# 10 Diseases and immunity

**Pathogens and transmission**
Definitions
Transmissible diseases

**Defences against diseases**
Defences of the body against pathogens
Vaccination
Controlling the spread of disease

How antibodies work
Active immunity, including definition
Vaccination
Passive immunity
Type 1 diabetes

## Pathogens and transmission

**Key definitions**
A **pathogen** is a disease-causing organism.
A **transmissible disease** is a disease in which the pathogen can be passed from one host to another.

### Pathogens

Pathogens include many bacteria, viruses and some fungi, as well as a number of protoctista and other organisms. Pathogenic bacteria may cause diseases because of the damage they do to the host's cells, but most bacteria also produce poisonous waste products called **toxins**. Toxins damage the cells in which the bacteria are growing. They also upset some of the systems in the body. This gives rise to a raised temperature, headache, tiredness and weakness, and sometimes diarrhoea and vomiting. The toxin produced by the *Clostridium* bacteria (which causes tetanus) is so poisonous that as little as 0.00023 g is fatal.

Many viruses cause diseases in plants and animals. Human virus diseases include the common cold, poliomyelitis, measles, mumps, chickenpox, herpes, rubella, influenza and AIDS (See 'Sexually transmitted infections' in Chapter 16). Tobacco mosaic virus affects tomato plants as well as tobacco. It causes mottling and discolouration of the leaves, eventually stunting the growth of the plant.

While most fungi are saprophytic (feeding on dead organic matter) some are parasitic, obtaining their nutrients from living organisms. The hyphae of parasitic fungi penetrate the tissues of their host plant and digest the cells and their contents. If the mycelium spreads extensively through the host, it usually causes the death of the plant. The bracket fungus shown in Chapter 1, Figure 1.27, is the fruiting body of a mycelium that is spreading through the tree and will eventually kill it.

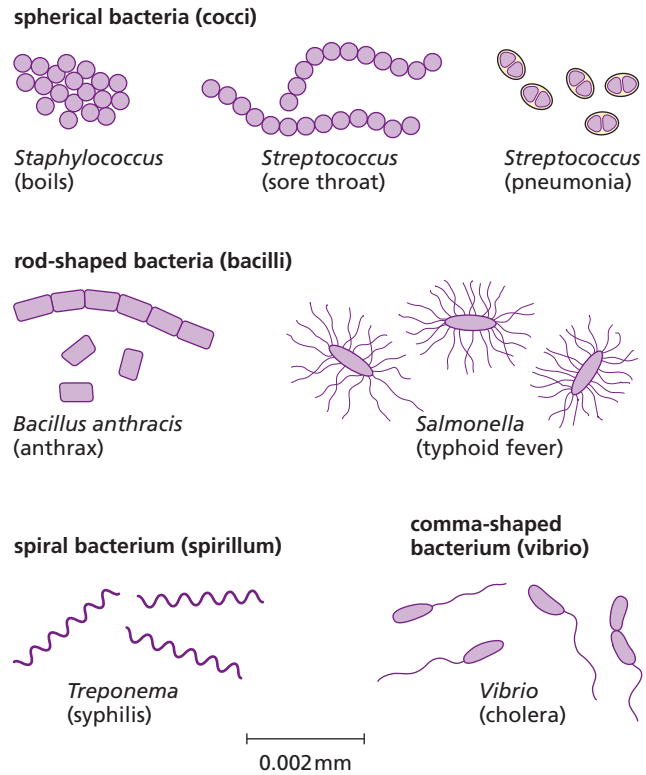



**Figure 10.1** Some pathogenic bacteria

Fungus diseases such as blight, mildews or rusts (see Chapter 1, Figure 1.28) are responsible for causing considerable losses to arable farmers, and there is a constant search for new varieties of crop plants that are resistant to fungus disease, and for new chemicals (fungicides) to kill parasitic fungi without harming the host.

A few parasitic fungi cause diseases in animals, including humans. One group of these fungi cause tinea or ringworm. The fungus grows in the epidermis of the skin and causes irritation and inflammation. One form of tinea is athlete's foot, in which the skin between the toes becomes infected. Tinea is very easily spread by contact with infected towels or clothing, but can usually be cured quickly with a fungicidal ointment.

## Transmission

Pathogens responsible for transmissible diseases can be spread either through direct contact or indirectly.

### Direct contact

This may involve transfer through blood or other body fluids. HIV is commonly passed on by drug addicts who inject the drug into their bloodstream, sharing needles with other drug users. If one user injects himself, the pathogens in his blood will contaminate the syringe needle. If this is then used by a second drug user, the pathogens are passed on. Anyone cleaning up dirty needles is at risk of infection if they accidently stab themselves. Surgeons carrying out operations have to be especially careful not to be in direct contact with the patient's blood, for example by cutting themselves while conducting an operation. A person with HIV or another sexually transmitted disease (see Chapters 15 and 16) who has unprotected sex, can pass on the pathogen to their partner through body fluids. It used to be said that HIV could be transferred from one person to another through saliva, but this is now considered to be a very low risk.

# Extension work

## Malaria

About 219 million people suffer from malaria in over 100 countries (Figure 10.2). In 2010 there were an estimated 660 000 malaria deaths according to the World Health Organization.

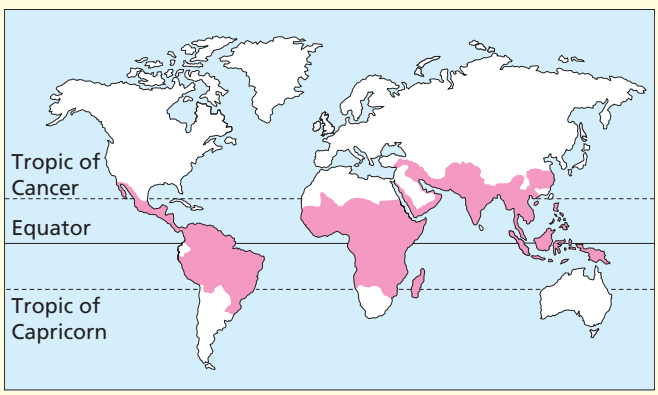
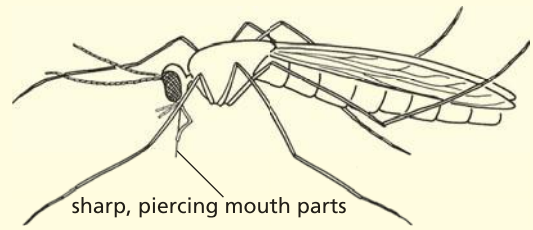
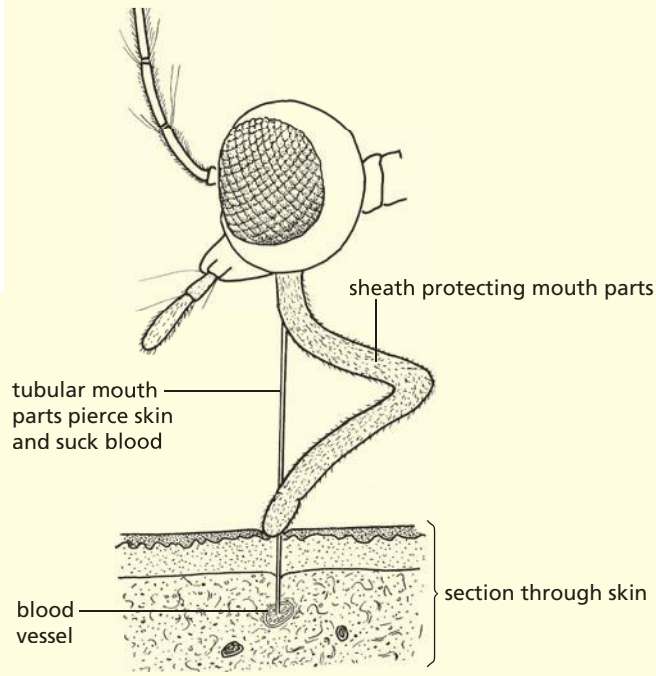



**Figure 10.2** The worldwide distribution of malaria

The disease is caused by a protozoan parasite called *Plasmodium* which is transmitted from person to person by the bites of infected mosquitoes of the genus *Anopheles*. The mosquito is said to be the **vector** of the disease. When a mosquito 'bites' a human, it inserts its sharp, pointed mouthparts through the skin till they reach a capillary (Figure 10.3). The mosquito then injects saliva, which stops the blood from clotting. If the mosquito is infected, it will also inject hundreds of malarial parasites.




**(a)** mosquito about to feed




**(b)** mosquito head and mouth parts

**Figure 10.3** Mosquito feeding on blood

The parasites reach the liver via the circulation and burrow into the liver cells where they reproduce. A week or two later, the daughter cells break out of the liver cells and invade the red blood cells. Here they reproduce rapidly and then escape from the original red cells to invade others (Figure 10.4).

The cycle of reproduction in the red cells takes 2 or 3 days (depending on the species of *Plasmodium*). Each time the daughter plasmodia are released simultaneously from thousands of red cells the patient experiences the symptoms of malaria. These are chills accompanied by violent shivering,

followed by a fever and profuse sweating. With so many red cells being destroyed, the patient will also become anaemic (see 'Diet' in Chapter 7).

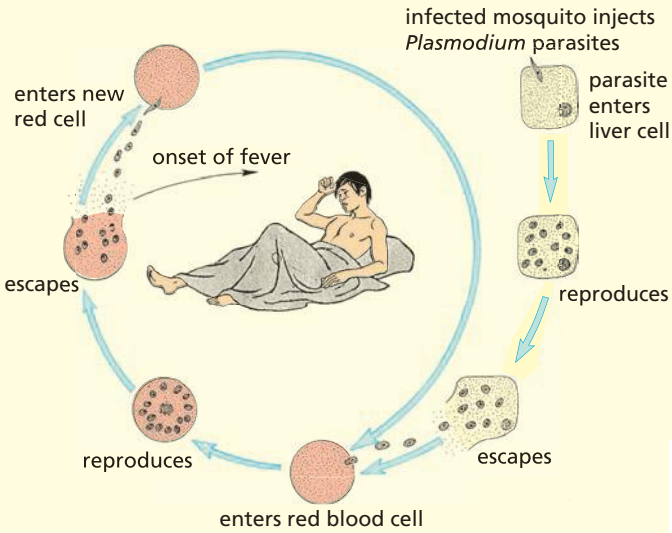



**Figure 10.4** *Plasmodium,* the malarial parasite

If a mosquito sucks blood from an infected person, it will take up the parasites in the red cells. The parasites reproduce in the mosquito and finally invade the salivary glands, ready to infect the next human.

## Control

There are drugs which kill the parasites in the bloodstream but they do not reach those in the liver. The parasites in the liver may emerge at any time and start the cycle again. If these drugs are taken by a healthy person before entering a malarious country, they kill any parasites as soon as they are injected. This is a protective or **prophylactic** use of the drug.

Unfortunately there are now many mutant forms of *Plasmodium* that have developed resistance to these drugs.

A great deal of work has been devoted to finding an effective vaccine, without much success. Trials are currently taking place of a vaccine that may offer at least partial protection against the disease.

The most far-reaching form of malarial control is based on the elimination of the mosquito. It is known that mosquitoes lay their eggs in stagnant water and that the larvae hatch, feed and grow in the water, but have to come to the surface to breathe air.

Spraying stagnant water with oil and insecticides suffocates or poisons the larvae and pupae. Spraying must include not only lakes and ponds but any accumulation of fresh water that mosquitoes can reach, e.g. drains, gutters, tanks, tin cans and old car tyres. By draining swamps and turning sluggish rivers into swifter streams, the breeding grounds of the mosquito are destroyed.

Spraying the walls of dwellings with chemicals like DDT was once very effective because the insecticide remained active for several months and the mosquito picked up a lethal dose merely by settling on the wall. See page 324 for further details about the use of DDT and its effects on the environment.

However, in at least 60 countries, many species of *Anopheles* have developed resistance to these insecticides and this method of control is now far less effective. The emphasis has changed back to the removal of the mosquito's breeding grounds or the destruction of the larvae and pupae.

## Indirect contact

This may involve infection from pathogens on contaminated surfaces, for example during food preparation. Raw meat carries bacteria, which are killed if the meat is adequately cooked. However, if the raw meat is prepared on a surface that is then used for other food preparation, such as cutting up fruit or vegetables that are later eaten raw, then the pathogens from meat can be transferred to the fresh food. The person handling the food is also a potential vector of disease if he or she does not wash their hands after using the toilet, moving rubbish or handling raw produce. In Britain there have been serious cases where customers in butchers' shops have been infected with the bacterium *Escherichia coli* (*E. coli*), because germs from raw meat were transferred to cooked meat unwittingly by shop assistants using poor hygiene practices. For example, in 1996, 21 people died after eating contaminated meat supplied by a butcher's shop in Scotland.

### *Salmonella* food poisoning

One of the commonest causes of food poisoning is the toxin produced by the bacteria *Salmonella typhimurium* and *S. enteritidis.* These bacteria live in the intestines of cattle, chickens and ducks without causing disease symptoms. Humans, however, may develop food poisoning if they drink milk or eat meat or eggs that are contaminated with *Salmonella* bacteria from the alimentary canal of an infected animal.

Intensive methods of animal rearing may contribute to a spread of infection unless care is taken to reduce the exposure of animals to infected faeces.

The symptoms of food poisoning are diarrhoea, vomiting and abdominal pain. They occur from 12 to 24 hours after eating the contaminated food. Although these symptoms are unpleasant, the disease is not usually serious and does not need treatment with drugs. Elderly people and very young children, however, may be made very ill by food poisoning.

The *Salmonella* bacteria are killed when meat is cooked or milk is pasteurised. Infection is most likely if untreated milk is drunk, meat is not properly cooked, or cooked meat is contaminated with bacteria transferred from raw meat (Figure 10.5). Frozen poultry must be thoroughly defrosted before cooking, otherwise the inside of the bird may not get hot enough during cooking to kill the *Salmonella*.

It follows that, to avoid the disease, all milk should be pasteurised and meat should be thoroughly cooked. People such as shop assistants and cooks should not handle cooked food at the same time as they handle raw meat. If they must do so, they should wash their hands thoroughly between the two activities.

The liquid that escapes when a frozen chicken is defrosted may contain *Salmonella* bacteria. The dishes and utensils used while the bird is defrosting must not be allowed to come into contact with any other food.

Uncooked meat or poultry should not be kept alongside any food that is likely to be eaten without cooking. Previously cooked meat should never be warmed up; the raised temperature accelerates the reproduction of any bacteria present. The meat should be eaten cold or cooked at a high temperature.

In the past few years there has been an increase in outbreaks of *Salmonella* food poisoning in which the bacteria are resistant to antibiotics. Some scientists suspect that this results from the practice of feeding antibiotics to farm animals to increase their growth rate. This could allow populations of drug-resistant salmonellae to develop.

*Salmonella* bacteria, and also bacteria that cause typhoid, are present in the faeces of infected people and may reach food from the unwashed hands of the sufferer.

People recovering from one of these diseases may feel quite well, but bacteria may still be present in their faeces. If they don't wash their hands thoroughly after going to the lavatory, they may have small numbers of bacteria on their fingers. If they then handle food, the bacteria may be transferred to the food. When this food is eaten by healthy people, the bacteria will multiply in their bodies and give them the disease.

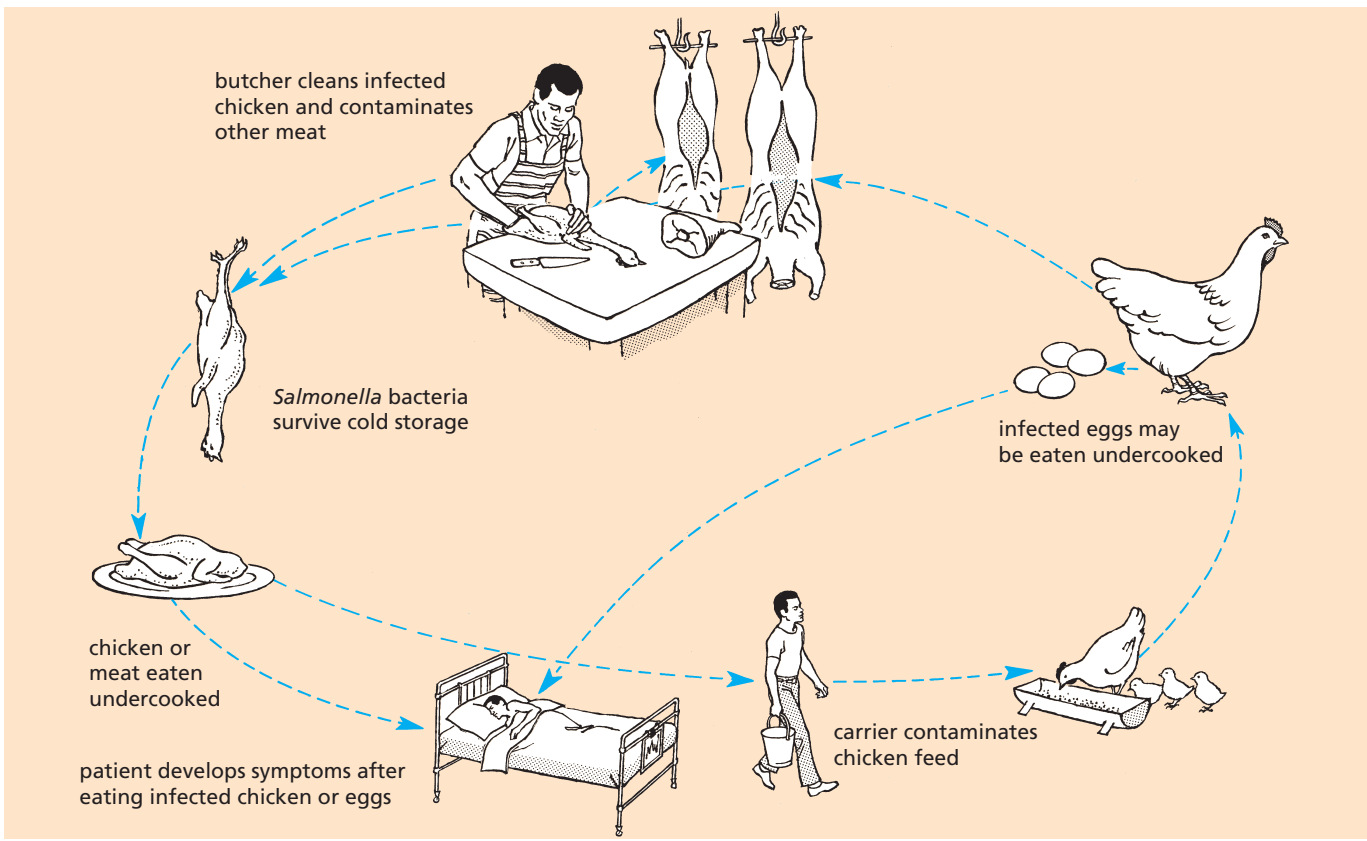



**Figure 10.5** Transmission of *Salmonella* food poisoning

People working in food shops, kitchens and food-processing factories could infect thousands of other people in this way if they were careless about their personal cleanliness.

Some forms of food poisoning result from poisons (toxins) that are produced by bacteria that get into food. Cooking kills the bacteria in the food but does not destroy the toxins that cause the illness. Only one form of this kind of food poisoning, called **botulism**, is dangerous. It is also very rare.

In the 1970s another genus of bacteria, *Campylobacter*, was identified as a cause of food poisoning. This bacterium causes acute abdominal pains and diarrhoea for about 24 hours. The sources of infection are thought to be undercooked meat, particularly 'burgers'.

In summary, people who handle and prepare food need to be extremely careful about their personal hygiene. It is essential that they wash their hands before touching food, particularly after they have visited the lavatory (Figure 10.6). Hand-washing is also important after handling raw meat, particularly poultry (see Figure 10.5). Food on display in shops needs to be protected (Figure 10.7).

Some people carry intestinal pathogens without showing any symptoms of disease. These people are called 'carriers'. Once identified, they should not be allowed to work in canteens or food-processing factories.

**Figure 10.6** Hygienic handling of food. Shop assistants avoid handling meat and shellfish with their fingers by using disposable gloves.


**Figure 10.7** Protection of food on display. The glass barrier stops customers from touching the products, keeps flies off the food and helps stop droplets from coughs and sneezes falling on the food.

## Contamination of water

If disease bacteria get into water supplies used for drinking, hundreds of people can become infected. Diseases of the alimentary canal, like typhoid and cholera (see 'Alimentary canal' in Chapter 7), are especially dangerous. Millions of bacteria infest the intestinal lining of a sick person.

Some of these bacteria will pass out with the faeces. If the faeces get into streams or rivers, the bacteria may be carried into reservoirs of water used for drinking. Even if faeces are left on the soil or buried, rainwater may wash the bacteria into a nearby stream.

To prevent this method of infection, drinking water needs to be purified and faeces must be made harmless, a process involving sewage treatment (see 'Conservation' in Chapter 21).

## Water treatment

On a small scale, simply boiling the water used for drinking will destroy any pathogens. On a large scale, water supplies are protected by (a) ensuring that untreated human sewage cannot reach them and (b) treating the water to make it safe.

The treatment needed to make water safe for drinking depends on the source of the water. Some sources, e.g. mountain streams, may be almost pure; others, e.g. sluggish rivers, may be contaminated.

The object of the treatment is to remove all micro-organisms that might cause disease. This is done by filtration and chlorination. The water

is passed through beds of sand in which harmless bacteria and protozoa are growing. These produce a gelatinous film which acts as a fine filter and removes pathogens.

Finally, chlorine gas is added to the filtered water and remains in contact with it for long enough to kill any bacteria that have passed through the filter. How much chlorine is added and the length of the contact time both depend on how contaminated the water source is likely to be. Most of the chlorine disappears before the water reaches the consumers.

The purified water is pumped to a high-level reservoir or water tower. These are enclosed to ensure that no pathogens can get into the water. The height of the reservoir provides the pressure needed to deliver the water to the consumer.

## Waste disposal

Waste from domestic or commercial premises should be stored in dustbins or garbage cans made of galvanised steel or strong plastic, with a closely fitted lid to exclude flies and keep out scavenging animals. If this is not done, pathogens will breed in the waste and become a source of disease organisms. The waste is taken away and disposed of by burning, or burying deep enough to prevent rats using it as food, or (less effectively) tightly packed to keep out flies and vermin.

## Contamination by houseflies

Flies walk about on food. They place their mouthparts on it and pump saliva onto the food. Then they suck up the digested food as a liquid.

This would not matter much if flies fed only on clean food, but they also visit decaying food or human faeces. Here they may pick up bacteria on their feet or their mouthparts. They then alight on our food and the bacteria on their bodies are transferred to the food. Figure 10.8 shows the many ways in which this can happen.

Food poisoning, amoebic dysentery and polio can be spread by houseflies.

## Tinea ('ringworm') – a fungal parasite

Several species of fungus give rise to the various forms of this disease. The fungus attacks the epidermis (see 'Homeostasis' in Chapter 14) and produces a patch of inflamed tissue. On the skin the infected patch spreads outwards and heals in the centre, giving a ring-like appearance ('ringworm').

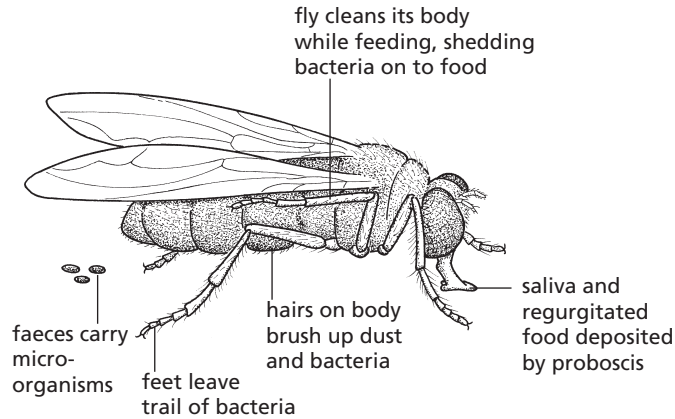



**Figure 10.8** Transmission of bacteria by houseflies

The different species of tinea fungi may live on the skin of humans or domestic animals, or in the soil. The region of the body affected will depend on the species of fungus.

One kind affects the scalp and causes circular bald patches. The hair usually grows again when the patient recovers from the disease.

The species of fungus that affects the feet usually causes cracks in the skin between the toes. This is known as 'athlete's foot'.

Tinea of the crutch is a fungus infection, occurring usually in males, which affects the inner part of the thighs on each side of the scrotum. It causes a spreading, inflamed area of skin with an itching or burning sensation.

All forms of the disease are very contagious. That means, they are spread by contact with an infected person or their personal property. Tinea of the scalp is spread by using infected hairbrushes, combs or pillows. Tinea of the crutch can be caught by using towels or bedclothes contaminated by the fungus or its spores, and 'athlete's foot' by wearing infected socks or shoes, or from the floors of showers and swimming pools.

When an infection is diagnosed, the clothing, bed linen, infected hairbrushes, combs or towels must be boiled to destroy the fungus. It is best, anyway, to avoid sharing these items as their owners may be carrying the infection without knowing or admitting it.

In young people, tinea infections often clear up without treatment. Where treatment is needed, a fungicide cream or dusting powder is applied to the affected areas of skin. Infected feet may be dipped in a solution of potassium permanganate (potassium manganate(VII)).

### Amoebic dysentery

*Entamoeba histolytica* is a species of small amoebae that normally live harmlessly in the human intestine, feeding on food particles or bacteria. In certain conditions, however, *Entamoeba* invades the lining of the intestine causing ulceration and bleeding, with pain, vomiting and diarrhoea: the symptoms of amoebic dysentery.

The diarrhoea and vomiting lead to a loss of water and salts from the body and if they persist for very long can cause **dehydration**. Dehydration, if untreated, can lead to kidney failure and death. The treatment for dehydration is to give the patient a carefully prepared mixture of water, salts and sugar. The intestine absorbs this solution more readily than water and it restores the volume and concentration of the body fluids. This simple, effective and inexpensive treatment is called **oral rehydration therapy** and has probably saved thousands of lives since it was first discovered. There are also drugs that attack *Entamoeba*.

The faeces of infected people contain *Entamoeba* amoebae which, if they reach food or drinking water, can infect other people. The disease is prevalent in tropical, sub-tropical and, to some extent, temperate countries and is associated with low standards of hygiene and sanitation.

### Airborne, 'droplet' or aerosol infection

When we sneeze, cough, laugh, speak or just breathe out, we send a fine spray of liquid drops into the air. These droplets are so tiny that they remain floating in the air for a long time. They may be breathed in by other people or fall on to exposed food (Figure 10.9). If the droplets contain viruses or bacteria, they may cause disease when they are eaten with food or inhaled.

Virus diseases such as colds, 'flu, measles and chickenpox are spread in this way. So are the bacteria (*Streptococci*) that cause sore throats. When the water in the droplets evaporates, the bacteria often die as they dry out. The viruses remain infectious, however, floating in the air for a long time.

In buses, trains, cinemas and night clubs the air is warm and moist, and full of floating droplets. These are places where you are likely to pick up one of these infections.

**Figure 10.9** Droplet infection. The visible drops expelled by this sneeze will soon sink to the floor, but smaller droplets will remain suspended in the air.

## Defences against diseases

The body has three main lines of defence against disease. These involve mechanical barriers, chemical barriers and cells.

### Mechanical barriers

Although many bacteria live on the surface of the skin, the outer layer of the epidermis (see 'Homeostasis' in Chapter 14) seems to act as a barrier that stops them getting into the body. But if the skin is cut or damaged, the bacteria may get into the deeper tissues and cause infection.

Hairs in the nose help to filter out bacteria that are breathed in. However, if air is breathed in through the mouth, this defence is by-passed.

### Chemical barriers

The acid conditions in the stomach destroy most of the bacteria that may be taken in with food. The moist lining of the nasal passages traps many bacteria, as does the mucus produced by the lining of the trachea and bronchi. The ciliated cells of these organs carry the trapped bacteria away from the lungs.

Tears contain an enzyme called **lysozyme**. This dissolves the cell walls of some bacteria and so protects the eyes from infection.

## Cells

When bacteria get through the mechanical and chemical barriers, the body has two more lines of defence – white blood cells and antibodies, produced by white blood cells. One type of white blood cells fights infection by engulfing bacteria (a process called phagocytosis) and digesting them. Further details of the way these work is also described in 'Blood' in Chapter 9. Another type produce antibodies that attach themselves to bacteria, making it easier for other white blood cells to engulf them.

## Vaccination

The body's defences can be enhanced by **vaccination**. This involves a harmless form of the pathogen (bacteria or virus) being introduced into the body by injection or swallowing. The presence of the pathogen triggers white blood cells to make specific antibodies to combat possible infection. If the person is exposed to the disease later, defences are already in place to prevent it developing (the person is **immune** to that disease). Without vaccination, white blood cells need to be exposed to the disease organism before they make the appropriate antibody. If the disease is potentially lethal, the patient could die before the white blood cells have time to act.

# Antibodies and immunity

**Key definition**
**Active immunity** is the defence against a pathogen by antibody production in the body.

On the surface of all cells there are chemical substances called **antigens**. Lymphocytes produce proteins called **antibodies** which attack the antigens of bacteria or any alien cells or proteins that invade the body. The antibodies may attach to the surface of the bacteria to mark them, making it easier for the phagocytes to find and ingest them, they may clump the bacteria together or they may neutralise the poisonous proteins (**toxins**) that the bacteria produce.

Each antibody is very **specific**. This means that an antibody that attacks a typhoid bacterium will not affect a pneumonia bacterium. This is illustrated in the form of a diagram in Figure 10.10.

Some of the lymphocytes that produced the specific antibodies remain in the lymph nodes for some time and divide rapidly and make more antibodies if the same antigen gets into the body again. This means that the body has become immune to the disease caused by the antigen and explains why, once you have recovered from measles or chickenpox, for example, you are very unlikely to catch the same disease again. This is called **active immunity**. Active immunity can also be gained by vaccination. You may also inherit some forms of immunity or acquire antibodies from your mother's milk (see 'Sexual reproduction in humans' in Chapter 16). This is **innate immunity**.

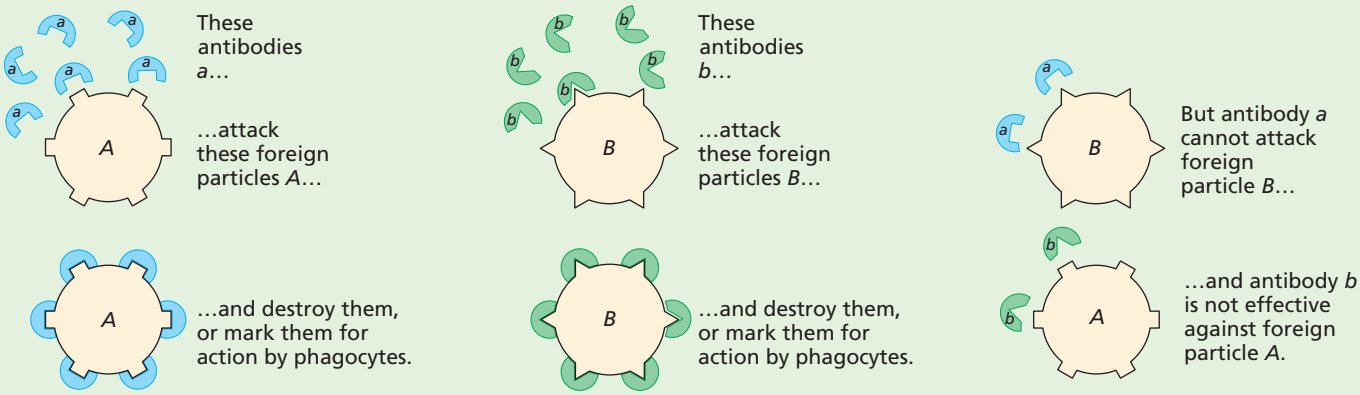



**Figure 10.10** Antibodies are specific

## Vaccination

When you are **inoculated** (vaccinated) against a disease, a harmless form of the bacteria or viruses is introduced into your body (Figure 10.11). The white cells make the correct antibodies, so that if the real micro-organisms get into the blood, the antibody is already present or very quickly made by the blood.

**Figure 10.11** Vaccination. The girl is being vaccinated against rubella (German measles).

The material that is injected or swallowed is called a **vaccine** and is one of the following:

- a harmless form of the micro-organism, e.g. the BCG inoculation against tuberculosis and the Sabin oral vaccine against polio (oral, in this context, means 'taken by mouth')
- the killed micro-organisms, e.g. the Salk anti-polio vaccine and the whooping cough vaccine
- a **toxoid**, i.e. the inactivated toxin from the bacteria, e.g. the diphtheria and tetanus vaccines. (A toxin is the poisonous substance produced by certain bacteria, which causes the symptoms of the disease.)

## B and T lymphocytes

There are two main types of lymphocyte. Both types undergo rapid cell division in response to the presence of specific antigens but their functions are different (though interdependent). The **B cells** (from **B**one marrow) become short-lived **plasma** cells and produce antibodies that are released into the blood. These antibodies may attack antigens directly or stick to the surface membrane of infected or alien cells, e.g. cells carrying a virus, bacteria, cancer cells or transplanted cells.

**'Killer' T cells** (from the **T**hymus gland) have receptor molecules on their surface, which attach them to these surface antibodies. The T cells then kill the cell by damaging its cell membrane.

**'Helper' T** cells stimulate the B cells to divide and produce antibodies. They also stimulate the phagocytes to ingest any cells carrying antibodies on their surface.

Some of the B cells remain in the lymph nodes as **memory cells**. These can reproduce swiftly and produce antibodies in response to any subsequent invasion of the body by the same foreign organism.

When mass vaccination fails, the population is at risk of infection with potential epidemics resulting. An example of this was with the MMR vaccine in Britain. MMR is a combination of vaccines protecting against measles, mumps and rubella (German measles). A researcher and surgeon called Andrew Wakefield claimed (incorrectly) to have found a link between the MMR vaccine and the incidence of autism and bowel disease in children. The story got into the national press and many parents reacted by refusing to allow their children to have the MMR vaccination, leaving them vulnerable to the three potentially life-threatening diseases. The drop in MMR vaccination rates left whole populations more susceptible to the spread of measles, mumps and rubella. There needs to be a significant proportion of a population immunised to prevent an epidemic of a disease, ideally over 90%. The percentage of people protected against measles, mumps and rubella dropped well below this figure in some areas after the MMR vaccine scare. It has taken years for doctors to restore parents' faith in the safety of the MMR vaccine.

There is a small risk of serious side-effects from vaccines, just as there is with all medicines. These risks are always far lower than the risk of catching the disease itself. For example, the measles vaccine carries a risk of 1 in 87 000 of causing encephalitis (inflammation of the brain). This is much less than the risk of getting encephalitis as a result of catching measles. Also, the vaccines themselves are becoming much safer, and the risk of side-effects is now almost nil.

Routine vaccination not only protects the individual but also prevents the spread of infectious disease. Diseases like diphtheria and whooping cough were once common, and are now quite rare. This is the result of improved social conditions

and routine vaccination. Smallpox was completely wiped out throughout the world by a World Health Organization programme of vaccination between 1959 and 1980.

## Global travel

In the 18th and 19th centuries, explorers, traders and missionaries carried European diseases to countries where the population had no natural immunity. It is thought that devastating epidemics of smallpox and measles in, for example, North American Indians and Australian aborigines resulted from contact with infected Europeans.

Today, the ease with which we can travel around the world raises the possibility that travellers may catch a disease in a region where it is **endemic** and subsequently introduce it into a region where the incidence of disease is low or non-existent.

An 'endemic' disease is one that is constantly present in a population. Figure 10.2 shows areas in which malaria is endemic. Small numbers of travellers returning to Britain from such a region may have become infected during their stay. Fortunately, British mosquitoes do not transmit malaria, but global warming might change this.

If you plan to visit a country where an infectious disease is endemic, you are likely to be offered advice on vaccination. There is no vaccine against malaria but, if you are travelling to a malarious country, you will probably be advised to take a drug (e.g. chloroquine) that kills malarial parasites, starting a week or more before your departure, throughout your stay and for a few weeks after your return. Drugs such as this, which help to *prevent* you getting a disease are called **prophylactics**.

Also, you may find your aircraft cabin being sprayed with insecticide to kill any malaria-carrying mosquitoes that might have entered.

If you visit a country where a disease, e.g. yellow fever, is endemic, you may be required to produce a certificate of vaccination (Figure 10.12) before being allowed into a country where the disease does not occur.

## Passive immunity

Some diseases can be prevented or cured by injecting the patient with serum from a person who has recovered from the disease. Serum is plasma with the fibrinogen removed. A serum is prepared from the plasma given by blood donors. People who have recently received an anti-tetanus inoculation will have made anti-tetanus antibodies in their blood. Some of these people volunteer to donate their blood, but their plasma is separated at once and the red cells returned to their circulation. The anti-tetanus antibodies are then extracted from the plasma and used to treat patients who are at risk of contracting tetanus, as a result of an accident, for example. Antibodies against chickenpox and rabies can be produced in a similar way.

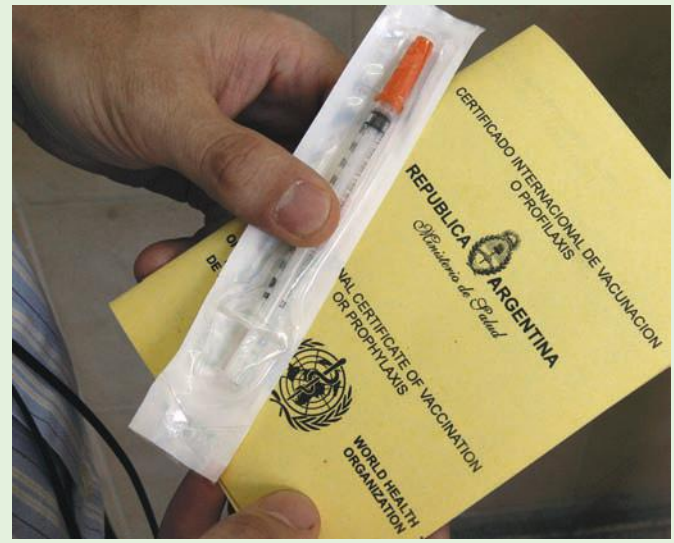



**Figure 10.12** International certificate of vaccination

The temporary immunity conferred by these methods is called **passive immunity** because the antibodies have not been produced by the patient. It is only temporary because it does not result in the formation of memory cells.

When a mother breastfeeds her baby, the milk contains some of the mother's white blood cells, which produce antibodies. These antibodies provide the baby with protection against infection at a vulnerable time: the baby's immune responses are not yet fully developed. However, this is another case of passive immunity as it is only short-term protection: memory cells are not produced.

## Type 1 diabetes

This type of diabetes, also known as juvenile-onset diabetes, mainly affects young people. It is due to the inability of islet cells in the pancreas to produce sufficient insulin. There is a slight

inherited tendency towards the disease, but it may be triggered by some event, possibly a virus infection, which causes the body's immune system to attack the islet cells that produce insulin. It is therefore classed as an **autoimmune** disease. The outcome is that the patient's blood is deficient in insulin and he or she needs regular injections of the hormone in order to control blood sugar levels and so lead a normal life. This form of the disease is, therefore, sometimes called 'insulin-dependent' diabetes (see 'Homeostasis' in Chapter 14).

# Extension work

## Ideas about disease transmission and micro-organisms

### Edward Jenner (1749–1823)

The history of immunisation centres on the disease **smallpox**, which is caused by a virus. Only a few years ago it was a serious, worldwide disease causing hundreds of thousands of deaths.

It had long been noticed that people who had recovered from smallpox never caught the disease again. In the late 1600s this observation was exploited in countries such as Greece, Turkey, China and India. Fluid from the blisters, which characterised the disease, was introduced into healthy people through cuts in the skin. The patient suffered a mild form of smallpox but was, thereafter, immune to the disease. It was a risky practice, however, and some people developed smallpox and died as a result of the vaccination.

In the 1750s, a Suffolk surgeon, Robert Sutton, refined the technique with considerable success. Edward Jenner is usually given the credit for smallpox vaccination. While using Sutton's technique he noticed that milkmaids who had caught 'cowpox' from infected cows did not develop the mild symptoms of illness after vaccination.

In 1796, Jenner conducted a crucial, if somewhat risky, experiment. He took fluid from a cowpox blister on a milkmaid's hand and injected it into a young boy. Two months later, he inoculated the boy with smallpox and demonstrated that the boy was immune. After publication of the results, the practice spread widely throughout Europe, reducing deaths from smallpox by about two-thirds.

Jenner called his technique 'vaccination' to distinguish it from inoculation with smallpox. 'Vacca' is Latin for 'cow' and 'vaccinia' is the medical name for cowpox. We now know that viruses and bacteria often lose much of their virulence if they are allowed to pass through different animals or are cultured in a particular way. Such non-virulent microbes are said to be **attenuated**. Jenner and his contemporaries, of course, knew nothing about viruses or attenuation but their shrewd observations, logical deductions and bold experiments led to a massive reduction in suffering.

In 1967, the World Health Organization embarked on a programme to eradicate smallpox from the whole world. The strategy was to trace all cases of smallpox and isolate the patients so that they could not pass on the disease. Everyone at risk was then vaccinated. By 1987 the disease had been eradicated.

### Louis Pasteur (1822–95)

Pasteur made outstanding contributions to chemistry, biology and medicine. In 1854, as professor of chemistry at the University of Lille, he was called in by the French wine industry to investigate the problem of wines going sour.

Under the microscope he observed the yeast cells that were present and proposed that these were responsible for the fermentation. Thus, he claimed, fermentation was the outcome of a living process in yeast and not caused solely by a chemical change in the grape juice. In time, Pasteur observed that the yeast cells were supplanted by microbes (which we now call 'bacteria'), which appeared to change the alcohol into acetic and lactic acids.

Pasteur showed that souring was prevented by heating the wine to 120 °F (49 °C). He reasoned that this was because the microbes responsible for souring had been killed by the heat and, if the wine was promptly bottled, they could not return. This process is now called 'pasteurisation'.

