, there is still much debate about the evidence for this.

Fibre

Many of the processed foods in Western diets contain too little fibre. White bread, for example, has had the fibre (bran) removed. A lack of fibre can result in **constipation** (see 'Classes of food'). Unprocessed foods, such as unskinned potatoes, vegetables and fruit, contain plenty of fibre. Food rich in fibre is usually bulky and makes you feel 'full up' so that you are unlikely to overeat. Fibre enables the process of peristalsis (Figure 7.14) to move food through the gut more efficiently and may also protect the intestines from cancer and other disorders. As explained later, fibre helps prevent constipation.

Overweight and obesity

These are different degrees of the same disorder. If you take in more food than your body needs for energy, growth and replacement, the excess is converted to fat and stored in fat deposits under the skin or in the abdomen.

Obese people are more likely to suffer from high blood pressure, coronary heart disease (see the previous section on malnutrition) and diabetes (Chapter 14). Having extra weight to carry also makes you reluctant to take exercise. By measuring a person's height and body mass, it is possible to use a chart to predict whether or not they have an ideal body mass (Figure 7.5).

Why some people should be prone to obesity is unclear. There may be a genetic predisposition, in which the brain centre that responds to food intake may not signal when sufficient food has been taken in; in some cases it may be the outcome of an infectious disease. Whatever the cause, the remedy is to reduce food intake to a level that matches but does not exceed the body's needs. Taking exercise helps, but it takes a great deal of exercise to 'burn off' even a small amount of surplus fat.

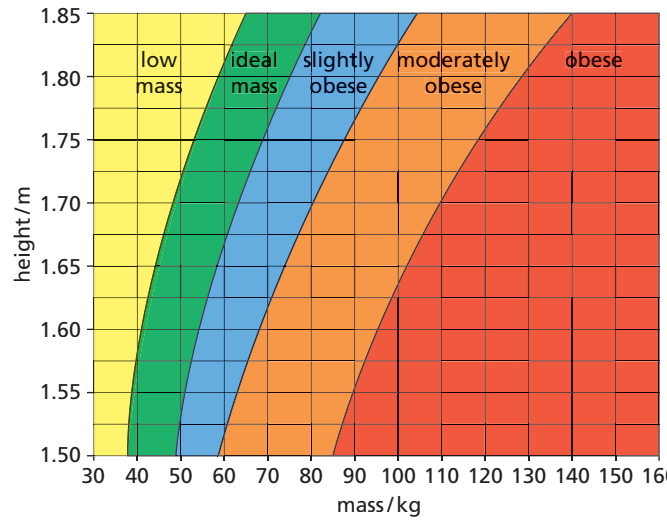


Figure 7.5 Ideal body mass chart

Classes of food

There are three classes of food: carbohydrates, proteins and fats. The chemical structure of these substances is described in Chapter 4. In addition

to proteins, carbohydrates and fats, the diet must include salts, vitamins, water and vegetable fibre (roughage). These substances are present in a balanced diet and do not normally have to be taken in separately. A summary of the three classes of food and their sources is shown in Table 7.3.

Carbohydrates

Sugar and **starch** are important carbohydrates in our diet. Starch is abundant in potatoes, bread, maize, rice and other cereals. Sugar appears in our diet mainly as **sucrose** (table sugar) which is added to drinks and many prepared foods such as jam, biscuits and cakes. Glucose and fructose are sugars that occur naturally in many fruits and some vegetables.

Although all foods provide us with energy, carbohydrates are the cheapest and most readily available source of energy. They contain the elements carbon, hydrogen and oxygen (e.g. glucose is $C_6H_{12}O_6$). When carbohydrates are oxidised to provide energy by respiration they are broken down to carbon dioxide and water (Chapter 12). One gram of carbohydrate can provide, on average, 16 kilojoules (kJ) of energy (see practical work 'Energy from food', p. 95).

If we eat more carbohydrates than we need for our energy requirements, the excess is converted in the liver to either glycogen or fat. The glycogen is stored in the liver and muscles; the fat is stored in fat deposits in the abdomen, round the kidneys or under the skin (Figure 7.6).

The **cellulose** in the cell walls of all plant tissues is a carbohydrate. We probably derive relatively little nourishment from cellulose but it is important in the diet as **fibre**, which helps to maintain a healthy digestive system.

Fats

Animal fats are found in meat, milk, cheese, butter and egg-yolk. Plant fats occur as oils in fruits (e.g. palm oil) and seeds (e.g. sunflower seed oil), and are used for cooking and making margarine. Fats and oils are sometimes collectively called **lipids**.

Lipids are used in the cells of the body to form part of the cell membrane and other membrane systems. Lipids can also be oxidised in respiration, to carbon dioxide and water. When used to provide energy in this way, 1 g fat gives 37 kJ of energy. This is more than twice as much energy as can be obtained from the same weight of carbohydrate or protein.

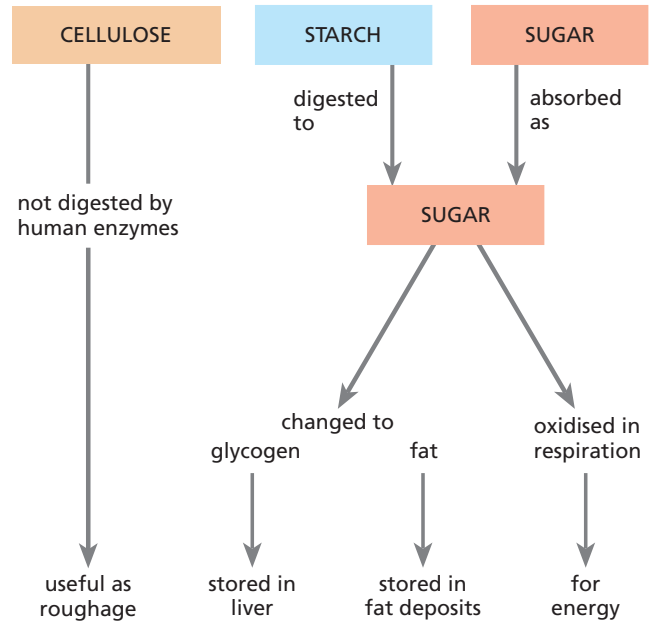


Figure 7.6 Digestion and use of carbohydrate

Fats can be stored in the body, so providing a means of long-term storage of energy in fat deposits. The fatty tissue, **adipose tissue**, under the skin forms a layer that, if its blood supply is restricted, can reduce heat losses from the body.

Proteins

Lean meat, fish, eggs, milk and cheese are important sources of animal protein. All plants contain some protein, but soybeans, seeds such as pumpkin, and nuts are the best sources (see Table 7.2).

Table 7.2 Comparing the protein content of foods (source: USDA database)

Food	Protein content/g per 100 g
soybeans	35
pumpkin seeds	30
beef, lean	27
peanuts	26
fish, e.g. salmon	25
cheese, e.g. cheddar	25
bacon	20
Tofu	18
beef sausage	18
chicken breast	17
Quorn sausage	14
eggs	13
wheat flour	13
yoghurt	4

Proteins, when digested, provide the chemical substances needed to build cells and tissues, e.g. skin, muscle, blood and bones. Neither carbohydrates nor fats can do this so it is essential to include some proteins in the diet.

Protein molecules consist of long chains of **amino acids** (see Chapter 4). When proteins are digested, the molecules are broken up into the constituent amino acids. The amino acids are absorbed into the bloodstream and used to build up different proteins. These proteins form part of the cytoplasm and enzymes of cells and tissues. Such a rearrangement of amino acids is shown in Figure 7.7.

The amino acids that are not used for making new tissues cannot be stored, but the liver removes their amino ($—NH_2$) groups and changes the residue to glycogen. The glycogen can be stored or oxidised to provide energy (Chapter 12). One gram of protein can provide 17 kJ of energy.

Chemically, proteins differ from both carbohydrates and fats because they contain nitrogen and sometimes sulfur as well as carbon, hydrogen and oxygen.

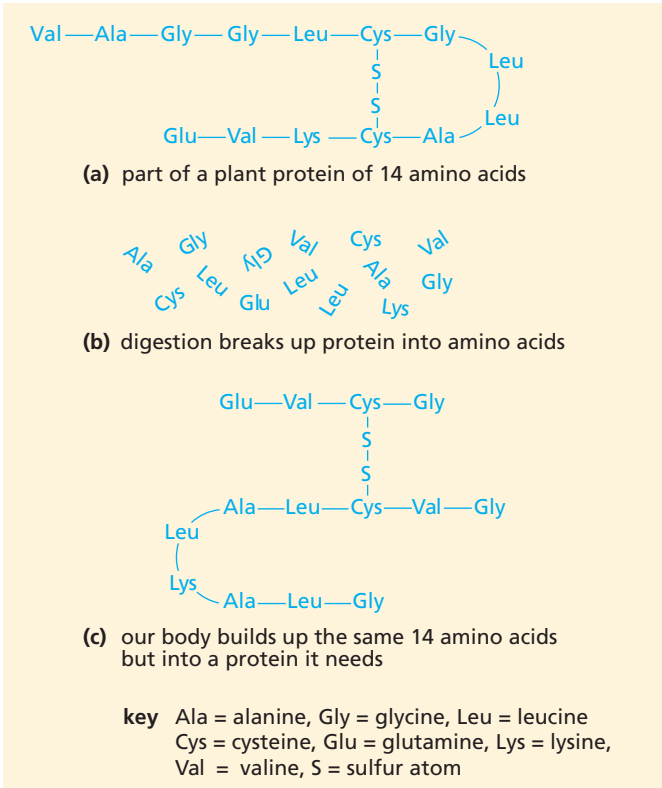


Figure 7.7 A model for digestion and use of a protein molecule

Table 7.3 Summary table for food classes

Nutrient	Good food sources	Use in the body
carbohydrate	rice, potato, yam, cassava, bread, millet, sugary foods (cake, jam, honey)	storage; source of energy
fat/oil (oils are liquid at room temperature, but fats are solid)	butter, milk, cheese, egg-yolk, animal fat, groundnuts (peanuts)	source of energy (twice as much as carbohydrate); insulation against heat loss; some hormones; cell membranes; insulation of nerve fibres
protein	meat, fish, eggs, soya, groundnuts, milk, Quorn, cowpeas	growth; tissue repair; enzymes; some hormones; cell membranes; hair; nails; can be broken down to provide energy

Vitamins

All proteins are similar to each other in their chemical structure, as are all carbohydrates. Vitamins, on the other hand, are a group of organic substances quite unrelated to each other in their chemical structure.

The features shared by all vitamins are:

- They are not digested or broken down for energy.
- Mostly, they are not built into the body structures.
- They are essential in small quantities for health.
- They are needed for chemical reactions in the cells, working in association with enzymes.

Plants can make these vitamins in their leaves, but animals have to obtain many of them ready-made either from plants or from other animals.

If any one of the vitamins is missing or deficient in the diet, a vitamin-deficiency disease may develop. Such a disease can be cured, at least in the early stages, simply by adding the vitamin to the diet.

Fifteen or more vitamins have been identified and they are sometimes grouped into two classes: water-soluble and fat-soluble. The fat-soluble vitamins are found mostly in animal fats or vegetable oils, which is one reason why our diet should include some of these fats. The water-soluble vitamins are present in green leaves, fruits and cereal grains.

See Table 7.4 for details of vitamins C and D.

Salts

These are sometimes called ‘mineral salts’ or just ‘minerals’. Proteins, carbohydrates and fats provide the body with carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorus but there are several more elements that the body needs and which occur as salts in the food we eat.

Iron

Red blood cells contain the pigment haemoglobin (see 'Blood' in Chapter 9). Part of the haemoglobin molecule contains iron and this plays an important role in carrying oxygen around the body. Millions of red cells break down each day and their iron is stored by the liver and used to make more haemoglobin. However, some iron is lost and needs to be replaced through dietary intake.

Red meat, especially liver and kidney, is the richest source of iron in the diet, but eggs, groundnuts, wholegrains such as brown rice, spinach and other green vegetables are also important sources.

If the diet is deficient in iron, a person may suffer from some form of **anaemia**. Insufficient haemoglobin is made and the oxygen-carrying capacity of the blood is reduced.

Calcium

Calcium, in the form of calcium phosphate, is deposited in the bones and the teeth and makes them hard. It is present in blood plasma and plays an essential part in normal blood clotting (see 'Blood' in Chapter 9). Calcium is also needed for the chemical changes that make muscles contract and for the transmission of nerve impulses.

The richest sources of calcium are milk (liquid, skimmed or dried) and cheese, but calcium is present in most foods in small quantities and also in 'hard' water.

Many calcium salts are not soluble in water and may pass through the alimentary canal without being absorbed. Simply increasing the calcium in the diet may not have much effect unless the calcium is in the right form, the diet is balanced and the intestine is healthy. Vitamin D and bile salts are needed for efficient absorption of calcium.

Dietary fibre (roughage)

When we eat vegetables and other fresh plant material, we take in a large quantity of plant cells. The cell walls of plants consist mainly of cellulose, but we do not have enzymes for digesting this substance. The result is that the plant cell walls reach the large intestine (colon) without being digested. This undigested part of the diet is called fibre or roughage. The colon contains many bacteria that can digest some of the substances in the plant cell walls to form fatty acids (Chapter 4). Vegetable fibre, therefore, may supply some useful food material, but it has other important functions.

The fibre itself and the bacteria, which multiply from feeding on it, add bulk to the contents of the colon and help it to retain water. This softens the faeces and reduces the time needed for the undigested residues to pass out of the body. Both effects help to prevent constipation and keep the colon healthy.

Most vegetables and whole cereal grains contain fibre, but white flour and white bread do not contain much. Good sources of dietary fibre are vegetables, fruit and wholemeal bread.

Water

About 70% of most tissue consists of water; it is an essential part of cytoplasm. The body fluids, blood, lymph and tissue fluid (Chapter 9) are composed mainly of water.

Digested food, salts and vitamins are carried around the body as a watery solution in the blood (Chapter 9) and excretory products such as excess salt and urea are removed from the body in solution by the kidneys (Chapter 13). Water thus acts as a solvent and as a transport medium for these substances.

Digestion is a process that uses water in a chemical reaction to break down insoluble substances to soluble ones. These products then pass, in solution, into the bloodstream. In all cells there are many reactions in which water plays an essential part as a reactant and a solvent.

Table 7.4 Vitamins

Name and source of vitamin	Importance of vitamin	Diseases and symptoms caused by lack of vitamin	Notes
vitamin C (ascorbic acid); water-soluble: oranges, lemons, grapefruit, tomatoes, fresh green vegetables, potatoes	prevents scurvy	Fibres in connective tissue of skin and blood vessels do not form properly, leading to bleeding under the skin, particularly at the joints, swollen, bleeding gums and poor healing of wounds. These are all symptoms of scurvy (Figure 7.8).	Possibly acts as a catalyst in cell respiration. Scurvy is only likely to occur when fresh food is not available. Cows' milk and milk powders contain little ascorbic acid so babies may need additional sources. Cannot be stored in the body; daily intake needed.
vitamin D (calciferol); fat-soluble: butter, milk, cheese, egg-yolk, liver, fish-liver oil	prevents rickets	Calcium is not deposited properly in the bones, causing **rickets** in young children. The bones remain soft and are deformed by the child's weight (Figure 7.9). Deficiency in adults causes **osteo-malacia**; fractures are likely.	Vitamin D helps the absorption of calcium from the intestine and the deposition of calcium salts in the bones. Natural fats in the skin are converted to a form of vitamin D by sunlight.

Since we lose water by evaporation, sweating, urinating and breathing, we have to make good this loss by taking in water with the diet.