**Spontaneous generation**

The micro-organisms in decaying products could be seen under the microscope, but where did they come from? Many scientists claimed that they were the *result* of decay rather than the *cause*; they had arisen 'spontaneously' in the decaying fluids.

In the 17th century, it was believed that organisms could be generated from decaying matter. The organisms were usually 'vermin' such as insects, worms and mice. To contest this notion, an experiment was conducted in 1668, comparing meat freely exposed to the air with meat protected from blowflies by a gauze lid on the container. Maggots appeared only in the meat to which blowflies had access.

This, and other experiments, laid to rest theories about spontaneous generation, as far as visible organisms were concerned, but the controversy about the origin of microbes continued into the 1870s.

It was already known that prolonged boiling, followed by enclosure, prevented liquids from putrefying. Exponents of spontaneous generation claimed that this was because the heat had affected some property of the air in the vessel. Pasteur designed experiments to put this to the test.

He made a variety of flasks, two of which are shown in Figure 10.13, and boiled meat broth in each of them. Fresh air was not excluded from the flask but could enter only through a tube, which was designed to prevent 'dust' (and microbes) from reaching the liquid. The broths remained sterile until either the flask was opened or until it was tilted to allow some broth to reach the U-bend and then tipped back again.

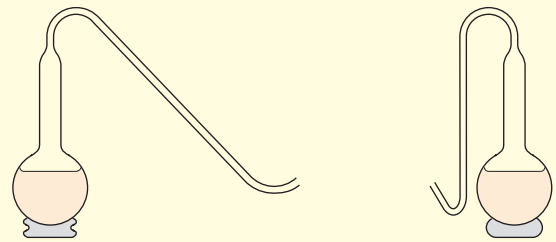


**Figure 10.13** Two of Pasteur's flask shapes. The thin tubes admitted air but microbes were trapped in the U-bend.

This series of experiments, and many others, supported the theory that micro-organisms *caused* decay and did not arise spontaneously in the liquids.

**The germ theory of disease**

In 1865, Pasteur was asked to investigate the cause of a disease of silkworms (silk-moth caterpillars) that was devastating the commercial production of silk. He observed that particular micro-organisms were present in the diseased caterpillars but not in the healthy ones. He demonstrated that, by removing all of the diseased caterpillars and moths, the disease could be controlled. This evidence supported the idea that the microbes passed from diseased caterpillars to healthy ones, thus causing the disease to spread.

He extended this observation to include many forms of transmissible disease, including anthrax. He also persuaded doctors to sterilise their instruments by boiling, and to steam-heat their bandages. In this way, the number of infections that followed surgery was much reduced.

Pasteur's discoveries led to the introduction of antiseptic surgery and also to the production of a rabies vaccine.

## Questions

### Core

1 a What are the two main lines of attack on malaria?
  b What is the connection between stagnant water and malaria?
  c What are the principal 'set-backs' in the battle against malaria?
2 Study the cartoon shown in Figure 10.14. Identify the potential hygiene risks in Sid's Store.
3 In what ways might improved sanitation and hygiene help to reduce the spread of amoebic dysentery?
4 How might a medical officer try to control an outbreak of amoebic dysentery?
5 Why should people who sell, handle and cook food be particularly careful about their personal hygiene?
6 Coughing or sneezing without covering the mouth and nose with a handkerchief is thought to be inconsiderate behaviour. Why is this?
7 Inhaling cigarette smoke can stop the action of cilia in the trachea and bronchi for about 20 minutes. Why should this increase a smoker's chance of catching a respiratory infection?

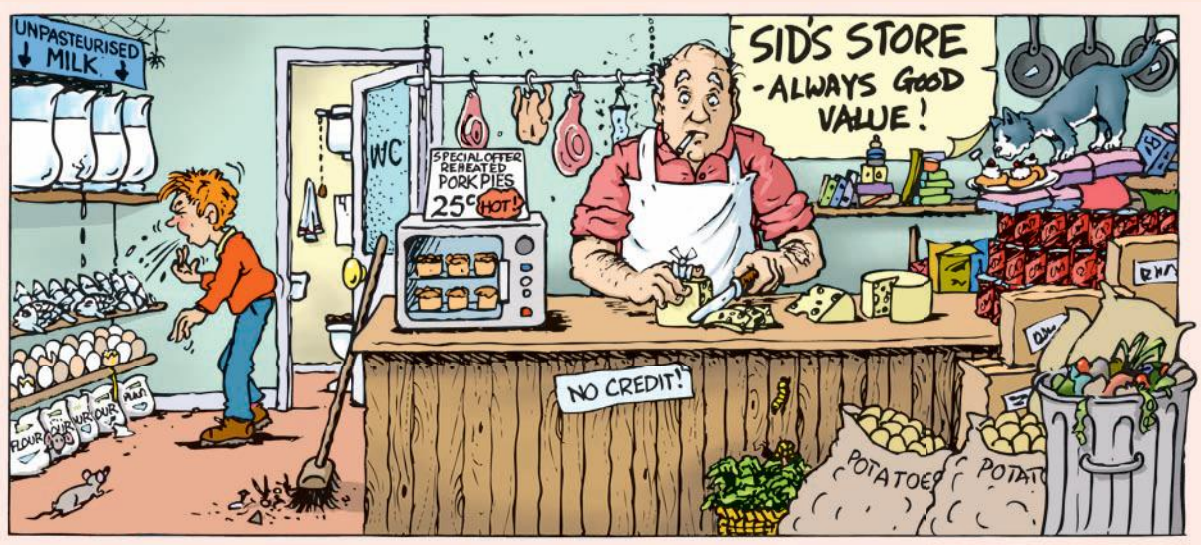



**Figure 10.14** An unhygienic shop

### Extended

8 Figure 10.15 shows the changes in the levels of antibody in response to an inoculation of a vaccine, followed by a booster injection 3 weeks later. Use your knowledge of the immune reaction to explain these changes.

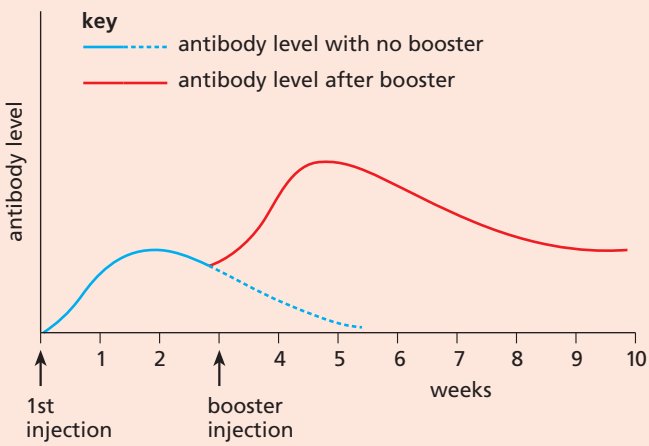



**Figure 10.15**

9 How might a harmful bacterium be destroyed or removed by the body if it arrived:
  a on the hand
  b in a bronchus
  c in the stomach?
10 After a disaster such as an earthquake, the survivors are urged to boil all drinking water. Why do you think this is so?
11 Explain why vaccination against diphtheria does not protect you against polio as well.
12 Even if there have been no cases of diphtheria in a country for many years, children may still be vaccinated against it. What do you think is the point of this?

## Checklist

After studying Chapter 10 you should know and understand the following:

- Transmissible diseases are infections caused by viruses, bacteria, fungi or protoctista.
- Infectious diseases may be transmitted by air, water, food or contact.
- The body has defences against pathogens, including mechanical and chemical barriers and white blood cells.
- A vaccine stimulates the blood system to produce antibodies against a disease, without causing the disease itself.
- The presence of antibodies in the blood, or the ability to produce them rapidly, gives immunity to a disease.
- Water-borne diseases are controlled by sewage treatment and water purification.
- Food-borne diseases can be controlled by hygienic food preparation, hygienic handling and good personal hygiene.
- The spread of disease can be controlled by waste disposal and sewage treatment.
- Antibodies, produced by lymphocytes, work by locking on to antigens.
- Antigens have specific shapes, so each type of antigen needs a different antibody.
- Active immunity is a defence against a pathogen by antibody production in the body.
- Vaccination involves the administration of a dead or inactive form of the pathogen to a patient to stimulate antibody production.
- Memory cells provide long-term immunity.
- Systematic immunisation can protect whole populations.
- Passive immunity only provides short-term protection because memory cells are not produced.
- Type 1 diabetes is caused by the immune system targeting and destroying cells in the pancreas.

# 11 Gas exchange in humans

**Gas exchange in humans**
Features of human gas exchange surfaces
Parts of the breathing system
Composition of inspired and expired air
Test for carbon dioxide

Identification of muscles associated with breathing
Roles of parts of the breathing system in ventilation
Explaining differences between inspired and expired air
Role of brain in monitoring carbon dioxide
Protection of the gas exchange system against pathogens

## Gas exchange in humans

All the processes carried out by the body, such as movement, growth and reproduction, require energy. In animals, this energy can be obtained only from the food they eat. Before the energy can be used by the cells of the body, it must be set free from the chemicals of the food by a process called 'respiration' (see Chapter 12). Aerobic respiration needs a supply of oxygen and produces carbon dioxide as a waste product. All cells, therefore, must be supplied with oxygen and must be able to get rid of carbon dioxide.

In humans and other mammals, the oxygen is obtained from the air by means of the lungs. In the lungs, the oxygen dissolves in the blood and is carried to the tissues by the circulatory system (Chapter 9).

### Characteristics of respiratory surfaces

The exchange of oxygen and carbon dioxide across a respiratory surface, as in the lungs, depends on the diffusion of these two gases. Diffusion occurs more rapidly if:

- there is a large surface area exposed to the gas
- the distance across which diffusion has to take place is small
- there is a good blood supply, and
- there is a big difference in the concentrations of the gas at two points brought about by **ventilation**.

#### Large surface area

The presence of millions of alveoli in the lungs provides a very large surface for gaseous exchange. The many branching filaments in a fish's gills have the same effect.

#### Thin epithelium

There is only a two-cell layer, at the most, separating the air in the alveoli from the blood in the capillaries (Figure 11.4). One layer is the alveolus wall; the other is the capillary wall. Thus, the distance for diffusion is very short.

#### Good blood supply

The alveoli are surrounded by networks of blood capillaries. The continual removal of oxygen by the blood in the capillaries lining the alveoli keeps its concentration low. In this way, a steep diffusion gradient is maintained, which favours the rapid diffusion of oxygen from the air passages to the alveolar lining.

The continual delivery of carbon dioxide from the blood into the alveoli, and its removal from the air passages by ventilation, similarly maintains a diffusion gradient that promotes the diffusion of carbon dioxide from the alveolar lining into the bronchioles.

#### Ventilation

Ventilation of the lungs helps to maintain a steep diffusion gradient (see 'Diffusion' in Chapter 3) between the air at the end of the air passages and the alveolar air. The concentration of the oxygen in the air at the end of the air passages is high, because the air is constantly replaced by the breathing actions.

The respiratory surfaces of land-dwelling mammals are invariably moist. Oxygen has to dissolve in the thin film of moisture before passing across the epithelium.

### Lung structure

The lungs are enclosed in the thorax (chest region) (see Figure 7.13). They have a spongy texture and can be expanded and compressed by movements of the thorax in such a way that air is sucked in and

blown out. The lungs are joined to the back of the mouth by the windpipe or **trachea** (Figure 11.1). The trachea divides into two smaller tubes, called **bronchi** (singular = bronchus), which enter the lungs and divide into even smaller branches. When these branches are only about 0.2 mm in diameter, they are called **bronchioles** (Figure 11.3(a)). These fine branches end in a mass of little, thin-walled, pouch-like air sacs called **alveoli** (Figures 11.3(b), (c) and 11.4).

The **epiglottis** and other structures at the top of the trachea stop food and drink from entering the air passages when we swallow.

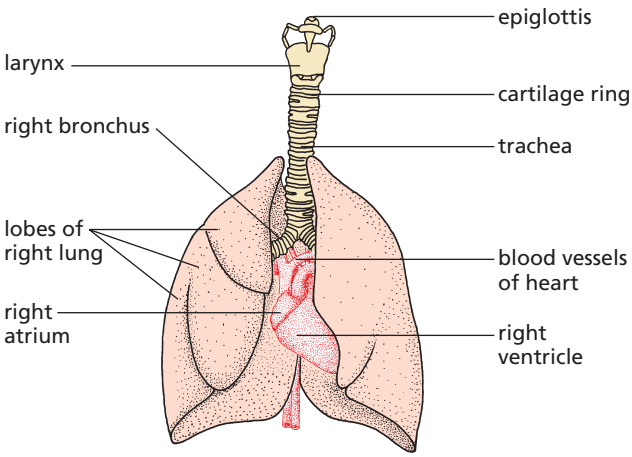



**Figure 11.1** Diagram of lungs, showing position of heart

Figure 11.2 shows a section through the thorax. The ribs, shown in cross section, form a cage, which has two main functions:

- to protect the lungs and heart
- to move to ventilate the lungs.

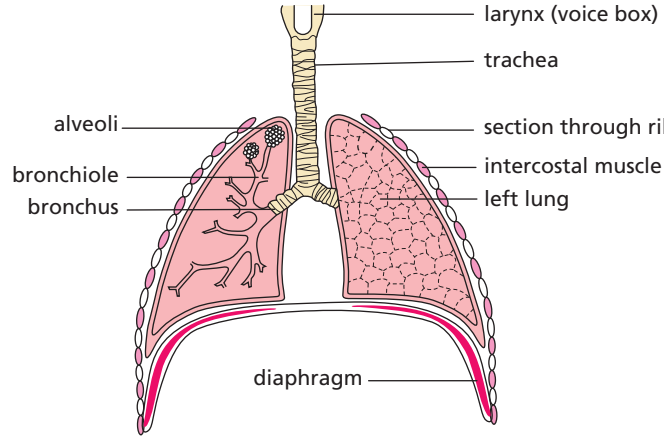
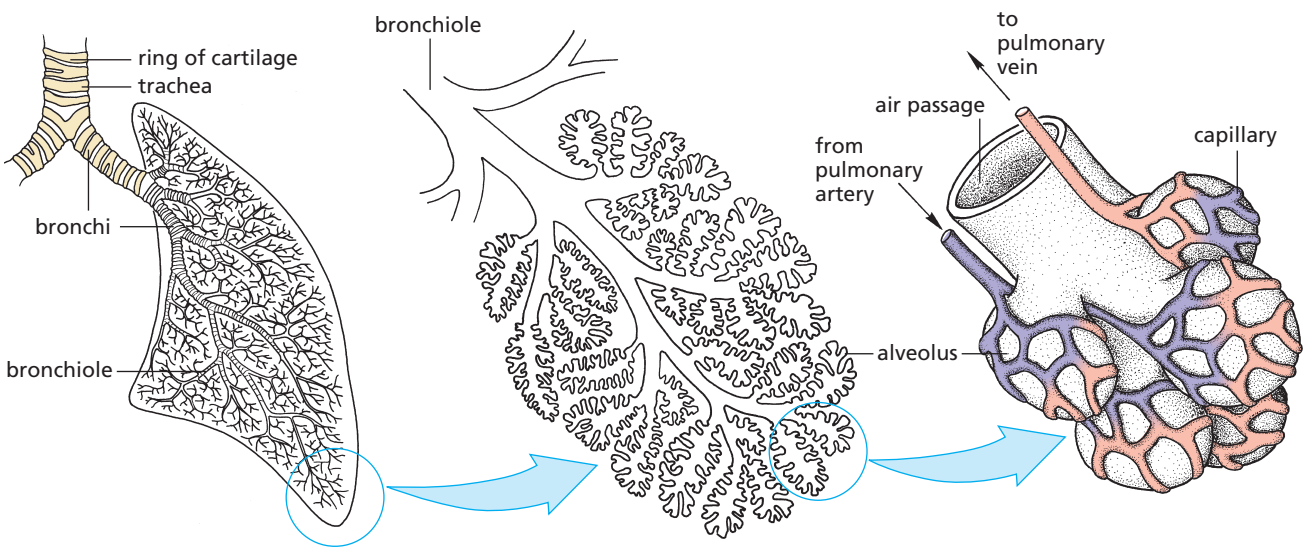



**Figure 11.2** Section through the thorax

The alveoli have thin elastic walls, formed from a single-cell layer or **epithelium**. Beneath the epithelium is a dense network of capillaries (Figure 11.3(c)) supplied with deoxygenated blood (see 'Blood' in Chapter 9). This blood, from which the body has taken oxygen, is pumped from the right ventricle, through the pulmonary artery (see Figure 9.20). In humans, there are about 350 million alveoli, with a total absorbing surface of about 90 m$^2$. This large absorbing surface makes it possible to take in oxygen and give out carbon dioxide at a rate to meet the body's needs.




**(a)** air passages in the lungs

**(b)** the air passages end in tiny pockets (alveoli)

**(c)** blood supply of the alveoli

**Figure 11.3** Lung structure

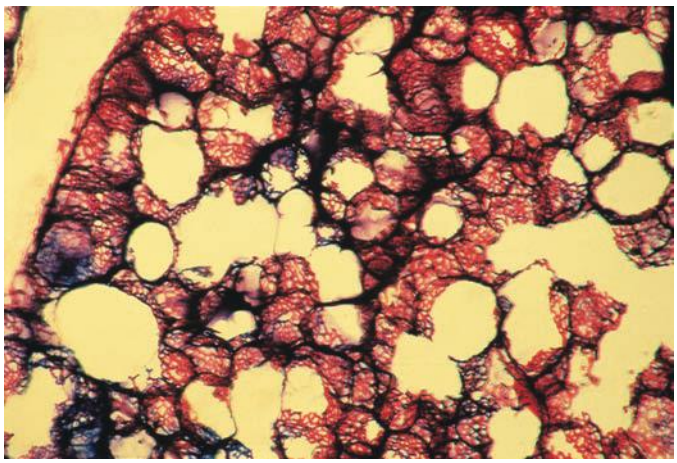


**Figure 11.4** Small piece of lung tissue (×40). The capillaries have been injected with red and blue dye. The networks surrounding the alveoli can be seen.

## Gaseous exchange

Ventilation refers to the movement of air into and out of the lungs. Gaseous exchange refers to the exchange of oxygen and carbon dioxide, which takes place between the air and the blood vessels in the lungs (Figure 11.5).

The 1.5 litres of residual air in the alveoli is not exchanged during ventilation and oxygen has to reach the capillaries by the slower process of diffusion. Figure 11.5 shows how oxygen reaches the red blood cells and how carbon dioxide escapes from the blood.

The oxygen combines with the haemoglobin in the red blood cells, forming **oxyhaemoglobin** (see 'Blood' in Chapter 9). The carbon dioxide in the plasma is released when the hydrogencarbonate ions ($—HCO_3$) break down to $CO_2$ and $H_2O$.

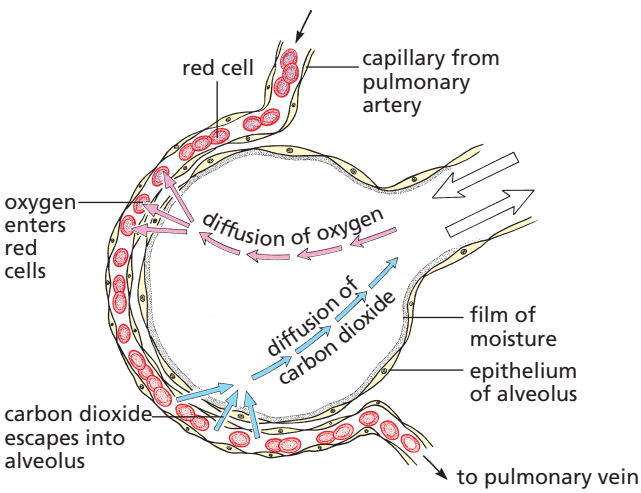



**Figure 11.5** Gaseous exchange in the alveolus

The capillaries carrying oxygenated blood from the alveoli join up to form the pulmonary vein (see Figure 9.20), which returns blood to the left atrium of the heart. From here it enters the left ventricle and is pumped all around the body, so supplying the tissues with oxygen.

Table 11.1 shows changes in the composition of air as it is breathed in and out.

**Table 11.1** Changes in the composition of breathed air

| | Inhaled/% | Exhaled/% |
|---|---|---|
| oxygen | 21 | 16 |
| carbon dioxide | 0.04 | 4 |
| water vapour | variable | saturated |

Sometimes the word **respiration** or **respiratory** is used in connection with breathing. The lungs, trachea and bronchi are called the **respiratory system**; a person's rate of breathing may be called his or her **respiration rate**. This use of the word should not be confused with the biological meaning of respiration, namely the release of energy in cells (Chapter 12). This chemical process is sometimes called **tissue respiration** or **internal respiration** to distinguish it from breathing.

## Lung capacity and breathing rate

The total volume of the lungs when fully inflated is about 5 litres in an adult. However, in quiet breathing, when asleep or at rest, you normally exchange only about 500 $cm^3$. During exercise you can take in and expel an extra 3 litres. There is a **residual volume** of 1.5 litres, which cannot be expelled no matter how hard you breathe out.

At rest, you normally inhale and exhale about 12 times per minute. During exercise, the breathing rate may rise to over 20 breaths per minute and the depth also increases.

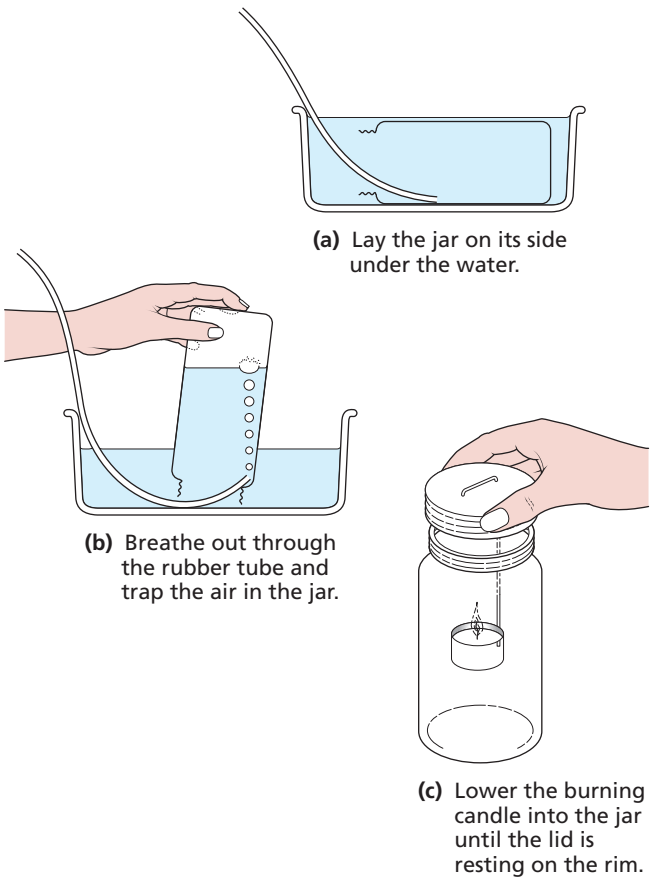
### Breathing rate and exercise

The increased rate and depth of breathing during exercise allows more oxygen to dissolve in the blood and supply the active muscles. The extra carbon dioxide that the muscles put into the blood is detected by the brain, which instructs the intercostal muscles and diaphragm muscles to contract and relax more rapidly, increasing the breathing rate. Carbon dioxide will be removed by the faster, deeper breathing.

# Practical work

## Oxygen in exhaled air

- Place a large screw-top jar on its side in a bowl of water (Figure 11.6(a)).
- Put a rubber tube in the mouth of the jar and then turn the jar upside-down, still full of water and with the rubber tube still in it.
- Start breathing out and when you feel your lungs must be about half empty, breathe the last part of the air down the rubber tubing so that the air collects in the upturned jar and fills it (Figure 11.6(b)).
- Put the screw top back on the jar under water, remove the jar from the bowl and place it upright on the bench.
- Light the candle on the special wire holder (Figure 11.6(c)), remove the lid of the jar, lower the burning candle into the jar and count the number of seconds the candle stays alight.
- Now take a fresh jar, with ordinary air, and see how long the candle stays alight in this.



**(a)** Lay the jar on its side under the water.

**(b)** Breathe out through the rubber tube and trap the air in the jar.

**(c)** Lower the burning candle into the jar until the lid is resting on the rim.

**Figure 11.6** Experiment to test exhaled air for oxygen

**Results**
The candle will burn for about 15–20 seconds in a large jar of ordinary air. In exhaled air it will go out in about 5 seconds.

**Interpretation**
Burning needs oxygen. When the oxygen is used up, the flame goes out. It looks as if exhaled air contains much less oxygen than atmospheric air.

## Carbon dioxide in exhaled air

- Prepare two large test-tubes, A and B, as shown in Figure 11.7, each containing a little clear limewater.
- Put the mouthpiece in your mouth and breathe in and out *gently* through it for about 15 seconds. Notice which tube is bubbling when you breathe out and which one bubbles when you breathe in.

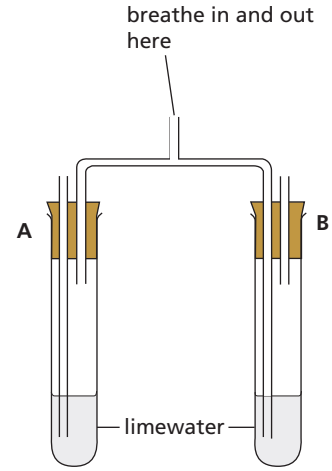



**Figure 11.7** Experiment to compare the carbon dioxide content of inhaled and exhaled air

If after 15 seconds there is no difference in the appearance of the limewater in the two tubes, continue breathing through them for another 15 seconds.

**Results**
The limewater in tube B goes milky. The limewater in tube A stays clear.

**Interpretation**
Carbon dioxide turns limewater milky. Exhaled air passes through tube B. Inhaled air passes through tube A. Exhaled air must, therefore, contain more carbon dioxide than inhaled air.

**Note 1:** if the breathing process is carried out for too long, the limewater that had turned milky will revert to being colourless. This is because the calcium carbonate formed (milky precipitate) reacts in water with carbon dioxide to form calcium hydrogencarbonate, which is soluble and colourless.

**Note 2:** Hydrogencarbonate indicator is an alternative to limewater. It changes from red to yellow when carbon dioxide is bubbled through it.

## Volume of air in the lungs

- Calibrate a large (5 litre) plastic bottle by filling it with water, half a litre at a time, and marking the water levels on the outside.
- Fill the bottle with water and put on the stopper.
- Put about 50 mm depth of water in a large plastic bowl.
- Hold the bottle upside-down with its neck under water and remove the screw top. Some of the water will run out but this does not matter.

- Push a rubber tube into the mouth of the bottle to position A, shown on the diagram (Figure 11.8).
- Take a deep breath and then exhale as much air as possible down the tubing into the bottle. The final water level inside the bottle will tell you how much air you can exchange in one deep breath.
- Now push the rubber tubing further into the bottle, to position B (Figure 11.8), and blow out any water left in the tube.
- Support the bottle with your hand and breathe gently in and out through the tube, keeping the water level inside and outside the bottle the same. This will give you an idea of how much air you exchange when breathing normally.

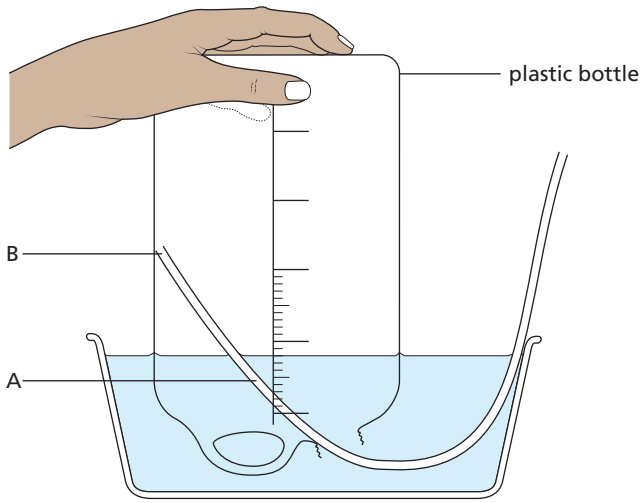



**Figure 11.8** Experiment to measure the volume of air exhaled from the lungs. (A) shows the position of the tube when measuring the maximum usable lung volume. (B) is the position for measuring the volume exchanged in gentle breathing.

## Investigating the effect of exercise on carbon dioxide production

- Half fill two clean boiling tubes with limewater.
- Place a drinking straw in one of the boiling tubes and gently blow into it, with normal, relaxed breaths.
- Count how many breaths are needed to turn the limewater milky.
- Now exercise for 1 to 2 minutes, e.g. running on the spot.
- Place a drinking straw in the second boiling tube, blowing into it as before.
- Count the number of breaths needed to turn the limewater milky.

**Results**

The number of breaths needed after exercise will be less than before exercise.

**Interpretation**

Cells in the body are constantly respiring, even when we are not doing physical work. They produce carbon dioxide, which is expired by the lungs. The carbon dioxide turns limewater milky. During exercise, cells (particularly in the skeletal muscles) respire more rapidly producing more carbon dioxide. This turns the limewater milky more rapidly.

## Investigating the effect of exercise on rate and depth of breathing

This investigation makes use of an instrument called a spirometer. It may be one as illustrated in Figure 11.9, or a digital version, connected to a computer. A traditional spirometer has a hinged chamber, which rises and falls as a person breathes through the mouthpiece. The chamber is filled with medical oxygen from a cylinder. There is a filter containing soda lime, which removes any carbon dioxide in the user's breath, so that it is not re-breathed. The hinged chamber has a pen attached (shown in red in Figure 11.9), which rests against the paper-covered drum of a kymograph. This can be set to revolve at a fixed rate so that the trace produced by the user progresses across the paper.

**Figure 11.9** A spirometer. This instrument measures the volume of air breathed in and out of the lungs and can be used to measure oxygen consumption.

- A volunteer is asked to breathe in and out through the mouthpiece and the kymograph is set to revolve slowly. This will generate a trace, which will provide information about the volunteer's tidal volume and breathing rate (each peak on the trace represents one breath and the depth between a peak and trough can be used to calculate the tidal volume).
- Next, the volunteer is asked to take a deep breath with the mouthpiece removed, then breathe out through the mouthpiece for one long continuous breath. The depth between the peak and trough produced can be used to calculate the vital capacity.
- Finally, the volunteer is asked insert the mouthpiece, then run on the spot or pedal an exercise bicycle, while breathing through the spirometer. The trace produced (Figure 11.10) can be used to compare the breathing rate and depth during exercise with that at rest. A study of the trace would also show a drop in the trace with time. This can be used to calculate the volume of oxygen consumed over time.

**Results**

Tidal volume is about 500 $cm^3$, but tends to appear higher if the person is nervous or influenced by the trace being created.

Vital capacity can be between 2.5 and 5.0 litres, depending on the sex, physical size and fitness of the person.

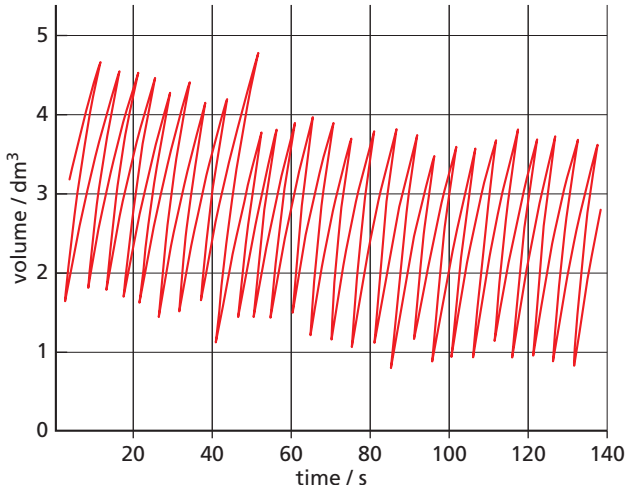



**Figure 11.10** Spirometer trace taken during exercise

The breathing rate at rest is around 12 breaths per minute. During exercise this increases and may reach 20 or more breaths per minute.

**Note**: this experiment makes use of medical oxygen. This has a high purity and is toxic if inhaled for a prolonged period of time. If the volunteer starts to feel dizzy while using the spirometer, he or she should remove the mouthpiece immediately and rest.

## Ventilation of the lungs

The movement of air into and out of the lungs, called **ventilation**, renews the oxygen supply in the lungs and removes the surplus carbon dioxide. Horseshoe-shaped hoops of cartilage are present in the trachea and bronchi to prevent them collapsing when we breathe in. The lungs contain no muscle fibres and are made to expand and contract by movements of the ribs and diaphragm.

The **diaphragm** is a sheet of tissue that separates the thorax from the abdomen (see Figure 7.13). When relaxed, it is domed slightly upwards. The ribs are moved by the **intercostal muscles**. The external intercostals (Figure 11.11) contract to pull the ribs upwards and outwards. The internal intercostals contract to pull them downwards and inwards. Figure 11.12 shows the contraction of the external intercostals making the ribs move upwards.

### Inhaling

1 The diaphragm muscles contract and pull it down (Figure 11.13(a)).

2 The internal intercostal muscles relax, while the external intercostal muscles contract and pull the ribcage upwards and outwards (Figure 11.14(a)).

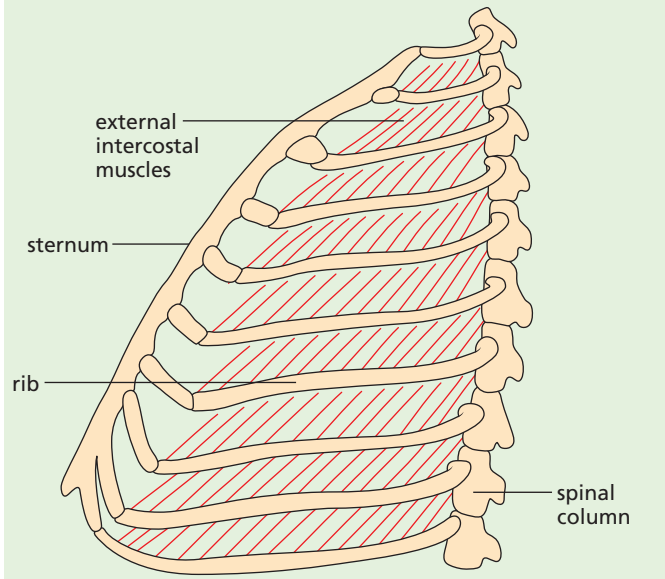



**Figure 11.11** Ribcage seen from left side, showing external intercostal muscles

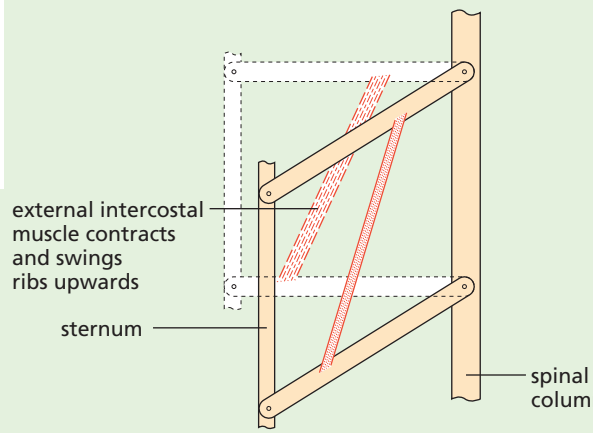



**Figure 11.12** Model to show action of intercostal muscles

These two movements make the volume in the thorax bigger, so forcing the lungs to expand. The reduction in air pressure in the lungs results in air being drawn in through the nose and trachea. This movement of air into the lungs is known as ventilation.

### Exhaling

1 The diaphragm muscles relax, allowing the diaphragm to return to its domed shape (Figure 11.13(b)).

2 The external intercostal muscles relax, while the internal intercostal muscles contract, pulling the ribs downwards to bring about a forced expiration (Figure 11.14(b)).

The lungs are elastic and shrink back to their relaxed volume, increasing the air pressure inside them. This results in air being forced out again.

The outside of the lungs and the inside of the thorax are lined with a smooth membrane called the **pleural membrane**. This produces a thin layer of liquid called **pleural fluid**, which reduces the friction between the lungs and the inside of the thorax.

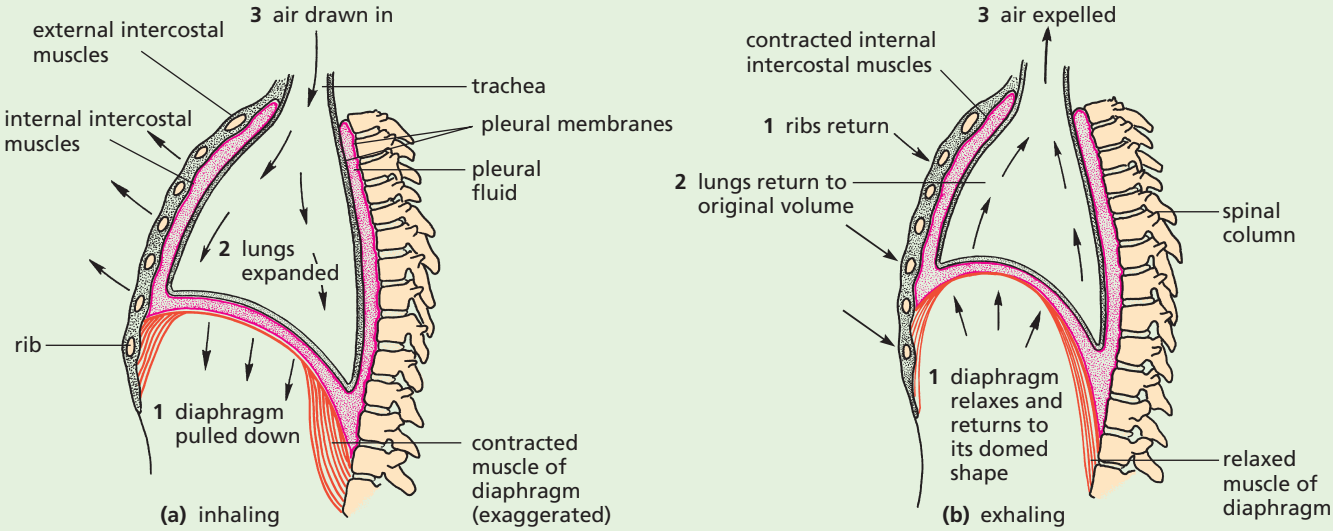



**Figure 11.13** Diagrams of thorax to show mechanism of breathing

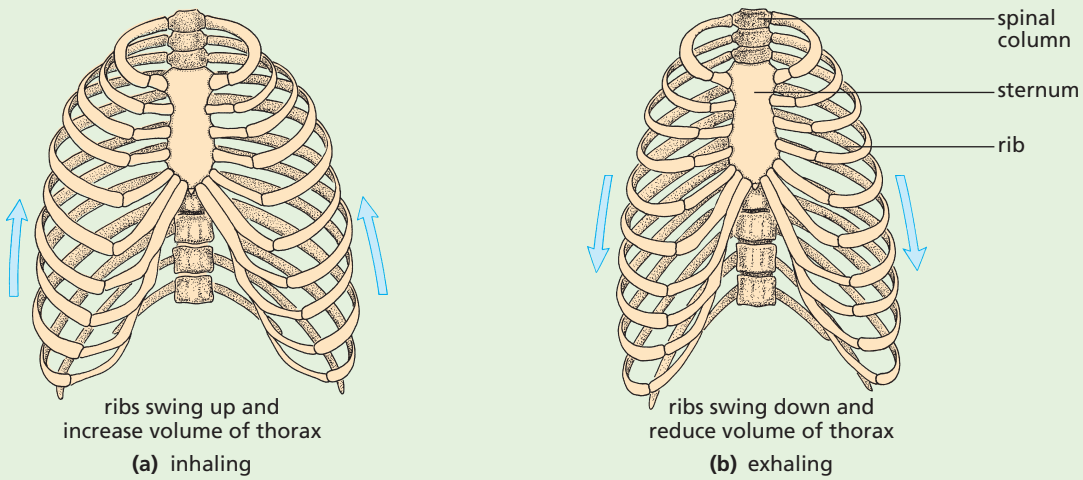



**Figure 11.14** Movement of ribcage during breathing

A piece of apparatus known as the 'bell-jar model' (Figure 11.15) can be used to show the way in which movement of the diaphragm results in inspiration and expiration. The balloons start off deflated. When the handle attached to the rubber sheet is pulled down, the balloons inflate. If the handle is released, the balloons deflate again.

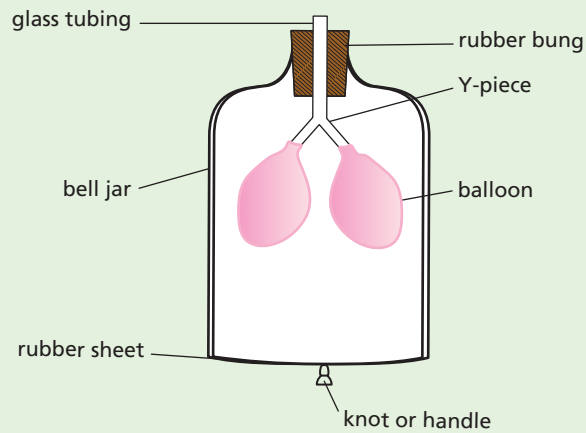



**Figure 11.15** Bell-jar model

When the rubber sheet is pulled down, the volume inside the bell jar increases. This reduces the air pressure inside, making it lower than outside. The air rushes in, through the glass tubing, to equalise the air pressure, causing the balloons to inflate.

### Differences in composition of inspired and expired air

Air in the atmosphere (which is breathed in) contains about 21% oxygen (see Table 11.1). Some of this is absorbed into the bloodstream when it enters the alveoli, resulting in a reduction of oxygen in exhaled air to 16% (the process of gaseous exchange in the alveoli does not remove all the oxygen from the air). Gas exchange relies on diffusion to transfer the oxygen into red blood cells and the air breathed in mixes with air that has not all been breathed out from the previous breath, so the process of gas exchange is not very efficient.

The remaining 79% of the air consists mainly of nitrogen, the percentage composition of which does not change significantly during breathing.