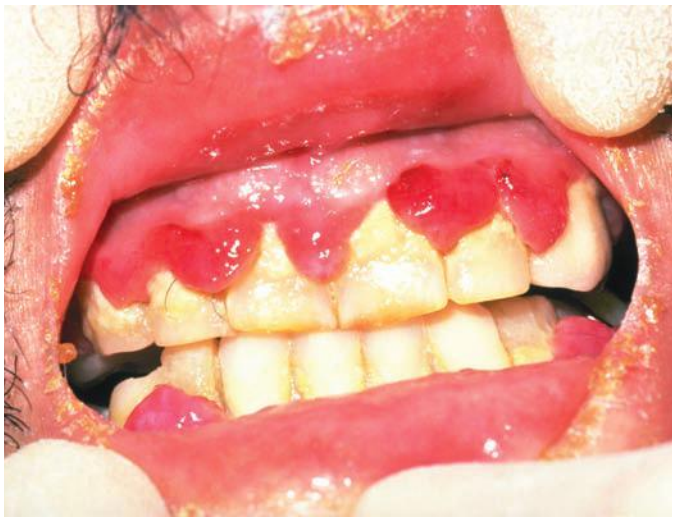


Figure 7.8 Symptoms of scurvy

Kwashiorkor
Kwashiorkor (roughly = 'deposed child') is an example of protein–energy malnutrition (PEM) in the developing world. When a mother has her second baby, the first baby is weaned on to a starchy diet of yam, cassava or sweet potato, all of which have inadequate protein. The first baby then develops symptoms of kwashiorkor (dry skin, pot-belly, changes to hair colour, weakness and irritability). Protein deficiency is not the only cause of kwashiorkor. Infection, plant toxins, digestive failure or even psychological effects may be involved. The good news, however, is that it can often be cured or prevented by an intake of protein in the form of dried skimmed milk.

Marasmus
The term 'marasmus' is derived from a Greek word, meaning decay. It is an acute form of malnutrition. The condition is due to a very poor diet with inadequate carbohydrate intake as well as a lack of protein. The incidence of marasmus increases in babies until they reach the age of 12 months. Sufferers are extremely emaciated with reduced fat and muscle tissue. Their skin is thin and hangs in folds. Marasmus is distinguished from kwashiorkor because kwashiorkor is due to lack of protein intake, while energy intake is adequate. Treatment involves provision of an energy-rich, balanced diet, but the complications of the disorder, which may include infections and dehydration, also need attention to increase chances of survival and recovery.

Causes and effects of mineral and vitamin deficiencies

Iron
Iron is present in red meat, eggs, nuts, brown rice, shellfish, soybean flour, dried fruit such as apricots, spinach and other dark-green leafy vegetables. Lack of iron in the diet can lead to iron-deficiency anaemia, which is a decrease in the number of red blood cells. Red blood cells, when mature, have no nucleus and this limits their life to about 3 months, after which they are broken down in the liver and replaced. Most of the iron is recycled, but some is lost as a chemical called bilirubin in the faeces and needs to be replaced. Adults need to take in about 15 mg each day. Without sufficient iron, your body is unable to produce enough haemoglobin, the protein in red blood cells responsible for transporting oxygen to respiring tissues. Iron is also needed by the muscles and for enzyme systems in all the body cells. The symptoms of anaemia are feeling weak, tired and irritable.

Vitamin D
Vitamin D is the only vitamin that the body can manufacture, when the skin is exposed to sunlight. However, for 6 months of the year (October to April), much of western Europe does not receive enough UV rays in sunlight to make vitamin D in the skin. So, many people living there are at risk of not getting enough vitamin D unless they get it in their diet. Also, people who have darker skin, such as people of African, African-Caribbean and South Asian origin, are at risk because their skin reduces UV light absorption.

Foods that provide vitamin D include oily fish such as sardines and mackerel, fish liver oil, butter, milk, cheese and egg-yolk. In addition, many manufactured food products contain vitamin D supplements.

Vitamin D helps in the absorption of calcium and phosphorus through the gut wall. Bone is made of the mineral calcium phosphate. A lack of the vitamin therefore results in poor calcium and phosphorus

deposition in bones, leading to softening. The weight of the body can deform bones in the legs, causing the condition called rickets in children (Figure 7.9). Adults deficient in vitamin D can suffer from **osteo-malacia**; they are very vulnerable to fracturing bones if they fall.

Figure 7.9 A child with rickets

Practical work

Energy from food

- Set up the apparatus as shown in Figure 7.10.
- Use a measuring cylinder to place 20 cm^3 cold water in the boiling tube.
- With a thermometer, find the temperature of the water and make a note of it.
- Weigh a peanut (or other piece of dried food), secure it onto a mounted needle and heat it with the Bunsen flame until it begins to burn. **Note**: make sure that no students have nut allergies.
- As soon as it starts burning, hold the nut under the boiling tube so that the flames heat the water.
- If the flame goes out, do not apply the Bunsen burner to the food while it is under the boiling tube, but return the nut to the Bunsen flame to start the nut burning again and replace it beneath the boiling tube as soon as the nut catches alight.
- When the nut has finished burning and cannot be ignited again, gently stir the water in the boiling tube with the thermometer and record its new temperature.

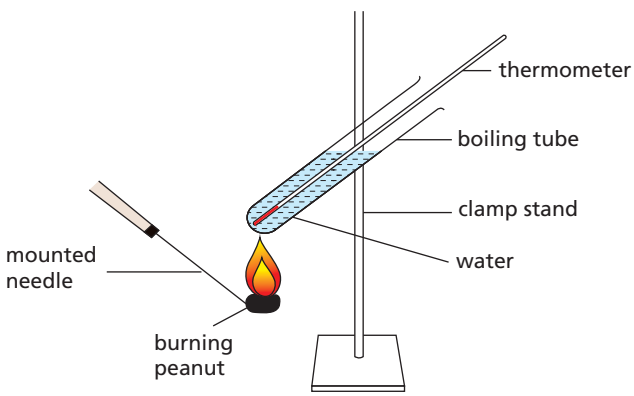


Figure 7.10 Experiment to show the energy in food

- Calculate the rise in temperature by subtracting the first from the second temperature.
- Work out the quantity of energy transferred to the water from the burning peanut as follows:

  4.2 J raise 1 g water by 1 °C
  20 cm^3 cold water weighs 20 g
  The energy (in joules) released by the burning nut = rise in temperature × mass of water × 4.2

Note: The value 4.2 in the equation is used to convert the answer from calories to joules, as the calorie is an obsolete unit.

- To calculate the energy from 1 g of nut, divide your answer by the mass of nut you used. This gives a value in $J\,g^{-1}$.
- The experiment can now be repeated using different sizes of nut, or different varieties of nut, or other types of food. Remember to replace the warm water in the boiling tube with 20 cm^3 cold water each time.
- The experiment is quite inaccurate: compare the value you obtained with an official value (2385 kJ per 100 g). There are plenty of websites with this sort of information if you use different nuts or other food. To make the comparison you may need to convert your energy value from joules to kilojoules (divide by 1000) and to 100 g of the food (multiply by 100).
- Try to list some of the faults in the design of the experiment to account for the difference you find. Where do you think some of the heat is going? Can you suggest ways of reducing this loss to make the results more accurate?

Alimentary canal

Key definitions

Ingestion is the taking of substances such as food and drink into the body through the mouth.
Mechanical digestion is the breakdown of food into smaller pieces without chemical change to the food molecules.
Chemical digestion is the breakdown of large insoluble molecules into small soluble molecules.
Absorption is the movement of small food molecules and ions through the wall of the intestine into the blood.
Assimilation is the movement of digested food molecules into the cells of the body where they are used, becoming part of the cells.
Egestion is the passing out of food that has not been digested or absorbed, as faeces, through the anus.

Feeding involves taking food into the mouth, chewing it and swallowing it down into the stomach. This satisfies our hunger, but for food to be of any use to the whole body it has first to be **digested**. This means that the solid food is dissolved and the molecules reduced in size. The soluble products then have to be **absorbed** into the bloodstream and carried by the blood all around the

body. In this way, the blood delivers dissolved food to the living cells in all parts of the body such as the muscles, brain, heart and kidneys. This section describes how the food is digested and absorbed. Chapter 9 describes how the blood carries it around the body.

Regions of the alimentary canal and their functions

The **alimentary canal** is a tube running through the body. Food is digested in the alimentary canal. The soluble products are absorbed and the indigestible residues expelled (egested). A simplified diagram of an alimentary canal is shown in Figure 7.11.