Inspired air contains 0.04% carbon dioxide. Cells of the body produce carbon dioxide as a waste product during aerobic respiration (see 'Aerobic respiration' in Chapter 12). The bloodstream carries carbon dioxide to the lungs for excretion. It diffuses across the walls of the alveoli to be expired. The percentage breathed out is 4%, 100 times greater than the percentage breathed in.

The lining of the alveoli is coated with a film of moisture in which the oxygen dissolves. Some of this moisture evaporates into the alveoli and saturates the air with water vapour. The air you breathe out, therefore, always contains a great deal more water vapour than the air you breathe in. The presence of water vapour in expired air is easily demonstrated by breathing onto a cold mirror: condensation quickly builds up on the glass surface. The exhaled air is warmer as well, so in cold and temperate climates you lose heat to the atmosphere by breathing.

### The relationship between physical activity and the rate and depth of breathing

It has already been stated that the rate and depth of breathing increase during exercise. In order for the limbs to move faster, aerobic respiration in the skeletal muscles increases. Carbon dioxide is a waste product of aerobic respiration. As a result, $CO_2$ builds up in the muscle cells and diffuses into the plasma in the bloodstream more rapidly. The brain detects increases in carbon dioxide concentration in the blood and stimulates the breathing mechanism to speed up, increasing the rate of expiration of the gas. An increase in the breathing rate also has the advantage of making more oxygen available to the more rapidly respiring muscle cells.

### Protection of the gas exchange system from pathogens and particles

Pathogens are disease-causing organisms (see Chapter 10). Pathogens, such as bacteria, and dust particles are present in the air we breathe in and are potentially dangerous if not actively removed. There are two types of cells that provide mechanisms to help achieve this.

**Goblet cells** are found in the epithelial lining of the trachea, bronchi and some bronchioles of the respiratory tract (Figure 11.16). Their role is to secrete **mucus**. The mucus forms a thin film over the internal lining. This sticky liquid traps pathogens and small particles, preventing them from entering the alveoli where they could cause infection or physical damage.

**Ciliated cells** are also present in the epithelial lining of the respiratory tract (Figure 11.16; see also 'Levels of organisation' in Chapter 2). They are in a continually flicking motion to move the mucus, secreted by the goblet cells, upwards and away from the lungs. When the mucus reaches the top of the trachea, it passes down the gullet during normal swallowing.

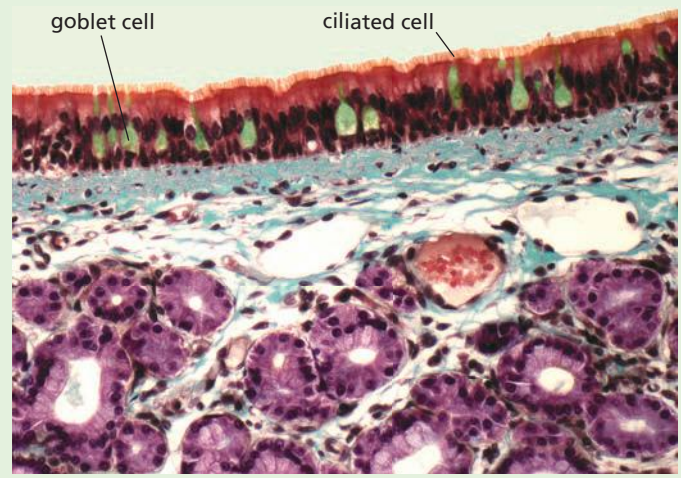



**Figure 11.16** Goblet cells and ciliated cells in the trachea

## Questions

Core

1 Place the following structures in the order in which air will reach them when breathing in: bronchus, trachea, nasal cavity, alveolus.

2 One function of the small intestine is to absorb food (see 'Absorption' in Chapter 7). One function of the lungs is to absorb oxygen. Point out the basic similarities in these two structures, which help to speed up the process of absorption.

Extended

3 a Compare the bell-jar model in Figure 11.15 with the diagram of the lungs (Figure 11.1). What do the following parts represent on the model?
   i glass tubing
   ii Y-piece
   iii balloons
   iv bell jar
   v rubber sheet

   b Explain why this model does not give a complete simulation of the process of breathing.

4 What are the two principal muscular contractions that cause air to be inhaled?

5 Place the following in the correct order:
lungs expand, ribs rise, air enters lungs, external intercostal muscles contract, thorax expands.

6 During inhalation, which parts of the lung structure would you expect to expand the most?

## Checklist

After studying Chapter 11 you should know and understand the following:

- Alveoli in the lungs are very numerous, provide a large surface area, have a thin, moist surface and are well-ventilated for efficient gas exchange.
- Alveoli have a good blood supply.
- Exchange of oxygen and carbon dioxide in the alveoli takes place by diffusion.
- The blood in the capillaries picks up oxygen from the air in the alveoli and gives out carbon dioxide. This is called gaseous exchange.
- The oxygen is carried around the body by the blood and used by the cells for their respiration.
- The ribs, rib muscles and diaphragm make the lungs expand and contract. This causes inhaling and exhaling.
- Air is drawn into the lungs through the trachea, bronchi and bronchioles.
- Inhaled air contains a higher percentage of oxygen and a lower percentage of carbon dioxide and (usually) water vapour than exhaled air.
- Limewater is used as a test for the presence of carbon dioxide. It turns milky.
- During exercise, the rate and depth of breathing increase.

- Cartilage, present in the trachea, keeps the airway open and unrestricted.
- The diaphragm, internal and external intercostal muscles play a part in ventilation of the lungs.
- During exercise, the rate and depth of breathing increase. This supplies extra oxygen to the muscles and removes their excess carbon dioxide.
- Movement of the ribcage and diaphragm results in volume and pressure changes in the thorax, leading to ventilation of the lungs.
- During physical activity, increases in levels of carbon dioxide in the blood are detected in the brain, causing an increased rate of breathing.
- Goblet cells make mucus to trap pathogens and particles to protect the gas exchange system.
- Ciliated cells move mucus away from the alveoli.

# 12 Respiration

**Respiration**
Use of energy in humans
Role of enzymes

**Aerobic respiration**
Define aerobic respiration
Word equation
Investigating uptake of oxygen in respiring organisms

Balanced chemical equation
Investigating the effect of temperature on respiration

**Anaerobic respiration**
Define anaerobic respiration
Word equations
Energy output compared with aerobic respiration

Balanced chemical equation
Effects of lactic acid
Oxygen debt

## Respiration

Most of the processes taking place in cells need energy to make them happen. Examples of energy-consuming processes in living organisms are:

- the contraction of muscle cells – to create movement of the organism, or peristalsis to move food along the alimentary canal, or contraction of the uterus wall during childbirth
- building up proteins from amino acids
- the process of cell division (Chapter 17) to create more cells, or replace damaged or worn out cells, or to make reproductive cells
- the process of active transport (Chapter 3), involving the movement of molecules across a cell membrane against a concentration gradient
- growth of an organism through the formation of new cells or a permanent increase in cell size
- the conduction of electrical impulses by nerve cells (Chapter 14)
- maintaining a constant body temperature in homoiothermic (warm-blooded) animals ('Homeostasis' in Chapter 14) to ensure that vital chemical reactions continue at a predictable rate and do not slow down or speed up as the surrounding temperature varies.

This energy comes from the food that cells take in. The food mainly used for energy in cells is glucose.

The process by which energy is produced from food is called **respiration**.

Respiration is a chemical process that takes place in cells and involves the action of enzymes. It must not be confused with the process of breathing, which is also sometimes called 'respiration'. To make the difference quite clear, the chemical process in cells is sometimes called **cellular respiration**, **internal respiration** or **tissue respiration**. The use of the word 'respiration' for breathing is best avoided altogether.

## Aerobic respiration

**Key definition**
**Aerobic respiration** is the term for the chemical reactions in cells that use oxygen to break down nutrient molecules to release energy.

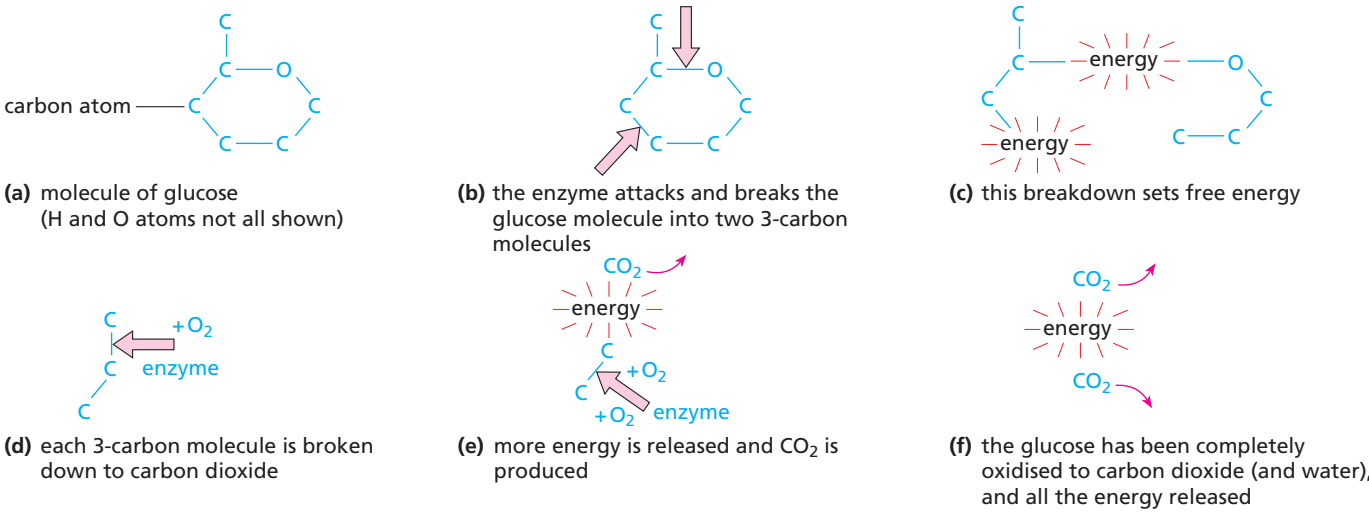
The word **aerobic** means that oxygen is needed for this chemical reaction. The food molecules are combined with oxygen. The process is called **oxidation** and the food is said to be **oxidised**. All food molecules contain carbon, hydrogen and oxygen atoms. The process of oxidation converts the carbon to carbon dioxide ($CO_2$) and the hydrogen to water ($H_2O$) and, at the same time, sets free energy, which the cell can use to drive other reactions.

Aerobic respiration can be summed up by the equation

$$\text{glucose} + \text{oxygen} \xrightarrow{\text{enzymes}} \underset{\text{dioxide}}{\text{carbon}} + \text{water} + \underset{\text{energy}}{2830\,\text{kJ}}$$

The amount of energy you would get by completely oxidising 180 grams (g) of glucose to carbon dioxide and water is 2830 kilojoules (kJ). In the cells, the energy is not released all at once. The oxidation takes place in a series of small steps and not in one jump as the equation suggests. Each small step needs its own enzyme and at each stage a little energy is released (Figure 12.1).

Although the energy is used for the processes mentioned above, some of it always appears as heat. In 'warm-blooded' animals (birds and mammals) some of this heat is retained to maintain their body temperature.




**(a)** molecule of glucose (H and O atoms not all shown)

**(b)** the enzyme attacks and breaks the glucose molecule into two 3-carbon molecules

**(c)** this breakdown sets free energy

**(d)** each 3-carbon molecule is broken down to carbon dioxide

**(e)** more energy is released and $CO_2$ is produced

**(f)** the glucose has been completely oxidised to carbon dioxide (and water), and all the energy released

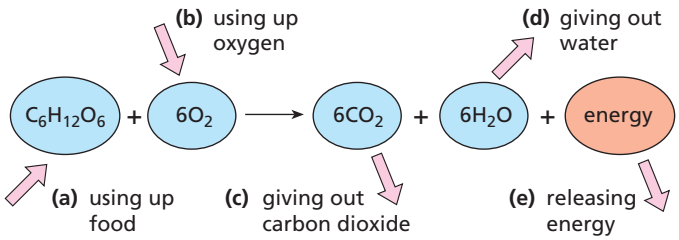
**Figure 12.1** Aerobic respiration

In 'cold-blooded' animals (e.g. reptiles and fish) the heat may build up for a time in the body and allow the animal to move about more quickly. In plants the heat is lost to the surroundings (by conduction, convection and evaporation) as fast as it is produced.

# Practical work

## Experiments on respiration and energy

If you look below at the chemical equation that represents aerobic respiration you will see that a tissue or an organism that is respiring should be (a) using up food, (b) using up oxygen, (c) giving off carbon dioxide, (d) giving out water and (e) releasing energy, which can be used for other processes.




If we wish to test whether aerobic respiration is taking place:

- '(d) giving out water' is not a good test because non-living material will give off water vapour if it is wet to start with.
- '(a) using up food' can be tested by seeing if an organism loses weight. This is not as easy as it seems because most organisms lose weight as a result of evaporation of water and this may have nothing to do with respiration. It is the decrease in 'dry weight' that must be measured.

We will focus on the uptake of oxygen and the production of carbon dioxide as indications that respiration is taking place.

Seeds are often used as the living organisms because when they start to grow (germinate) there is a high level of chemical activity in the cells. Seeds are easy to obtain and to handle and they fit into small-scale apparatus. In some cases blowfly maggots or woodlice can be used as animal material. Yeast is useful when studying anaerobic respiration.

### 1 Using up oxygen during respiration

The apparatus in Figure 12.2 is a **respirometer** (a 'respire meter'), which can measure the rate of respiration by seeing how quickly oxygen is taken up. Germinating seeds, or blowfly larvae or woodlice are placed in the test-tube and, as they use up the oxygen for respiration, the level of liquid in the delivery tubing will go up.

There are two drawbacks to this. One is that the organisms usually give out as much carbon dioxide as they take in oxygen. So there may be no change in the total amount of air in the test-tube and the liquid level will not move. This drawback is overcome by placing **soda-lime** in the test-tube. Soda-lime will absorb carbon dioxide as fast as the organisms give it out. So only the uptake of oxygen will affect the amount of air in the tube. The second drawback is that quite small changes in temperature will make the air in the test-tube expand or contract and so cause the liquid to rise or fall whether or not respiration is taking place. To overcome this, the test-tube is kept in a beaker of water (a water bath). The temperature of water changes far more slowly than that of air, so there will not be much change during a 30-minute experiment.

#### Control

To show that it is a living process that uses up oxygen, a similar respirometer is prepared but containing an equal quantity of germinating seeds that have been killed by boiling. (If blowfly larvae or woodlice are used, the control can consist of an equivalent volume of glass beads. This is not a very good control but is probably more acceptable than killing an equivalent number of animals.)

The apparatus is finally set up as shown in Figure 12.2 and left for 30 minutes (10 minutes if blowfly larvae or woodlice are used).

The capillary tube and reservoir of liquid are called a **manometer**.

**Result**
The level of liquid in the experiment goes up more than in the control. The level in the control may not move at all.

**Interpretation**
The rise of liquid in the delivery tubing shows that the living seedlings have taken up part of the air. It does not prove that it is oxygen that has been taken up. Oxygen seems the most likely gas, however, because (1) there is only 0.03% carbon dioxide in the air to start with and (2) the other gas, nitrogen, is known to be less active than oxygen.

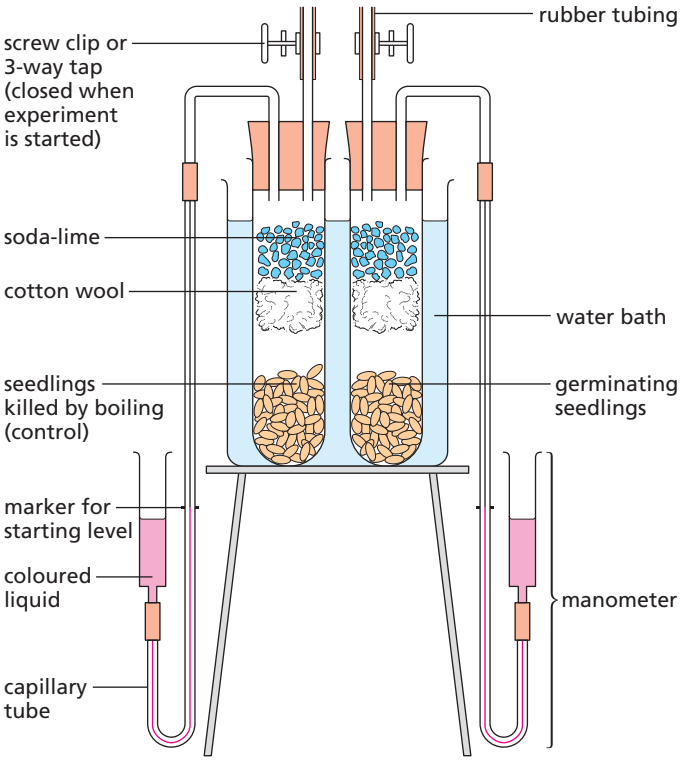



**Figure 12.2** Experiment to see if oxygen is taken up in respiration

If the experiment is allowed to run for a long time, the uptake of oxygen could be checked at the end by placing a lighted splint in each test-tube in turn. If some of the oxygen has been removed by the living seedlings, the flame should go out more quickly than it does in the tube with dead seedlings.

## 2 Using up oxygen during respiration (alternative method)

A respirometer such as the one illustrated in Figure 12.2 is not an easy piece of apparatus to set up and collect data from. An alternative way of showing that oxygen is used up during respiration can be achieved using a simple respirometer (Figure 12.3).

- A larger invertebrate such as a locust, or a group of woodlice or blowfly maggots, is placed in the boiling tube (an alternative is a large plastic syringe, linked to the capillary tube with a short section of rubber or silicone tubing). The organisms are protected from the soda-lime by means of cotton wool or a wire gauze (soda-lime is caustic).

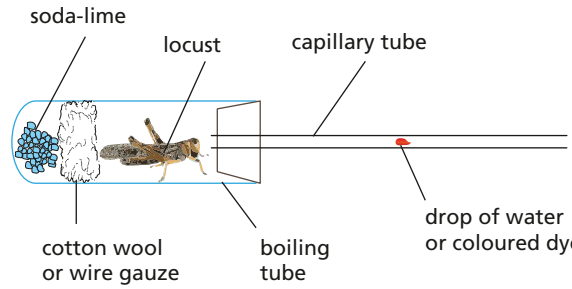



**Figure 12.3** A simple respirometer

- A drop of water or coloured dye is introduced to the capillary tube by touching it against the liquid.
- The capillary tube is rested against a ruler and the position of the water drop is noted.
- After 1 minute (or longer if the drop moves very slowly) the new position of the water drop is recorded.

**Note:** Care must be taken when handling living organisms. Wash hands thoroughly with water if they come into contact with caustic soda.

**Results**
The water drop moves towards the organism. If the diameter of the bore of the capillary tube is measured, the volume of air taken in by the organism can be calculated:

$$\text{volume} = \pi r^2 l$$

where $r$ = radius of the capillary tube bore

$l$ = distance travelled by the water drop

This value can be converted into a rate if the volume is divided by the time taken.

**Interpretation**
The movement of the water drop towards the organism shows that it is taking in air. By using a range of organisms (locust, woodlice, blowfly larvae, germinating seeds) the rates of uptake can be compared to see which is respiring most actively.

A control could be set up using the same apparatus, but with glass beads instead of the organism(s). The bubble may still move because the soda-lime will absorb any carbon dioxide in the air in the boiling tube, but the movement should be less than that for living organisms.

If you are following the extended curriculum you need to be able to state the balanced chemical equation for aerobic respiration:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2830\,kJ$$

glucose oxygen carbon dioxide water energy

## Mitochondria

It is in the mitochondria that the chemistry of aerobic respiration takes place (Chapter 2). The mitochondria generate a compound called **ATP**, which is used by the cell as the source of energy for driving other chemical reactions in the cytoplasm and nucleus.

## Practical work

### More experiments on respiration and energy

#### 3 Investigating the effect of temperature on the rate of respiration of germinating seeds

- Use the same apparatus as shown in Experiment 2, but set up the boiling tube so it is vertical and supported in a water bath such as a beaker (Figure 12.4).
- Use wheat grains or pea seeds that have been soaked for 24 hours and rinsed in 1% formaldehyde (or domestic bleach diluted 1:4) for 5 minutes. These solutions will kill any bacteria or fungi on the surface of the seeds.
- Kill an equal quantity of soaked seeds by boiling them for 5 minutes.
- Cool the boiled seeds in cold tap water; rinse them in bleach or formaldehyde for 5 minutes as before. These can be used as the control (or, alternatively, use an equivalent volume of glass beads).
- Start with a water bath at about 20 °C and allow the seeds to acclimatise to that temperature for a few minutes before taking any readings. The initial and final positions of the water drop could be recorded on the capillary tube with a permanent marker or chinagraph pencil, or by sticking a small label onto the glass. The distance travelled can then be measured with a ruler.
- Repeat the procedure (introducing a new bubble each time) at a range of different temperatures, remembering to allow time for the seeds to acclimatise to the new conditions before taking further readings.

**Results**
As the temperature is increased the rate of movement of the water bubble towards the seeds increases. The movement may stop at higher temperatures.

**Interpretation**
As the temperature increases, the rate of respiration in the germinating seeds increases. This is because the enzymes controlling respiration are more active at higher temperatures. However, respiration may stop above around 40 °C because the enzymes become denatured if they get too hot.

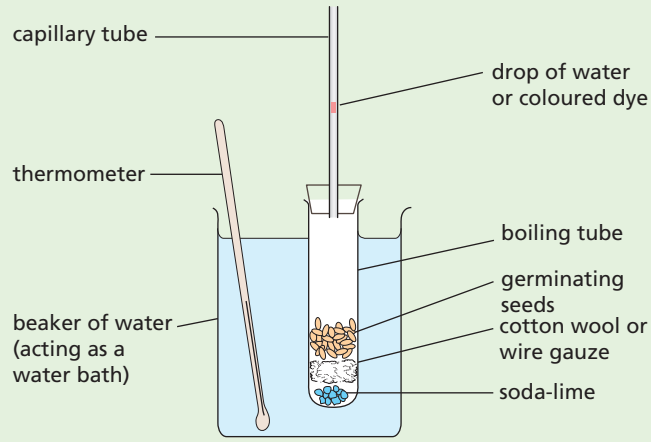



**Figure 12.4** Simple respirometer for investigating the effect of temperature on germinating seeds

## Controlled experiments

In most biological experiments, a second experiment called a **control** is set up. This is to make sure that the results of the first experiment are due to the conditions being studied and not to some other cause that has been overlooked.

In the experiment in Figure 12.2, the liquid rising up the capillary tube could have been the result of the test-tube cooling down, so making the air inside it contract. The identical experiment with dead seeds – the control – showed that the result was not due to a temperature change, because the level of liquid in the control did not move.

The term 'controlled experiment' refers to the fact that the experimenter (1) sets up a control and (2) controls the conditions in the experiment. In the experiment shown in Figure 12.2 the seeds are enclosed in a test-tube and soda-lime is added. This makes sure that any uptake or output of oxygen will make the liquid go up or down, and that the output of carbon dioxide will not affect the results. The experimenter had controlled both the amount and the composition of the air available to the germinating seeds.

If you did an experiment to compare the growth of plants in the house and in a greenhouse, you could not be sure whether it was the extra light or the high temperature of the greenhouse that caused better growth. This would not, therefore, be a properly controlled experiment. You must alter only

one condition (called a **variable**) at a time, either the light or the temperature, and then you can compare the results with the control experiment.

A properly controlled experiment, therefore, alters only one variable at a time and includes a control, which shows that it is this condition and nothing else that gave the result.

## Anaerobic respiration

**Key definition**

**Anaerobic respiration** is the term for the chemical reactions in cells that break down nutrient molecules to release energy without using oxygen.

The word **anaerobic** means 'in the absence of oxygen'. In this process, energy is still released from food by breaking it down chemically but the reactions do not use oxygen though they do often produce carbon dioxide. A common example is the action of yeast on sugar solution to produce alcohol. The sugar is not completely oxidised to carbon dioxide and water but converted to carbon dioxide and alcohol. This process is called **fermentation** and is shown by the following equation:

$$\text{glucose} \xrightarrow{\text{enzymes}} \text{alcohol} + \text{carbon dioxide} + \underset{\text{energy}}{118\,\text{kJ}}$$

The processes of brewing and bread-making rely on anaerobic respiration by yeast. As with aerobic respiration, the reaction takes place in small steps and needs several different enzymes. The yeast uses the energy for its growth and living activities, but you can see from the equation that less energy is produced by anaerobic respiration than in aerobic respiration. This is because the alcohol still contains a great deal of energy that the yeast is unable to use.

Anaerobic respiration also occurs in muscles during vigorous exercise, because oxygen cannot be delivered fast enough to satisfy the needs of the respiring muscle cells. The products are different to those produced by anaerobic respiration in yeast. The process is shown by the following equation:

$$\text{glucose} \longrightarrow \text{lactic acid}$$

The lactic acid builds up in the muscles and causes muscle fatigue (cramp).

Anaerobic respiration is much less efficient than aerobic respiration because it releases much less energy per glucose molecule broken down (respired).

## Practical work

### More experiments on respiration and energy

#### 4 Releasing energy in respiration

- Fill a small vacuum flask with wheat grains or pea seeds that have been soaked for 24 hours and rinsed in 1% formaldehyde (or domestic bleach diluted 1:4) for 5 minutes. These solutions will kill any bacteria or fungi on the surface of the seeds.
- Kill an equal quantity of soaked seeds by boiling them for 5 minutes.
- Cool the boiled seeds in cold tap water, rinse them in bleach or formaldehyde for 5 minutes as before and then put them in a vacuum flask of the same size as the first one. This flask is the control.
- Place a thermometer in each flask so that its bulb is in the middle of the seeds (Figure 12.5).
- Plug the mouth of each flask with cotton wool and leave both flasks for 2 days, noting the thermometer readings whenever possible.

**Result**

The temperature in the flask with the living seeds will be 5–10 °C higher than that of the dead seeds.

**Interpretation**

Provided there are no signs of the living seeds going mouldy, the heat produced must have come from living processes in the seeds, because the dead seeds in the control did not give out any heat. There is no evidence that this process is respiration rather than any other chemical change but the result is what you would expect if respiration does produce energy.

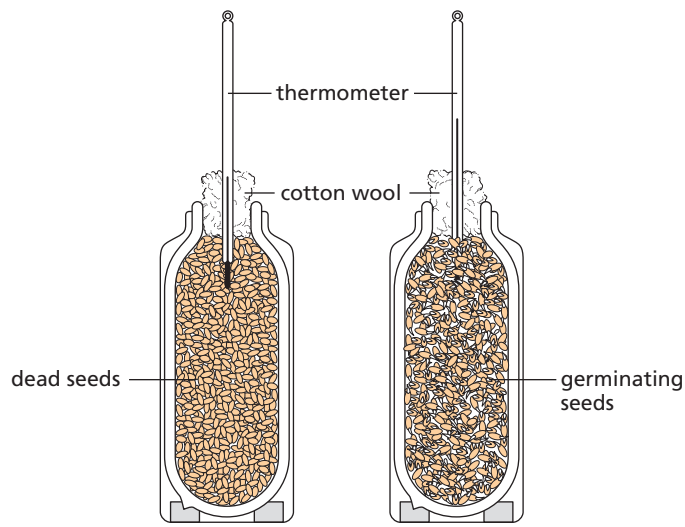



**Figure 12.5** Experiment to show energy release in germinating seeds

## 5 Anaerobic respiration in yeast

- Boil some water to expel all the dissolved oxygen.
- When cool, use the boiled water to make up a 5% solution of glucose and a 10% suspension of dried yeast.
- Place 5 cm³ of the glucose solution and 1 cm³ of the yeast suspension in a test-tube and cover the mixture with a thin layer of liquid paraffin to exclude atmospheric oxygen.
- Fit a delivery tube as shown in Figure 12.6 and allow it to dip into clear limewater.

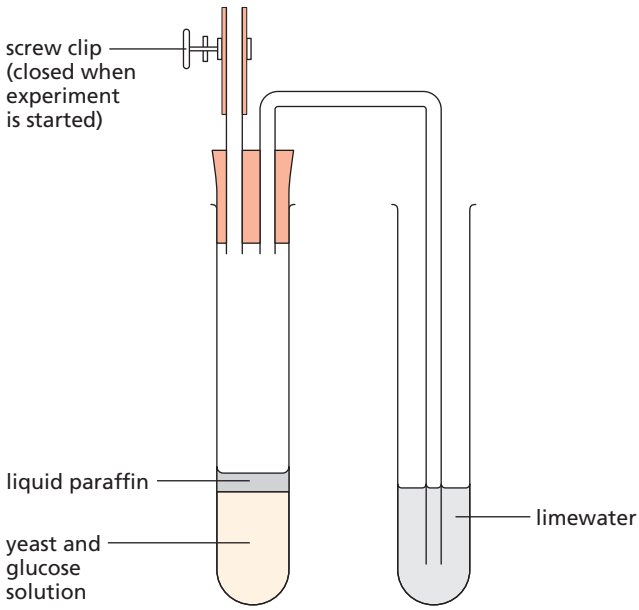



**Figure 12.6** Experiment to show anaerobic respiration in yeast

**Result**
After 10–15 minutes, with gentle warming if necessary, there should be signs of fermentation in the yeast–glucose mixture and the bubbles of gas escaping through the limewater should turn it milky.

**Interpretation**
The fact that the limewater goes milky shows that the yeast–glucose mixture is producing carbon dioxide. If we assume that the production of carbon dioxide is evidence of respiration, then it looks as if the yeast is respiring. In setting up the experiment, you took care to see that oxygen was removed from the glucose solution and the yeast suspension, and the liquid paraffin excluded air (including oxygen) from the mixture. Any respiration taking place must, therefore, be anaerobic (i.e. without oxygen).

**Control**
It might be suggested that the carbon dioxide came from a chemical reaction between yeast and glucose (as between chalk and acid), which had nothing to do with respiration or any other living process. A control should, therefore, be set up using the same procedure as before but with yeast that has been killed by boiling. The failure, in this case, to produce carbon dioxide supports the claim that it was a living process in the yeast in the first experiment that produced the carbon dioxide.

The balanced chemical equation for anaerobic respiration in organisms such as yeast is shown below:

$$C_6H_{12}O_6 \xrightarrow{\text{enzymes}} 2C_2H_5OH + 2CO_2 + 118\,kJ$$

glucose — alcohol — carbon dioxide — energy

This amount of energy released per mole of glucose respired is much less than that released in aerobic respiration (2830 kJ per mole).

During vigorous exercise, **lactic acid** may build up in a muscle. In this case it is removed in the bloodstream. The blood needs to move more quickly during and after exercise to maintain this lactic acid removal process, so the heart rate is rapid. On reaching the liver, some of the lactic acid is oxidised to carbon dioxide and water, using up oxygen in the process. After exercise has stopped, a high level of oxygen consumption may persist until the excess of lactic acid has been oxidised. This is characterised by deeper breathing (an athlete pants for breath). The build-up of lactic acid that is oxidised later is said to create an **oxygen debt**.

Accumulation of lactic acid in the muscles results in muscular fatigue, leading to cramp.

Athletes and climbers who are used to working at low altitude (normal air pressure) have problems if they then perform at high altitude (low air pressure). High-altitude air has a lower percentage of oxygen, so an oxygen debt can be experienced much more easily than at low altitude. The problem can be resolved if the person spends time at high altitude before performing to allow the body to acclimatise (making more red blood cells and increasing blood volume).

# Extension work

## Metabolism

All the chemical changes taking place inside a cell or a living organism are called its **metabolism**. The minimum turnover of energy needed simply to keep an organism alive, without movement or growth, is called the **basal metabolism**. Our basal metabolism maintains vital processes such as breathing, heartbeat, digestion and excretion.

The processes that break substances down are sometimes called **catabolism**. Respiration is an example of catabolism in which carbohydrates

are broken down to carbon dioxide and water. Chemical reactions that build up substances are called **anabolism**. Building up a protein from amino acids is an example of anabolism. The energy released by the **catabolic** process of respiration is used to drive the **anabolic** reactions that build up proteins.

You may have heard of anabolic steroids in connection with drug taking by athletes. These chemicals reduce the rate of protein breakdown and may enhance the build-up of certain proteins. However, their effects are complicated and not fully understood, they have undesirable side-effects and their use contravenes athletics codes (see 'Misused drugs' in Chapter 15).

## Practical work

### More experiments on respiration and energy

#### 6 The effect of temperature on yeast respiration

- Make some bread dough using flour, water and activated yeast (yeast in a warm sugar solution).
- Rub the inside of a boiling tube with oil (this makes it easier to remove the dough after the experiment).
- Use a glass rod or the end of an old pencil to push a piece of dough into the bottom of the boiling tube, so that the tube is about a quarter full of dough.
- Mark the height of the top of the dough on the boiling tube, using a chinagraph pencil or permanent marker pen.
- Place the boiling tube into a beaker of water set to a preselected temperature, e.g. 20 °C.
- Leave the dough for 20 minutes, checking to make sure the temperature of the water bath remains constant (adding warm or cold water to maintain this).
- Record the new height of the dough.
- Repeat the procedure at different temperatures and compare the rate of rising of the bread dough.

**Results**

The dough rises faster as the temperature is increased to 35 or 40 °C. Higher temperatures slow down the rate. Low temperatures may result in no change in height of the dough.

**Explanation**

Yeast respires anaerobically, producing carbon dioxide. This causes the dough to rise. The process is controlled by enzymes, which work faster as the temperature is increased to the optimum (around 35–40 °C). Higher temperatures cause the enzymes to denature (Chapter 5).

## Extension work

### Hypothesis testing

You will have noticed that none of the experiments described above claim to have *proved* that respiration is taking place. The most we can claim is that they have not disproved the proposal that energy is produced from respiration. There are many reactions taking place in living organisms and, for all we know at this stage, some of them may be using oxygen or giving out carbon dioxide without releasing energy, i.e. they would not fit our definition of respiration.

This inability to 'prove' that a particular proposal is 'true' is not restricted to experiments on respiration. It is a feature of many scientific experiments. One way in which science makes progress is by putting forward a **hypothesis**, making predictions from the hypothesis, and then testing these predictions by experiments.

A hypothesis is an attempt to explain some event or observation using the information currently available. If an experiment's results do not confirm the predictions, the hypothesis must be abandoned or altered.

For example, biologists observing that living organisms take up oxygen might put forward the hypothesis that 'oxygen is used to convert food to carbon dioxide, so producing energy for movement, growth, reproduction, etc.' This hypothesis can be tested by predicting that, '*if* the oxygen is used to oxidise food *then* an organism that takes up oxygen will also produce carbon dioxide'. Experiment 1 on page 166 tests this and fulfils this prediction and, therefore, supports the hypothesis. Looking at the equation for respiration, we might also predict that an organism that is respiring will produce carbon dioxide and take up oxygen. Experiment 5 with yeast, however, does not fulfil this prediction and so does not support the hypothesis as it stands, because here is an organism producing carbon dioxide without taking up oxygen. The hypothesis will have to be modified, e.g. 'energy is released from food by breaking it down to carbon dioxide; some organisms use oxygen for this process, others do not'.

There are still plenty of tests that we have not done. For example, we have not attempted to see whether it is food that is the source of energy and carbon dioxide. One way of doing this is to provide the organism with food, e.g. glucose, in which the

carbon atoms are radioactive. Carbon-14 ($^{14}C$) is a radioactive form of carbon and can be detected by using a Geiger counter. If the organism produces radioactive carbon dioxide, it is reasonable to suppose that the carbon dioxide comes from the glucose.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

This is **direct evidence** in support of the hypothesis. All the previous experiments have provided only **indirect evidence**.

### Criteria for a good hypothesis

A good hypothesis must:

- explain *all* aspects of the observation
- be the simplest possible explanation
- be expressed in such a way that predictions can be made from it
- be testable by experiment.

## Questions

Core

1 a If, in one word, you had to say what respiration was about, which word would you choose from this list: breathing, energy, oxygen, cells, food?
  b In which parts of a living organism does respiration take place?
2 What are the main differences between aerobic and anaerobic respiration?
3 What chemical substances must be provided for aerobic respiration to take place:
  a from outside the cell
  b from inside the cell?
  c What are the products of aerobic respiration?
4 Which of the following statements are true? If an organism is respiring you would expect it to be:
  a giving out carbon dioxide
  b losing heat
  c breaking down food
  d using up oxygen
  e gaining weight
  f moving about.
5 What was the purpose of:
  a the soda-lime in the respirometer in Figure 12.2
  b the limewater in Figure 12.6?

Extended

6 What is the difference between aerobic and anaerobic respiration in the amount of energy released from one molecule of glucose?
7 Victims of drowning who have stopped breathing are sometimes revived by a process called 'artificial respiration'. Why would a biologist object to the use of this expression? ('Resuscitation' is a better word to use.)
8 Why do you think your breathing rate and heart rate stay high for some time after completing a spell of vigorous exercise?
9 In an experiment like the one shown in Figure 12.2, the growing seeds took in 5 $cm^3$ oxygen and gave out 7 $cm^3$ carbon dioxide. How does the volume change:
  a if no soda-lime is present
  b if soda-lime is present?
10 The germinating seeds in Figure 12.5 will release the same amount of heat whether they are in a beaker or a vacuum flask. Why then is it necessary to use a vacuum flask for this experiment?
11 Experiment 5 with yeast supported the claim that anaerobic respiration was taking place. The experiment was repeated using unboiled water and without the liquid paraffin. Fermentation still took place and carbon dioxide was produced. Does this mean that the design or the interpretation of the first experiment was wrong? Explain your answer.
12 Twenty seeds are placed on soaked cotton wool in a closed glass dish. After 5 days in the light 15 of the seeds had germinated. If the experiment is intended to see if light is needed for germination, which of the following would be a suitable control:
  a exactly the same set-up but with dead seeds
  b the same set-up but with 50 seeds
  c an identical experiment but with 20 seeds of a different species
  d an identical experiment but left in darkness for 5 days?
13 Certain bacteria that live in sulfurous springs in areas of volcanic activity take up hydrogen sulfide ($H_2S$) and produce sulfates ($-SO_4$). Put forward a hypothesis to account for this chemical activity. Suggest one way of testing your hypothesis.

14 The table below shows the energy used up each day either as kilojoules per kilogram of body mass or as kilojoules per square metre of body surface.

| Animal | Mass/kg | kJ per day | |
|---|---|---|---|
| | | per kg body mass | per $m^2$ body surface |
| man | 64.3 | 134 | 4360 |
| mouse | 0.018 | 2736 | 4971 |

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a According to the table, what is the total amount of energy used each day by
   i a man
   ii a mouse?
b Which of these two shows a greater rate of respiration in its body cells?
c Why, do you think, is there so little difference in the energy expenditure per square metre of body surface?

## Checklist

After studying Chapter 12 you should know and understand the following:

- The word equation for aerobic respiration is

  glucose + oxygen $\xrightarrow{\text{enzymes}}$ carbon dioxide + water + energy

- Aerobic respiration is the term for the chemical reactions in cells that convert energy in nutrient molecules using oxygen so that cells can use this energy.
- The word equation for anaerobic respiration in muscles is

  glucose $\xrightarrow{\text{enzymes}}$ lactic acid + energy

- The word equation for anaerobic respiration in yeast is

  glucose $\xrightarrow{\text{enzymes}}$ alcohol + carbon dioxide + energy

- Anaerobic respiration is the term for the chemical reactions in cells that convert energy in nutrient molecules without the use of oxygen so that cells can use this energy.
- Respiration is the process in cells that releases energy from food.
- Aerobic respiration needs oxygen; anaerobic respiration does not.
- Aerobic respiration releases much more energy per glucose molecule than anaerobic respiration.
- The oxidation of food produces carbon dioxide as well as releasing energy.
- Experiments to investigate respiration try to detect uptake of oxygen, production of carbon dioxide, release of energy as heat or a reduction in dry weight.
- The balanced chemical equation for aerobic respiration is

  $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2830\,kJ$

- Experiments to investigate the effect of temperature on the rate of respiration of germinating seeds.
- The balanced chemical equation for anaerobic respiration in yeast is

  $C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 + 118\,kJ$

- Lactic acid builds up in muscles due to anaerobic respiration, causing an oxygen debt.
- An outline of how oxygen is removed during recovery.
- In a controlled experiment, the scientist tries to alter only one condition at a time, and sets up a control to check this.
- A control is a second experiment, identical to the first experiment except for the one condition being investigated.
- The control is designed to show that only the condition under investigation is responsible for the results.
- Experiments are designed to test predictions made from hypotheses; they cannot 'prove' a hypothesis.

# 13 Excretion in humans

**Excretion**
Excretory products: urea, carbon dioxide
Contents of urine
Urine output
Parts of urinary system

Role of liver in conversion of amino acids to proteins
Define deamination
Explain the need for excretion
Structure and function of kidney tubule
Dialysis
Compare dialysis with kidney transplant

## Excretion

**Excretion** is the removal from organisms of toxic materials and substances in excess of requirements. These include:

- the waste products of its chemical reactions
- the excess water and salts taken in with the diet
- spent hormones.

Excretion also includes the removal of drugs or other foreign substances taken into the alimentary canal and absorbed by the blood.

Many chemical reactions take place inside the cells of an organism in order to keep it alive. Some products of these reactions are poisonous and must be removed from the body. For example, the breakdown of glucose during respiration (see 'Aerobic respiration' in Chapter 12) produces carbon dioxide. This is carried away by the blood and removed in the lungs. Excess amino acids are deaminated in the liver to form glycogen and **urea**. The urea is removed from the tissues by the blood and expelled by the kidneys.

Urea and similar waste products, like **uric acid**, from the breakdown of proteins, contain the element nitrogen. For this reason they are often called **nitrogenous waste products**.

During feeding, more water and salts are taken in with the food than are needed by the body. So these excess substances need to be removed as fast as they build up.

The hormones produced by the endocrine glands (Chapter 14) affect the rate at which various body systems work. Adrenaline, for example, speeds up the heartbeat. When hormones have done their job, they are modified in the liver and excreted by the kidneys.

The nitrogenous waste products, excess salts and spent hormones are excreted by the kidneys as a watery solution called **urine**.

### Excretory organs

#### Liver

The liver breaks down excess amino acids and produces urea. The yellow/green bile pigment, **bilirubin**, is a breakdown product of haemoglobin (Chapter 9). Bilirubin is excreted with the bile into the small intestine and expelled with the faeces. The pigment undergoes changes in the intestine and is largely responsible for the brown colour of the faeces.

#### Lungs

The lungs supply the body with oxygen, but they are also excretory organs because they get rid of carbon dioxide. They also lose a great deal of water vapour but this loss is unavoidable and is not a method of controlling the water content of the body (Table 13.1).

#### Kidneys

The kidneys remove urea and other nitrogenous waste from the blood. They also expel excess water, salts, hormones (Chapter 14) and drugs (Chapter 15).

#### Skin

Sweat consists of water, with sodium chloride and traces of urea dissolved in it. When you sweat, you will expel these substances from your body so, in one sense, they are being excreted. However, sweating is a response to a rise in temperature and not to a change in the blood composition. In this sense, therefore, skin is not an excretory organ like the lungs and kidneys. See 'Homeostasis' in Chapter 14 for more details of skin structure and its functions.

**Table 13.1** Excretory products and incidental losses

| Excretory organ | Excretory products | Incidental losses |
|---|---|---|
| lungs | carbon dioxide | water |
| kidneys | nitrogenous waste, water, salts, toxins, hormones, drugs | |
| liver | bile pigments | |
| skin | | water, salt, urea |

## The kidneys

The two kidneys are fairly solid, oval structures. They are red-brown, enclosed in a transparent membrane and attached to the back of the abdominal cavity (Figure 13.1). The **renal artery** branches off from the aorta and brings oxygenated blood to them. The **renal vein** takes deoxygenated blood away from the kidneys to the vena cava (see Figure 9.20). A tube, called the **ureter**, runs from each kidney to the bladder in the lower part of the abdomen.

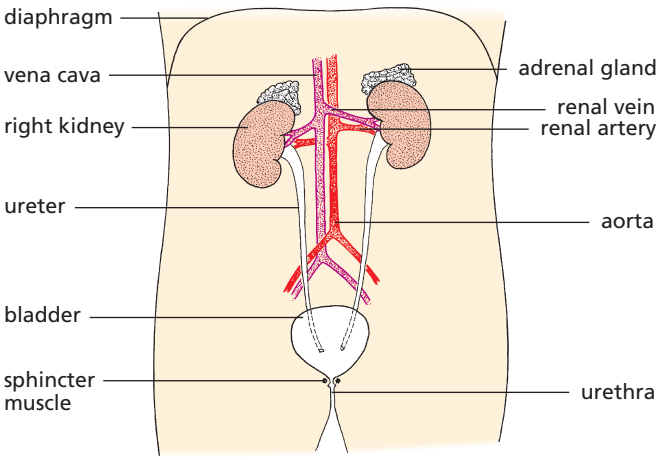



**Figure 13.1** Position of the kidneys in the body

## Water balance and osmoregulation

Your body gains water from food and drink. It loses water by evaporation, urination and defecation (Chapter 7). Evaporation from the skin takes place all the time but is particularly rapid when we sweat. Air from the lungs is saturated with water vapour, which is lost to the atmosphere every time we exhale. Despite these gains and losses of water, the concentration of body fluids is kept within very narrow limits by the kidneys, which adjust the concentration of the blood flowing through them. If it is too dilute (i.e. has too much water), less water is reabsorbed, leaving more to enter the bladder. After drinking a lot of fluid, a large volume of dilute urine is produced. On a cold day, sweating decreases so more water is removed from the blood by the kidneys, again increasing the volume of dilute urine.

If the blood is too concentrated, more water is absorbed back into the blood from the kidney tubules. So, if the body is short of water, e.g. after sweating profusely on a hot day, or through doing a lot of physical activity, or not having enough to drink, only a small quantity of concentrated urine is produced.

**Key definition**
**Deamination** is the removal of the nitrogen-containing part of amino acids to form urea.

## The liver and its role in producing proteins

As well as being an excretory organ, the liver plays a very important role in **assimilating** amino acids. Assimilation means the absorption of substances, which are then built into other compounds in the organism. The liver removes amino acids from the plasma of the bloodstream and builds them up into proteins. Proteins are long chains of amino acids, joined together by peptide bonds (see Chapter 4 for details of protein structure). These include plasma proteins such as fibrinogen (Chapter 9), which have a role in blood clotting.

## The need for excretion

Some of the compounds made in reactions in the body are potentially toxic (poisonous) if their concentrations build up. Carbon dioxide dissolves in fluids such as tissue fluid and blood plasma to form carbonic acid. This increase in acidity can affect the actions of enzymes and can be fatal. Ammonia is made in the liver when excess amino acids are broken down. However, ammonia is very alkaline and toxic. It is converted to urea which is much less poisonous, making it a safe way of excreting excess nitrogen.

## Microscopic structure of the kidneys

The kidney tissue consists of many capillaries and tiny tubes, called **renal tubules**, held together with connective tissue. If the kidney is cut down its length (sectioned), it is seen to have a dark, outer region called the **cortex** and a lighter, inner zone, the **medulla**. Where the ureter joins the kidney there is a space called the **pelvis** (Figure 13.2).

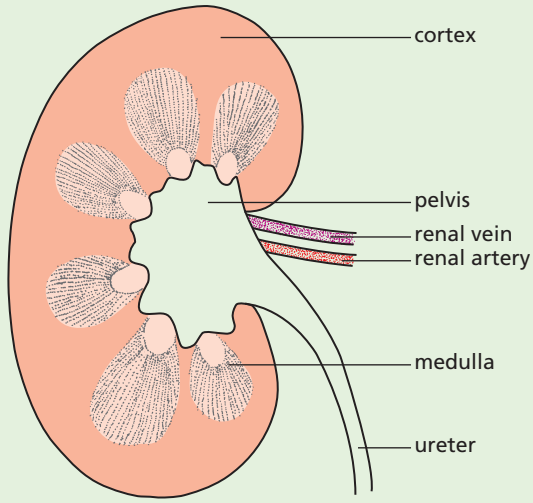



**Figure 13.2** Section through the kidney to show regions

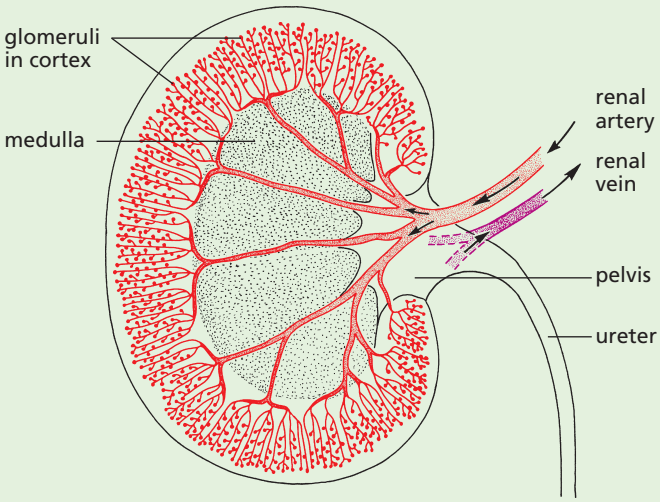



**Figure 13.3** Section through kidney to show distribution of glomeruli

The renal artery divides up into a great many arterioles and capillaries, mostly in the cortex (Figure 13.3). Each arteriole leads to a **glomerulus**. This is a capillary repeatedly divided and coiled, making a knot of vessels (Figure 13.4). Each glomerulus is almost entirely surrounded by a cup-shaped organ called a **renal capsule**, which leads to a coiled **renal tubule**. This tubule, after a series of coils and loops, joins a **collecting duct**, which passes through the medulla to open into the pelvis (Figure 13.5). There are thousands of glomeruli in the kidney cortex and the total surface area of their capillaries is very great.

A **nephron** is a single glomerulus with its renal capsule, renal tubule and blood capillaries (see Figure 13.6).

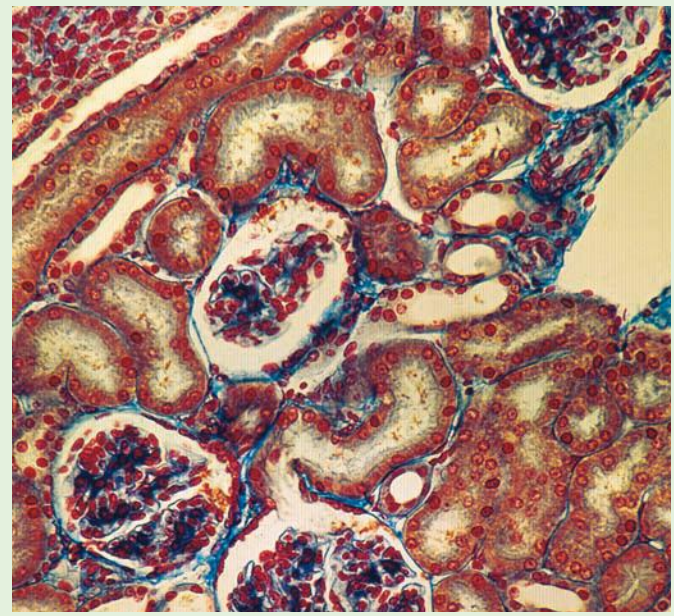


**Figure 13.4** Glomeruli in the kidney cortex (×300). The three glomeruli are surrounded by kidney tubules sectioned at different angles. The light space around each glomerulus represents the renal capsule.

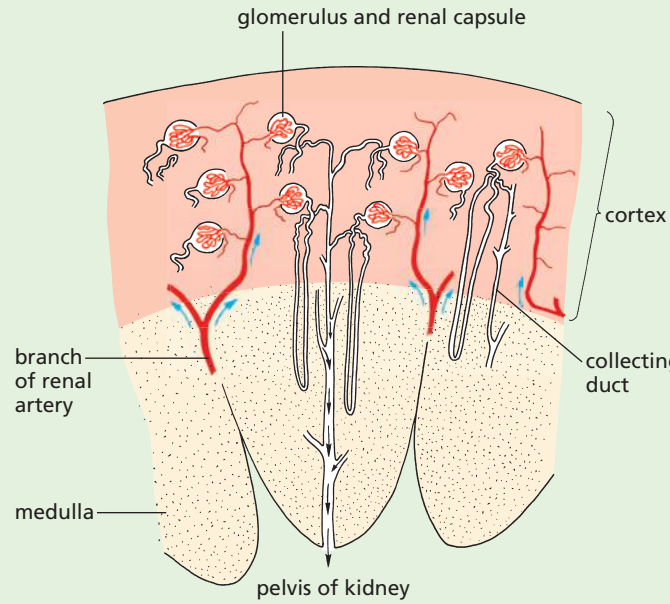



**Figure 13.5** There are up to 4 million nephrons in a kidney. Only a few can be represented here, and not to scale.

## Function of the kidneys

The blood pressure in a glomerulus causes part of the blood plasma to leak through the capillary walls.

The red blood cells and the plasma proteins are too big to pass out of the capillary, so the fluid that does filter through is plasma without the protein, i.e. similar to tissue fluid (Chapter 9). The fluid thus consists mainly of water with dissolved salts, glucose, urea and uric acid. The process by which the fluid is filtered out of the blood by the glomerulus is called **ultrafiltration**.

The filtrate from the glomerulus collects in the renal capsule and trickles down the renal tubule (Figure 13.6). As it does so, the capillaries that surround the tubule absorb back into the blood those substances which the body needs. First, all the glucose is reabsorbed, with much of the water. Then some of the salts are taken back to keep the correct concentration in the blood. The process of absorbing back the substances needed by the body is called **selective reabsorption**.

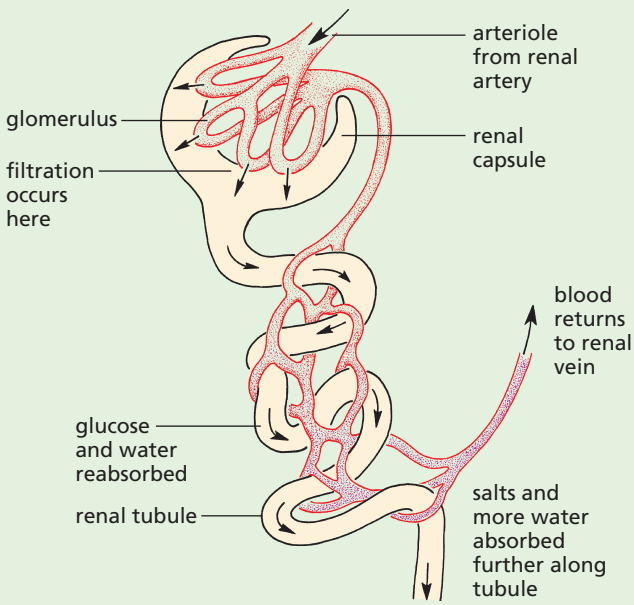



**Figure 13.6** Part of a nephron (glomerulus, renal capsule and renal tubule)

Salts not needed by the body are left to pass on down the kidney tubule together with the urea and uric acid. So, these nitrogenous waste products, excess salts and water continue down the renal tube into the pelvis of the kidney. From here the fluid, now called **urine**, passes down the ureter to the bladder.

Table 13.2 shows some of the differences in composition between the blood plasma and the urine. The figures represent average values because the composition of the urine varies a great deal according to the diet, activity, temperature and intake of liquid.

**Table 13.2** Composition of blood plasma and urine

| | Plasma/% | Urine/% |
|---|---|---|
| water | 90–93 | 95.0 |
| urea | 0.03 | 2.0 |
| uric acid | 0.003 | 0.05 |
| ammonia | 0.0001 | 0.05 |
| sodium | 0.3 | 0.6 |
| potassium | 0.02 | 0.15 |
| chloride | 0.37 | 0.6 |
| phosphate | 0.003 | 0.12 |

The **bladder** can expand to hold about 400 $cm^3$ of urine. The urine cannot escape from the bladder because a band of circular muscle, called a **sphincter**, is contracted, so shutting off the exit. When this sphincter muscle relaxes, the muscular walls of the bladder expel the urine through the **urethra**. Adults can control this sphincter muscle and relax it only when they want to urinate. In babies, the sphincter relaxes by a reflex action (Chapter 14), set off by pressure in the bladder. By 3 years old, most children can control the sphincter voluntarily.

## The dialysis machine ('artificial kidney')

Kidney failure may result from an accident involving a drop in blood pressure, or from a disease of the kidneys. In the former case, recovery is usually spontaneous, but if it takes longer than 2 weeks, the patient may die as a result of a potassium imbalance in the blood, which causes heart failure. In the case of kidney disease, the patient can survive with only one kidney, but if both fail, the patient's blood composition has to be regulated by a **dialysis** machine. Similarly, the accident victim can be kept alive on a dialysis machine until his or her blood pressure is restored.

In principle, a dialysis machine consists of a long cellulose tube coiled up in a water bath. The patient's blood is led from a vein in the arm and pumped through the cellulose (dialysis) tubing (Figures 13.7 and 13.8). The tiny pores in the dialysis tubing allow small molecules, such as those of salts, glucose and urea, to leak out into the water bath. Blood cells and protein molecules are too large to get through the pores (see Experiment 5, Chapter 4). This stage is similar to the filtration process in the glomerulus.

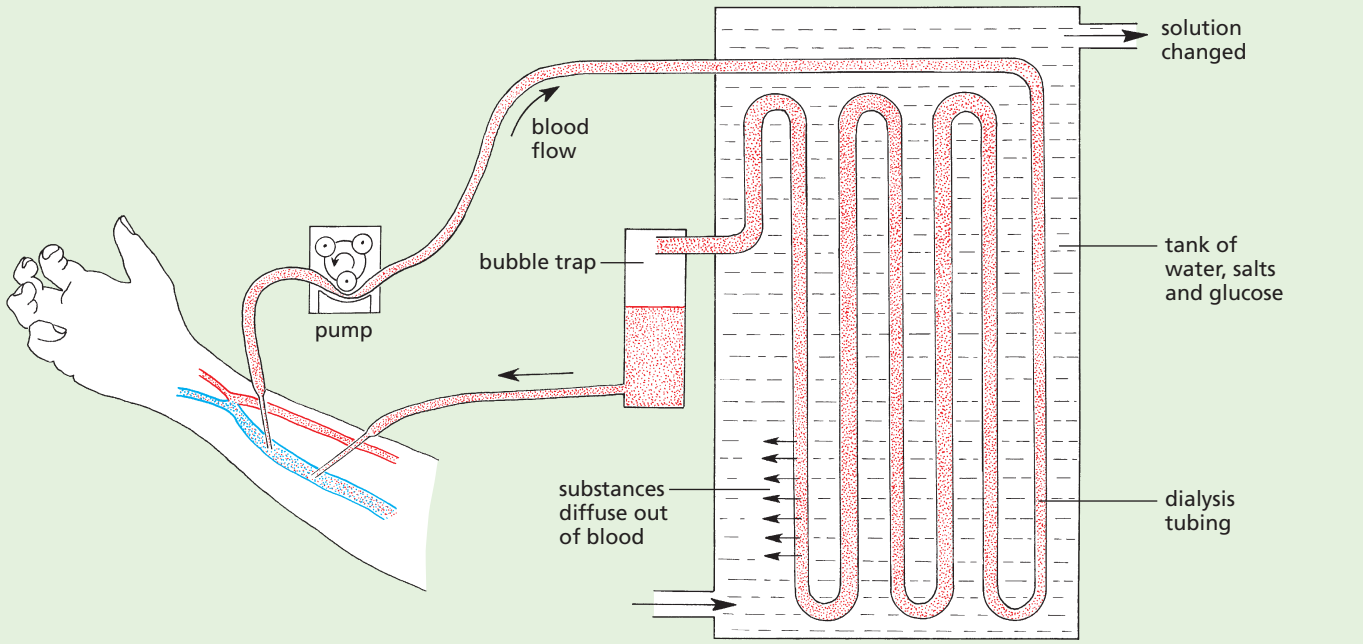



**Figure 13.7** The principle of the kidney dialysis machine

To prevent a loss of glucose and essential salts from the blood, the liquid in the water bath consists of a solution of salts and sugar of the correct composition, so that only the substances above this concentration can diffuse out of the blood into the bathing solution. Thus, urea, uric acid and excess salts are removed.

The bathing solution is also kept at body temperature and is constantly changed as the unwanted blood solutes accumulate in it. The blood is then returned to the patient's arm vein.

A patient with total kidney failure has to spend 2 or 3 nights each week connected to the machine (Figure 13.8). With this treatment and a carefully controlled diet, the patient can lead a fairly normal life. A kidney transplant, however, is a better solution because the patient is not obliged to return to the dialysis machine.

The problem with kidney transplants is to find enough suitable donors of healthy kidneys and to prevent the transplanted kidney from being rejected.

The donor may be a close relative who is prepared to donate one of his or her kidneys (you can survive adequately with one kidney). Alternatively, the donated kidney may be taken from a healthy person who dies, for example, as a result of a road accident. People willing for their kidneys to be used after their death can carry a kidney donor card but the relatives must give their permission for the kidneys to be used.

The problem with rejection is that the body reacts to any transplanted cells or tissues as it does to all foreign proteins and produces lymphocytes, which attack and destroy them. This rejection can be overcome by:

- choosing a donor whose tissues are as similar as possible to those of the patient, e.g. a close relative
- using immunosuppressive drugs, which suppress the production of lymphocytes and their antibodies against the transplanted organ.

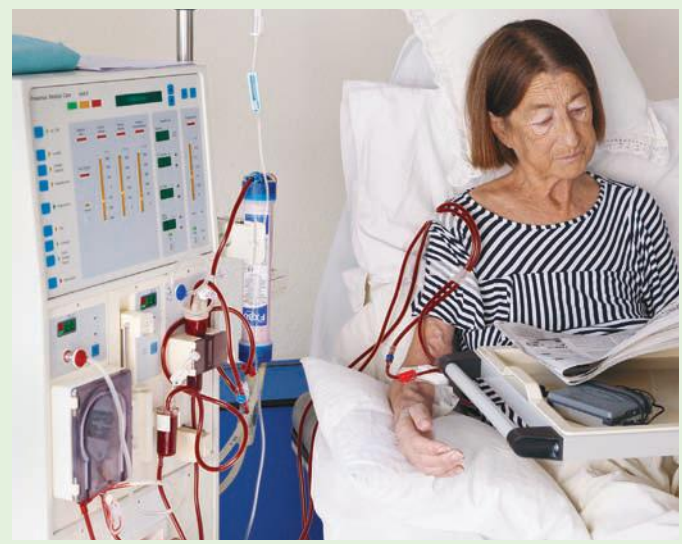


**Figure 13.8** Kidney dialysis machine. The patient's blood is pumped to the dialyser, which removes urea and excess salts.

The advantages and disadvantages of kidney transplants, compared with dialysis

**Advantages**

- The patient can return to a normal lifestyle – dialysis may require a lengthy session in hospital, three times a week, leaving the patient very tired after each session.
- The dialysis machine will be available for other patients to use.
- Dialysis machines are expensive to buy and maintain.

**Disadvantages**

- Transplants require a suitable donor – with a good tissue match. The donor may be from a dead person, or from a close living relative who is prepared to donate a healthy kidney (we can survive with one kidney).
- The operation is very expensive.
- There is a risk of rejection of the donated kidney – immunosuppressive drugs have to be used.
- Transplants are not accepted by some religions.

## Questions

Core

1 Write a list of the substances that are likely to be excreted from the body during the day.
2 Why do you think that urine analysis is an important part of medical diagnosis?

Extended

3 How does the dialysis machine:
   a resemble and
   b differ from
   the nephron of a kidney in the way it functions?

## Checklist

After studying Chapter 13 you should know and understand the following:

- Excretion is getting rid of toxic, surplus or unwanted substances produced by chemical reactions in the body or taken in with the diet.
- The lungs excrete carbon dioxide.
- The kidneys excrete urea, unwanted salts and excess water.
- Part of the blood plasma entering the kidneys is filtered out by the capillaries. Substances which the body needs, like glucose, are absorbed back into the blood. The unwanted substances are left to pass down the ureters into the bladder.
- The bladder stores urine, which is discharged at intervals.
- The kidneys help to keep the blood at a steady concentration by excreting excess salts and by adjusting the amounts of water (osmoregulation).
- The volume and concentration of urine produced is affected by water intake, temperature and exercise.
- The ureters, bladder and urethra on diagrams.
- The liver produces urea, formed from excess amino acids.
- Deamination is the removal of the nitrogen-containing part of amino acids to form urea.
- The liver has a role in the assimilation of amino acids by converting them to proteins, including plasma proteins.
- Outline of the structure and function of a kidney tubule.
- Explain the process of dialysis.
- Treatment, in response to damage to kidneys, may involve dialysis or transplant.
- The advantages and disadvantages of kidney transplants and dialysis.

# 14 Co-ordination and response

**Nervous control in humans**
Human nervous system
Structure of neurones
Nerve impulse
Reflex arc, spinal cord and reflexes
Define synapse
Structure of synapse

Voluntary and involuntary actions
Transfer of impulse across synapse
Effects of drugs on synapses

**Sense organs**
Define sense organ
Structure of eye
Pupil reflex

Explanation of pupil reflex
Accommodation
Function of rods and cones

**Hormones in humans**
Define hormone
Endocrine glands
Adrenaline
Functions of hormones

Role of adrenaline
Compare nervous and hormonal control systems

**Homeostasis**
Define homeostasis
Skin structure
Control of body temperature
Homeostasis

Negative feedback
Regulation of blood sugar
Type 1 diabetes
Vasodilation and vasoconstriction

**Tropic responses**
Define phototropism and gravitropism
Investigate tropic responses

Role of auxins in tropisms
Use of plant hormones in weedkillers

**Co-ordination** is the way all the organs and systems of the body are made to work efficiently together (Figure 14.1). If, for example, the leg muscles are being used for running, they will need extra supplies of glucose and oxygen. To meet this demand, the lungs breathe faster and deeper to obtain the extra oxygen and the heart pumps more rapidly to get the oxygen and glucose to the muscles more quickly.

The brain detects changes in the oxygen and carbon dioxide content of the blood and sends nervous impulses to the diaphragm, intercostal muscles and heart. In this example, the co-ordination of the systems is brought about by the **nervous system**.

The extra supplies of glucose needed for running come from the liver. Glycogen in the liver is changed to glucose, which is released into the bloodstream (see 'Homeostasis' on page 192). The conversion of glycogen to glucose is stimulated by, among other things, a chemical called adrenaline (see 'Hormones in humans' on page 190). Co-ordination by chemicals is brought about by the **endocrine system**.

The nervous system works by sending electrical impulses along nerves. The endocrine system depends on the release of chemicals, called **hormones**, from **endocrine glands**. Hormones are carried by the bloodstream. For example, insulin is carried from the pancreas to the liver by the circulatory system.

**Figure 14.1** Co-ordination. The badminton player's brain is receiving sensory impulses from his eyes, ears (sound and balance) and muscle stretch receptors. Using this information, the brain co-ordinates the muscles of his limbs so that even while running or leaping he can control his stroke.

# Nervous control in humans

The human nervous system is shown in Figure 14.2. The brain and spinal cord together form the **central nervous system**. Nerves carry electrical impulses from the central nervous system to all parts of the body, making muscles contract or glands produce enzymes or hormones. Electrical impulses are electrical signals that pass along nerve cells (neurones).

Glands and muscles are called **effectors** because they go into action when they receive nerve impulses or hormones. The biceps muscle is an effector that flexes the arm; the salivary gland (see 'Alimentary canal' in Chapter 7) is an effector that produces saliva when it receives a nerve impulse from the brain.

The nerves also carry impulses back to the central nervous system from receptors in the sense organs of the body. These impulses from the eyes, ears, skin, etc. make us aware of changes in our surroundings or in ourselves. Nerve impulses from the sense organs to the central nervous system are called **sensory impulses**; those from the central nervous system to the effectors, resulting in action, are called **motor impulses**.

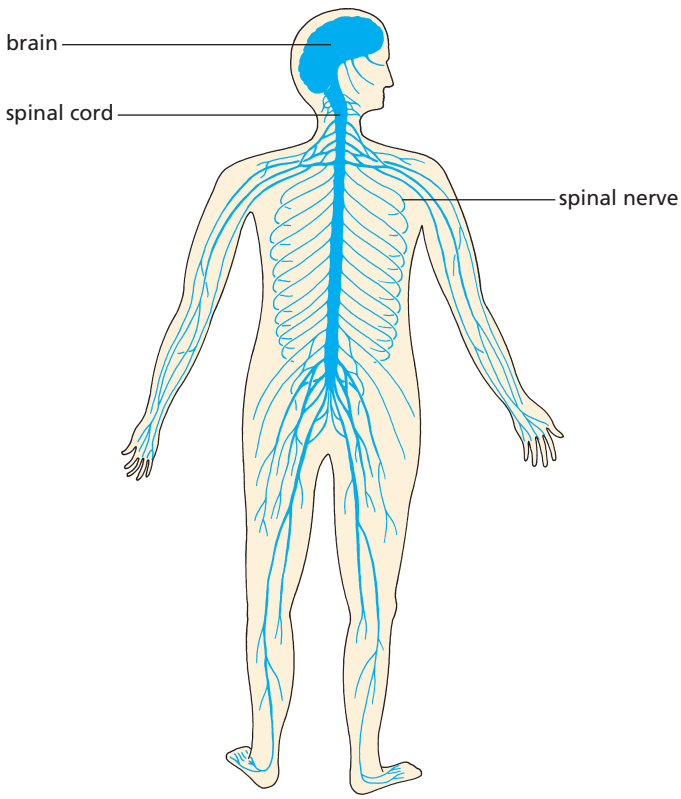



**Figure 14.2** The human nervous system

The nerves that connect the body to the central nervous system make up the **peripheral** nervous system.

## Nerve cells (neurones)

The central nervous system and the peripheral nerves are made up of nerve cells, called **neurones**. Three types of neurone are shown in Figure 14.3. **Motor neurones** carry impulses from the central nervous system to muscles and glands. **Sensory neurones** carry impulses from the sense organs to the central nervous system. **Relay neurones** (also called multi-polar or connector neurones) are neither sensory nor motor but make connections to other neurones inside the central nervous system.

Each neurone has a **cell body** consisting of a nucleus surrounded by a little cytoplasm. Branching fibres, called **dendrites**, from the cell body make contact with other neurones. A long filament of cytoplasm, surrounded by an insulating sheath, runs from the cell body of the neurone. This filament is called a **nerve fibre** (Figure 14.3(a) and (b)). The cell bodies of the neurones are mostly located in the brain or in the spinal cord and it is the nerve fibres that run in the nerves. A **nerve** is easily visible, white, tough and stringy and consists of hundreds of microscopic nerve fibres bundled together (Figure 14.4). Most nerves will contain a mixture of sensory and motor fibres. So a nerve can carry many different impulses. These impulses will travel in one direction in sensory fibres and in the opposite direction in motor fibres.

Some of the nerve fibres are very long. The nerve fibres to the foot have their cell bodies in the spinal cord and the fibres run inside the nerves, without a break, to the skin of the toes or the muscles of the foot. A single nerve cell may have a fibre 1 m long.

## The nerve impulse

The nerve fibres do not carry sensations like pain or cold. These sensations are felt only when a nerve impulse reaches the brain. The impulse itself is a series of electrical pulses that travel down the fibre. Each pulse lasts about 0.001 s and travels at speeds of up to 100 $m\,s^{-1}$. All nerve impulses are similar; there is no difference between nerve impulses from the eyes, ears or hands.

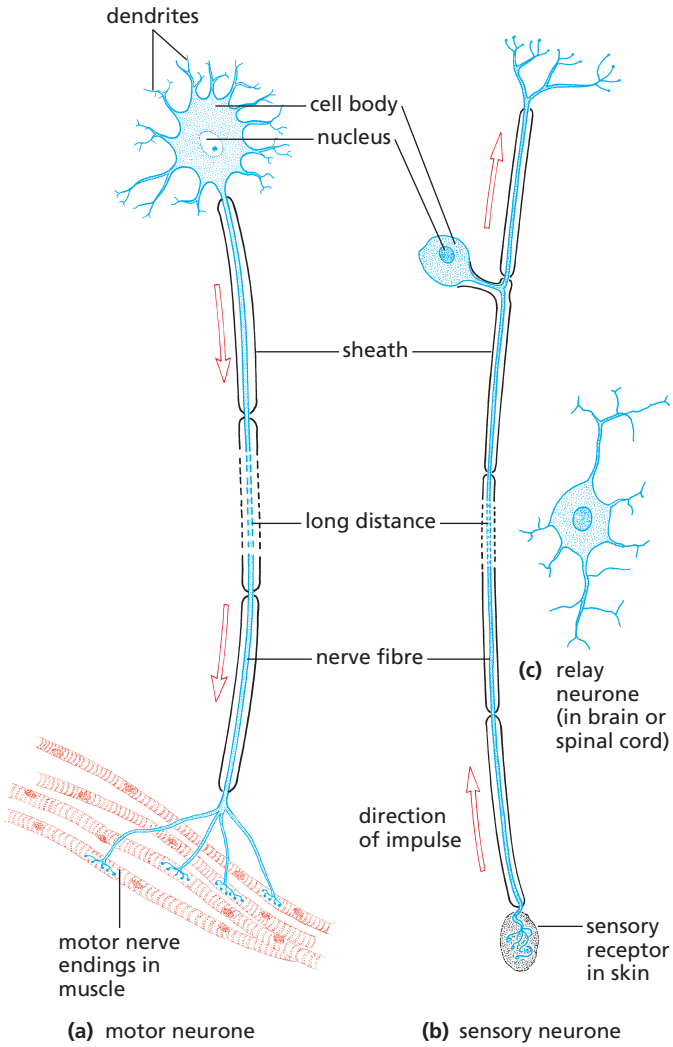



**Figure 14.3** Nerve cells (neurones)

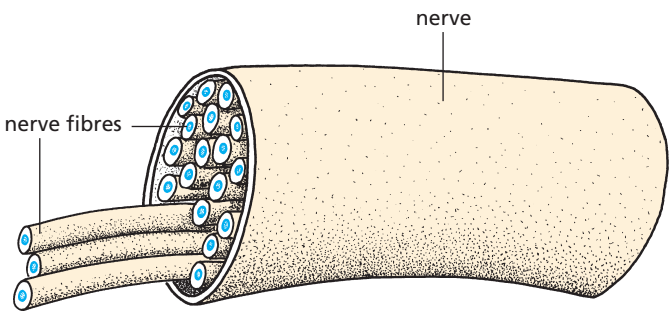



**Figure 14.4** Nerve fibres grouped into a nerve

We are able to tell where the sensory impulses have come from and what caused them only because the impulses are sent to different parts of the brain. The nerves from the eye go to the part of the brain concerned with sight. So when impulses are received in this area, the brain recognises that they have come from the eyes and we 'see' something.

## The reflex arc

One of the simplest situations where impulses cross synapses to produce action is in the reflex arc. A **reflex action** is an automatic response to a **stimulus**. (A stimulus is a change in the external or internal environment of an organism.) It provides a means of rapidly integrating and co-ordinating a stimulus with the response of an effector (a muscle or a gland) without the need for thought or a decision. When a particle of dust touches the cornea of the eye, you will blink; you cannot prevent yourself from blinking. A particle of food touching the lining of the windpipe will set off a coughing reflex that cannot be suppressed. When a bright light shines in the eye, the pupil contracts (see 'Sense organs' later in this chapter). You cannot stop this reflex and you are not even aware that it is happening.

The nervous pathway for such reflexes is called a **reflex arc**. In Figure 14.5 the nervous pathway for a well-known reflex called the 'knee-jerk' reflex is shown.

One leg is crossed over the other and the muscles are totally relaxed. If the tendon just below the kneecap of the upper leg is tapped sharply, a reflex arc makes the thigh muscle contract and the lower part of the leg swings forward.

The pathway of this reflex arc is traced in Figure 14.6. Hitting the tendon stretches the muscle and stimulates a stretch receptor. The receptor sends off impulses in a sensory fibre. These sensory impulses travel in the nerve to the spinal cord.

In the central region of the spinal cord, the sensory fibre passes the impulse across a synapse to a motor neurone, which conducts the impulse down the fibre, back to the thigh muscle (the effector). The arrival of the impulses at the muscle makes it contract and jerk the lower part of the limb forward. You are aware that this is happening (which means that sensory impulses must be reaching the brain), but there is nothing you can do to stop it.

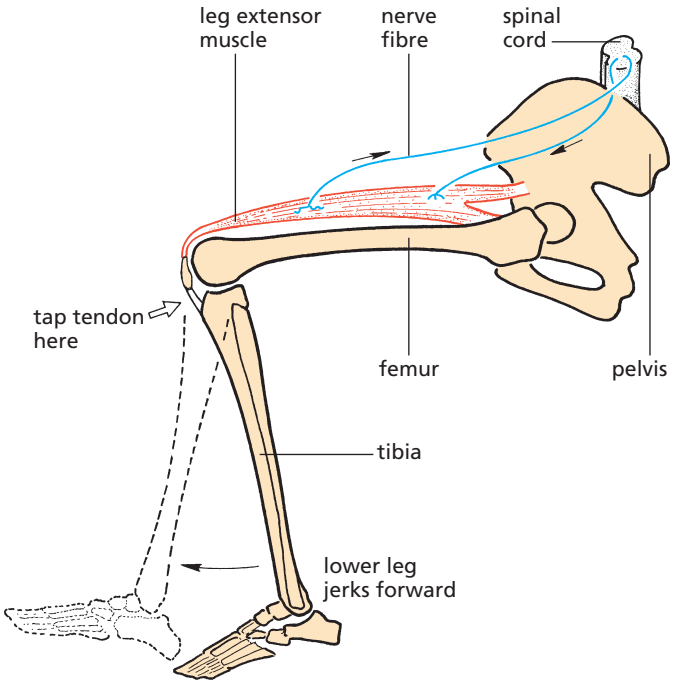



**Figure 14.5** The reflex knee jerk

The sequence of events in a simple reflex arc is shown below.

stimulus (tapping the tendon below the kneecap)
↓
receptor (stretch receptor)
↓
sensory neurone
↓
co-ordinator (spinal cord)
↓
motor neurone
↓
effector (leg extensor muscle)
↓
response (leg extensor muscle contracts, making the leg kick forwards)

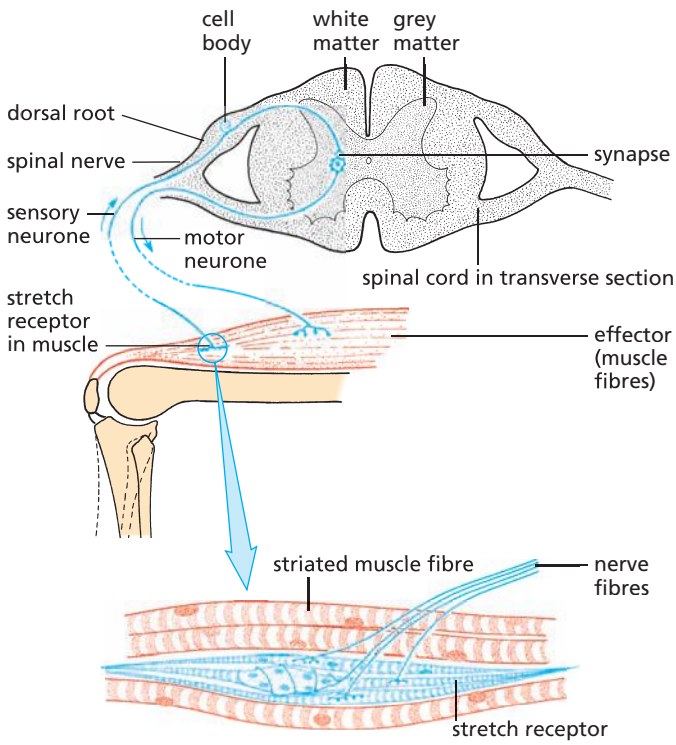



**Figure 14.6** The reflex arc. This reflex arc needs only one synapse for making the response. Most reflex actions need many more synapses (i) to adjust other muscles in the body and (ii) to send impulses to the brain.

## Extension work

### The spinal cord

Like all other parts of the nervous system, the spinal cord consists of thousands of nerve cells. The structure of the spinal cord is shown in Figures 14.6, 14.7 and 14.8.

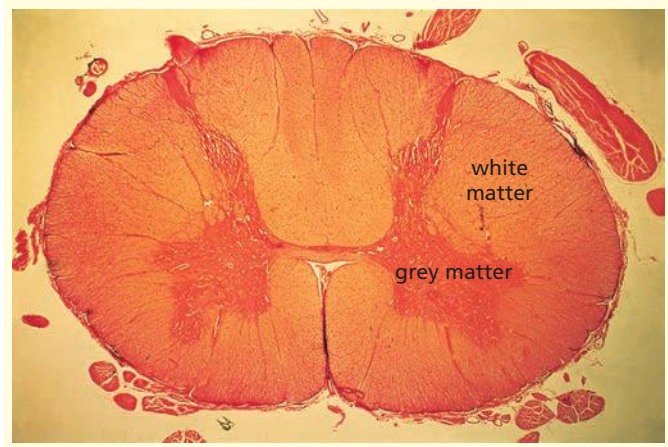



**Figure 14.7** Section through spinal cord (×7). The light area is the white matter, consisting largely of nerve fibres running to and from the brain. The darker central area is the grey matter, consisting largely of nerve cell bodies.

All the cell bodies, apart from those in the dorsal root ganglia, are concentrated in the central region called the **grey matter**. The **white matter** consists of nerve fibres. Some of these will be passing from the grey matter to the spinal nerves and others

will be running along the spinal cord connecting the spinal nerve fibres to the brain. The spinal cord is thus concerned with:

- reflex actions involving body structures below the neck
- conducting sensory impulses from the skin and muscles to the brain, and
- carrying motor impulses from the brain to the muscles of the trunk and limbs.

In Figure 14.6 the spinal cord is drawn in transverse section. The spinal nerve divides into two 'roots' at the point where it joins the spinal cord. All the sensory fibres enter through the **dorsal root** and the motor fibres all leave through the **ventral root**, but both kinds of fibre are contained in the same spinal nerve. This is like a group of insulated wires in the same electric cable. The cell bodies of all the sensory fibres are situated in the dorsal root and they make a bulge called a **ganglion** (Figure 14.9).

In even the simplest reflex action, many more nerve fibres, synapses and muscles are involved than are described here. Figure 14.8 illustrates the reflex arc that would result in the hand being removed from a painful stimulus. On the left side of the spinal cord, an incoming sensory fibre makes its first synapse with a relay neurone. This can pass the impulse on to many other motor neurones, although only one is shown in the diagram. On the right side of the spinal cord, some of the incoming sensory fibres are shown making synapses with neurones that send nerve fibres to the brain, thus keeping the brain informed about events in the body. Also, nerve fibres from the brain make synapses with motor neurones in the spinal cord so that 'commands' from the brain can be sent to muscles of the body.