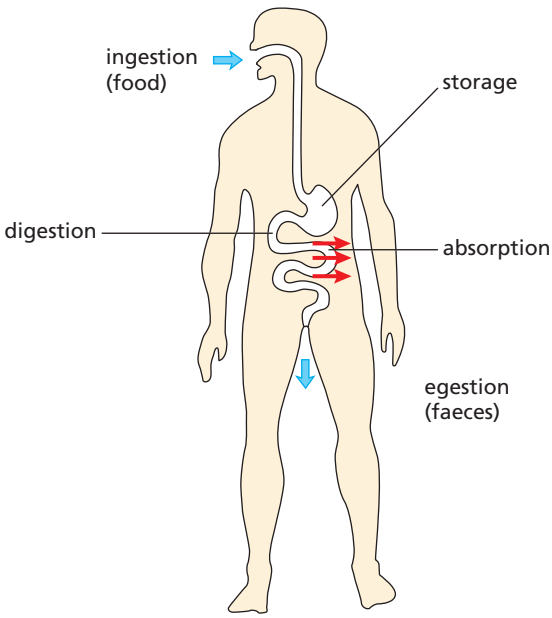


Figure 7.11 The alimentary canal (generalised)

The inside of the alimentary canal is lined with layers of cells forming what is called an **epithelium**. New cells in the epithelium are being produced all the time to replace the cells worn away by the movement of the food. There are also cells in the lining that produce **mucus**. Mucus is a slimy liquid that lubricates the lining of the canal and protects it from wear and tear. Mucus may also protect the lining from attack by the **digestive enzymes** which are released into the alimentary canal.

Some of the digestive enzymes are produced by cells in the lining of the alimentary canal, as in the stomach lining. Others are produced by **glands** that are outside the alimentary canal but pour their enzymes through tubes (called **ducts**) into the alimentary canal (Figure 7.12). The **salivary glands** and the **pancreas** (see Figure 7.13) are examples of such digestive glands.

The alimentary canal has a great many blood vessels in its walls, close to the lining. These bring oxygen needed by the cells and take away the carbon dioxide they produce. They also absorb the digested food from the alimentary canal.

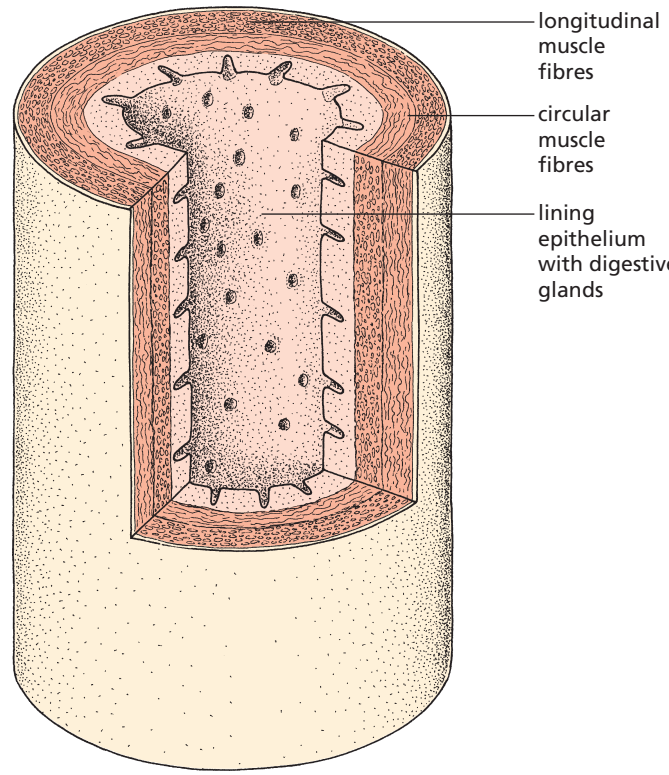


Figure 7.12 The general structure of the alimentary canal

Five main processes associated with digestion occur in the alimentary canal. These are ingestion, digestion, absorption, assimilation and egestion. The main parts of the alimentary canal are shown in Figure 7.13. An outline of the functions of its main parts is given in Table 7.5.

Peristalsis

The alimentary canal has layers of muscle in its walls (Figure 7.12). The fibres of one layer of muscles run around the canal (**circular muscle**) and the others run along its length (**longitudinal muscle**). When the circular muscles in one region contract, they make the alimentary canal narrow in that region.

A contraction in one region of the alimentary canal is followed by another contraction just below it so that a wave of contraction passes along the

canal, pushing food in front of it. The wave of contraction, called **peristalsis**, is illustrated in Figure 7.14.

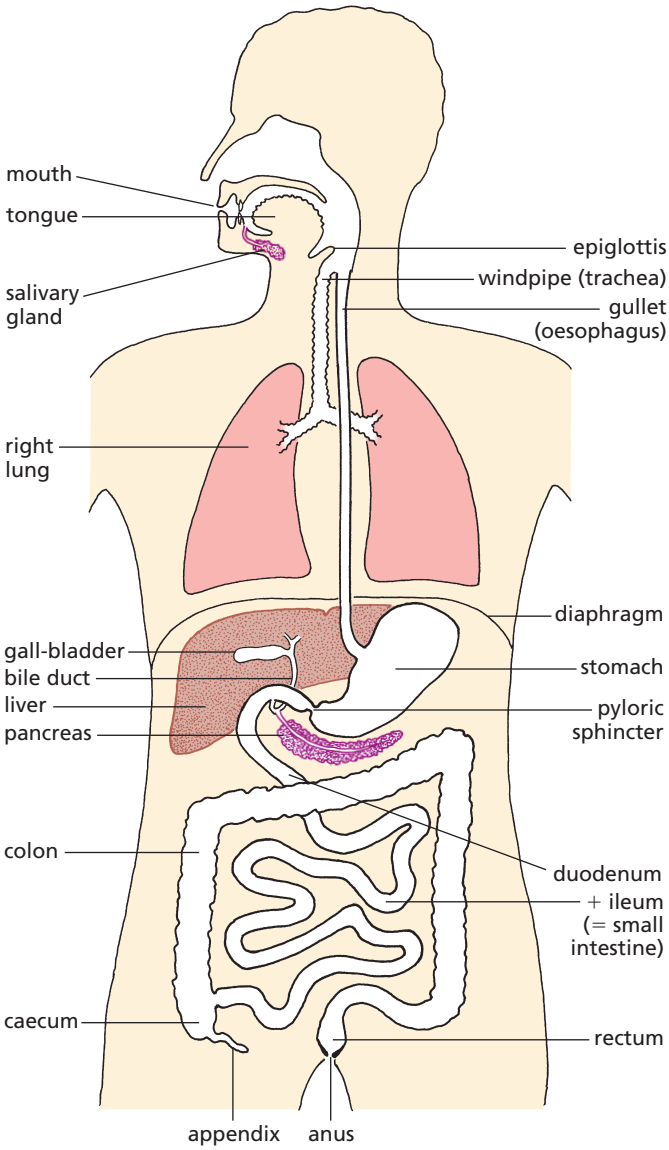


Figure 7.13 The alimentary canal

Diarrhoea

Diarrhoea is the loss of watery faeces. It is sometimes caused by bacterial or viral infection, for example from food or water. Once infected, the lining of the digestive system is damaged by the pathogens, resulting in the intestines being unable to absorb fluid from the contents of the colon or too much fluid being secreted into the colon. Undigested food then moves through the large intestine too quickly, resulting in insufficient time to absorb water from it. Unless the condition is treated, dehydration can occur.

Table 7.5 Functions of main parts of the alimentary canal

Region of alimentary canal	Function
mouth	**ingestion** of food; **mechanical digestion** by teeth; **chemical digestion** of starch by amylase; formation of a bolus for swallowing
salivary glands	saliva contains amylase for **chemical digestion** of starch in food; also liquid to lubricate food and make small pieces stick together
oesophagus (gullet)	transfers food from the mouth to the stomach, by peristalsis
stomach	produces gastric juice containing pepsin, for **chemical digestion** of protein; also hydrochloric acid to kill bacteria; peristalsis churns food up into a liquid
duodenum	first part of the small intestine; receives pancreatic juice for **chemical digestion** of proteins, fats and starch as well as neutralising the acid from the stomach; receives bile to emulsify fats (a form of **physical digestion**)
ileum	second part of the small intestine; enzymes in the epithelial lining carry out **chemical digestion** of maltose and peptides; very long and has villi (see Figures 7.22 and 7.23) to increase surface area for **absorption** of digested food molecules
pancreas	secretes pancreatic juice into the duodenum via pancreatic duct (see Figure 7.21) for **chemical digestion** of proteins, fats and starch
liver	makes bile, containing salts to emulsify fats (**physical digestion**); **assimilation** of digested food such as glucose; **deamination** of excess amino acids (see Chapter 13)
gall bladder	stores bile, made in the liver, to be secreted into the duodenum via the bile duct (see Figure 7.21)
colon	first part of the large intestine; **absorption** of water from undigested food; **absorption** of bile salts to pass back to the liver
rectum	second part of the large intestine; stores faeces
anus	**egestion** of faeces

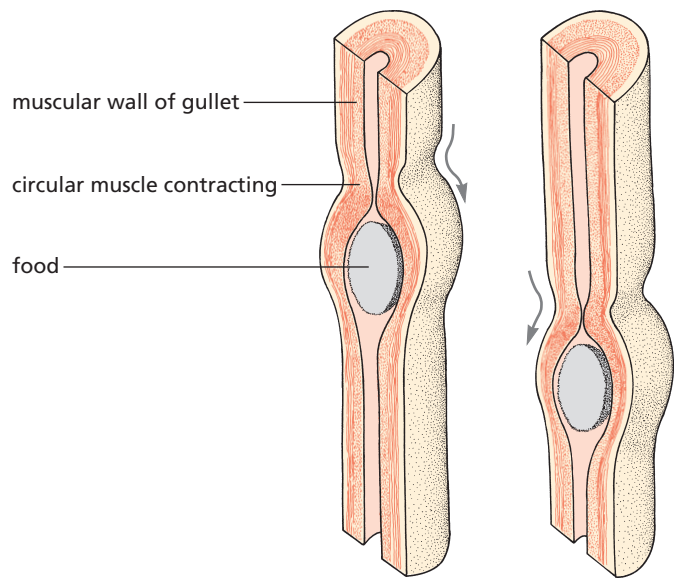


Figure 7.14 Diagram to illustrate peristalsis

Treatment is known as **oral hydration therapy**. This involves drinking plenty of fluids – sipping small amounts of water at a time to rehydrate the body.

Other possible causes of diarrhoea include anxiety, food allergies, lactose intolerance, a side-effect of antibiotics and bowel cancer.

Cholera

This disease is caused by the bacterium *Vibrio cholera* which causes acute diarrhoea. Treatment involves rehydration and restoration of the salts lost (administered by injecting a carefully controlled solution into the bloodstream) and use of an antibiotic such as tetracycline to kill the bacteria. The bacteria thrive in dirty water (often that contaminated by sewage) and are transmitted when the water is drunk or used to wash food. Long-term methods of control are to dispose of human sewage safely, ensuring that drinking water is free from bacteria and preventing food from being contaminated.

How cholera causes diarrhoea

When the *Vibrio cholera* bacteria are ingested, they multiply in the small intestine and invade its epithelial cells. As the bacteria become embedded, they release toxins (poisons) which irritate the intestinal lining and lead to the secretion of large amounts of water and salts, including chloride ions. The salts decrease the osmotic potential of the gut contents, drawing more water from surrounding tissues and blood by osmosis (see 'Osmosis' in Chapter 3). This makes the undigested food much more watery, leading to acute diarrhoea, and the loss of body fluids and salt leads to dehydration and kidney failure.

Mechanical digestion

The process of mechanical digestion mainly occurs in the mouth by means of the teeth, through a process called **mastication**.

Humans are omnivores (organisms that eat animal and plant material). Broadly, we have the same types of teeth as carnivores, but human teeth are not used for catching, holding, killing or tearing up prey, and we cannot cope with bones. Thus, although we have incisors, canines, premolars and molars, they do not show such big variations in size and shape as, for example, a wolf's. Figure 7.15 shows the position of teeth in the upper jaw and Figure 7.16 shows how they appear in both jaws when seen from the side.

Table 7.6 gives a summary of the types of human teeth and their functions.

Our top incisors pass in front of our bottom incisors and cut pieces off the food, such as when biting into an apple or taking a bite out of a piece of toast.

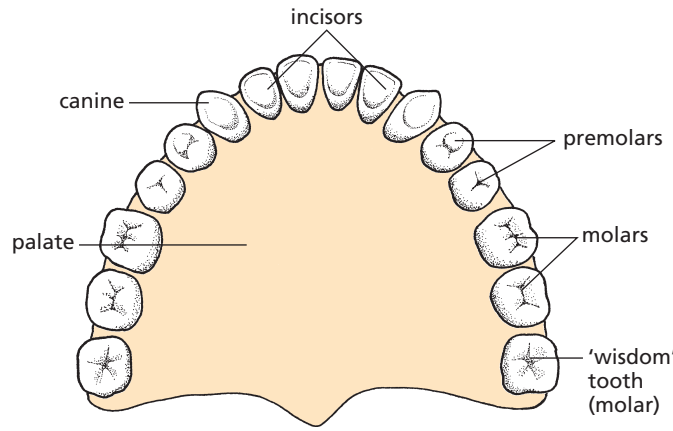


Figure 7.15 Teeth in human upper jaw

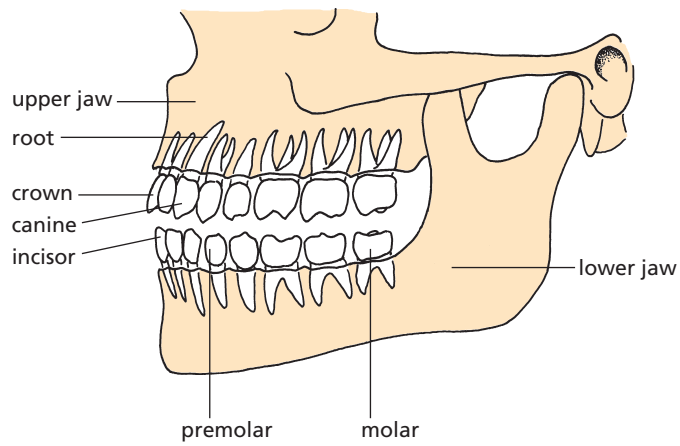
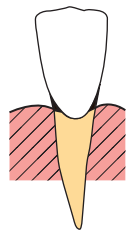
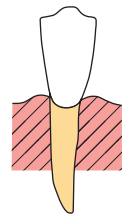
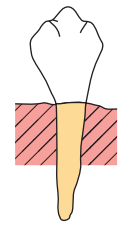
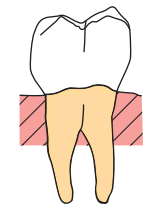


Figure 7.16 Human jaws and teeth

Our canines are more pointed than the incisors but are not much larger. They function like extra incisors.

Our premolars and molars are similar in shape and function. Their knobbly surfaces, called cusps, meet when the jaws are closed, and crush the food into small pieces. Small particles of food are easier to digest than large chunks.

Table 7.6 Summary of types of human teeth and their functions

Type	Incisor	Canine	Premolar	Molar
Diagram				
Position in mouth	front	either side of incisors	behind canines	back
Description	chisel-shaped (sharp edge)	slightly more pointed than incisors	have two points (cusps); have one or two roots	have four or five cusps; have two or three roots
Function	biting off pieces of food	similar function to incisors	tearing and grinding food	chewing and grinding food

Tooth structure

The part of a tooth that is visible above the gum line is called the **crown**. The **gum** is tissue that overlays the jaws. The rest, embedded in the jaw bone, is called the **root** (Figure 7.17). The surface of the crown is covered by a very hard layer of **enamel**. This layer is replaced by **cement** in the root, which enables the tooth to grip to its bony socket in the jaw. Below the enamel is a layer of **dentine**. Dentine is softer than enamel. Inside the dentine is a **pulp cavity**, containing nerves and blood vessels. These enter the tooth through a small hole at the base of the root.