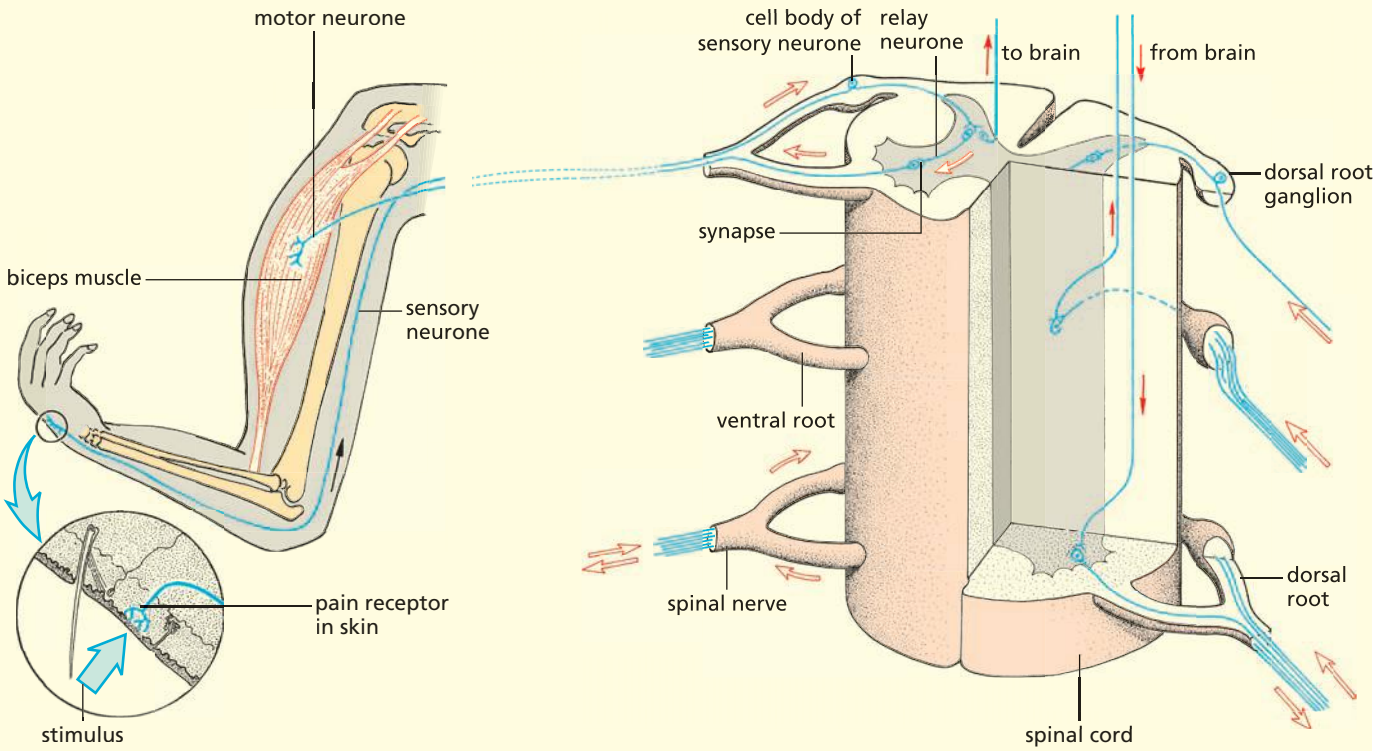



**Figure 14.8** Reflex arc (withdrawal reflex)

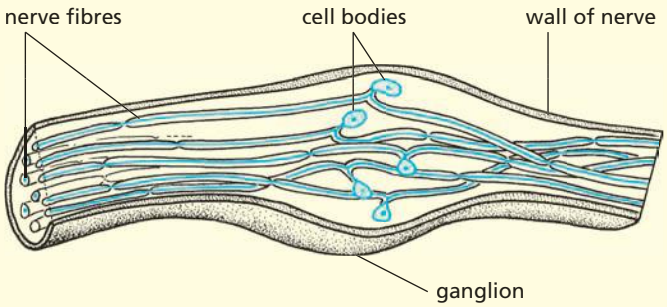



**Figure 14.9** Cell bodies forming a ganglion

## Reflexes

The reflex just described is a **spinal reflex**. The brain, theoretically, is not needed for it to happen. Responses that take place in the head, such as blinking, coughing and iris contraction, have their reflex arcs in the brain, but may still not be consciously controlled.

Bright light stimulates the light-sensitive cells of the retina. The nerve impulses in the sensory fibres from these receptors travel through the optic nerve

to the brain. In the mid-brain the fibres synapse with relay and motor fibres, which carry impulses back through the optic nerve to the circular muscle of the iris and stimulate it to contract.

## Synapses

**Key definition**
A **synapse** is a junction between two neurones.

Although nerve fibres are insulated, it is necessary for impulses to pass from one neurone to another. An impulse from the fingertips has to pass through at least three neurones before reaching the brain and so produce a conscious sensation. The regions where impulses are able to cross from one neurone to the next are called **synapses**.

# Voluntary and involuntary actions

### Voluntary actions

A **voluntary action** starts in the brain. It may be the result of external events, such as seeing a book on the floor, but any resulting action, such as picking up the book, is entirely voluntary. Unlike a reflex action it does not happen automatically; you can decide whether or not you carry out the action.

The brain sends motor impulses down the spinal cord in the nerve fibres. These make synapses with motor fibres, which enter spinal nerves and make connections to the sets of muscles needed to produce effective action. Many sets of muscles in the arms, legs and trunk would be brought into play in order to stoop and pick up the book, and impulses passing between the eyes, brain and arm would direct the hand to the right place and 'tell' the fingers when to close on the book.

One of the main functions of the brain is to co-ordinate these actions so that they happen in the right sequence and at the right time and place.

### Involuntary actions

The reflex closure of the iris (see 'Sense organs' later in this chapter) protects the retina from bright light; the withdrawal reflex removes the hand from a dangerously hot object; the coughing reflex dislodges a foreign particle from the windpipe. Thus, these reflexes have a protective function and all are **involuntary actions**.

There are many other reflexes going on inside our bodies. We are usually unaware of these, but they maintain our blood pressure, breathing rate, heartbeat, etc. and so maintain the body processes.

# How a synapse transmits an electrical impulse

At a synapse, a branch at the end of one fibre is in close contact with the cell body or dendrite of another neurone (Figure 14.10).

When an impulse arrives at the synapse, vesicles in the cytoplasm release a tiny amount of the neurotransmitter substance. It rapidly diffuses across the gap (also known as the **synaptic cleft**) and binds with neurotransmitter receptor molecules in the membrane of the neurone on the other side of the synapse. This then sets off an impulse in the neurone. Sometimes several impulses have to arrive at the synapse before enough transmitter substance is released to cause an impulse to be fired off in the next neurone.

Synapses control the direction of impulses because neurotransmitter substances are only synthesised on one side of the synapse, while receptor molecules are only present on the other side. They slow down the speed of nerve impulses slightly because of the time taken for the chemical to diffuse across the **synaptic gap**.

Many drugs produce their effects by interacting with receptor molecules at synapses. **Heroin**, for example, stimulates receptor molecules in synapses in the brain, triggering the release of dopamine (a neurotransmitter), which gives a short-lived 'high'.

Spider toxin, and also the toxin released by tetanus (an infection caused by *Clostridium* bacteria), breaks down vesicles, releasing massive amounts of transmitter substance and disrupting normal synaptic function. Symptoms caused by the tetanus toxin include muscle spasms, lock-jaw and heart failure.

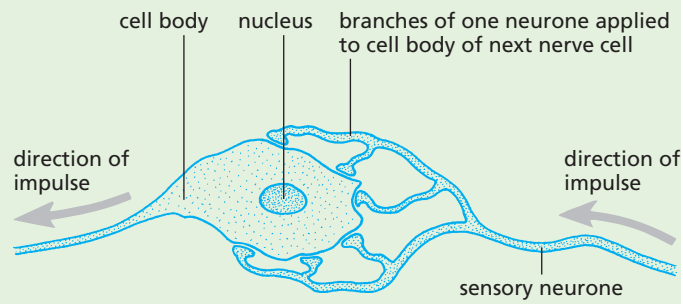



**Figure 14.10** Synapses between nerve neurones

# Sense organs

**Key definition**
**Sense organs** are groups of sensory cells responding to specific stimuli, such as light, sound, touch, temperature and chemicals.

Our senses make us aware of changes in our surroundings and in our own bodies. We have sense cells that respond to stimuli (singular = stimulus). A **stimulus** is a change in light, temperature, pressure, etc., which produces a reaction in a living organism. Structures that detect stimuli are called **receptors**. Some of these receptors are scattered through the skin: this organ has a number of different types of receptor, as shown in Figure 14.21. Other receptors are concentrated into special **sense organs** such as the eye and the ear. Table 14.1 gives examples of these and their stimuli.

**Table 14.1** Sense organs and their stimuli

| Sense organ | Stimulus |
|---|---|
| ear | sound, body movement (balance) |
| eye | light |
| nose | chemicals (smells) |
| tongue | chemicals (taste) |
| skin | temperature, pressure, touch, pain |

The special property of sensory cells and sense organs is that they are able to convert one form of energy to another. The eyes can convert light energy into the electrical energy of a nerve impulse. The ears convert the energy in sound vibrations into nerve impulses. The forms of energy that make up the stimuli may be very different, e.g. mechanical, chemical, light, but they are all transduced into pulses of electrical energy in the nerves.

When a receptor responds to a stimulus, it sends a nerve impulse to the brain, which makes us aware of the sensation.

## The eye

Note: details of conjunctiva, humours, choroid and tear glands are **not** a syllabus requirement, but are included here to put parts seen in a diagram of the eye in context.

The structure of the eye is shown in Figures 14.11 and 14.12. The **sclera** is the tough, white outer coating. The front part of the sclera is clear and allows light to enter the eye. This part is called the **cornea**. The **conjunctiva** is a thin epithelium, which lines the inside of the eyelids and the front of the sclera and is continuous with the epithelium of the cornea.

The eye contains a clear liquid whose outward pressure on the sclera keeps the spherical shape of the eyeball. The liquid behind the lens is jelly-like and called **vitreous humour**. The **aqueous humour** in front of the lens is watery.

The **lens** is a transparent structure, held in place by a ring of fibres called the **suspensory ligament**. Unlike the lens of a camera or a telescope, the eye lens is flexible and can change its shape. In front of the lens is a disc of tissue called the **iris**. It is the iris we refer to when we describe the colour of the eye as brown or blue. The iris controls how much light enters the **pupil**, which is a hole in the centre of the iris. The pupil lets in light to the rest of the eye.

The pupil looks black because all the light entering the eye is absorbed by the black pigment in the **choroid**. The choroid layer, which contains many blood vessels, lies between the retina and the sclera. In the front of the eyeball, it forms the iris and the **ciliary body**. The ciliary body produces aqueous humour.

The internal lining at the back of the eye is the **retina** and it consists of many thousands of cells that respond to light. When light falls on these cells, they send off nervous impulses, which travel in nerve fibres, through the **optic nerve**, to the brain and so give rise to the sensation of sight. The part of the retina lying directly in front of the optic nerve contains no light-sensitive cells. This region is called the **blind spot**.

**Tear glands** under the top eyelid produce tear fluid. This is a dilute solution of sodium chloride and sodium hydrogencarbonate. The fluid is spread over the eye surface by the blinking of the eyelids, keeping the surface moist and washing away any dust particles or foreign bodies. Tear fluid also contains an enzyme, **lysozyme**, which attacks bacteria.

Table 14.2 gives the functions of the parts of the eye required for the Core section of the syllabus.

**Table 14.2** Functions of parts of the eye

| Part | Function |
|---|---|
| cornea | a transparent, curved layer at the front of the eye that refracts the light entering and helps to focus it |
| iris | a coloured ring of circular and radial muscle that controls the size of the pupil |
| lens | a transparent, convex, flexible, jelly-like structure that refracts light to focus it onto the retina |
| retina | a light-sensitive layer made up of rods, which detect light of low intensity, and cones, which detect different colours |
| optic nerve | transmits electrical impulses from the retina to the brain |

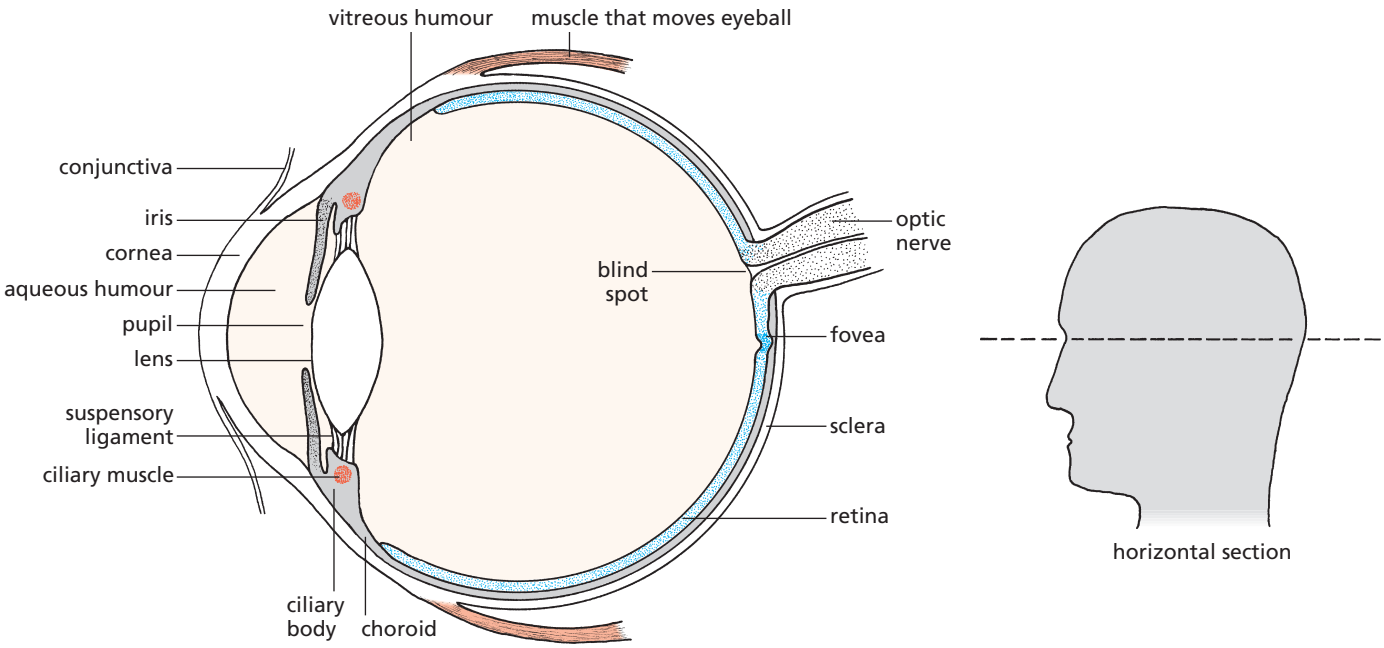



**Figure 14.11** Horizontal section through left eye

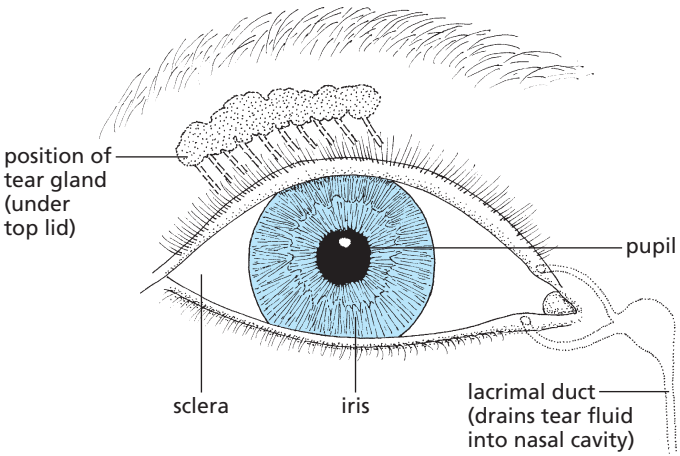



**Figure 14.12** Appearance of right eye from the front

## Vision

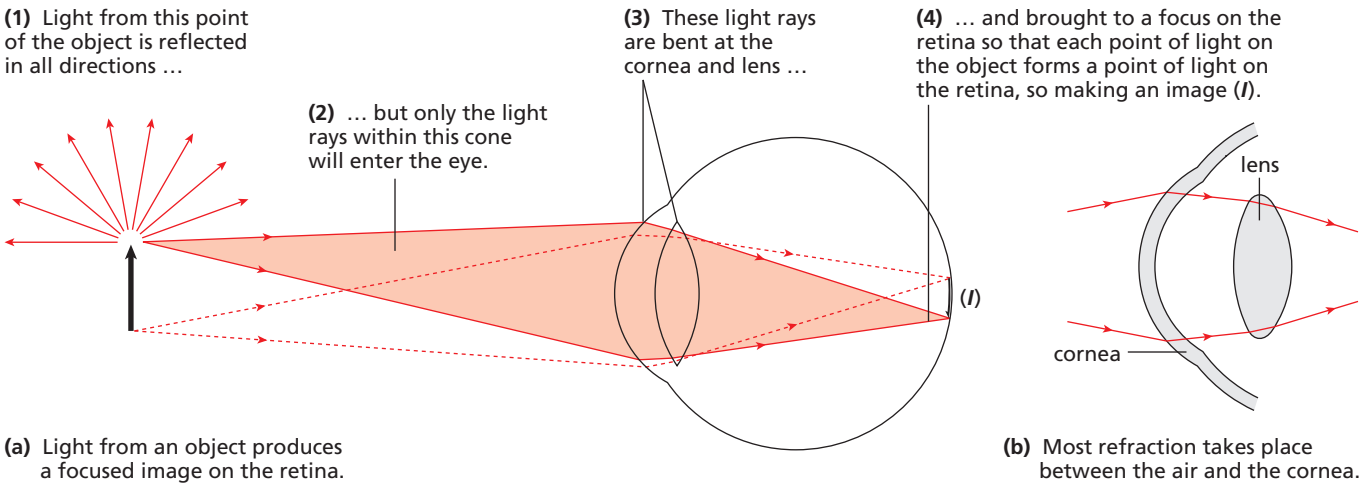
Light from an object produces a focused **image** on the retina (like a 'picture' on a cinema screen) (Figures 14.13 and 14.17). The curved surfaces of the cornea and lens both refract ('bend') the light rays that enter the eye, in such a way that each 'point of light' from the object forms a 'point of light' on the retina. These points of light will form an image, upside-down and smaller than the object.

The cornea and the aqueous and vitreous humours are mainly responsible for the refraction of light. The lens makes the final adjustments to the focus (Figure 14.13(b)).

The pattern of sensory cells stimulated by the image will produce a pattern of nerve impulses sent to the brain. The brain interprets this pattern, using past experience and learning, and forms an impression of the size, distance and upright nature of the object.

## The pupil reflex

The change in size of the pupil is caused by exposure of the eye to different light intensities. It is an automatic reaction: you cannot control it. When bright light falls on the eye, the iris responds by making the diameter of the pupil smaller. This restricts the amount of light reaching the retina, which contains the light-sensitive cells. If dim light falls on the eye, the iris responds by making the diameter of the pupil larger, so that as much light as is available can reach the retina to stimulate the light-sensitive cells. Figure 14.12 shows an eye exposed to bright light: the pupil is small. It would become much larger if the light intensity was reduced.




**(a)** Light from an object produces a focused image on the retina.

**(b)** Most refraction takes place between the air and the cornea.

**Figure 14.13** Image formation on the retina

### Control of light intensity

This section gives more detail about the roles of the iris and pupil in controlling light intensity falling on the retina, needed if you are following the extended syllabus.

The amount of light entering the eye is controlled by altering the size of the pupil (Figure 14.14). If the light intensity is high, it causes a contraction in a ring of muscle fibres (**circular muscle**) in the iris. This reduces the size of the pupil and cuts down the intensity of light entering the eye. High-intensity light can damage the retina, so this reaction has a protective function.

In low light intensities, the circular muscle of the iris relaxes and **radial muscle** fibres (which are arranged like the spokes of a bicycle wheel) contract. This makes the pupil enlarge and allows more light to enter. The circular and radial muscles act **antagonistically**. This means that they oppose each other in their actions – when the circular muscles contract they constrict the pupil and when the radial muscles contract the pupil dilates.

The change in size of the pupil is caused by an automatic reflex action; you cannot control it consciously.

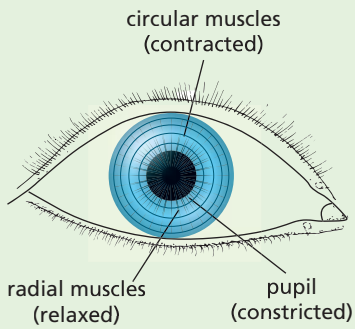



**Figure 14.14** The iris reflex

### Accommodation (focusing)

The eye can produce a focused image of either a near object or a distant object. To do this the lens changes its shape, becoming thinner for distant objects and fatter for near objects. This change in shape is caused by contracting or relaxing the **ciliary muscle**, which forms a circular band of muscle in the **ciliary body** (Figure 14.15). When the ciliary muscle is relaxed, the outward pressure of the humours on the sclera pulls on the suspensory ligament and stretches the lens to its thin shape. The eye is now accommodated (i.e. focused) for distant objects (Figures 14.15(a) and 14.16(a)). To focus a near object, the ciliary muscle contracts to a smaller circle and this takes the tension out of the suspensory ligament (Figures 14.15(b) and 14.16(b)). The lens is elastic and flexible and so is able to change to its fatter shape. This shape is better at bending the light rays from a close object.

### Retina

The millions of light-sensitive cells in the retina are of two kinds, the **rods** and the **cones** (according to shape). The cones enable us to distinguish colours, but the rods are more sensitive to low intensities of light and therefore play an important part in night vision when the light intensity is not sufficient to stimulate the cone cells. Images formed at night appear as shades of grey, with no bright colours detected. There are thought to be three types of cone cell. One type responds best to red light, one to green and one to blue. If all three types are equally stimulated we get the sensation of white. The cone cells are concentrated in a central part of the retina, called the **fovea** (Figure 14.11); when you study an object closely you are making its image fall on the fovea.

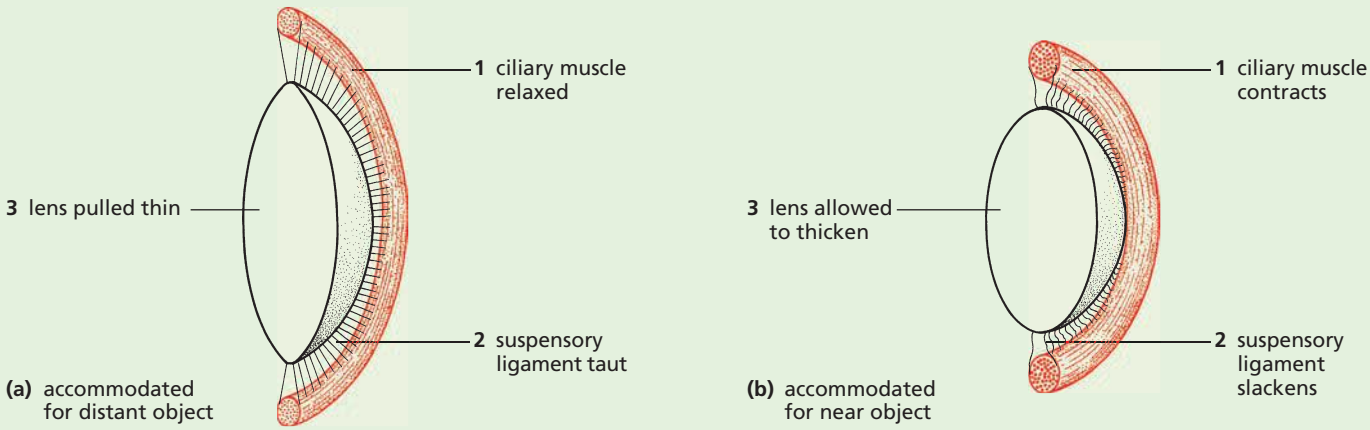



**Figure 14.15** How accommodation is brought about

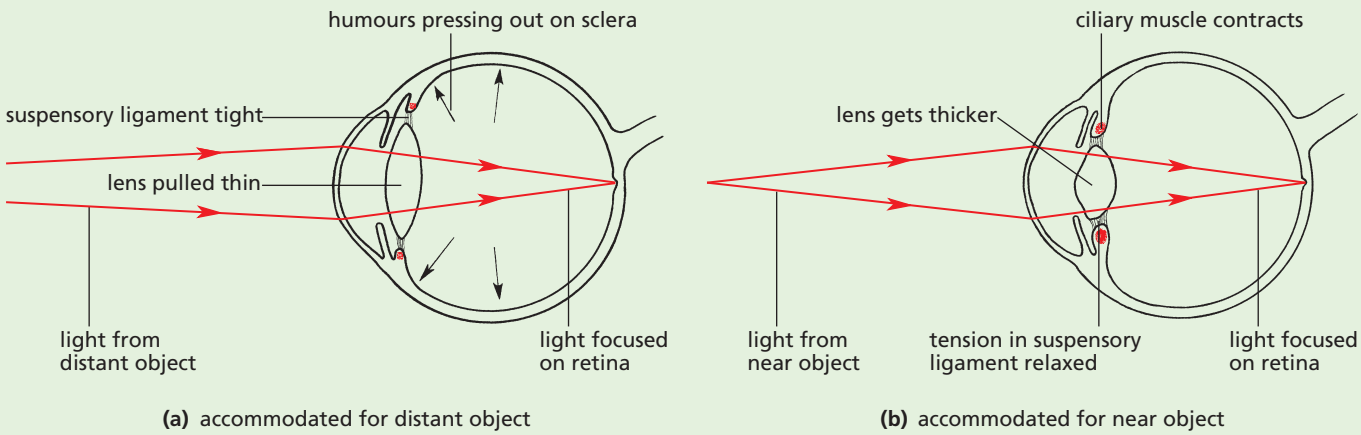



**Figure 14.16** Accommodation

## Fovea

It is in the fovea that the image on the retina is analysed in detail. Only objects within a 2° cone from the eye form an image on the fovea. This means that only about two letters in any word on this page can be seen in detail. It is the constant scanning movements of the eye that enable you to build up an accurate 'picture' of a scene. The centre of the fovea contains only cones: it is here that colour discrimination occurs.

## Blind spot

At the point where the optic nerve leaves the retina, there are no sensory cells and so no information reaches the brain about that part of the image which falls on this blind spot (Figure 14.18).

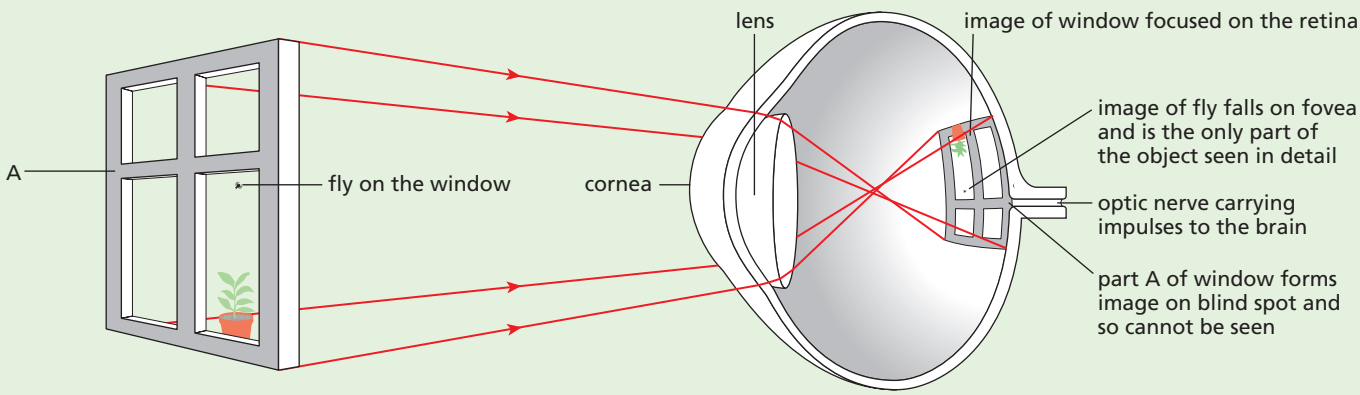



**Figure 14.17** Image formation in the eye

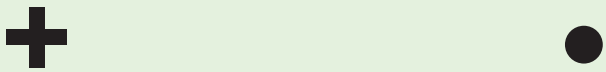


**Figure 14.18** The blind spot. Hold the book about 50 cm away. Close your left eye and concentrate on the cross with your right eye. Slowly bring the book closer to your face. When the image of the dot falls on the blind spot it will seem to disappear.

## Hormones in humans

**Key definition**

A **hormone** is a chemical substance, produced by a gland and carried by the blood, which alters the activity of one or more specific target organs.

Co-ordination by the nervous system is usually rapid and precise. Nerve impulses, travelling at up to 100 metres per second, are delivered to specific parts of the body and produce an almost immediate response. A different kind of co-ordination is brought about by the **endocrine system**. This system depends on chemicals, called **hormones**, which are released from special glands, called **endocrine glands**, into the bloodstream. The hormones circulate around the body in the blood and eventually reach certain organs, called **target organs**. Hormones speed up, slow down or alter the activity of those organs. After being secreted, hormones do not remain permanently in the blood but are changed by the liver into inactive compounds and excreted by the kidneys. Insulin, for example, may stay in the bloodstream for just 4–8 hours before being broken down. Table 14.3 compares control by the endocrine and nervous systems.

**Table 14.3** Endocrine and nervous control compared

| Endocrine | Nervous |
|---|---|
| transmission of chemicals | transmission of electrical impulses |
| transmission via blood | transmission in nerves |
| slow transmission | rapid transmission |
| hormones dispersed throughout body | impulse sent directly to target organ |
| long-term effects | short-lived effects |

Unlike the digestive glands, endocrine glands do not deliver their secretions through ducts (tubes). For this reason, the endocrine glands are sometimes called 'ductless glands'. The hormones are picked up directly from the glands by the blood circulation.

Responses of the body to hormones are much slower than responses to nerve impulses. They depend, in the first instance, on the speed of the circulatory system and then on the time it takes for the cells to change their chemical activities. Many hormones affect long-term changes such as growth rate, puberty and pregnancy. Nerve impulses often cause a response in a very limited area of the body, such as an eye-blink or a finger movement. Hormones often affect many organ systems at once.

Serious deficiencies or excesses of hormone production give rise to illnesses. Small differences in hormone activity between individuals probably contribute to differences of personality and temperament.

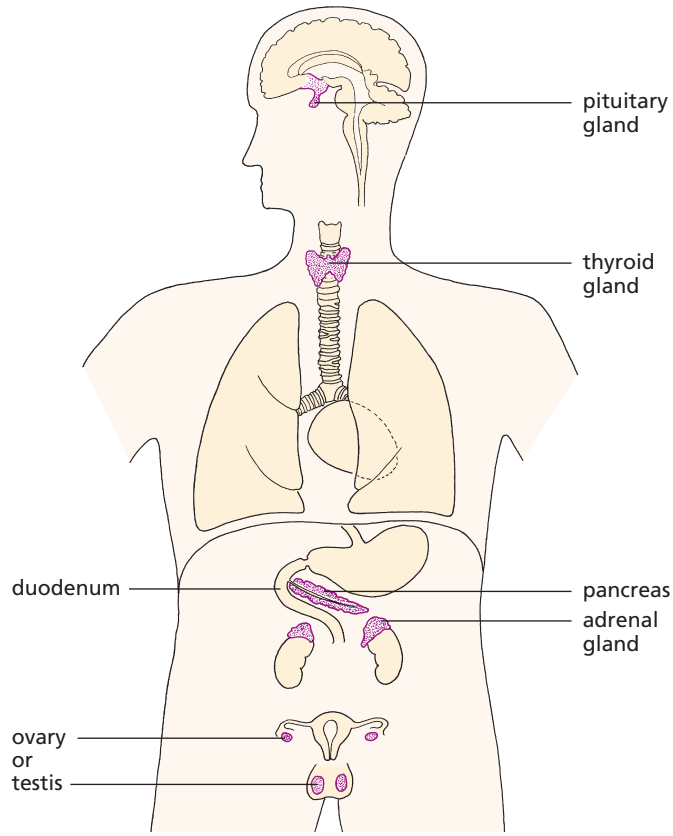



**Figure 14.19** Position of endocrine glands in the body

Note: knowledge of the pituitary and thyroid glands is **not** a syllabus requirement

The position of the endocrine glands in the body is shown in Figure 14.19. Notice that the pancreas and the reproductive organs have a dual function.

## Extension work

### Thyroid gland

The thyroid gland is situated in the front part of the neck and lies in front of the windpipe. It produces a hormone called **thyroxine**. This hormone has a stimulatory effect on the metabolic rate of nearly all the body cells, such as the speed or rate of

cell respiration (Chapter 12) and other chemical reactions. It controls our level of activity, promotes skeletal growth and is essential for the normal development of the brain.

## Pituitary gland

This gland is attached to the base of the brain. It produces many hormones. For example, the pituitary releases into the blood **follicle-stimulating hormone** (FSH) which, when it reaches the ovaries, makes one of the follicles start to mature and to produce oestrogen. **Luteinising hormone** (LH), also known as lutropin, is also produced from the pituitary and, together with FSH, induces ovulation (see 'Sex hormones in humans' in Chapter 16).

## Adrenal glands

These glands are attached to the back of the abdominal cavity, one above each kidney (see also Figure 13.1). One part of the adrenal gland is a zone called the **adrenal medulla**. The medulla receives nerves from the brain and produces the hormone **adrenaline**.

Adrenaline has obvious effects on the body:

- In response to a stressful situation, nerve impulses are sent from the brain to the adrenal medulla, which releases adrenaline into the blood.
- Its presence causes breathing to become faster and deeper. This may be particularly apparent as we pant for breath.
- The heart beats faster, resulting in an increase in pulse rate. This increase in heart rate can be quite alarming, making us feel as if our heart is going to burst out of our chest.
- The pupils of our eyes dilate, making them look much blacker.

These effects all make us more able to react quickly and vigorously in dangerous situations (known as 'fight or flight situations') that might require us to run away or put up a struggle. However, in many stressful situations, such as taking examinations or giving a public performance, vigorous activity is not called for. So the extra adrenaline in our bodies just makes us feel tense and anxious.

## The pancreas

The pancreas is a digestive gland that secretes enzymes into the duodenum through the pancreatic duct (Chapter 7). It is also an endocrine (ductless) gland. Most of the pancreas cells produce digestive enzymes but some of them produce hormones. The hormone-producing cells are arranged in small isolated groups called islets (Figure 14.20) and secrete their hormones directly into the bloodstream. One of the hormones is called **insulin**.

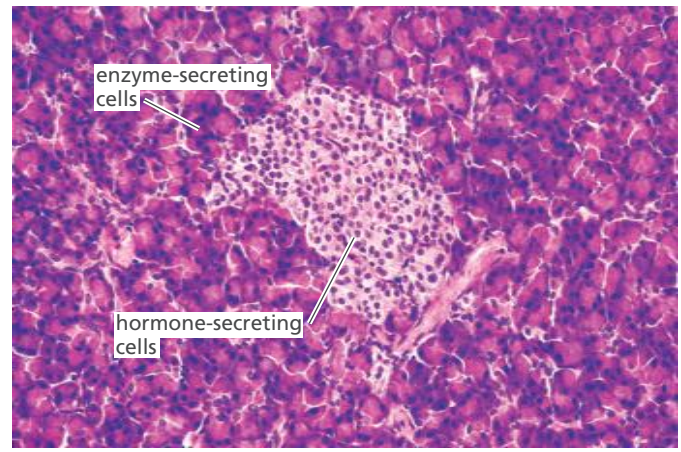



**Figure 14.20** Section of pancreas tissue showing an islet (×250)

Insulin controls the levels of glucose in the blood by instructing the liver to remove the sugars and store them. This happens when levels get too high, such as after a meal rich in carbohydrate. (See page 196 for further details of the action of insulin.)

## Reproductive organs

The ovaries and testes produce hormones as well as gametes (sperms and ova) and their effects are described in Chapter 16.

One of the hormones from the ovary, **oestrogen**, prepares the uterus for the implantation of the embryo, by making its lining thicker and increasing its blood supply.

The hormones **testosterone** (from the testes) and oestrogen (from the ovaries) play a part in the development of the secondary sexual characteristics.

## The role of adrenaline

As adrenaline circulates around the body it affects a number of organs, as shown in Table 14.4.

You will recognise the sensations described in column four of Table 14.4 as characteristic of fear and anxiety.

**Table 14.4** Responses to adrenaline

| Target organ | Effects of adrenaline | Biological advantage | Effect or sensation |
|---|---|---|---|
| heart | beats faster | sends more glucose and oxygen to the muscles | thumping heart |
| breathing centre of the brain | faster and deeper breathing | increased oxygenation of the blood; rapid removal of carbon dioxide | panting |
| arterioles of the skin | constricts them (see 'Homeostasis') | less blood going to the skin means more is available to the muscles | person goes paler |
| arterioles of the digestive system | constricts them | less blood for the digestive system allows more to reach the muscles | dry mouth |
| muscles of alimentary canal | relax | peristalsis and digestion slow down; more energy available for action | 'hollow' feeling in stomach |
| muscles of body | tenses them | ready for immediate action | tense feeling; shivering |
| liver | conversion of glycogen to glucose | more glucose available in blood for energy production, to allow metabolic activity to increase | no sensation |
| fat deposits | conversion of fats to fatty acids | fatty acids available in blood for muscle contraction | |

Adrenaline is quickly converted by the liver to a less active compound, which is excreted by the kidneys. All hormones are similarly altered and excreted, some within minutes, others within days.

Thus their effects are not long-lasting. The long-term hormones, such as thyroxine, are secreted continuously to maintain a steady level.

# Homeostasis

**Key definition**
**Homeostasis** is the maintenance of a constant internal environment.

Homeostasis literally means 'staying similar'. It refers to the fact that the composition of the tissue fluid (see 'Blood' in Chapter 9) in the body is kept within narrow limits. The concentration, acidity and temperature of this fluid are being adjusted all the time to prevent any big changes.

## The skin and temperature control

### Skin structure

Figure 14.21 shows a section through skin. In the **basal layer** some of the cells are continually dividing and pushing the older cells nearer the surface. Here they die and are shed at the same rate as they are replaced. The basal layer and the cells above it constitute the **epidermis**. The basal layer also contributes to the hair follicles. The dividing cells give rise to the hair.

There are specialised pigment cells in the basal layer and epidermis. These produce a black pigment, **melanin**, which gives the skin its colour. The more melanin, the darker is the skin.

The thickness of the epidermis and the abundance of hairs vary in different parts of the body (Figure 14.22).

The **dermis** contains connective tissue with hair follicles, sebaceous glands, sweat glands, blood vessels and nerve endings. There is usually a layer of adipose tissue (a fat deposit) beneath the dermis.

### Skin function

**Protection**
The outermost layer of dead cells of the epidermis helps to reduce water loss and provides a barrier against bacteria. The pigment cells protect the skin from damage by the ultraviolet rays in sunlight. In white-skinned people, more melanin is produced in response to exposure to sunlight, giving rise to a tan.

**Sensitivity**
Scattered throughout the skin are large numbers of tiny sense receptors, which give rise to sensations of touch, pressure, heat, cold and pain. These make us aware of changes in our surroundings and enable us to take action to avoid damage, to recognise objects by touch and to manipulate objects with our hands.

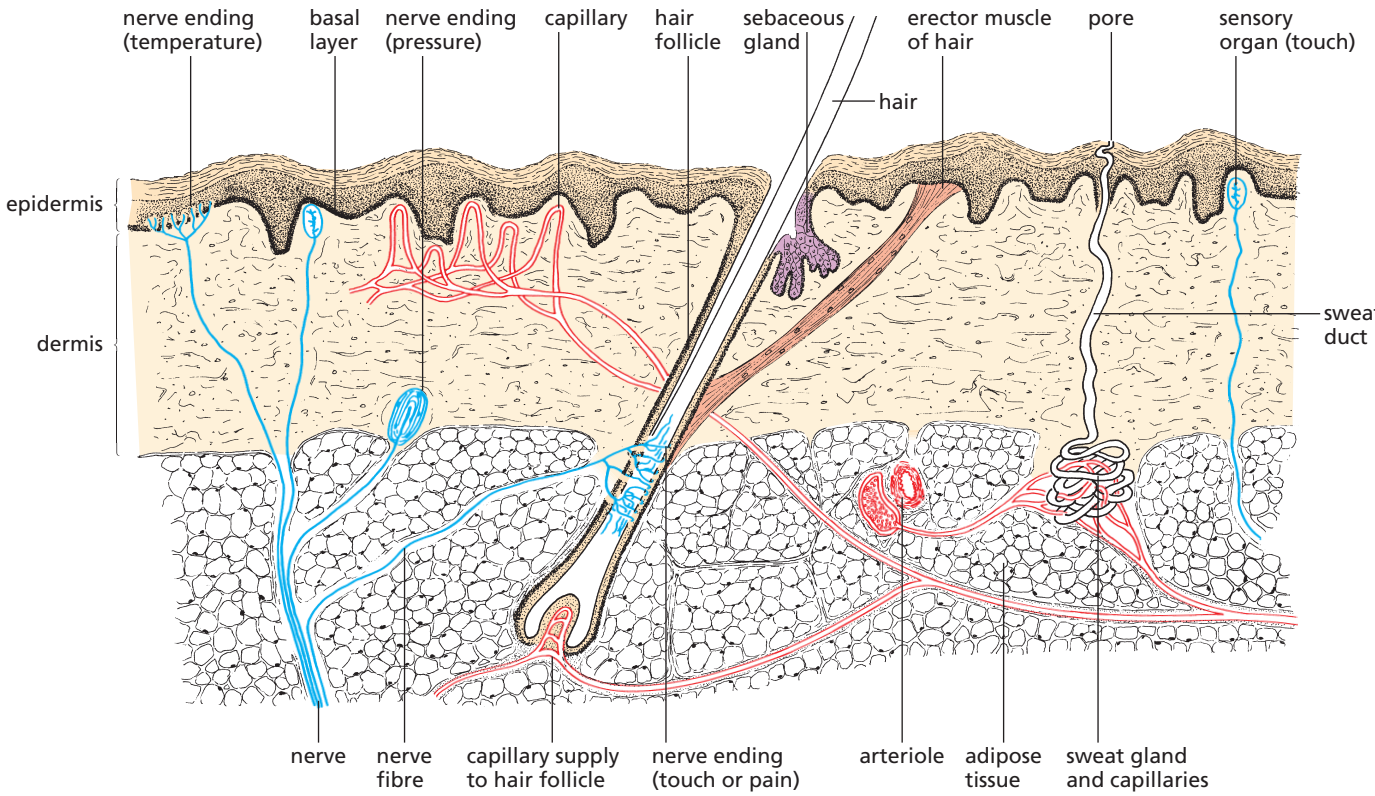



**Figure 14.21** Generalised section through the skin

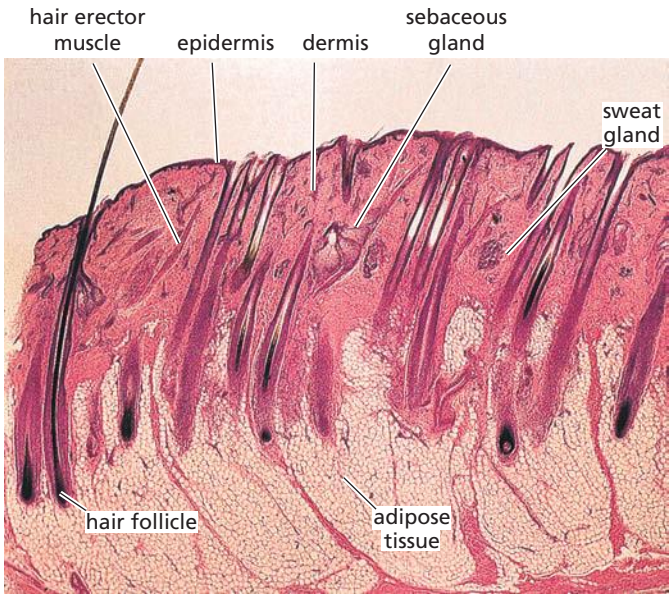



**Figure 14.22** Section through hairy skin (×20)

### Temperature regulation

The skin helps to keep the body temperature more or less constant. This is done by adjusting the flow of blood near the skin surface and by sweating. These processes are described more fully below.