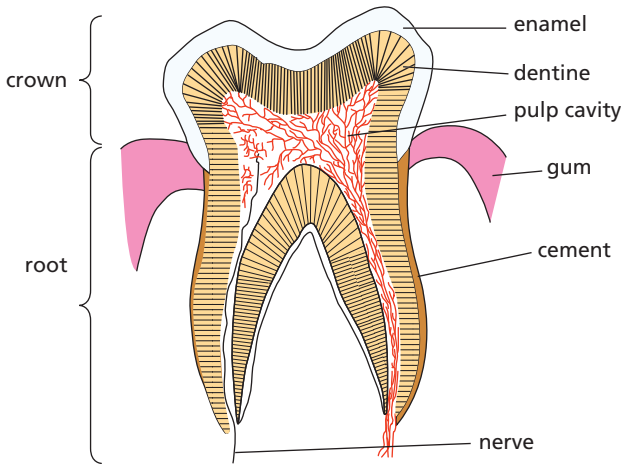


Figure 7.17 Section through a molar tooth

Dental decay (dental caries)

Decay begins when small holes (cavities) appear in the enamel. The cavities are caused by bacteria on the tooth surface. The bacteria feed on the sugars deposited on the teeth, respiring them and producing acid, which dissolves the calcium salts in the tooth enamel. The enamel is dissolved away in patches, exposing the dentine to the acids. Dentine is softer than enamel and dissolves more quickly so cavities are formed. The cavities reduce the distance between the outside of the tooth and the nerve endings. The acids produced by the bacteria irritate the nerve endings and cause toothache. If the cavity is not cleaned and filled by a dentist, the bacteria will get into the pulp cavity and cause a painful abscess at the root. Often, the only way to treat this is to have the tooth pulled out.

Although some people's teeth are more resistant to decay than others, it seems that it is the presence of refined sugar (sucrose) in the diet that contributes to decay.

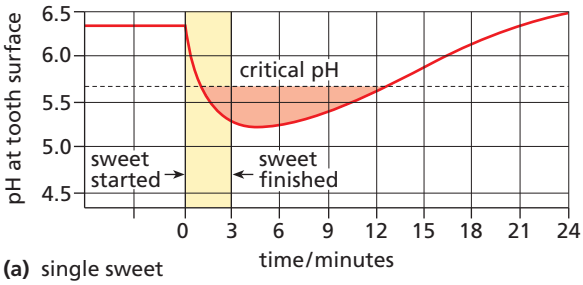
Western diets contain a good deal of refined sugar and children suck sweets between one meal and the next. The high level of dental decay in Western society is thought to be caused mainly by keeping sugar in the mouth for long periods of time.

The graph in Figure 7.18(a) shows how the pH in the mouth falls (i.e. becomes more acid) when a single sweet is sucked. The pH below which the enamel is attacked is called the **critical pH** (between 5.5 and 6). In this case, the enamel is under acid attack for about 10 minutes.

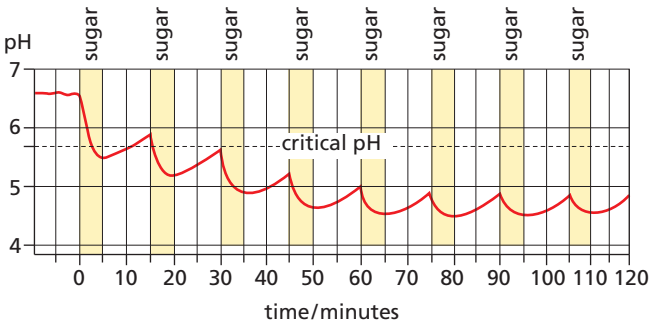
The graph in Figure 7.18(b) shows the effect of sucking sweets at the rate of four an hour. In this case the teeth are exposed to acid attack almost continually.

The best way to prevent tooth decay, therefore, is to avoid eating sugar at frequent intervals either in the form of sweets or in sweet drinks such as orange squash or soft (fizzy) drinks.

It is advisable also to visit the dentist every 6 months or so for a 'check-up' so that any caries or gum disease can be treated at an early stage.



(a) single sweet



(b) succession of sweets

Figure 7.18 pH in the mouth when sweets are sucked

Brushing the teeth is very important in the prevention of gum disease. It may not be so effective in preventing caries, although the use of fluoride toothpaste does help to reduce the bacterial population on the teeth and to increase their resistance to decay (see below).

Extension work

Gum disease (periodontal disease)

There is usually a layer of saliva and mucus over the teeth. This layer contains bacteria that live on the food residues in the mouth, building up a coating on the teeth called **plaque**. If the plaque is not removed, mineral salts of calcium and magnesium are deposited on it, forming a hard layer of 'tartar' or **calculus**. If the bacterial plaque that forms on teeth is not removed regularly, it spreads down the tooth into the narrow gap between the gum and enamel. Here it causes inflammation, called **gingivitis**, which leads to redness and bleeding of the gums and to bad breath. It also causes the gums to recede and expose the cement. If gingivitis is not treated, it progresses to **periodontitis**; the fibres holding the tooth in the jaw are destroyed, so the tooth becomes loose and falls out or has to be pulled out.

There is evidence that cleaning the teeth does help to prevent gum disease. It is best to clean the teeth about twice a day using a toothbrush. No one method of cleaning has proved to be any better than any other, but the cleaning should attempt to remove all the plaque from the narrow crevice between the gums and the teeth. Rinsing the mouth regularly with mouthwashes helps reduce the number of bacteria residing in the mouth.

Drawing a waxed thread ('dental floss') between the teeth, or using interdental brushes, helps to remove plaque in these regions.

Chemical digestion

Digestion is mainly a chemical process and consists of breaking down large molecules to small molecules. The large molecules are usually not soluble in water, while the smaller ones are. The small molecules can be absorbed through the epithelium of the alimentary canal, through the walls of the blood vessels and into the blood.

Some food can be absorbed without digestion. The **glucose** in fruit juice, for example, could pass through the walls of the alimentary canal and enter the blood vessels without further change. Most food, however, is solid and cannot get into blood vessels. Digestion is the process by which solid food is dissolved to make a solution.

The chemicals that dissolve the food are **enzymes**, described in Chapter 5. A protein might take 50 years to dissolve if just placed in water but is completely digested by enzymes in a few hours. All the solid starch in foods such as bread and potatoes is digested to glucose, which is soluble in water. The solid proteins in meat, eggs and beans are digested to soluble substances called amino acids. Fats are digested to two soluble products called **glycerol** and **fatty acids** (see Chapter 4).

The chemical breakdown usually takes place in stages. For example, the starch molecule is made up of hundreds of carbon, hydrogen and oxygen atoms. The first stage of digestion breaks it down to a 12-carbon sugar molecule called **maltose**. The last stage of digestion breaks the maltose molecule into two 6-carbon sugar molecules called glucose (Figure 7.19). Protein molecules are digested first to smaller molecules called **peptides** and finally into completely soluble molecules called amino acids.

starch → maltose → glucose
protein → peptide → amino acid

These stages take place in different parts of the alimentary canal. The progress of food through the canal and the stages of digestion will now be described.

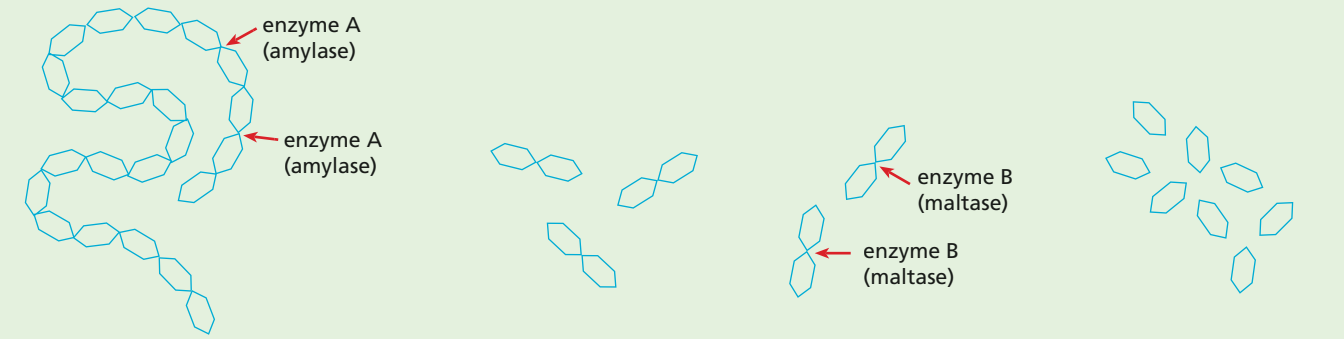


Figure 7.19 Enzymes acting on starch

The mouth

The act of taking food into the mouth is called **ingestion**. In the mouth, the food is chewed and mixed with **saliva**. The chewing breaks the food into pieces that can be swallowed and it also increases the surface area for the enzymes to work on later. Saliva is a digestive juice produced by three pairs of glands whose ducts lead into the mouth. It helps to lubricate the food and make the small pieces stick together. Saliva contains one enzyme, **salivary amylase** (sometimes called **ptyalin**), which acts on cooked starch and begins to break it down into maltose.