## Temperature control

Normal human body temperature varies between 35.8 °C and 37.7 °C. Temperatures below 34 °C or above 40 °C, if maintained for long, are considered dangerous. Different body regions, e.g. the hands, feet, head or internal organs, will be at different temperatures, but the **core** temperature, as measured with a thermometer under the tongue, will vary by only 1 or 2 degrees.

Heat is lost from the body surface by conduction, convection, radiation and evaporation. The amount of heat lost is reduced to an extent due to the insulating properties of adipose (fatty) tissue in the dermis. Some mammals living in extreme conditions, such as whales and seals, make much greater use of this: they have thick layers of blubber to reduce heat loss more effectively. Just how much insulation the blubber gives depends on the amount of water in the tissue: a smaller proportion of water and more fat provide better insulating properties.

Heat is gained, internally, from the process of respiration (Chapter 12) in the tissues and, externally, from the surroundings or from the Sun.

The two processes of heat gain and heat loss are normally in balance but any imbalance is corrected by a number of methods, including those described below.

**Overheating**

- More blood flows near the surface of the skin, allowing more heat to be exchanged with the surroundings.
- **Sweating** – the sweat glands secrete sweat on to the skin surface. When this layer of liquid evaporates, it takes heat (latent heat) from the body and cools it down (Figure 14.23).

**Overcooling**

- Less blood flows near the surface of the skin, reducing the amount of heat lost to the surroundings.
- Sweat production stops – thus the heat lost by evaporation is reduced.
- **Shivering** – uncontrollable bursts of rapid muscular contraction in the limbs release heat as a result of respiration in the muscles.

In these ways, the body temperature remains at about 37 °C. We also control our temperature by adding or removing clothing or deliberately taking exercise.

Whether we feel hot or cold depends on the sensory nerve endings in the skin, which respond to heat loss or gain. You cannot consciously detect changes in your core temperature. The brain plays a direct role in detecting any changes from normal by monitoring the temperature of the blood. A region called the **hypothalamus** contains a thermoregulatory centre in which temperature receptors detect temperature changes in the blood and co-ordinate a response to them. Temperature receptors are also present in the skin. They send information to the brain about temperature changes.

**Figure 14.23** Sweating. During vigorous activity the sweat evaporates from the skin and helps to cool the body. When the activity stops, continued evaporation of sweat may overcool the body unless it is towelled off.

## Homeostasis

It is vital that there are homeostatic mechanisms in the body to control internal conditions within set limits.

In Chapter 5 it was explained that, in living cells, all the chemical reactions are controlled by enzymes. The enzymes are very sensitive to the conditions in which they work. A slight fall in temperature or a rise in acidity may slow down or stop an enzyme from working and thus prevent an important reaction from taking place in the cell.

The cell membrane controls the substances that enter and leave the cell, but it is the tissue fluid that supplies or removes these substances, and it is therefore important to keep the composition of the tissue fluid as steady as possible. If the tissue fluid were to become too concentrated, it would withdraw water from the cells by osmosis (Chapter 3) and the body would be dehydrated. If the tissue fluid were to become too dilute, the cells would take up too much water from it by osmosis and the tissues would become waterlogged and swollen.

Many systems in the body contribute to homeostasis (Figure 14.24). The obvious example is the kidneys, which remove substances that might poison the enzymes. The kidneys also control the level of salts, water and acids in the blood. The composition of the blood affects the tissue fluid which, in turn, affects the cells.

Another example of a homeostatic organ is the liver, which regulates the level of glucose in the blood. The liver stores any excess glucose as glycogen, or turns glycogen back into glucose if the concentration in the blood gets too low. The brain cells are very sensitive to the glucose concentration in the blood and if the level drops too far, they stop working properly, and the person becomes unconscious and will die unless glucose is injected into the blood system. This shows how important homeostasis is to the body.

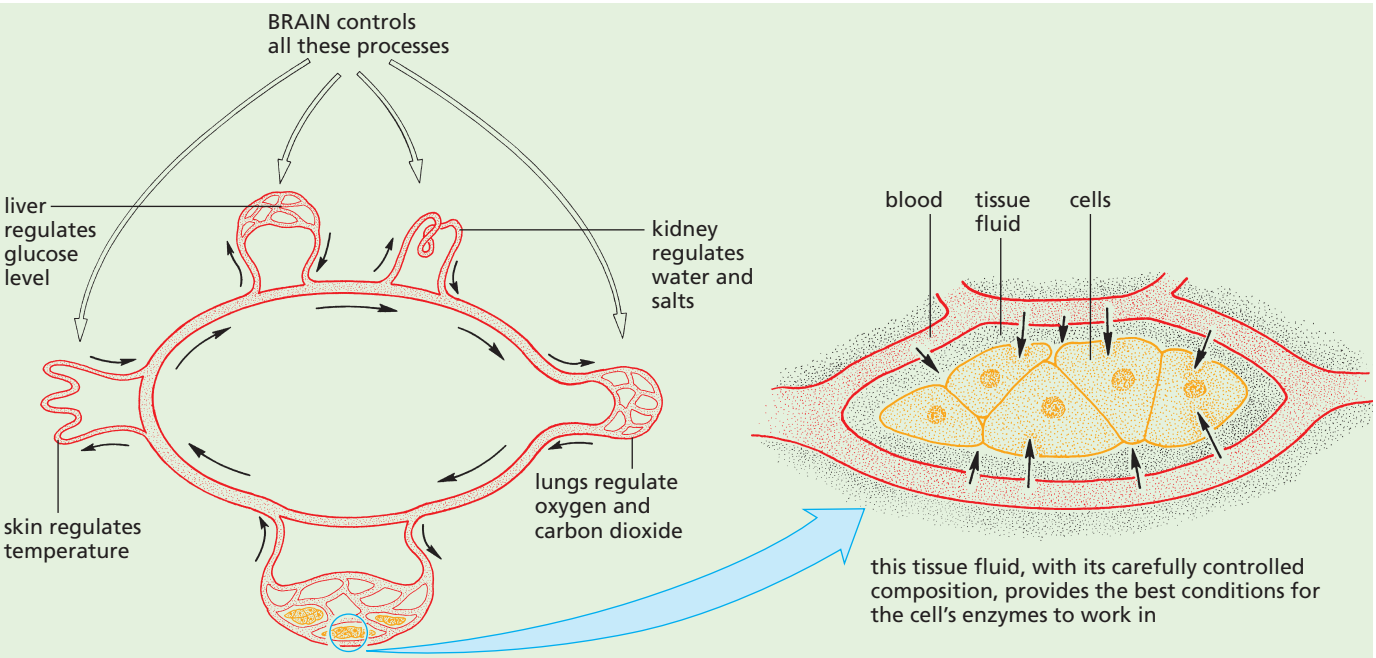



**Figure 14.24** The homeostatic mechanisms of the body

The lungs (Chapter 11) play a part in homeostasis by keeping the concentrations of oxygen and carbon dioxide in the blood at the best level for the cells' chemical reactions, especially respiration.

The skin regulates the temperature of the blood. If the cells were to get too cold, the chemical reactions would become too slow to maintain life. If they became too hot, the enzymes would be destroyed.

The brain has overall control of the homeostatic processes in the body. It checks the composition of the blood flowing through it and if it is too warm, too cold, too concentrated or has too little glucose, nerve impulses or hormones are sent to the organs concerned, causing them to make the necessary adjustments.

## Homeostasis and negative feedback

Temperature regulation is an example of homeostasis. Maintenance of a constant body temperature ensures that vital chemical reactions continue at a predictable rate and do not speed up or slow down when the surrounding temperature changes. The constant-temperature or **homoiothermic** ('warm-blooded') animals, the birds and mammals, therefore have an advantage over the variable-temperature or **poikilothermic** ('cold-blooded') animals. Poikilotherms such as reptiles and insects can regulate their body temperature to some extent by, for example, basking in the sun or seeking shade. Nevertheless, if their body temperature falls, their vital chemistry slows down and their reactions become more sluggish. They are then more vulnerable to predators.

The 'price' that homoiotherms have to pay is the intake of enough food to maintain their body temperature, usually above that of their surroundings.

In the hypothalamus of a homoiotherm's brain there is a thermoregulatory centre. This centre monitors the temperature of the blood passing through it and also receives sensory nerve impulses from temperature receptors in the skin. A rise in body temperature is detected by the thermoregulatory centre and it sends nerve impulses to the skin, which result in vasodilation and sweating. Similarly, a fall in body temperature will be detected and will promote impulses that produce vasoconstriction and shivering.

This system of control is called **negative feedback**. The outgoing impulses counteract the effects that produced the incoming impulses. For example, a rise in temperature triggers responses that counteract the rise.

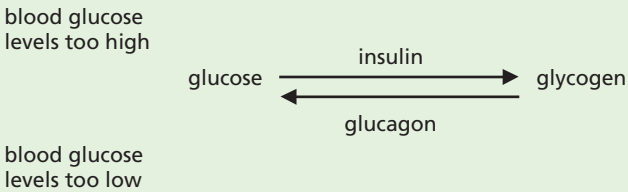
### Regulation of blood sugar

If the level of sugar in the blood falls, the islets release a hormone called **glucagon** into the bloodstream. Glucagon acts on the cells in the liver and causes them to convert some of their stored glycogen into glucose and so restore the blood sugar level.

Insulin has the opposite effect to glucagon. If the concentration of blood sugar increases (e.g. after a meal rich in carbohydrate), insulin is released from the islet cells. When the insulin reaches the liver it stimulates the liver cells to take up glucose from the blood and store it as glycogen.

Insulin has many other effects; it increases the uptake of glucose in all cells for use in respiration; it promotes the conversion of carbohydrates to fats and slows down the conversion of protein to carbohydrate.

All these changes have the effect of regulating the level of glucose in the blood to within narrow limits – a very important example of homeostasis.




The concentration of glucose in the blood of a person who has not eaten for 8 hours is usually between 90 and 100 mg 100 $cm^{-3}$ blood. After a meal containing carbohydrate, the blood sugar level may rise to 140 mg 100 $cm^{-3}$ but 2 hours later, the level returns to about 95 mg as the liver has converted the excess glucose to glycogen.

About 100 g glycogen is stored in the liver of a healthy man. If the concentration of glucose in the blood falls below about 80 mg 100 $cm^{-3}$ blood, some of the glycogen stored in the liver is converted by enzyme action into glucose, which enters the circulation. If the blood sugar level rises above 160 mg 100 $cm^{-3}$, glucose is excreted by the kidneys.

A blood glucose level below 40 mg 100 $cm^{-3}$ affects the brain cells adversely, leading to convulsions and coma. By helping to keep the glucose concentration between 80 and 150 mg, the liver prevents these undesirable effects and so contributes to the homeostasis of the body.

If anything goes wrong with the production or function of insulin, the person will show the symptoms of **diabetes**.

### Type 1 diabetes

There are two types of diabetes and type 1 is the less common form, the cause of which has been outlined in Chapter 10. It results from a failure of the islet cells to produce sufficient insulin. The outcome is that the patient's blood is deficient in insulin and he or she needs regular injections of the hormone in order to control blood sugar level and so lead a normal life. This form of the disease is, therefore, sometimes called 'insulin-dependent' diabetes. The patient is unable to regulate the level of glucose in the blood. It may rise to such a high level that it is excreted in the urine, or fall so low that the brain cells cannot work properly and the person goes into a coma.

The symptoms of type 1 diabetes include feeling tired, feeling very thirsty, frequent urination and weight loss. Weight loss is experienced because the body starts to break down muscle and fat.

Diabetics need a carefully regulated diet to keep the blood sugar within reasonable limits. They should have regular blood tests to monitor their blood sugar levels and take regular exercise.

### Temperature control

In addition to the methods already described, the skin has another very important mechanism for maintaining a constant body temperature. This involves arterioles in the dermis of the skin, which can widen or narrow to allow more or less blood to flow near the skin surface through the blood capillaries. Further details of this process, involving the use of shunt vessels, are given in Chapter 9.

**Vasodilation** – the widening of the arterioles in the dermis allows more warm blood to flow through blood capillaries near the skin surface and so lose more heat (Figure 14.25(a)).

**Vasoconstriction** – narrowing (constriction) of the arterioles in the skin reduces the amount of warm blood flowing through blood capillaries near the surface (Figure 14.25(b)).

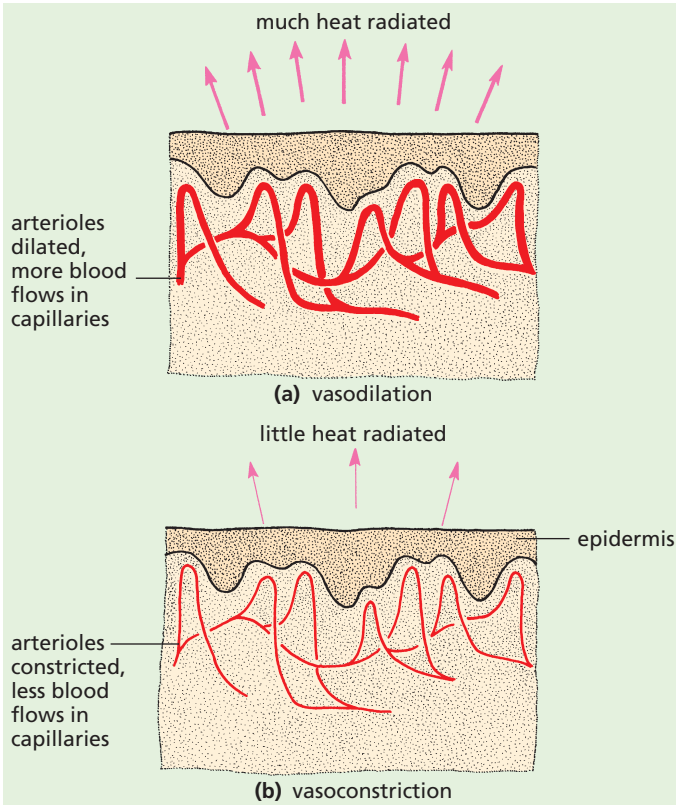



**Figure 14.25** Vasodilation and vasoconstriction

# Tropic responses

Sensitivity is the ability of living organisms to respond to stimuli. Although plants do not respond by moving their whole bodies, parts of them do respond to stimuli. Some of these responses are described as tropic responses or **tropisms**.

## Tropisms

Tropisms are growth movements related to directional stimuli, e.g. a shoot will grow towards a source of light but away from the direction of gravity. Growth movements of this kind are usually in response to the *direction* of light or gravity. Responses to light are called **phototropisms**; responses to gravity are **gravitropisms** (or **geotropisms**).

**Key definitions**

**Gravitropism** is a response in which a plant grows towards or away from gravity.

**Phototropism** is a response in which a plant grows towards or away from the direction from which light is coming.

If the plant organ responds by growing towards the stimulus, the response is said to be 'positive'. If the response is growth away from the stimulus it is said to be 'negative'. For example, if a plant is placed horizontally, its stem will change its direction and grow upwards, away from gravity (Figure 14.26).

**Figure 14.26** Negative gravitropism. The tomato plant has been left on its side for 24 hours.

The shoot is **negatively gravitropic**. The roots, however, will change their direction of growth to grow vertically downwards towards the pull of gravity (Experiment 1). Roots, therefore, are **positively gravitropic**.

Phototropism and gravitropism are best illustrated by some simple controlled experiments. Seedlings are good material for experiments on sensitivity because their growing roots (radicles) and shoots respond readily to the stimuli of light and gravity.

## Practical work

### Experiments on tropisms

#### 1 Gravitropism in pea radicles

- Soak about 20 peas in water for a day and then let them germinate in a vertical roll of moist blotting-paper.
- After 3 days, choose 12 seedlings with straight radicles and pin six of these to the turntable of a clinostat so that the radicles are horizontal.
- Pin another six seedlings to a cork that will fit in a wide-mouthed jar. Leave the jar on its side.
- A **clinostat** is a clockwork or electric turntable, which rotates the seedlings slowly about four times an hour. Although gravity is pulling sideways on their roots, it will pull equally on all sides as they rotate.
- Place the jar and the clinostat in the same conditions of lighting or leave them in darkness for 2 days.

**Result**
The radicles in the clinostat will continue to grow horizontally but those in the jar will have changed their direction of growth, to grow vertically downwards (Figure 14.27).

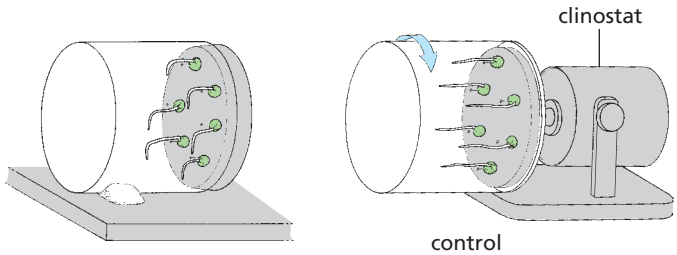



**Figure 14.27** Results of an experiment to show gravitropism in roots

**Interpretation**
The stationary radicles have responded to the stimulus of one-sided gravity by growing towards it. The radicles are positively gravitropic.

The radicles in the clinostat are the controls. Rotation of the clinostat has allowed gravity to act on all sides equally and there is no one-sided stimulus, even though the radicles were horizontal.

## 2 Phototropism in shoots

- Select two potted seedlings, e.g. sunflower or runner bean, of similar size and water them both.
- Place one of them under a cardboard box with a window cut in one side so that light reaches the shoot from one direction only (Figure 14.28).
- Place the other plant in an identical situation but on a clinostat. This will rotate the plant about four times per hour and expose each side of the shoot equally to the source of light. This is the control.

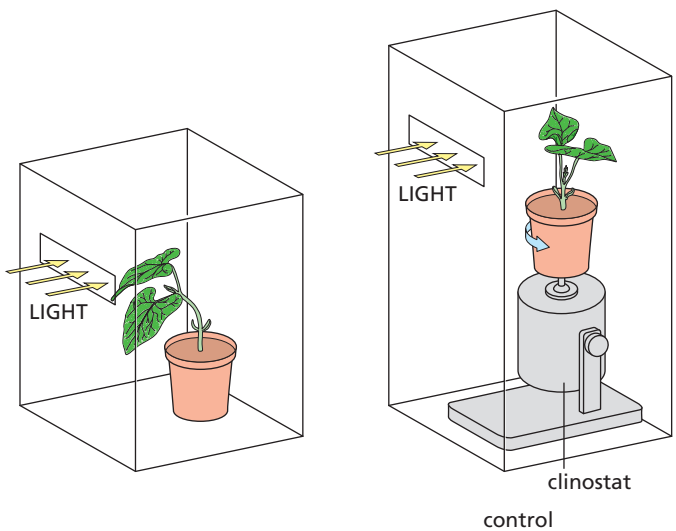



**Figure 14.28** Experiment to show phototropism in a shoot

**Result**
After 1 or 2 days, the two plants are removed from the boxes and compared. It will be found that the stem of the plant with one-sided illumination has changed its direction of growth and is growing towards the light (Figure 14.29). The control shoot has continued to grow vertically.

**Figure 14.29** Positive phototropism. The sunflower seedlings have received one-sided lighting for a day.

**Interpretation**
The results suggest that the young shoot has responded to one-sided lighting by growing towards the light. The shoot is said to be positively phototropic because it grows towards the direction of the stimulus.

However, the results of an experiment with a single plant cannot be used to draw conclusions that apply to green plants as a whole. The experiment described here is more of an illustration than a critical investigation. To investigate phototropisms thoroughly, a large number of plants from a wide variety of species would have to be used.

## Advantages of tropic responses

### Positive phototropism of shoots

By growing towards the source of light, a shoot brings its leaves into the best situation for photosynthesis. Similarly, the flowers are brought into an exposed position where they are most likely to be seen and pollinated by flying insects.

### Negative gravitropism in shoots

Shoots that are negatively gravitropic grow vertically. This lifts the leaves and flowers above the ground and helps the plant to compete for light and carbon dioxide. The flowers are brought into an advantageous position for insect or wind pollination. Seed dispersal may be more effective from fruits on a long, vertical stem. However, these advantages are a product of a tall shoot rather than negative gravitropism.

Stems that form rhizomes (stems that grow underground) are not negatively gravitropic; they grow horizontally below the ground, though the shoots that grow up from them are negatively gravitropic.

Branches from upright stems are not negatively gravitropic; they grow at 90 degrees or, usually, at a more acute angle to the directional pull of gravity. The lower branches of a potato plant must be partially *positively* gravitropic when they grow down into the soil and produce potato tubers (see 'Asexual reproduction' in Chapter 16).

**Positive gravitropism in roots**

By growing towards gravity, roots penetrate the soil, which is their means of anchorage and their source of water and mineral salts. Lateral roots are not positively gravitropic; they grow at right angles or slightly downwards from the main root. This response enables a large volume of soil to be exploited and helps to anchor the plants securely.

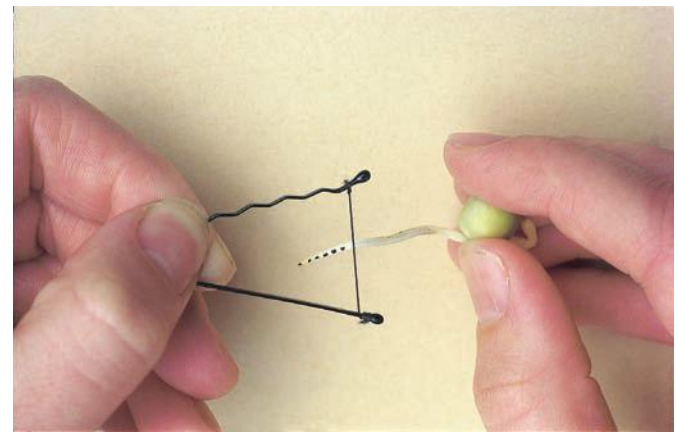


**Figure 14.30** Marking a root. A piece of cotton is held by the hairpin and dipped into black ink.

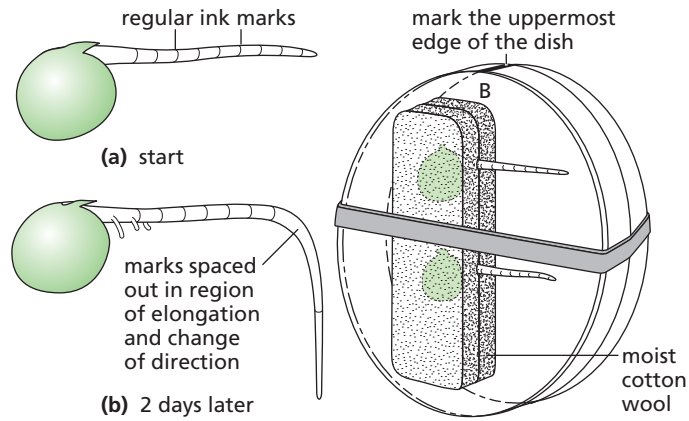



**Figure 14.31** Region of response in radicles. Result of Experiment 3 on the B seedlings

## Practical work

### More experiments on tropisms

#### 3 Region of response

- Grow pea seedlings in a vertical roll of blotting paper and select four with straight radicles about 25 mm long.
- Mark all the radicles with lines about 1 mm apart (Figures 14.30 and 14.31(a)).
- Use four strips of moist cotton wool to wedge two seedlings in each of two Petri dishes (Figure 14.31).
- Leave the dishes on their sides for 2 days, one (A) with the radicles vertical and the other (B) with the radicles horizontal.

**Result**

The ink marks will be more widely spaced in the region of greatest extension (Figure 14.31(b)). By comparing the seedlings in the two dishes, it can be seen that the region of curvature in the B seedlings corresponds to the region of extension in the A seedlings.

**Interpretation**

The response to the stimulus of one-sided gravity takes place in the region of extension. It does not necessarily mean that this is also the region which detects the stimulus.

## Plant growth substances and tropisms

### Control of growth

In animals and plants, the growth rate and extent of growth are controlled by chemicals: **hormones** in animals and **growth substances** in plants. Additionally, growth may be limited in animals by the availability of food, and in plants by light, water and minerals.

There are many different growth substances ('plant hormones') in plants. They are similar in some ways to animal hormones because they are produced in specific regions of the plant and transported to 'target' organs such as roots, shoots and buds. However, the sites of production are not specialised organs, as in animals, but regions of actively dividing cells such as the tips of shoots and roots. Also, plant growth substances are not transported in vessels.

One of the growth substances is **auxin**. Chemically it is indoleacetic acid (IAA). It is produced in the tips of actively growing roots and shoots and carried by active transport (Chapter 3) to the regions of extension where it promotes cell enlargement (Figure 14.32).

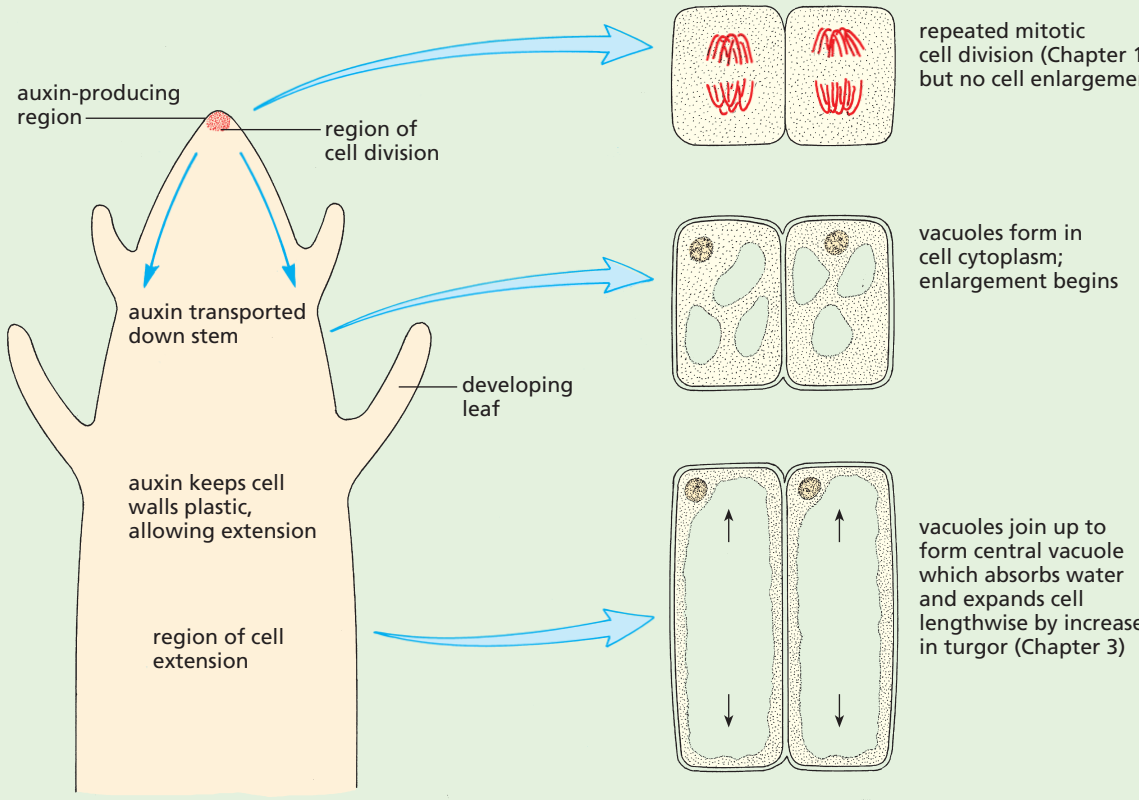



**Figure 14.32** Extension growth at shoot tip

The responses made by shoots and roots to light and gravity are influenced by growth substances.

Growth substances also control seed germination, bud burst, leaf fall, initiation of lateral roots and many other processes.

It has already been explained that growth substances, e.g. auxin, are produced by the tips of roots and shoots and can stimulate or, in some cases, inhibit extension growth. Tropic responses could be explained if the one-sided stimuli produced a corresponding one-sided distribution of growth substance.

In the case of positive gravitropism in roots there is evidence that, in a horizontal root, more growth substance accumulates on the lower side. In this case the growth substance is presumed to inhibit extension growth, so that the root tip curves downwards (Figure 14.33).

In the case of phototropism, it is generally accepted that the distribution of growth substance causes reduced extension on the illuminated side and/or increased extension on the non-illuminated side.

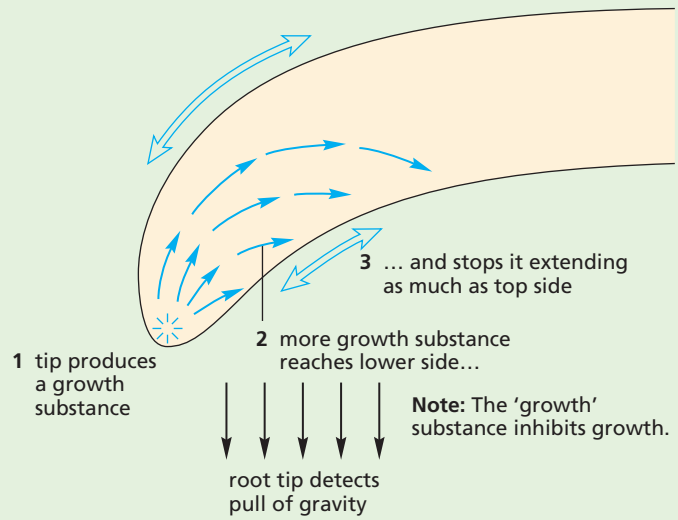



**Figure 14.33** Possible explanation of positive gravitropism in roots

### Summary of control of shoot growth by auxin

When a shoot is exposed to light from one side, auxins that have been produced by the tip move towards the shaded side of the shoot (or the auxins are destroyed on the light side, causing an unequal

distribution). Cells on the shaded side are stimulated to absorb *more* water than those on the light side, so the unequal growth causes the stem to bend towards the light. Growth of a shoot towards light is called **positive phototropism**.

If a shoot is placed horizontally in the absence of light, auxins accumulate on the lower side of the shoot, due to gravity. This makes the cells on the lower side grow *faster* than those on the upper side, so the shoot bends upwards. This is called **negative gravitropism**.

The opposite applies to roots because root cell elongation appears to be slowed down by exposure to auxin.

### Classic experiments to test how auxins work

Wheat and other grass species belong to the monocotyledon group of flowering plants (Chapter 1). When wheat seeds germinate (start to grow) they produce a shoot covered by a protective sheath called a **coleoptile**. This helps to prevent damage to the new leaves as they push through the soil. The coleoptile shows responses to light and gravity in a similar way to other plant parts. Wheat coleoptiles only take 2 or 3 days to grow and they show responses very quickly, so they are ideal for tropism experiments. The tip of the coleoptile, where it is expected that auxins would be produced, can be cut off without killing the plant, but effectively removing the source of the auxin. Figure 14.34 shows an investigation, treating coleoptiles in different ways.

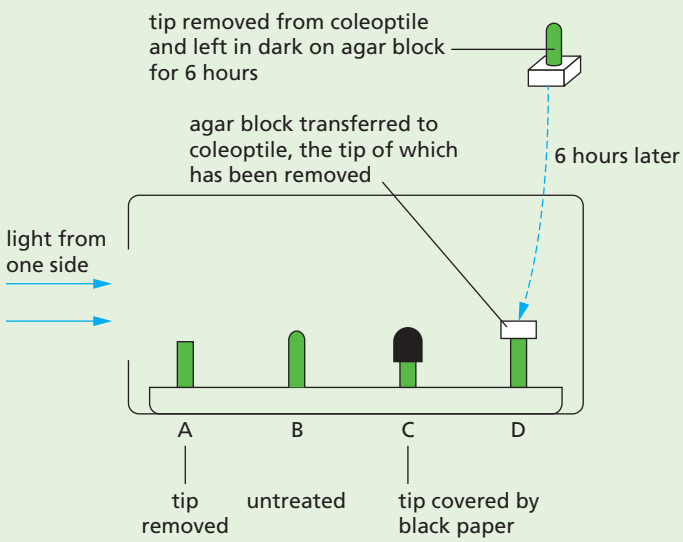



**Figure 14.34** Investigation into how auxin works

**Results**

A No growth of the coleoptile occurs and there is no bending.

B The coleoptile grows taller and bends towards the light.

C The coleoptile grows taller, but there is no bending.

D The coleoptile grows taller and bends towards the light.

**Interpretation**

In **A**, the source of auxin has been removed. Auxin is needed to stimulate growth and stimulates a response to light. It could also be argued that the tip provides cells for growth and this source of cells has been removed.

In **B**, auxin is produced by the tip of the coleoptile. It diffuses down the coleoptile and collects on the shaded side of the coleoptile (or is destroyed by the light on the light side). Cells on the shaded side respond to the auxin by growing faster than on the light side causing the coleoptile to grow towards the light.

In **C**, auxin is produced by the tip and diffuses down, causing all cells on both sides of the coleoptile to grow at an equal rate, causing an increase in length. However, the black paper prevents the light influencing the auxin, so there is no response to the direction of light.

In **D**, auxin is produced by the tip of the coleoptile. It diffuses into the agar block. When the agar block is replaced on the cut coleoptile, the auxin diffuses down from the agar and collects on the shaded side of the coleoptile (or is destroyed by the light on the light side). Cells on the shaded side respond to the auxin by growing faster than on the light side causing the coleoptile to grow towards the light.

### Use of plant growth substances

Chemicals can be manufactured which closely resemble natural growth substances and may be used to control various aspects of growth and development of crop plants.

The weedkiller, 2,4-D, is very similar to one of the auxins. When sprayed on a lawn, it affects the broad-leaved weeds (e.g. daisies and dandelions) but not the grasses. (It is called a 'selective weedkiller'.) Among other effects, it distorts the weeds' growth and speeds up their rate of respiration to the extent that they exhaust their food reserves and die.

## Questions

### Core

1 What is the difference between a nerve and a nerve fibre?
2 a In what ways are sensory neurones and motor neurones similar:
  i in structure
  ii in function?
  b How do they differ?
3 Can a nerve fibre and a nerve carry both sensory and motor impulses? Explain your answers.
  a a nerve fibre
  b a nerve
4 Put the following in the correct order for a simple reflex arc
  a impulse travels in motor fibre
  b impulse travels in sensory fibre
  c effector organ stimulated
  d receptor organ stimulated
  e impulse crosses synapse.
5 Which receptors and effectors are involved in the reflex actions of:
  a sneezing
  b blinking
  c contraction of the iris?
6 Explain why the tongue may be considered to be both a receptor and an effector organ.
7 Discuss whether coughing is a voluntary or reflex action.
8 What sensation would you expect to feel if a warm pin-head was pressed on to a touch receptor in your skin? Explain your answer.
9 If a piece of ice is pressed on to the skin, which receptors are likely to send impulses to the brain?
10 Apart from the cells that detect chemicals, what other types of receptor must be present in the tongue?
11 a To what directional stimuli do:
  i roots respond
  ii shoots respond?
  b Name the plant organs which are
  i positively phototropic
  ii positively gravitropic
  iii negatively gravitropic.
12 Why is it incorrect to say:
  a 'Plants grow towards the light.'
  b 'If a root is placed horizontally, it will bend towards gravity'?
13 Explain why a clinostat is used for the controls in tropism experiments.
14 Look at Figure 14.26. What will the shoot look like in 24 hours after the pot has been stood upright again? (Just draw the outline of the stem.)
15 What do you think might happen if a potted plant were placed on its side and the shoot illuminated from below (i.e. light and gravity are acting from the same direction)?

### Extended

16 Look at Figures 14.6 and Figure 14.8. For each diagram, state
  a how many cell bodies are drawn
  b how many synapses are shown.
17 If you could intercept and 'listen to' the nerve impulses travelling in the spinal cord, could you tell which ones came from pain receptors and which from temperature receptors? Explain your answer.
18 Would you expect synapses to occur in grey matter or in white matter? Explain your answer.
19 Study Figure 14.2. If the spinal cord were damaged at a point about one-third of the way up the vertebral column, what effect would you expect this to have on the bodily functions?
20 Study Table 14.3 and give one example for each point of comparison.
21 The pancreas has a dual function in producing digestive enzymes as well as hormones. Which other endocrine glands have a dual function and what are their other functions? (See also 'Sex hormones in humans' in Chapter 16.)
22 What are the effects on body functions of:
  a too much insulin
  b too little insulin?
23 Why do you think urine tests are carried out to see if a woman is pregnant?
24 What conscious actions do we take to reduce the heat lost from the body?
25 a What sort of chemical reaction in active muscle will produce heat?
  b How does this heat get to other parts of the body?
26 Draw up a balance sheet to show all the possible ways the human body can gain or lose heat. Make two columns, with 'Gains' on the left and 'Losses' on the right.
27 a Which structures in the skin of a furry mammal help to reduce heat loss?
  b What changes take place in the skin of humans to reduce heat loss?
28 Sweating cools you down only if the sweat can evaporate.
  a In what conditions might the sweat be unable to evaporate from your skin?
  b What conditions might speed up the evaporation of sweat and so make you feel very cold?
29 In Figure 14.35 the two sets of pea seedlings were sown at the same time, but the pot on the left was kept under a lightproof box. From the evidence in the picture:
  a what effects does light appear to have on growing seedlings
  b how might this explain positive phototropism?

**Figure 14.35** Effect of light on shoots

30 It is suggested that it is the very tip of the radicle that detects the one-sided pull of gravity even though it is the region of extension that responds. How could you modify Experiment 3 to test this hypothesis?

## Checklist

After studying Chapter 14 you should know and understand the following:

**The nervous system**

- The central nervous system consists of the brain and the spinal cord.
- The peripheral nervous system consists of the nerves.
- The nerves consist of bundles of nerve fibres.
- Each nerve fibre is a thin filament that grows out of a nerve cell body.
- The nerve cell bodies are mostly in the brain and spinal cord.
- Nerve fibres carry electrical impulses from sense organs to the brain or from the brain to muscles and glands.
- A reflex is an automatic nervous reaction that cannot be consciously controlled.
- A reflex arc is the nervous pathway that carries the impulses causing a reflex action.
- The simplest reflex involves a sensory nerve cell and a motor nerve cell, connected by synapses in the spinal cord.
- The brain and spinal cord contain millions of nerve cells.
- The millions of possible connections between the nerve cells in the brain allow complicated actions, learning, memory and intelligence.

- Voluntary actions start in the brain, while involuntary actions are automatic.
- Reflexes have a protective function.
- A synapse is a junction between two neurones consisting of a minute gap across which impulses pass by diffusion of a neurotransmitter.
- Identify parts of a synapse and describe how it transmits an impulse from one neurone to another.
- Drugs such as morphine and heroin can affect synapses.
- In reflex arcs, synapses ensure the movement of impulses in one direction.

**Sense organs**

- Sense organs are groups of receptor cells responding to specific stimuli: light, sound, touch, temperature and chemicals.
- Describe the structure of the eye.
- Describe the function of the parts of the eye.
- Describe the pupil reflex.

- Explain the pupil reflex.
- Explain accommodation to view near and distant objects.
- Describe the roles of parts of the eye in accommodation.
- State the distribution of rods and cones in the retina of a human.
- Describe the function of rods and cones.

**Hormones in humans**

- A hormone is a chemical substance, produced by a gland, carried by the blood, which alters the activity of one or more specific target organs
- The testes, ovaries and pancreas are also endocrine glands in addition to their other functions.
- The endocrine glands release hormones into the blood system.
- When the hormones reach certain organs they change the rate or kind of activity of the organ.
- Too much or too little of a hormone can cause a metabolic disorder.
- Adrenalin is secreted in 'fight or flight' situations.
- It causes an increased breathing and pulse rate and widened pupils.

- Adrenaline has a role in the chemical control of metabolic activity, including increasing the blood glucose concentration and pulse rate.
- The nervous system is much faster and its action tends to be over a shorter time span than hormonal control systems.

**Homeostasis**

- Homeostasis is the maintenance of a constant internal environment.
- Skin consists of an outer layer of epidermis and an inner dermis.
- The epidermis is growing all the time and has an outer layer of dead cells.
- The dermis contains the sweat glands, hair follicles, sense organs and capillaries.
- Skin (1) protects the body from bacteria and drying out, (2) contains sense organs which give us the sense of touch, warmth, cold and pain, and (3) controls the body temperature.
- Chemical activity in the body and muscular contractions produce heat.
- Heat is lost to the surroundings by conduction, convection, radiation and evaporation.
- If the body temperature rises too much, the skin cools it down by sweating and vasodilation.
- If the body loses too much heat, vasoconstriction and shivering help to keep it warm.

- Negative feedback provides a means of control: if levels of substances in the body change, the change is monitored and a response to adjust levels to normal is brought about.
- Glucose concentration in the blood is controlled using insulin and glucagon.
- Type 1 diabetes is the result of islet cells in the pancreas failing to produce enough insulin.
- Vasodilation and vasoconstriction of arterioles in the skin are mechanisms to control body temperature.