Strictly speaking, the 'mouth' is the aperture between the lips. The space inside, containing the tongue and teeth, is called the **buccal cavity**. Beyond the buccal cavity is the 'throat' or **pharynx**.

Swallowing

For food to enter the **gullet** (oesophagus), it has to pass over the windpipe. To ensure that food does not enter the windpipe and cause choking during swallowing, the **epiglottis** (a flap of cartilage) guides the food into the gullet.

The beginning of the swallowing action is voluntary, but once the food reaches the back of the mouth, swallowing becomes an automatic or reflex action. The food is forced into and down the gullet by peristalsis. This takes about 6 seconds with relatively solid food; the food is then admitted to the stomach. Liquid travels more rapidly down the gullet.

The stomach

The stomach has elastic walls, which stretch as the food collects in it. The **pyloric sphincter** is a circular band of muscle at the lower end of the stomach that stops solid pieces of food from passing through. The main function of the stomach is to store the food from a meal, turn it into a liquid and release it in small quantities at a time to the rest of the alimentary canal. An example of physical digestion is the peristaltic action of muscles in the wall of the stomach. These muscles alternately contract and relax, churning and squeezing the food in the stomach and mixing it with gastric juice, turning the mixture into a creamy liquid called **chyme**. This action gives the food a greater surface area so that it can be digested more efficiently.

Glands in the lining of the stomach (Figure 7.20) produce **gastric juice** containing the **protease** enzyme. It helps in the process of breaking down large protein molecules into small, soluble amino acids. The stomach lining also produces hydrochloric acid, which makes a weak solution in the gastric juice. This acid provides the best degree of acidity for stomach protease to work in (Chapter 4) and kills many of the bacteria taken in with the food.

The regular, peristaltic movements of the stomach, about once every 20 seconds, mix up the food and gastric juice into a creamy liquid. How long food remains in the stomach depends on its nature. Water may pass through in a few minutes; a meal of carbohydrate such as porridge may be held in the stomach for less than an hour, but a mixed meal containing protein and fat may be in the stomach for 1 or 2 hours.

The pyloric sphincter lets the liquid products of digestion pass, a little at a time, into the first part of the small intestine called the **duodenum**.

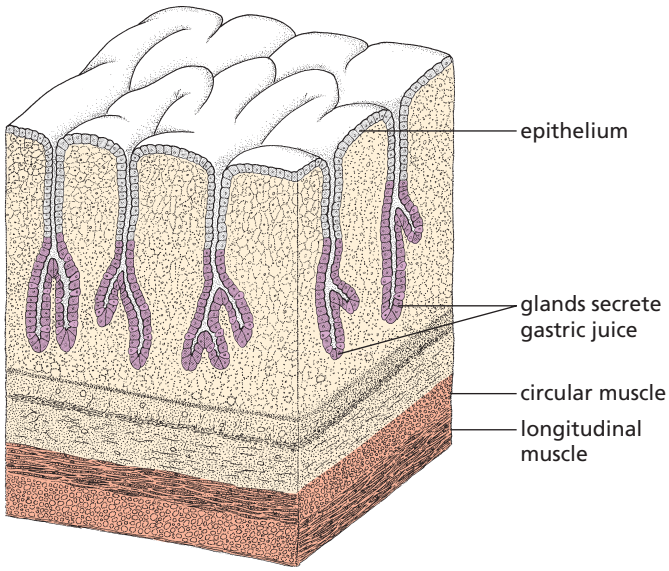


Figure 7.20 Diagram of section through stomach wall

The small intestine

A digestive juice from the pancreas (**pancreatic juice**) and bile from the liver are poured into the duodenum to act on food there. The pancreas is a digestive gland lying below the stomach (Figure 7.21). It makes a number of enzymes, which act on all classes of food. **Protease** breaks down proteins into amino acids. **Pancreatic amylase** attacks starch and converts it to maltose. **Lipase** digests fats (lipids) to fatty acids and glycerol.

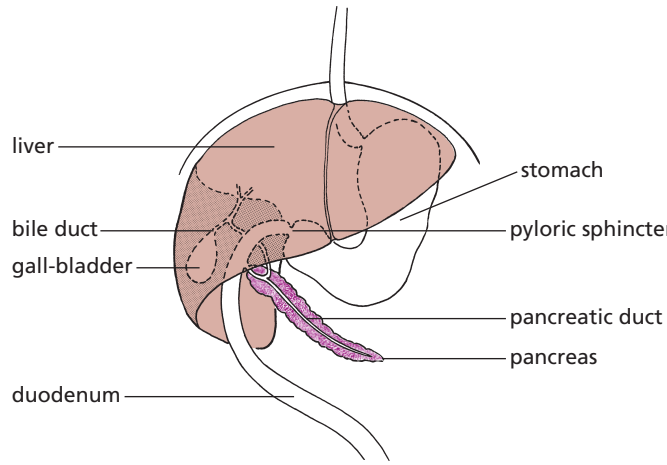


Figure 7.21 Relationship between stomach, liver and pancreas

Pancreatic juice contains sodium hydrogencarbonate, which partly neutralises the acidic liquid from the stomach. This is necessary because the enzymes of the pancreas do not work well in acid conditions.

All the digestible material is thus changed to soluble compounds, which can pass through the lining of the intestine and into the bloodstream. The final products of digestion are:

Food		Final products
starch	→	glucose (a simple sugar)
proteins	→	amino acids
fats (lipids)	→	fatty acids and glycerol

Bile

Bile is a green, watery fluid made in the liver, stored in the gall-bladder and delivered to the duodenum by the bile duct (Figure 7.21). It contains no enzymes, but its green colour is caused by bile pigments, which are formed from the breakdown of haemoglobin in the liver. Bile also contains bile salts, which act on fats rather like a detergent. The bile salts **emulsify** the fats. That is, they break them up into small droplets with a large surface area, which are more efficiently digested by lipase.

Bile is slightly alkaline as it contains sodium hydrogencarbonate and, along with pancreatic juice, has the function of neutralising the acidic mixture of food and gastric juices as it enters the duodenum. This is important because enzymes secreted into the duodenum need alkaline conditions to work at their optimum rate.

Digestion of protein

There are actually several proteases (or proteinases) which break down proteins. One protease is **pepsin** and is secreted in the stomach. Pepsin acts on proteins and breaks them down into soluble compounds called peptides. These are shorter chains of amino acids than proteins. Another protease is called **trypsin**. Trypsin is secreted by the pancreas in an inactive form, which is changed to an active enzyme in the duodenum. It has a similar role to pepsin, breaking down proteins to peptides.

The small intestine itself does not appear to produce digestive enzymes. The structure labelled 'crypt' in Figure 7.23 is not a digestive gland, though some of its cells do produce mucus and other secretions. The main function of the crypts is to produce new epithelial cells (see 'Absorption') to replace those lost from the tips of the villi.

The epithelial cells of the villi contain enzymes in their cell membranes that complete the breakdown of sugars and peptides, before they pass through the cells on their way to the bloodstream. For example, **peptidase** breaks down polypeptides and peptides into amino acids.

Digestion of starch

Starch is digested in two places in the alimentary canal: by salivary amylase in the mouth and by pancreatic amylase in the duodenum. Amylase works best in a neutral or slightly alkaline pH and converts large, insoluble starch molecules into smaller, soluble maltose molecules. Maltose is a disaccharide sugar and is still too big to be absorbed through the wall of the intestine. Maltose is broken down to glucose by the enzyme **maltase**, which is present in the membranes of the epithelial cells of the villi.