**Tropic responses**

- A response related to the direction of the stimulus is a tropism.
- The roots and shoots of plants may respond to the stimuli of light or gravity.
- Gravitropism is a response in which a plant grows towards or away from gravity.
- Phototropism is a response in which a plant grows towards or away from the direction from which light is coming.

- Growth towards the direction of the stimulus is called 'positive'; growth away from the stimulus is called 'negative'.
- Tropic responses bring shoots and roots into the most favourable positions for their life-supporting functions.
- Describe investigations into gravitropism and phototropism in shoots and roots.

- Explain phototropism and gravitropism of a shoot as examples of the chemical control of plant growth by auxin.
- Auxin is only made in the shoot tip and moves through the plant, dissolved in water.
- Auxin is unequally distributed in response to light and gravity.
- Auxin stimulates cell elongation.
- The synthetic plant hormone 2,4-D is used in weedkillers.

# 15 Drugs

**Drugs**
Define drug

**Medicinal drugs**
Use of antibiotics
Development of resistance in bacteria to antibiotics

Development of resistant bacteria
Antibiotics and viral diseases

**Misused drugs**
Effects of heroin, alcohol, tobacco
Role of liver in breaking down toxins

Effects of heroin on the nervous system
Link between smoking and cancer
Use of performance-enhancing drugs

## Drugs

**Key definition**
A **drug** is any substance taken into the body that modifies or affects chemical reactions in the body.

The drug may be one taken legally to reduce a symptom such as a headache or to treat a bacterial infection (medicinal drugs), but it could also be one taken – often illegally – to provide stimulation or induce sleep or create hallucinations (recreational drugs). Drugs are present in many products such as: tea, coffee and 'energy drinks' (caffeine); tobacco (nicotine); and alcoholic drinks (alcohol) which, although legal, can cause serious effects when taken excessively or over extended periods of time.

## Medicinal drugs

Any substance used in medicine to help our bodies fight illness or disease is called a drug.

### Antibiotics

The ideal drug for curing disease would be a chemical that destroyed the pathogen without harming the tissues of the host. In practice, modern antibiotics such as penicillin come pretty close to this ideal for bacterial infections.

A tiny minority of bacteria are harmful (pathogenic). Figure 10.1 shows some examples and the diseases they cause.

Most of the antibiotics we use come from bacteria or fungi that live in the soil. The function of the antibiotics in this situation is not clear. One theory suggests that the chemicals help to suppress competition for limited food resources, but the evidence does not support this theory.

One of the most prolific sources of antibiotics is *Actinomycetes*. These are filamentous bacteria that resemble microscopic mould fungi. The actinomycete *Streptomyces* produces the antibiotic **streptomycin**.

Perhaps the best known antibiotic is **penicillin**, which is produced by the mould fungus *Penicillium* and was discovered by Sir Alexander Fleming in 1928. Penicillin is still an important antibiotic but it is produced by mutant forms of a different species of *Penicillium* from that studied by Fleming. The different mutant forms of the fungus produce different types of penicillin.

The penicillin types are chemically altered in the laboratory to make them more effective and to 'tailor' them for use with different diseases. 'Ampicillin', 'methicillin' and 'oxacillin' are examples.

Antibiotics attack bacteria in a variety of ways. Some of them disrupt the production of the cell wall and so prevent the bacteria from reproducing, or even cause them to burst open; some interfere with protein synthesis and thus arrest bacterial growth.

Animal cells do not have cell walls, and the cell structures involved in protein production are different. Consequently, antibiotics do not damage human cells although they may produce some side-effects such as allergic reactions.

Not all bacteria are killed by antibiotics. Some bacteria have a nasty habit of mutating to forms that are resistant to these drugs.

For this reason it is important not to use antibiotics in a diluted form, for too short a period or for trivial complaints. These practices lead to a build-up of a resistant population of bacteria. The drug resistance can be passed from harmless bacteria to pathogens.

It is important to note that antibiotics are ineffective in the treatment of viral diseases.

### Development of resistant bacteria

If a course of antibiotics is not completed, some of the bacteria it is being used to destroy will not be killed, but will have been exposed to the drug. Some of the survivors may be drug-resistant mutants. When they reproduce, all their offspring will have the drug resistance, so the antibiotic will become less effective (Figure 15.1).

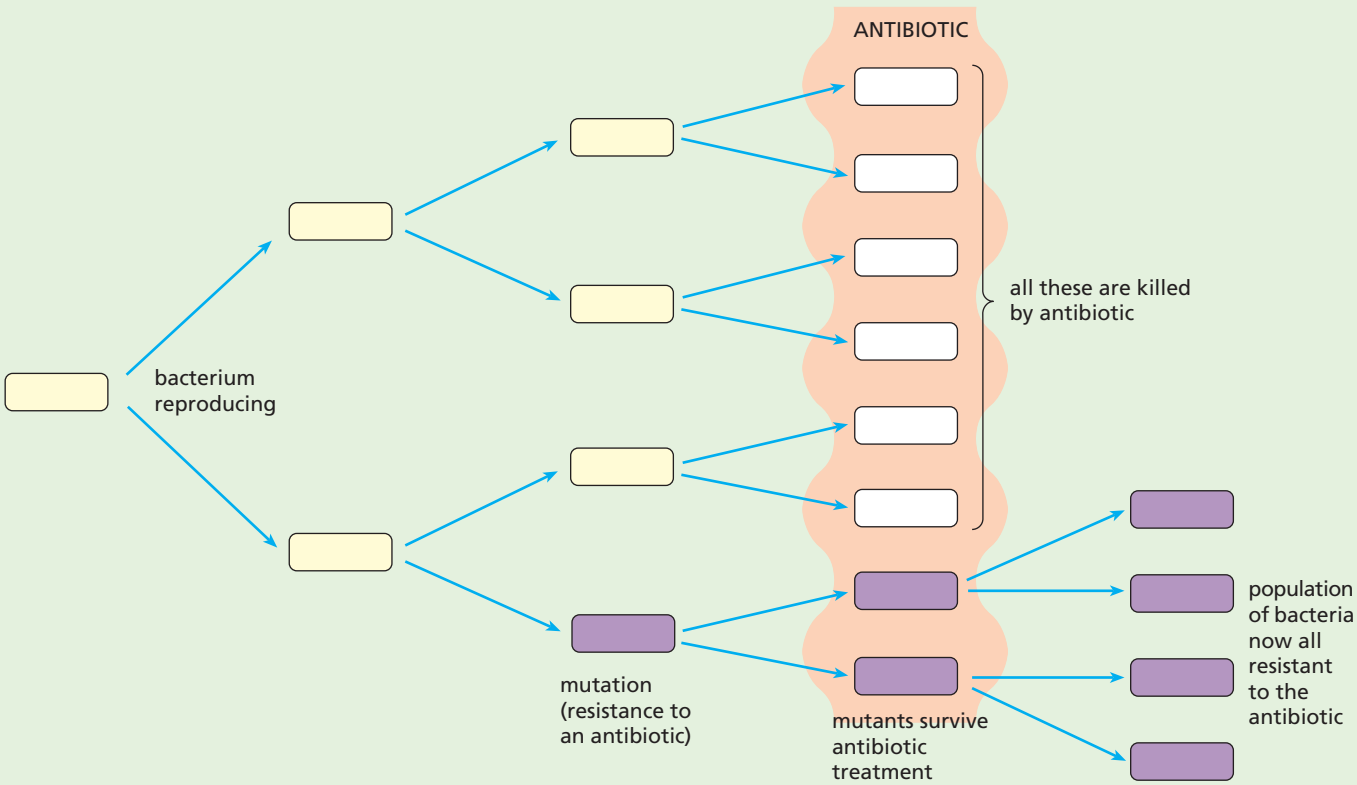



**Figure 15.1** Mutation in bacteria can lead to drug resistance

One type of bacteria that has developed resistance to a number of widely used antibiotics is called MRSA (methicillin-resistant *Staphylococcus aureus*). These types of bacteria are sometime referred to as 'superbugs' because they are so difficult to treat. *Staphylococcus aureus* is very common and is found living harmlessly on the skin, the nose and throat, sometimes causing mild infections. It becomes dangerous if there is a break in the skin, allowing it to infect internal organs and causing blood poisoning. This can happen in hospitals with infection during operations, especially if hygiene precautions are not adequate.

Doctors now have to be much more cautious about prescribing antibiotics, to reduce the risk of resistant strains developing. Patients need to be aware of the importance of completing a course of antibiotics, again to reduce the risk of development of resistant strains.

## Antibiotics and viral diseases

Antibiotics are not effective against viral diseases. This is because antibiotics work by disrupting structures in bacteria such as cell walls and membranes, or processes associated with protein synthesis and replication of DNA. Viruses have totally different characteristics to bacteria, so antibiotics do not affect them. Compare the image of a virus in Figure 1.34 with that of a bacterium in Figure 1.29.

# Extension work

## Ideas about antibiotics

### Alexander Fleming (1881–1955)

Before 1934 there were few effective drugs. Some herbal preparations may have been useful; after all, many of our present-day drugs are derived from or based on plant products. Quinine, for example, was used for the treatment of malaria and was extracted from a specific kind of tree bark.

In 1935, a group of chemicals called **sulfanilamides** were found to be effective against some bacterial diseases such as blood poisoning, pneumonia and septic wounds.

Fleming had discovered penicillin in 1928, 7 years before the use of sulfanilamides, but he had been unable to purify it and test it on humans. Fleming was a bacteriologist working at St Mary's Hospital in London. In 1928, he was studying different strains of *Staphylococcus* bacteria. He had made some cultures on agar plates and left them on the laboratory bench during a 4-week holiday. When he returned he noticed that one of the plates had been contaminated by a mould fungus and that around the margins of the mould there was a clear zone with no bacteria growing (Figure 15.2).

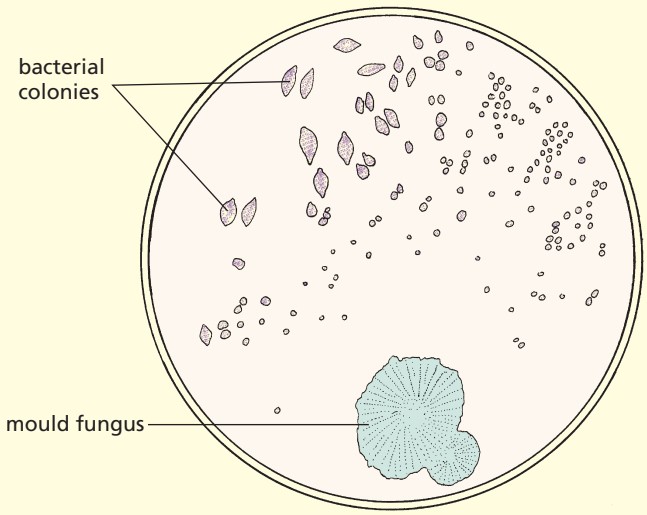



**Figure 15.2** Appearance of the *Staphylococcus* colonies on Fleming's petri dish

Fleming reasoned that a substance had diffused out of the mould colony and killed the bacteria. The mould was identified as *Penicillium notatum* and the supposed anti-bacterial chemical was called penicillin. Fleming went on to culture the *Penicillium* on a liquid meat broth medium and showed that the broth contained penicillin, which suppressed the growth of a wide range of bacteria.

Two research assistants at St Mary's then tried to obtain a pure sample of penicillin, free from all the other substances in the broth. Although they succeeded, the procedure was cumbersome and the product was unstable. By this time, Fleming seemed to have lost interest and to assume that penicillin would be too difficult to extract and too unstable to be of medical value.

In 1939, **Howard Florey** (a pathologist) and **Ernst Chain** (a biochemist), working at Oxford University, succeeded in preparing reasonably pure penicillin and making it stable. Techniques of extraction had improved dramatically in 10 years and, in particular, freeze-drying enabled a stable water-soluble powder form of penicillin to be produced.

World War II was an urgent incentive for the production of penicillin in large quantities and this undoubtedly saved many lives that would otherwise have been lost as a result of infected wounds.

Once Ernst Chain had worked out the molecular structure of penicillin, it became possible to modify it chemically and produce other forms of penicillin that attacked a different range of bacteria or had different properties. For example, ampicillin is a modified penicillin that can be taken by mouth rather than by injection.

Because penicillin was the product of a mould, chemists searched for other moulds, particularly those present in the soil, which might produce antibiotics. A large number of these were discovered, including streptomycin (for tuberculosis), chloramphenicol (for typhoid), aureomycin and terramycin (broad spectrum antibiotics, which attack a wide range of bacteria). The ideal drug is one that kills or suppresses the growth of harmful cells, such as bacteria or cancer cells, without damaging the body cells. Scientists have been trying for years to find a 'magic bullet' that 'homes in' exclusively on its target cells. For bacterial diseases, antibiotics come pretty close to the ideal, though the bacteria do seem able to develop resistant forms after a few years.

# Misused drugs

## Narcotics

Heroin, morphine and codeine belong to a group of drugs called **narcotics**, made from opium. Heroin and morphine act as powerful depressants: they relieve severe pain and produce short-lived feelings of wellbeing and freedom from anxiety. They can both lead to tolerance and physical dependence within weeks, so they are prescribed with caution, to patients in severe pain.

The illegal use of heroin has terrible effects on the unfortunate addict. The overwhelming dependence on the drug leads many addicts into prostitution and crime in order to obtain the money to buy it.

There are severe withdrawal symptoms when an addict tries to give up the drug abruptly. These symptoms are called going 'cold turkey' and can include anxiety, muscle aches, sweating, abdominal cramping, diarrhoea, nausea and vomiting. A 'cure' is a long and often unsuccessful process.

Additional hazards are that blood poisoning, hepatitis and AIDS may result from the use of unsterilised needles when injecting the drug.

Codeine is a less effective analgesic than morphine, but does not lead so easily to dependence. It is still addictive if used in large enough doses.

## Alcohol

The alcohol in wines, beer and spirits is a depressant of the central nervous system. Small amounts give a sense of wellbeing, with a release from anxiety. However, this is accompanied by a fall-off in performance in any activity requiring skill. It also gives a misleading sense of confidence in spite of the fact that one's judgement is clouded. A drunken driver usually thinks he or she is driving extremely well.

Even a small amount of alcohol in the blood increases our reaction time (the interval between receiving a stimulus and making a response). In some people, the reaction time is doubled even when the alcohol in the blood is well below the legal limit laid down for car drivers (Figure 15.3). This can make a big difference to the time needed for a driver to apply the brakes after seeing a hazard such as a child running into the road.

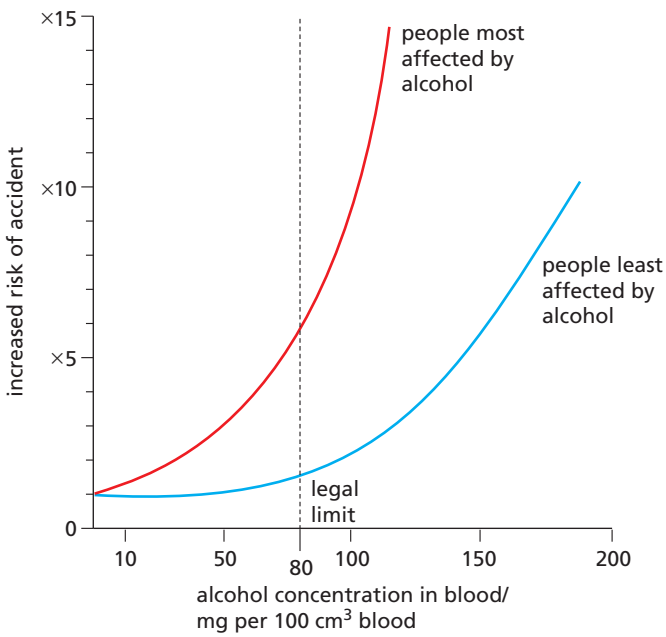



**Figure 15.3** Increased risk of accidents after drinking alcohol. People vary in their reactions to alcohol. Body weight, for example, makes a difference.

Alcohol causes vasodilation in the skin, giving a sensation of warmth but in fact leading to a greater loss of body heat (see 'Homeostasis' in Chapter 14). A concentration of 500 mg of alcohol in 100 $cm^3$ of blood results in unconsciousness. More than this will cause death because it stops the breathing centre in the brain. The liver treats alcohol as a toxin: 90% of alcohol taken in is **detoxified** in the liver (along with other toxins). The process of detoxification involves the oxidation of alcohol to carbon dioxide and water. Only 10% is excreted by the kidneys. On average, the liver can oxidise about 75 mg alcohol per 1 kg body weight per hour. This rate varies considerably from one individual to the next but it indicates that it would take about 3 hours to oxidise the alcohol in a pint of beer or a glass of wine. If the alcohol intake exceeds this rate of oxidation, the level of alcohol in the blood builds up to toxic proportions; that is, it leads to **intoxication**.

Some people build up a tolerance to alcohol and this may lead to both emotional and physical dependence (alcoholism). High doses of alcohol can cause the liver cells to form too many fat droplets, leading to the disease called **cirrhosis**. A cirrhotic liver is less able to stop poisonous substances in the intestinal blood from reaching the general circulation.

### Pregnancy

Drinking alcohol during pregnancy can present a major risk to the developing fetus. Further details are given in Chapter 16.

### Behaviour

Alcohol reduces inhibitions because it depresses that part of the brain which causes shyness. This may be considered an advantage in 'breaking the ice' at parties. But it can also lead to irresponsible behaviour such as vandalism and aggression.

### Moderate drinking

A moderate intake of alcoholic drink seems to do little physiological harm (except in pregnant women). But what is a 'moderate' intake?

A variety of drinks that all contain the same amount of alcohol is shown in Figure 15.4. Beer is a fairly dilute form of alcohol. Whisky, however, is about 40% alcohol. Even so, half a pint of beer contains the same amount of alcohol as a single whisky. This amount of alcohol can be called a 'unit'.

It is the number of units of alcohol, not the type of drink, which has a physiological effect on the body. In Britain, the Health Development Agency recommends upper limits of 21–28 units for men and 14–21 units for women over a 1-week period at the time of publication of this book. Pregnant women should avoid alcohol altogether.


**Figure 15.4** Alcohol content of drinks. All these drinks contain the same amount of alcohol (1 unit). Although the alcohol is more dilute in the beer than in the whisky, it has the same effect on the body.

## Smoking

The short-term effects of smoking cause the bronchioles to constrict and the cilia lining the air passages to stop beating. The smoke also makes the lining produce more mucus. **Nicotine**, the addictive component of tobacco smoke, produces an increase in the rate of the heartbeat and a rise in blood pressure. It may, in some cases, cause an erratic and irregular heart beat. Tar in cigarette smoke is thought to be the main cause of lung cancer in smokers. **Carbon monoxide** permanently binds with haemoglobin in red blood cells, reducing the smoker's ability to provide oxygen to respiring cells. This results in a smoker getting out of breath more easily and it reduces physical fitness.

The long-term effects of smoking may take many years to develop but they are severe, disabling and often lethal.

### Lung cancer

**Cancer** is a term used for diseases in which cells become abnormal and divide out-of-control. They can then move around the body and invade other tissues. A chemical that causes cancer is known as a **carcinogen**. Carcinogens present in cigarette smoke, such as tar, increase the risk of lung cells becoming cancerous. Tumours develop. These are balls of abnormal cells, which do not allow gaseous exchange like normal lung cells.

Many studies have now demonstrated how cigarette smoke damages lung cells, confirming that smoking does cause cancer. The higher the number of cigarettes smoked, the greater the risk of lung cancer.

### Chronic obstructive pulmonary disease (COPD)

This term covers a number of lung diseases, which include chronic bronchitis, emphysema and chronic obstructive airways disease. A person suffering from COPD will experience difficulties with breathing, mainly because of narrowing of the airways (bronchi and bronchioles). Symptoms of COPD include breathlessness when active, frequent chest infections and a persistent cough with phlegm (sticky mucus).

### Emphysema

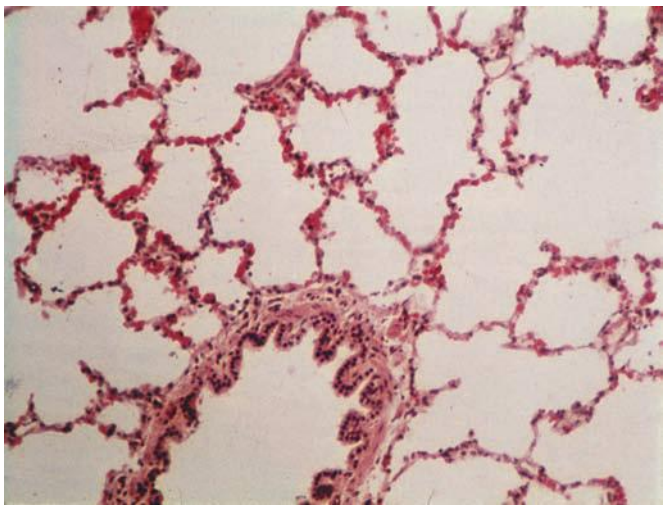
**Emphysema** is a breakdown of the alveoli. The action of one or more of the substances in tobacco smoke weakens the walls of the alveoli. The irritant substances in the smoke cause a 'smokers' cough' and the coughing bursts some of the weakened alveoli. In time, the absorbing surface of the lungs is greatly reduced (Figure 15.5). Then the smoker cannot oxygenate his or her blood properly and the least exertion makes the person breathless and exhausted.

### Chronic bronchitis

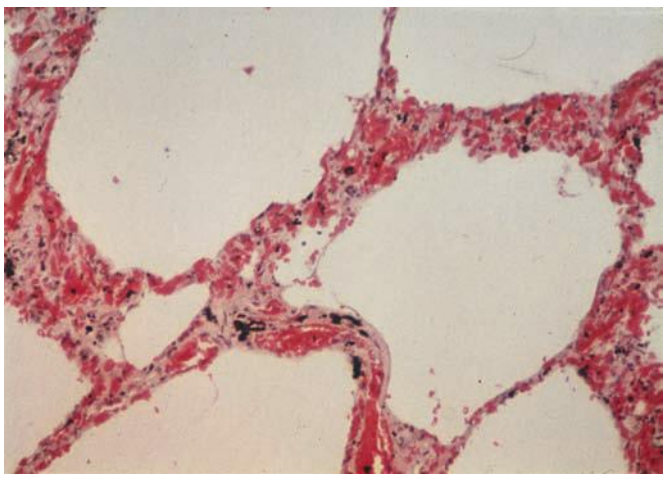
The smoke stops the cilia in the air passages from beating, so the irritant substances in the smoke and the excess mucus collect in the bronchi. This leads to inflammation known as **bronchitis**. Over 95% of people suffering from bronchitis are smokers and they have a 20 times greater chance of dying from bronchitis than non-smokers.

### Heart disease

**Coronary heart disease** is the leading cause of death in most developed countries. It results from a blockage of coronary arteries by fatty deposits. This reduces the supply of oxygenated blood to the heart muscle and sooner or later leads to heart failure (see Chapter 9). High blood pressure, diets with too much animal fat and lack of exercise are also thought to be causes of heart attack, but about a quarter of all deaths due to coronary heart disease are thought to be caused by smoking (see Figure 9.12).



**(a)** Normal lung tissue showing a bronchiole and about 20 alveoli (×200)



**(b)** Lung tissue from a person with emphysema. This is the same magnification as **(a)**. The alveoli have broken down leaving only about five air sacs, which provide a much reduced absorbing surface.

**Figure 15.5** Emphysema

The nicotine and carbon monoxide from cigarette smoke increase the tendency for the blood to clot and so block the coronary arteries, already partly blocked by fatty deposits. The carbon monoxide increases the rate at which the fatty material is deposited in the arteries.

## Other risks

About 95% of patients with disease of the leg arteries are cigarette smokers; this condition is the most frequent cause of leg amputations.

Strokes due to arterial disease in the brain are more frequent in smokers.

Cancer of the bladder, ulcers in the stomach and duodenum, tooth decay, gum disease and tuberculosis all occur more frequently in smokers.

Babies born to women who smoke during pregnancy are smaller than average, probably as a result of reduced oxygen supply caused by the carbon monoxide in the blood. In smokers, there is twice the frequency of miscarriages, a 50% higher still-birth rate and a 26% higher death rate of babies.

A recent estimate is that one in every three smokers will die as a result of their smoking habits. Those who do not die at an early age will probably be seriously disabled by one of the conditions described above.

## Passive smoking

It is not only the smokers themselves who are harmed by tobacco smoke. Non-smokers in the same room are also affected. One study has shown that children whose parents both smoke breathe in as much nicotine as if they were themselves smoking 80 cigarettes a year.

Statistical studies also suggest that the non-smoking wives of smokers have an increased chance of lung cancer.

## Reducing the risks

By giving up smoking, a person who smokes up to 20 cigarettes a day will, after 10 years, be at no greater risk than a non-smoker of the same age. A pipe or cigar smoker, provided he or she does not inhale, is at less risk than a cigarette smoker but still at greater risk than a non-smoker.

## How heroin affects the nervous system

As described in Chapter 14, heroin produces its effects by interacting with receptor molecules at synapses. Synapses are tiny gaps between neurones, across which electrical impulses cannot jump. To maintain the transmission of the impulse, a chemical messenger called a neurotransmitter is released into the gap. When it reaches the neurone on the other side, receptor molecules are stimulated to generate and release new electrical impulses. Heroin mimics the transmitter substances in synapses in the brain, causing the stimulation of receptor molecules. This causes the release of **dopamine** (a neurotransmitter), which gives a short-lived 'high'.

## Evidence for a link between smoking and lung cancer

Although all forms of air pollution are likely to increase the chances of lung cancer, many scientific studies show, beyond all reasonable doubt, that the vast increase in lung cancer (4000% in the last century) is almost entirely due to cigarette smoking (Figure 15.6).

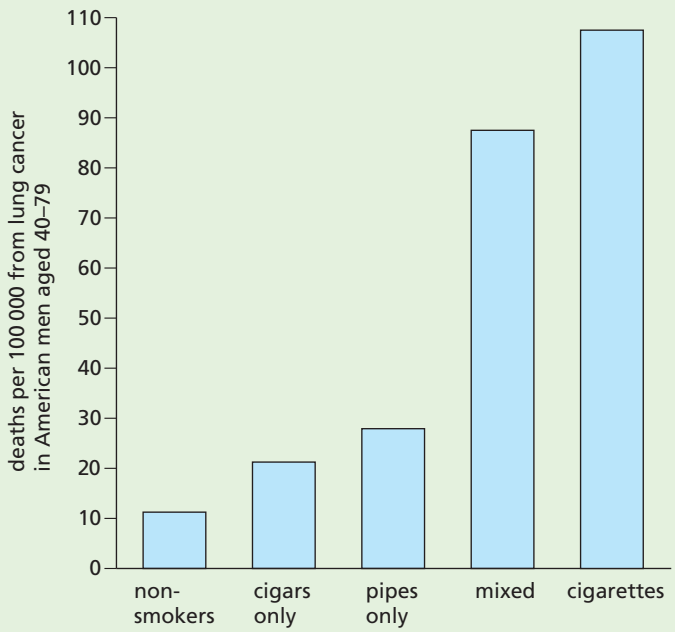



**Figure 15.6** Smoking and lung cancer. Cigar and pipe smokers are probably at less risk because they often do not inhale. But notice that their death rate from lung cancer is still twice that of non-smokers. They are also at risk of other cancers such as mouth and throat cancer.

There are at least 17 substances in tobacco smoke known to cause cancer in experimental animals, and it is now thought that 90% of lung cancer is caused by smoking. Table 15.1 shows the relationship between smoking cigarettes and the risk of developing lung cancer.

**Table 15.1** Cigarette smoking and lung cancer

| Number of cigarettes per day | Increased risk of lung cancer |
|---|---|
| 1–14 | ×8 |
| 15–24 | ×13 |
| 25+ | ×25 |

## Correlations and causes

In Chapter 9 it was explained that a correlation between two variables does not prove that one of the variables causes the other. The fact that a higher risk of dying from lung cancer is correlated with heavy smoking does not actually prove that smoking is the cause of lung cancer. The alternative explanation is that people who become heavy smokers are, in some way, exposed to other potential causes of lung cancer, e.g. they live in areas of high air pollution or they have an inherited tendency to cancer of the lung. These alternatives are not very convincing, particularly when there is such an extensive list of ailments associated with smoking.

This is not to say that smoking is the only cause of lung cancer or that everyone who smokes will eventually develop lung cancer. There are likely to be complex interactions between life-styles, environments and genetic backgrounds which could lead, in some cases, to lung cancer. Smoking may be only a part, but a very important part, of these interactions.

## Performance-enhancing hormones

In the last 30 years or so, some athletes and sports persons have made use of drugs to boost their performance. Some of these drugs are synthetic forms of hormones.

**Testosterone** is made in the testes of males and is responsible for promoting male primary and secondary sexual characteristics. Taking testosterone supplements (known as 'doping') leads to increased muscle and bone mass. The practice therefore has the potential to enhance a sportsperson's performance.

**Anabolic steroids** are synthetic derivatives of testosterone. They affect protein metabolism, increasing muscle development and reducing body fat. Athletic performance is thus enhanced. There are serious long-term effects of taking anabolic steroids. The list is a long one but the main effects are sterility, masculinisation in women, and liver and kidney malfunction.

An internationally famous athlete caught using performance enhancing drugs was Ben Johnson (Figure 15.7), who represented Canada as a sprinter. He gained medals in the 1987 World Championships and the 1988 Olympics, but these were withdrawn after a urine sample tested positive for anabolic steroids.


**Figure 15.7** Ben Johnson (in red) beating his arch rival Carl Lewis (in blue). Johnson would later be banned from international athletics for life for using anabolic steroids.

Because these drugs enhance performance beyond what could be achieved by normal training, they are deemed unfair and banned by most sports organisations. Anabolic steroids are universally banned but different sports regulatory bodies have different rules for other substances.

The products of the steroid hormones can be detected in the urine and this is the basis of most tests for banned substances. Without these regulations, sport would become a competition between synthetic chemical substances rather than between individuals and teams.

## Questions

Core

1 Why are doctors concerned about the over-use of antibiotics?
2 List at least four effects of the excessive consumption of alcohol.
3 Find out the cost of a packet of 20 cigarettes. If a person smokes 20 cigarettes a day, how much would this cost in a year?

Extended

4 What are:
   a the immediate effects and
   b the long-term effects
   of tobacco smoke on the trachea, bronchi and lungs?
5 Why does a regular smoker get out of breath sooner than a non-smoker of similar age and build?
6 If you smoke 20 cigarettes a day, by how much are your chances of getting lung cancer increased?
7 Apart from lung cancer, what other diseases are probably caused by smoking?

## Checklist

After studying Chapter 15 you should know and understand the following:

- A drug is any substance taken into the body that modifies or affects chemical reactions in the body.
- Antibiotics are used in the treatment of bacterial infections.
- Some bacteria become resistant to antibiotics, which reduces their effectiveness.
- Antibiotics kill bacteria but not viruses.
- It is possible to minimise the development of resistant bacteria such as MRSA.
- Viruses have a different structure to bacteria, so they are not affected by antibiotics.
- Smoking and excessive drinking contribute to ill-health.
- Mood-influencing drugs may be useful for treating certain illnesses but are dangerous if used for other purposes.
- Tolerance means that the body needs more and more of a particular drug to produce the same effect.
- Dependence means that a person cannot do without a particular drug.
- Withdrawal symptoms are unpleasant physical effects experienced by an addict when the drug is not taken.
- Tobacco smoke affects the gaseous exchange system because it contains toxic components.
- Alcohol is a depressant drug, which slows down reaction time and reduces inhibitions.
- Alcohol in a pregnant woman's blood can damage her fetus.
- The liver is the site of breakdown of alcohol and other toxins.
- Heroin is a strongly addictive drug, which affects the nervous system.
- There is now strong enough evidence to provide a link between smoking and lung cancer.
- Some hormones are used to improve sporting performance.

# 16 Reproduction

**Asexual reproduction**
Define asexual reproduction
Examples of asexual reproduction

Advantages and disadvantages of asexual reproduction

**Sexual reproduction**
Define sexual reproduction and fertilisation

Haploid and diploid cells
Advantages and disadvantages of sexual reproduction

**Sexual reproduction in plants**
Parts of insect-pollinated and wind-pollinated flowers and their functions
Define pollination
Fertilisation
Adaptations of insect-pollinated and wind-pollinated flowers
Investigate conditions needed for germination

Define self-pollination and cross-pollination
Implications of self-pollination to a species
Growth of pollen tube and fertilisation

**Sexual reproduction in humans**
Parts of male and female reproductive systems
Describe fertilisation
Adaptive features of sperm and eggs
Development of embryo
Growth and development of fetus
Antenatal care
Labour and birth

Compare male and female gametes
Functions of the placenta and umbilical cord
Passage of toxins and viruses across placenta
Comparing breast feeding and bottle feeding

**Sex hormones in humans**
Puberty, hormones and secondary sexual characteristics
Menstrual cycle

Sites of production and roles of hormones related to menstrual cycle and pregnancy

**Methods of birth control in humans**
Methods of birth control

Use of hormones in fertility treatment and contraception
Artificial insemination
*In vitro* fertilisation
Social implications of contraception and fertility treatments

**Sexually transmitted infections (STIs)**
Define sexually transmitted infection
HIV
Spread and control of STIs

How HIV affects the immune system

No organism can live for ever, but part of it lives on in its offspring. Offspring are produced by the process of reproduction. This process may be **sexual** or **asexual**, but in either case it results in the continuation of the species.

## Asexual reproduction

**Key definition**
**Asexual reproduction** is the process resulting in the production of genetically identical offspring from one parent.

Asexual means 'without sex' and this method of reproduction does not involve gametes (sex cells). In the single-celled protoctista or in bacteria, the cell simply divides into two and each new cell becomes an independent organism.

In more complex organisms, part of the body may grow and develop into a separate individual. For example, a small piece of stem planted in the soil may form roots and grow into a complete plant.

**Bacteria** reproduce by cell division or **fission**. Any bacterial cell can divide into two and each daughter cell becomes an independent bacterium (Figure 1.31). In some cases, this cell division can take place every 20 minutes so that, in a very short time, a large colony of bacteria can be produced. This is one reason why a small number of bacteria can seriously contaminate our food products (see Chapter 10). This kind of reproduction, without the formation of gametes (sex cells), is called **asexual reproduction**.

### Asexual reproduction in fungi

Fungi have sexual and asexual methods of reproduction. In the asexual method they produce single-celled, haploid spores. These are dispersed, often by air currents and, if they reach a suitable situation, they grow new hyphae, which develop into a mycelium (see Figures 1.25 and 1.26).

*Penicillium* and *Mucor* are examples of mould fungi that grow on decaying food or vegetable matter. *Penicillium* is a genus of mould fungi that grows on decaying vegetable matter, damp leather

and citrus fruits. The mycelium grows over the food, digesting it and absorbing nutrients. Vertical hyphae grow from the mycelium and, at their tips, produce chains of spores (Figures 16.1 and 16.2). These give the colony a blue-green colour and a powdery appearance (see Figure 19.17). The spores are dispersed by air currents and, if they reach a suitable substrate, grow into a new mycelium.

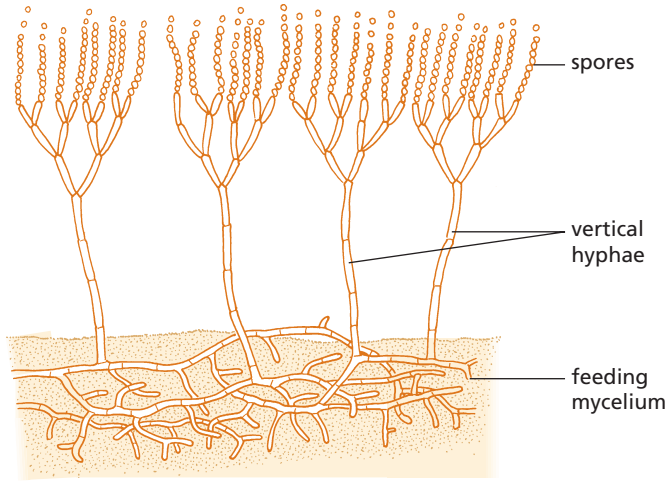



**Figure 16.1** *Penicillium sp.*

**Figure 16.2** Scanning electron micrograph of *Penicillium* spores

*Mucor* feeds, grows and reproduces in a similar way to *Penicillium*, but *Mucor* produces spores in a slightly different way. Instead of chains of spores at the tips of the vertical hyphae, *Mucor* forms spherical sporangia, each containing hundreds of spores (Figure 16.3). These are dispersed on the feet of insects or by the splashes of rain drops.

The gills on the underside of a mushroom or toadstool (Figures 16.4 and 16.5) produce spores. Puffballs release clouds of spores (Figure 16.6).

**Figure 16.3** Asexual reproduction in *Mucor*. The black spheres are sporangia that have not yet discharged their spores (×160).

**Figure 16.4** Toadstools growing on a fallen tree. The toadstools are the reproductive structures that produce spores. The feeding hyphae are inside the tree, digesting the wood.

**Figure 16.5** A bracket fungus. The 'brackets' are the reproductive structures. The mycelium in the trunk feeds on living tissue and will eventually kill the tree.

**Figure 16.6** Puffball dispersing spores. When a raindrop hits the ripe puffball, a cloud of spores is ejected.

**Figure 16.7** Bryophyllum. The plantlets are produced from the leaf margin. When they fall to the soil below, they grow into independent plants.

## Asexual reproduction in flowering plants (vegetative propagation)

Although all flowering plants reproduce sexually (that is why they have flowers), many of them also have asexual methods.

Several of these asexual methods (also called '**vegetative propagation**') are described below. When vegetative propagation takes place naturally, it usually results from the growth of a lateral bud on a stem which is close to, or under, the soil. Instead of just making a branch, the bud produces a complete plant with roots, stem and leaves. When the old stem dies, the new plant is independent of the parent that produced it.

An unusual method of vegetative propagation is shown by Bryophyllum (Figure 16.7).

### Stolons and rhizomes

The flowering shoots of plants such as the strawberry and the creeping buttercup are very short and, for the most part, below ground. The stems of shoots such as these are called **rootstocks**. The rootstocks bear leaves and flowers. After the main shoot has flowered, the lateral buds produce long shoots, which grow horizontally over the ground (Figure 16.8). These shoots are called **stolons** (or 'runners'), and have only small, scale-leaves at their nodes and very long internodes. At each node there is a bud that can produce not only a shoot, but roots as well. Thus a complete plant may develop and take root at the node, nourished for a time by food sent from the parent plant through the stolon. Eventually, the stolon dries up and withers, leaving an independent daughter plant growing a short distance away from the parent. In this way a strawberry plant can produce many daughter plants by vegetative propagation in addition to producing seeds.

In many plants, horizontal shoots arise from lateral buds near the stem base, and grow under the ground. Such underground horizontal stems are called **rhizomes**. At the nodes of the rhizome are buds, which may develop to produce shoots above the ground. The shoots become independent plants when the connecting rhizome dies.

Many grasses propagate by rhizomes; the couch grass (Figure 16.9) is a good example. Even a small piece of rhizome, provided it has a bud, can produce a new plant.

In the bracken, the entire stem is horizontal and below ground. The bracken fronds you see in summer are produced from lateral buds on a rhizome many centimetres below the soil.

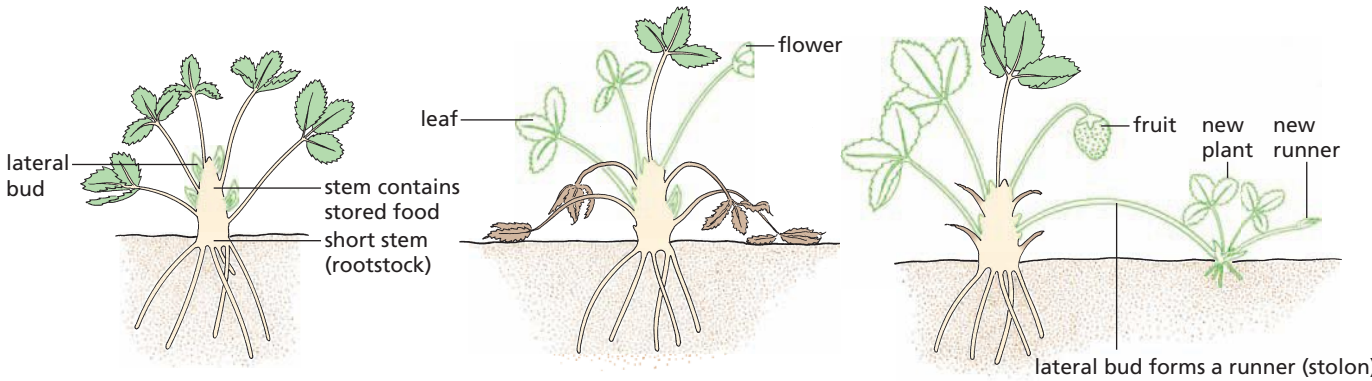



**Figure 16.8** Strawberry runner developing from rootstock

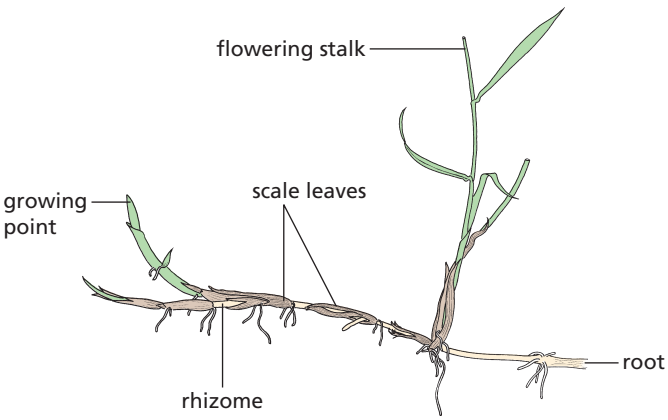



**Figure 16.9** Couch grass rhizome

## Bulbs and corms

**Bulbs** such as those of the daffodil and snowdrop are very short shoots. The stem is only a few millimetres long and the leaves which encircle the stem are thick and fleshy with stored food.

In spring, the stored food is used by a rapidly growing terminal bud, which produces a flowering stalk and a small number of leaves. During the growing season, food made in the leaves is sent to the leaf bases and stored. The leaf bases swell and form a new bulb ready for growth in the following year.