Functions of hydrochloric acid in gastric juice

The hydrochloric acid, secreted by cells in the wall of the stomach, creates a very acid pH of 2. This pH is important because it denatures enzymes in harmful organisms in food, such as bacteria (which may otherwise cause food poisoning) and it provides the optimum pH for the protein-digesting enzyme pepsin to work.

Table 7.7 Principal substances produced by digestion

Region of alimentary canal	Digestive gland	Digestive juice produced	Enzymes in the juice/ cells	Class of food acted upon	Substances produced
mouth	salivary glands	saliva	salivary amylase	starch	maltose
stomach	glands in stomach lining	gastric juice	pepsin	proteins	peptides
duodenum	pancreas	pancreatic juice	proteases, such as trypsin amylase lipase	proteins and peptides starch fats	peptides and amino acids maltose fatty acids and glycerol
ileum	epithelial cells	(none)	maltase peptidase	maltose peptides	glucose amino acids

(Note: details of peptidase and peptides are **not** a syllabus requirement)

Extension work

Prevention of self-digestion

The gland cells of the stomach and pancreas make protein-digesting enzymes (proteases) and yet the proteins of the cells that make these enzymes are not digested. One reason for this is that the proteases are secreted in an inactive form. Pepsin is produced as **pepsinogen** and does not become the active enzyme until it encounters the hydrochloric acid in the stomach. The lining of the stomach is protected from the action of pepsin probably by the layer of mucus.

Similarly, trypsin, one of the proteases from the pancreas, is secreted as the inactive **trypsinogen** and is activated by **enterokinase**, an enzyme secreted by the lining of the duodenum.

Absorption

The small intestine consists of the duodenum and the **ileum**. Nearly all the absorption of digested food takes place in the ileum, along with most of the water. Small molecules of the digested food such as glucose and amino acids pass into the bloodstream, while fatty acids and glycerol pass into the **lacteals** (Figure 7.23) connected to the **lymphatic system**.

The large intestine (colon and rectum)

The material passing into the large intestine consists of water with undigested matter, largely cellulose and vegetable fibres (roughage), mucus and dead cells from the lining of the alimentary canal. The large intestine secretes no enzymes but the bacteria in the colon digest part of the fibre to form fatty acids, which the colon can absorb. Bile salts are absorbed and returned to the liver by the blood circulation. The colon also absorbs much of the water from the undigested residues. About 7 litres of digestive juices are poured into the alimentary canal each day. If the water from these was not absorbed by the ileum and colon, the body would soon become dehydrated.

The semi-solid waste, the **faeces** or 'stool', is passed into the rectum by peristalsis and is expelled at intervals through the anus. The residues may spend from 12 to 24 hours in the intestine. The act of expelling the faeces is called **egestion** or **defecation**.

The ileum is efficient in the absorption of digested food for the following reasons:

- It is fairly long and presents a large absorbing surface to the digested food.
- Its internal surface is greatly increased by circular folds (Figure 7.22) bearing thousands of tiny projections called **villi** (singular = villus) (Figures 7.23 and 7.24). These villi are about 0.5 mm long and may be finger-like or flattened in shape.
- The lining epithelium is very thin and the fluids can pass rapidly through it. The outer membrane of each epithelial cell has **microvilli**, which increase by 20 times the exposed surface of the cell.
- There is a dense network of blood capillaries (tiny blood vessels, see 'Blood and lymphatic vessels' in Chapter 9) in each villus (Figure 7.22).

The small molecules of digested food, for example glucose and amino acids, pass into the epithelial cells and then through the wall of the capillaries in the villus and into the bloodstream. They are then carried away in the capillaries, which join up to form veins. These veins unite to form one large vein, the hepatic portal vein (see Chapter 9). This vein carries all the blood from the intestines to the liver, which may store or alter any of the digestion products. When these products are released from the liver, they enter the general blood circulation.

Some of the fatty acids and glycerol from the digestion of fats enter the blood capillaries of the villi. However, a large proportion of the fatty acids and glycerol may be combined to form fats again in the intestinal epithelium. These fats then pass into the lacteals (Figure 7.23). The fluid in the lacteals flows into the lymphatic system, which forms a network all over the body and eventually empties its contents into the bloodstream (see 'Blood and lymphatic vessels' in Chapter 9).

Water-soluble vitamins may diffuse into the epithelium but fat-soluble vitamins are carried in the microscopic fat droplets that enter the cells. The ions of mineral salts are probably absorbed by active transport. Calcium ions need vitamin D for their effective absorption.

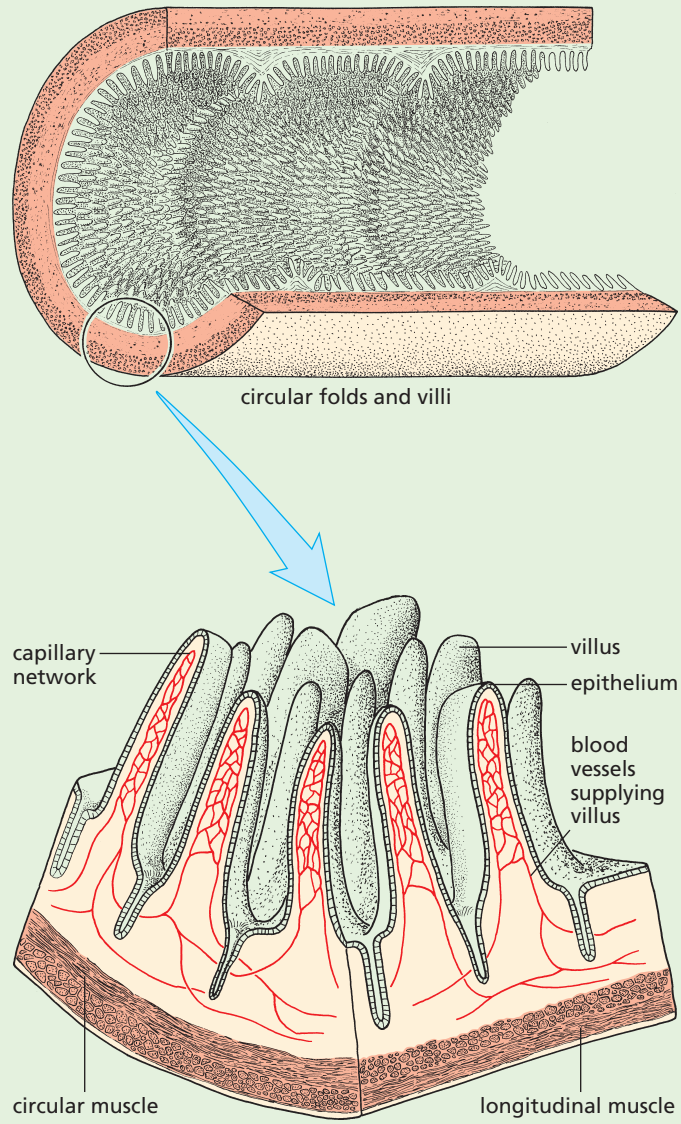


Figure 7.22 The absorbing surface of the ileum

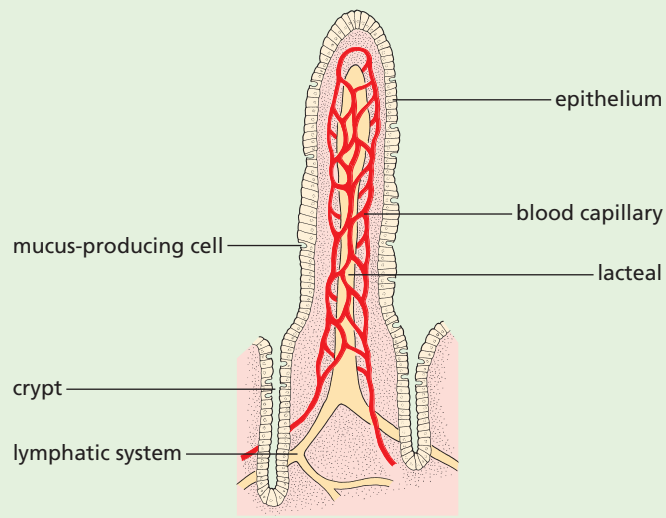


Figure 7.23 Structure of a single villus