Vegetative reproduction occurs when some of the food is sent to a lateral bud as well as to the leaf bases. The lateral bud grows inside the parent bulb and, next year, will produce an independent plant (Figure 16.10).

The **corms** of crocuses and anemones have life cycles similar to those of bulbs but it is the stem, rather than the leaf bases, which swells with stored food. Vegetative reproduction takes place when a lateral bud on the short, fat stem grows into an independent plant.

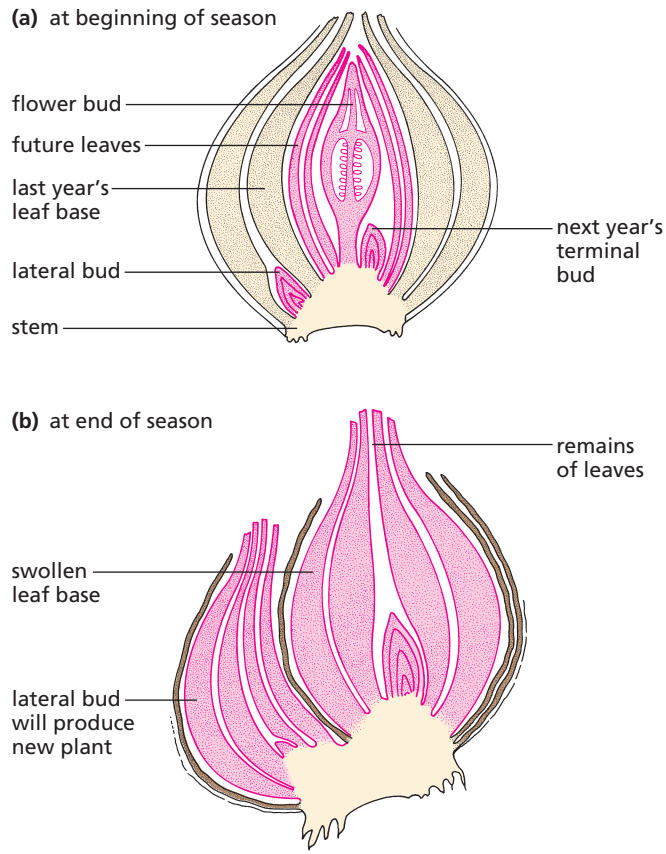



**Figure 16.10** Daffodil bulb; vegetative reproduction

In many cases the organs associated with asexual reproduction also serve as food stores. Food in the storage organs enables very rapid growth in the spring. A great many of the spring and early summer plants have bulbs, corms, rhizomes or tubers: daffodil, snowdrop and bluebell, crocus and cuckoo pint, iris and lily-of-the-valley and lesser celandine.

Potatoes are **stem tubers**. Lateral buds at the base of the potato shoot produce underground shoots

(rhizomes). These rhizomes swell up with stored starch and form tubers (Figure 16.11(a)). Because the tubers are stems, they have buds. If the tubers are left in the ground or transplanted, the buds will produce shoots, using food stored in the tuber (Figure 16.11(b)). In this way, the potato plant can propagate vegetatively.

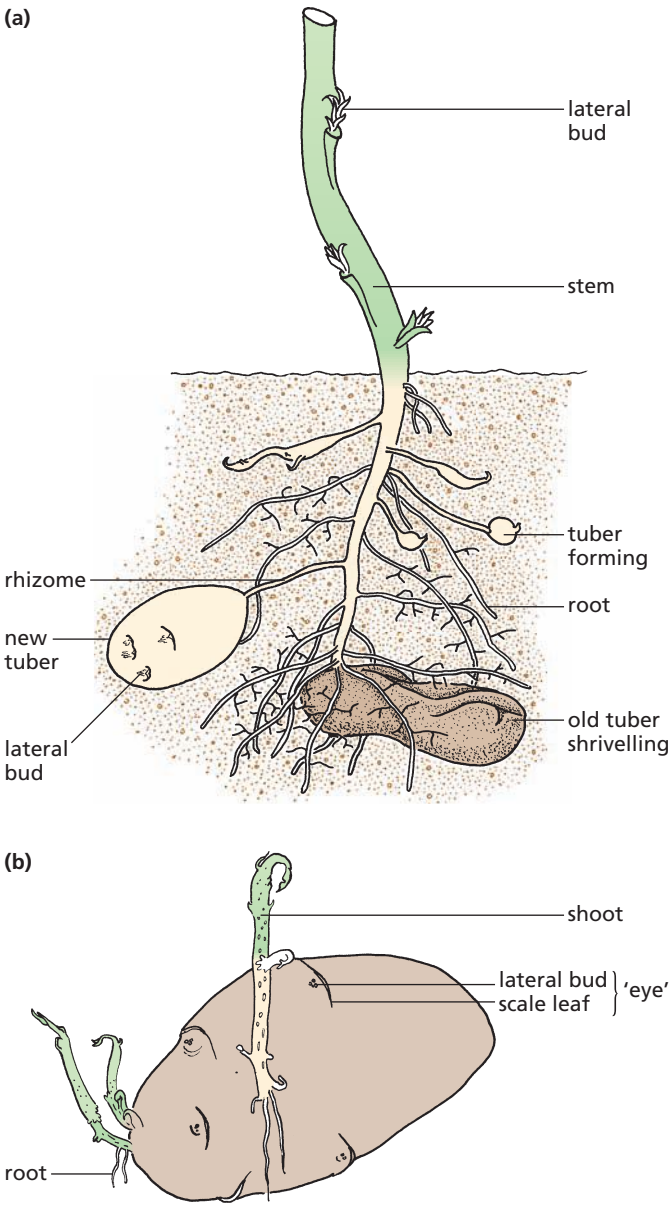



**Figure 16.11** Stem tubers growing on a potato plant and a potato tuber sprouting

## Artificial propagation

Agriculture and horticulture exploit vegetative reproduction in order to produce fresh stocks of plants. This can be done naturally, e.g. by planting potatoes, dividing up rootstocks or pegging down stolons at their nodes to make them take root. There are also methods that would not occur naturally in the plant's life cycle. Two methods of **artificial propagation** are by taking cuttings and by tissue culture.

### Cuttings

It is possible to produce new individuals from certain plants by putting the cut end of a shoot into water or moist earth. Roots (Figure 16.12) grow from the base of the stem into the soil while the shoot continues to grow and produce leaves.

**(a)** **roots** developing from Busy Lizzie stem

**(b)** **roots** growing from Coleus cutting

**Figure 16.12** Rooted cuttings

In practice, the cut end of the stem may be treated with a rooting 'hormone' (a type of auxin – see 'Tropic responses' in Chapter 14) to promote root growth, and evaporation from the shoot is reduced by covering it with polythene or a glass jar. Carnations, geraniums and chrysanthemums are commonly propagated from cuttings.

### Tissue culture

Once a cell has become part of a tissue it usually loses the ability to reproduce. However, the nucleus of any cell in a plant still holds all the 'instructions' (Chapter 17) for making a complete plant and in certain circumstances they can be brought back into action.

In laboratory conditions, single plant cells can be induced to divide and grow into complete plants. One technique is to take small pieces of plant tissue

from a root or stem and treat it with enzymes to separate it into individual cells. The cells are then provided with particular plant 'hormones', which induce cell division and, eventually, the formation of roots, stems and leaves.

An alternative method is to start with a small piece of tissue and place it on a nutrient jelly. Cells in the tissue start to divide and produce many cells, forming a shapeless mass called a **callus**. If the callus is then provided with the appropriate hormones it develops into a complete plant (Figure 16.13).

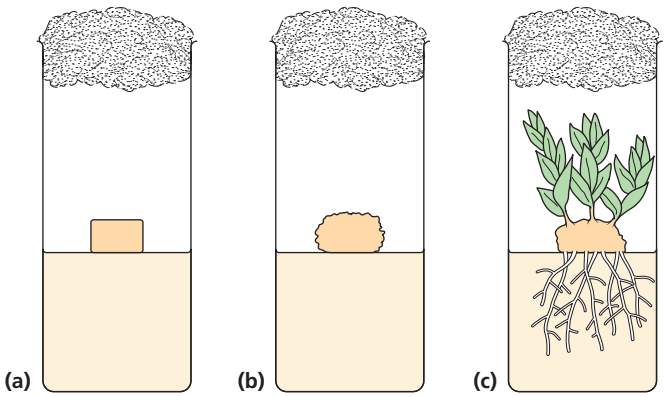



**Figure 16.13** Propagation by tissue culture using nutrient jelly

Using the technique of tissue culture, large numbers of plants can be produced from small amounts of tissue (Figure 16.14) and they have the advantage of being free from fungal or bacterial infections. The plants produced in this way form **clones**, because they have been produced from a single parent plant.

**Figure 16.14** Tissue culture. Plants grown from small amounts of unspecialised tissue on an agar culture medium

## Asexual reproduction in animals

Some species of invertebrate animals are able to reproduce asexually.

*Hydra* is a small animal, 5–10 mm long, which lives in ponds attached to pondweed. It traps small animals with its tentacles, swallows and digests them. *Hydra* reproduces sexually by releasing its male and female gametes into the water but it also has an asexual method, which is shown in Figure 16.15.

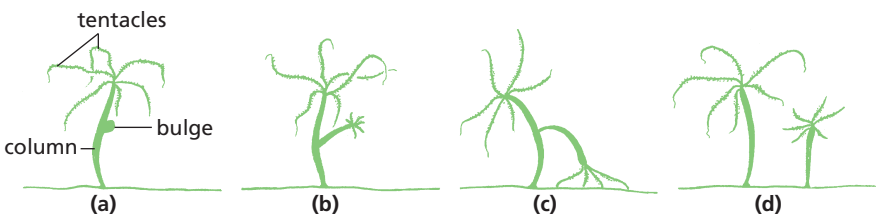



**Figure 16.15** Asexual reproduction in *Hydra*

**(a)** a group of cells on the column start dividing rapidly and produce a bulge

**(b)** the bulge develops tentacles

**(c)** the daughter *Hydra* pulls itself off the parent

**(d)** the daughter becomes an independent animal

**(e)** *Hydra* with bud

## The advantages and disadvantages of asexual reproduction

The advantages and disadvantages of asexual reproduction discussed below are in the context of flowering plants. However, the points made are equally applicable to most forms of asexual reproduction.

In asexual reproduction no gametes are involved and all the new plants are produced by cell division ('Mitosis', Chapter 17) from only one parent. Consequently they are genetically identical; there is no variation. A population of genetically identical individuals produced from a single parent is called a clone. This has the advantage of preserving the 'good' characteristics of a successful species from generation to generation. The disadvantage is that there is no variability for natural selection (Chapter 18) to act on in the process of evolution.

In **agriculture** and **horticulture**, asexual reproduction (vegetative propagation) is exploited to preserve desirable qualities in crops: the good characteristics of the parent are passed on to all the offspring. With a flower such as a daffodil, the bulbs produced can be guaranteed to produce the same shape and colour of flower from one generation to the next. In some cases, such as tissue culture, the young plants grown can be transported much more cheaply than, for example, potato tubers as the latter are much heavier and more bulky. Growth of new plants by asexual reproduction tends to be a quick process.

In natural conditions in the wild it might be a disadvantage to have no variation in a species. If the climate or other conditions change and a vegetatively produced plant has no resistance to a particular disease, the whole population could be wiped out.

### Dispersal

A plant that reproduces vegetatively will already be growing in a favourable situation, so all the offspring will find themselves in a suitable environment. However, there is no vegetative dispersal mechanism and the plants will grow in dense colonies, competing with each other for water and minerals. The dense colonies, on the other hand, leave little room for competitors of other species.

As mentioned before, most plants that reproduce vegetatively also produce flowers and seeds. In this way they are able to colonise more distant habitats.

### Food storage

The store of food in tubers, tap roots, bulbs, etc. enables the plants to grow rapidly as soon as conditions become favourable. Early growth enables the plant to flower and produce seeds before competition with other plants (for water, mineral salts and light) reaches its maximum. This must be particularly important in woods where, in summer, the leaf canopy prevents much light from reaching the ground and the tree roots tend to drain the soil of moisture over a wide area.

**Table 16.1** Summary: advantages and disadvantages of asexual reproduction

| Advantages | Disadvantages |
|---|---|
| No mate is needed.<br>No gametes are needed.<br>All the good characteristics of the parent are passed on to the offspring.<br>Where there is no dispersal (e.g. with potato tubers), offspring will grow in the same favourable environment as the parent.<br>Plants that reproduce asexually usually store large amounts of food that allow rapid growth when conditions are suitable. | There is little variation created, so adaptation to a changing environment (evolution) is unlikely.<br>If the parent has no resistance to a particular disease, none of the offspring will have resistance.<br>Lack of dispersal (e.g. with potato tubers) can lead to competition for nutrients, water and light. |

# Sexual reproduction

**Key definitions**

**Sexual reproduction** is a process involving the fusion of two gametes (sex cells) to form a zygote and the production of offspring that are genetically different from each other.

**Fertilisation** is the fusion of gamete nuclei.

The following statements apply equally to plants and animals. Sexual reproduction involves the production of sex cells. These sex cells are called **gametes** and they are made in reproductive organs. The process of cell division that produces the gametes is called **meiosis** (Chapter 17). In sexual reproduction, the male and female gametes come together and **fuse**, that is, their cytoplasm and nuclei

join together to form a single cell called a **zygote**. The zygote then grows into a new individual (see Figure 16.30).

In flowering plants the male gametes are found in pollen grains and the female gametes, called **egg cells**, are present in **ovules**. In animals, male gametes are sperm and female gametes are eggs. Details of **fertilisation** are given later in this chapter.

In both plants and animals, the male gamete is microscopic and mobile (i.e. can move from one place to another). The sperm swim to the ovum; the pollen cell moves down the pollen tube (Figure 16.16). The female gametes are always larger than the male gametes and are not mobile. Pollination in seed-bearing plants and mating in most animals bring the male and female gametes close together.

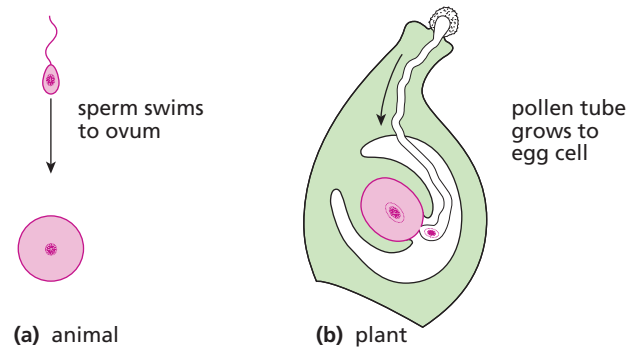



**Figure 16.16** The male gamete is small and mobile; the female gamete is larger.

## Chromosome numbers

In normal body cells (somatic cells) the chromosomes are present in the nucleus in pairs. Humans, for example, have 46 chromosomes: 23 pairs. Maize (sweetcorn) has 10 pairs. This is known as the **diploid** number. When gametes are formed, the number of chromosomes in the nucleus of each sex cell is halved. This is the **haploid** number. During fertilisation, when the nuclei of the sex cells fuse, a zygote is formed. It gains the chromosomes from both gametes, so it is a diploid cell (see Chapter 17).

## The advantages and disadvantages of sexual reproduction

In plants, the gametes may come from the same plant or from different plants of the same species. In either case, the production and subsequent fusion of gametes produce a good deal of variation among the offspring (see Chapter 18). This may result from new combinations of characteristics, e.g. petal colour of one parent combined with fruit size of the other. It may also be the result of spontaneous changes in the gametes when they are produced.

Variation can have its disadvantages: some combinations will produce less successful individuals. On the other hand, there are likely to be some more successful combinations that have greater survival value or produce individuals which can thrive in new or changing environments.

In a population of plants that have been produced sexually, there is a chance that at least some of the offspring will have resistance to disease. These plants will survive and produce further offspring with disease resistance.

The seeds produced as a result of sexual reproduction will be scattered over a relatively wide range. Some will land in unsuitable environments, perhaps lacking light or water. These seeds will fail to germinate. Nevertheless, most methods of seed dispersal result in some of the seeds establishing populations in new habitats.

The seeds produced by sexual reproduction all contain some stored food but it is quickly used up during germination, which produces only a miniature plant. It takes a long time for a seedling to become established and eventually produce seeds of its own.

Sexual reproduction is exploited in agriculture and horticulture to produce new varieties of animals and plants by cross-breeding.

## Cross-breeding

It is possible for biologists to use their knowledge of genetics (see 'Monohybrid inheritance' in Chapter 17) to produce new varieties of plants and animals. For example, suppose one variety of wheat produces a lot of grain but is not resistant to a fungus disease. Another variety is resistant to the disease but has only a poor yield of grain. If these two varieties are cross-pollinated (Figure 16.17), the $F_1$ (which means 'first filial generation') offspring should be disease-resistant and give a good yield of grain (assuming that the useful characteristics are controlled by dominant genes).

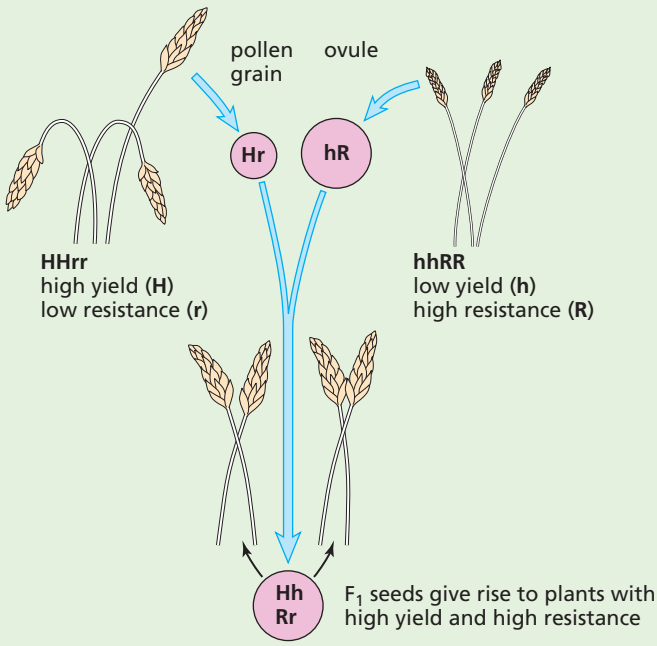



**Figure 16.17** Combining useful characteristics

A long-term disadvantage of selective breeding is the loss of variability. By eliminating all the offspring who do not bear the desired characteristics, many genes are lost from the population. At some future date, when new combinations of genes are sought, some of the potentially useful ones may no longer be available.

You will find more information on cross-breeding in 'Selection', Chapter 18.

**Table 16.2** Summary: advantages and disadvantages of sexual reproduction

| Advantages | Disadvantages |
|---|---|
| There is variation in the offspring, so adaptation to a changing or new environment is likely, enabling survival of the species.<br>New varieties can be created, which may have resistance to disease.<br>In plants, seeds are produced, which allow dispersal away from the parent plant, reducing competition. | Two parents are usually needed (though not always – some plants can self-pollinate).<br>Growth of a new plant to maturity from a seed is slow. |

# Sexual reproduction in plants

Flowers are reproductive structures; they contain the reproductive organs of the plant. The male organs are the **stamens**, which produce pollen. The female organs are the **carpels**. After fertilisation, part of the carpel becomes the fruit of the plant and contains the seeds. In the flowers of most plants there are both stamens and carpels. These flowers are, therefore, both male and female, a condition known as **bisexual** or **hermaphrodite**.

Some species of plants have unisexual flowers, i.e. any one flower will contain either stamens or carpels but not both. Sometimes both male and female flowers are present on the same plant, e.g. the hazel, which has male and female catkins on the same tree. In the willow tree, on the other hand, the male and female catkins are on different trees.

The male gamete is a cell in the pollen grain. The female gamete is an egg cell in the ovule. The process that brings the male gamete within reach of the female gamete (i.e. from stamen to stigma) is called **pollination**. The pollen grain grows a microscopic tube, which carries the male gamete the last few millimetres to reach the female gamete for fertilisation. The zygote then grows to form the seed. These processes are all described in more detail later in this chapter.

## Flower structure

The basic structure of a flower is shown in Figures 16.18 and 16.21.

### Petals

**Petals** are usually brightly coloured and sometimes scented. They are arranged in a circle (Figure 16.18) or a cylinder. Most flowers have from four to ten petals. Sometimes they are joined together to form a tube (Figures 16.20 and 16.21) and the individual petals can no longer be distinguished. The colour and scent of the petals attract insects to the flower; the insects may bring about pollination.

The flowers of grasses and many trees do not have petals but small, leaf-like structures that enclose the reproductive organs (Figures 16.28 and 16.29).

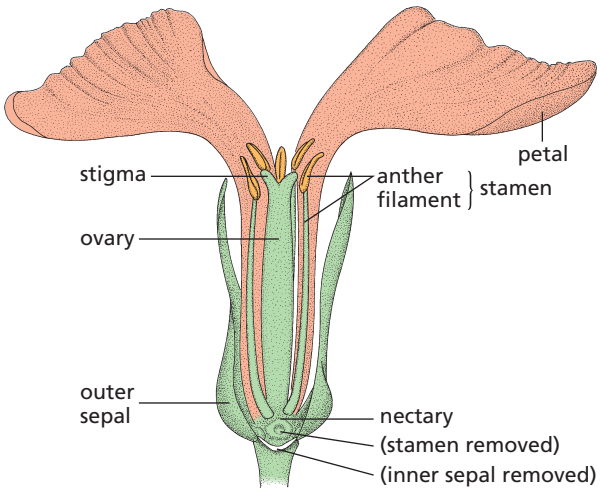



**Figure 16.18** Wallflower; structure of flower (one sepal, two petals and stamen removed)

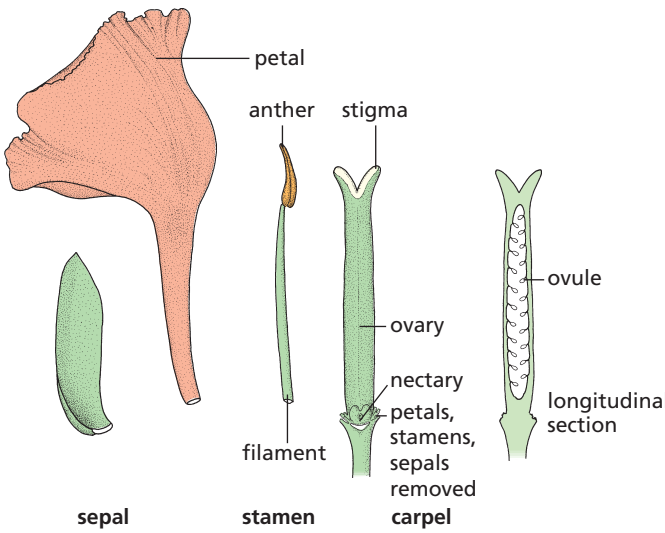



**Figure 16.19** Floral parts of wallflower

**Figure 16.20** Daffodil flower cut in half. The inner petals form a tube. Three stamens are visible round the long style and the ovary contains many ovules.

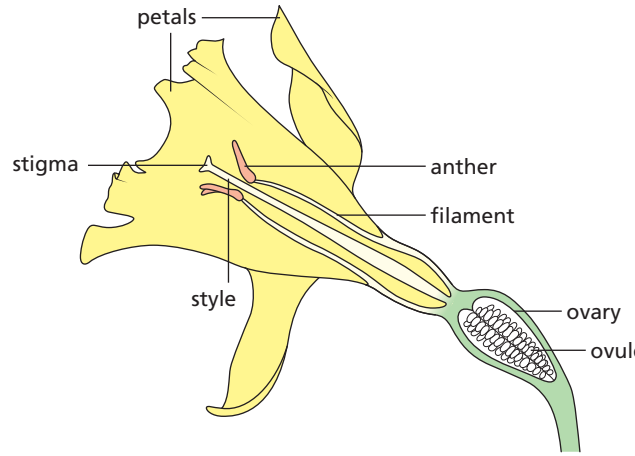



**Figure 16.21** Daffodil flower. Outline drawing of Figure 16.20. In daffodils, lilies, tulips, etc. (monocots) there is no distinction between sepals and petals.

### Sepals

Outside the petals is a ring of **sepals**. They are often green and much smaller than the petals. They may protect the flower when it is in the bud.

### Stamens

The stamens are the male reproductive organs of a flower. Each stamen has a stalk called the **filament**, with an **anther** on the end. Flowers such as the buttercup and blackberry have many stamens; others such as the tulip have a small number, often the same as, or double, the number of petals or sepals. Each anther consists of four **pollen sacs** in which the pollen grains are produced by cell division. When the anthers are ripe, the pollen sacs split open and release their pollen (see Figure 16.26).

### Pollen

Insect-pollinated flowers tend to produce smaller amounts of pollen grains (Figure 16.22(a)), which are often round and sticky, or covered in tiny spikes to attach to the furry bodies of insects.

Wind-pollinated flowers tend to produce larger amounts of smooth, light pollen grains (Figure 16.22(b)), which are easily carried by the wind. Large amounts are needed because much of the pollen is lost: there is a low chance of it reaching another flower of the same species.

### Carpels

These are the female reproductive organs. Flowers such as the buttercup and blackberry have a large number of carpels while others, such as the lupin, have a single carpel. Each carpel consists of an **ovary**, bearing a **style** and a **stigma**.

**(a)** insect-borne pollen grains **(b)** wind-borne pollen grains

**Figure 16.22** Pollen grains

Inside the ovary there are one or more ovules. Each blackberry ovary contains one ovule but the wallflower ovary contains several. The ovule will become a **seed**, and the whole ovary will become a **fruit**. (In biology, a fruit is the fertilised ovary of a flower, not necessarily something to eat.)

The style and stigma project from the top of the ovary. The stigma has a sticky surface and pollen grains will stick to it during pollination. The style may be quite short (e.g. wallflower, Figure 16.18) or very long (e.g. daffodil, Figures 16.20 and 16.21).

### Receptacle

The flower structures just described are all attached to the expanded end of a flower stalk. This is called the **receptacle** and, in a few cases after fertilisation, it becomes fleshy and edible (e.g. apple and pear).

## Lupin

The lupin flower is shown in Figures 16.23 to 16.25. There are five sepals but these are joined together forming a short tube. The five petals are of different shapes and sizes. The uppermost, called the **standard**, is held vertically. Two petals at the sides are called **wings** and are partly joined together.

Inside the wings are two more petals joined together to form a boat-shaped **keel**.

The single carpel is long, narrow and pod shaped, with about ten ovules in the ovary. The long style ends in a stigma just inside the pointed end of the keel. There are ten stamens: five long ones and five short ones. Their filaments are joined together at the base to form a sheath around the ovary.

The flowers of peas and beans are very similar to those of lupins.

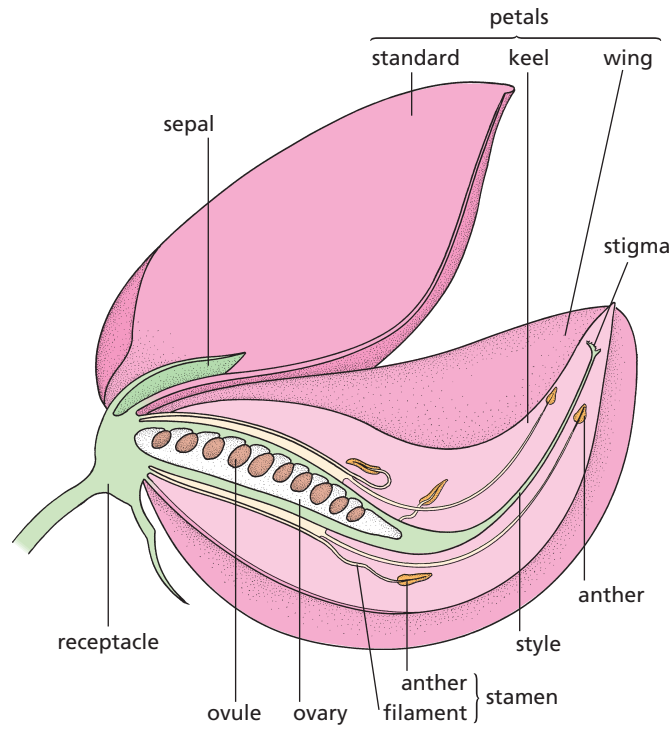
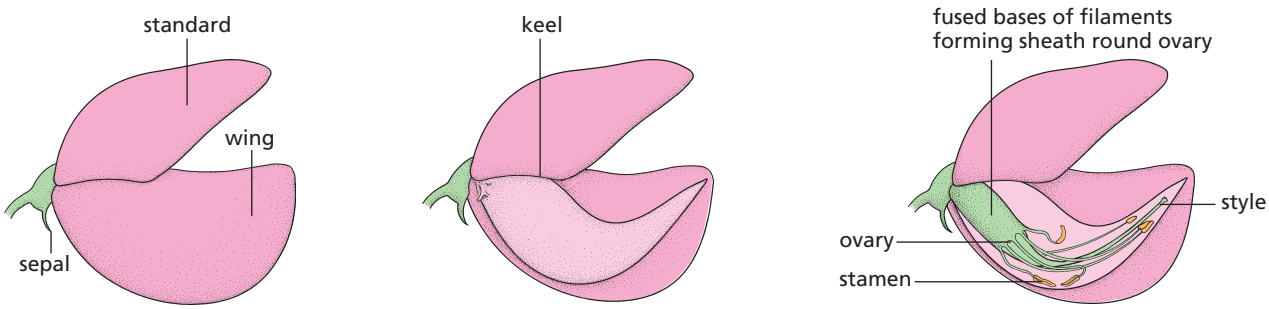



**Figure 16.23** Half-flower of lupin

The shoots or branches of a plant carrying groups of flowers are called **inflorescences**. The flowering shoots of the lupin in Figure 16.25 are inflorescences, each one carrying about a hundred individual flowers.




**(a)** intact **(b)** one wing removed **(c)** one side of keel removed

**Figure 16.24** Lupin flower dissected

**Figure 16.25** Lupin inflorescence. There are a hundred or more flowers in each inflorescence. The youngest flowers, at the top, have not yet opened. The oldest flowers are at the bottom and have already been pollinated.

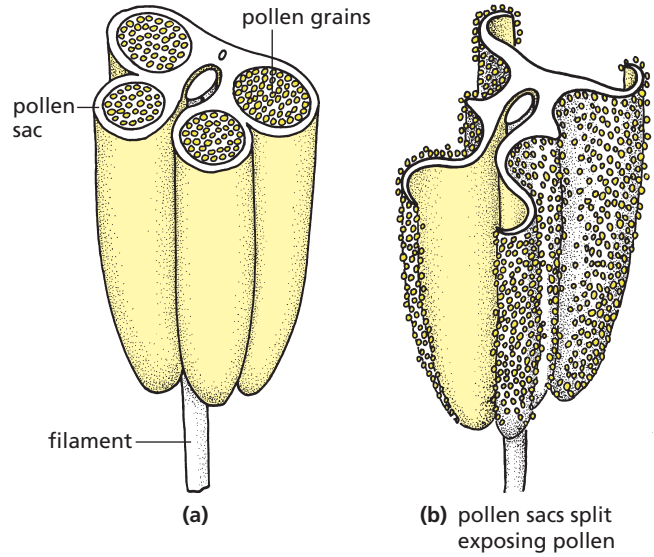



**Figure 16.26** Structure of an anther (top cut off)

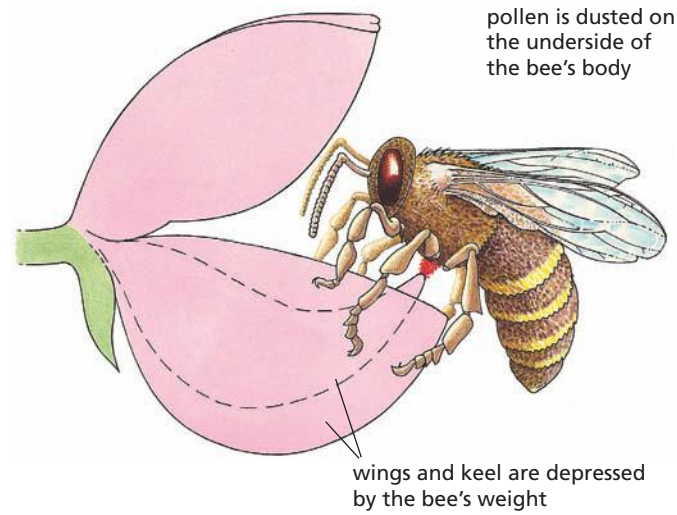



**Figure 16.27** Pollination of the lupin

## Pollination

**Key definition**
**Pollination** is the transfer of pollen grains from the anther to the stigma.

The transfer of pollen from the anthers to the stigma is called **pollination**. The anthers split open, exposing the microscopic pollen grains (Figure 16.26). The pollen grains are then carried away on the bodies of insects, or simply blown by the wind, and may land on the stigma of another flower.

### Insect pollination

Lupin flowers have no nectar. The bees that visit them come to collect pollen, which they take back to the hive for food. Other members of the lupin family (Leguminosae, e.g. clover) do produce nectar.

The weight of the bee, when it lands on the flower's wings, pushes down these two petals and the petals of the keel. The pollen from the anthers has collected in the tip of the keel and, as the petals are pressed down, the stigma and long stamens push the pollen out from the keel on to the underside of the bee (Figure 16.27). The bee, with pollen grains sticking to its body, then flies to another flower. If this flower is older than the first one, it will already have lost its pollen. When the bee's weight pushes the keel down, only the stigma comes out and touches the insect's body, picking up pollen grains on its sticky surface.

Lupin and wallflower are examples of **insect-pollinated flowers**.

### Wind pollination

Grasses, cereals and many trees are pollinated not by insects but by wind currents. The flowers are

often quite small with inconspicuous, green, leaf-like bracts, rather than petals. They produce no nectar. The anthers and stigma are not enclosed by the bracts but are exposed to the air. The pollen grains, being light and smooth, may be carried long distances by the moving air and some of them will be trapped on the stigmas of other flowers.

In the grasses, at first, the feathery stigmas protrude from the flower, and pollen grains floating in the air are trapped by them. Later, the anthers hang outside the flower (Figures 16.28 and 16.29), the pollen sacs split and the wind blows the pollen away. This sequence varies between species.

If the branches of a birch or hazel tree with ripe male catkins, or the flowers of the ornamental pampas grass, are shaken, a shower of pollen can easily be seen.

**Figure 16.28** Grass flowers. Note that the anthers hang freely outside the bracts.

## Adaptation

Insect-pollinated flowers are considered to be adapted in various ways to their method of pollination. The term '**adaptation**' implies that, in the course of evolution, the structure and physiology of a flower have been modified in ways that improve the chances of successful pollination by insects.

Most insect-pollinated flowers have brightly coloured petals and scent, which attract a variety of insects. Some flowers produce nectar, which is also attractive to many insects. The dark lines ('honey guides') on petals are believed to help direct the insects to the nectar source and thus bring them into contact with the stamens and stigma.

These features are adaptations to insect pollination in general, but are not necessarily associated with any particular insect species. The various petal colours and the nectaries of the wallflower attract a variety of insects. Many flowers, however, have modifications that adapt them to pollination by only one type or species of insect. Flowers such as the honeysuckle, with narrow, deep petal tubes, are likely to be pollinated only by moths or butterflies, whose long 'tongues' can reach down the tube to the nectar.

Tube-like flowers such as foxgloves need to be visited by fairly large insects to effect pollination. The petal tube is often lined with dense hairs, which impede small insects that would take the nectar without pollinating the flower. A large bumble-bee, however, pushing into the petal tube, is forced to rub against the anthers and stigma.

Many tropical and sub-tropical flowers are adapted to pollination by birds, or even by mammals such as bats and mice.

Wind-pollinated flowers are adapted to their method of pollination by producing large quantities of light pollen, and having anthers and stigmas that project outside the flower (Figures 16.28 and 16.29). Many grasses have anthers that are not rigidly attached to the filaments and can be shaken by the wind. The stigmas of grasses are feathery, providing a large surface area, and act as a net that traps passing pollen grains.

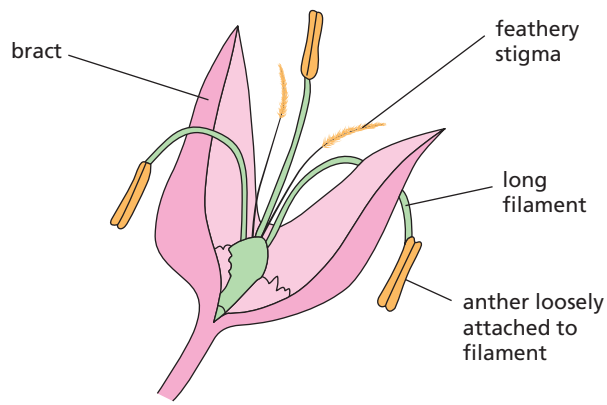



**Figure 16.29** Wind-pollinated grass flower

Table 16.3 compares the features of wind- and insect-pollinated flowers.

**Table 16.3** Features of wind- and insect-pollinated flowers

| Feature | Insect-pollinated | Wind-pollinated |
|---|---|---|
| petals | present – often large, coloured and scented, with guidelines to guide insects into the flower | absent, or small, green and inconspicuous |
| nectar | produced by nectaries, to attract insects | absent |
| stamen | present inside the flower | long filaments, allowing the anthers to hang freely outside the flower so the pollen is exposed to the wind |
| stigmas | small surface area; inside the flower | large and feathery; hanging outside the flower to catch pollen carried by the wind |
| pollen | smaller amounts; grains are often round and sticky or covered in spikes to attach to the furry bodies of insects | larger amounts of smooth and light pollen grains, which are easily carried by the wind |
| bracts (modified leaves) | absent | sometimes present |

# Practical work

## The growth of pollen tubes

### Method A

- Make a solution of 15 g sucrose and 0.1 g sodium borate in 100 $cm^3$ water.
- Put a drop of this solution on a cavity slide and scatter some pollen grains on the drop. This can be done by scraping an anther (which must already have opened to expose the pollen) with a mounted needle, or simply by touching the anther on the liquid drop.
- Cover the drop with a coverslip and examine the slide under the microscope at intervals of about 15 minutes. In some cases, pollen tubes may be seen growing from the grains.
- Suitable plants include lily, narcissus, tulip, bluebell, lupin, wallflower, sweet pea or deadnettle, but a 15% sucrose solution may not be equally suitable for all of them. It may be necessary to experiment with solutions ranging from 5 to 20%.

### Method B

- Cut the stigma from a mature flower, e.g. honeysuckle, crocus, evening primrose or chickweed, and place it on a slide in a drop of 0.5% methylene blue.
- Squash the stigma under a coverslip (if the stigma is large, it may be safer to squash it between two slides), and leave it for 5 minutes.
- Put a drop of water on one side of the slide, just touching the edge of the coverslip, and draw it under the coverslip by holding a piece of filter paper against the opposite edge. This will remove excess stain.
- If the squash preparation is now examined under the microscope, pollen tubes may be seen growing between the spread-out cells of the stigma.

## Fertilisation

Pollination is complete when pollen from an anther has landed on a stigma. If the flower is to produce seeds, pollination has to be followed by a process called **fertilisation**. In all living organisms, fertilisation happens when a male sex cell and a female sex cell meet and join together (they are said to fuse together). The cell that is formed by this fusion is called a **zygote** and develops into an embryo of an animal or a plant (Figure 16.30). The sex cells of all living organisms are called **gametes**.

In flowering plants, the male gamete is in the pollen grain; the female gamete, called the egg cell, is in the ovule. For fertilisation to occur, the nucleus of the male cell from the pollen grain has to reach the female nucleus of the egg cell in the ovule, and fuse with it.

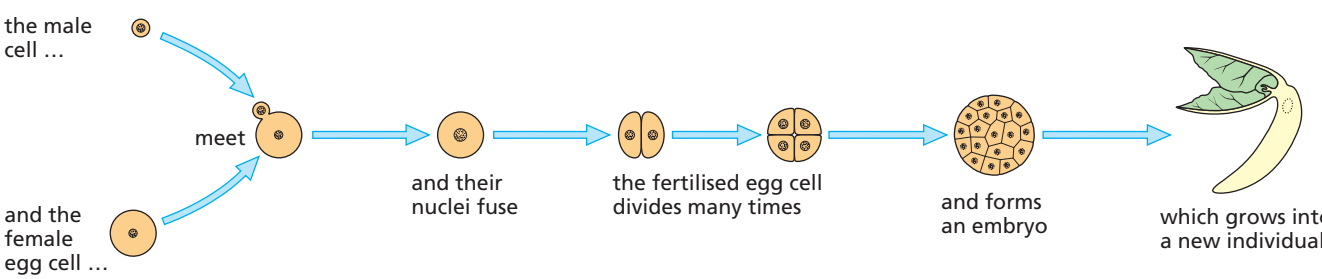



**Figure 16.30** Fertilisation. The male and female gametes fuse to form a zygote, which grows into a new individual.

# Extension work

## Germination

The stages of germination of a French bean are shown in Figure 16.31.

A seed just shed from its parent plant contains only 5–20% water, compared with 80–90% in mature plant tissues. Once in the soil, some seeds will absorb water and swell up, but will not necessarily start to germinate until other conditions are suitable.

The **radicle** grows first and bursts through the **testa** (Figure 16.31(a)). The radicle continues to grow down into the soil, pushing its way between soil particles and small stones. Its tip is protected by the root cap (see 'Water uptake' in Chapter 8). Branches, called lateral roots, grow out from the side of the main root and help to anchor it firmly in the soil. On the main root and the lateral roots, microscopic root hairs grow out. These are fine outgrowths from some of the outer cells. They make close contact with the soil particles and absorb water from the spaces between them.

In the French bean a region of the embryo's stem, the **hypocotyl**, just above the radicle (Figure 16.31(b)), now starts to elongate. The radicle is by now firmly anchored in the soil, so the rapidly growing hypocotyl arches upwards through the soil, pulling the **cotyledons** with it (Figure 16.31(c)). Sometimes the cotyledons are pulled out of the testa, leaving it below the soil, and sometimes the cotyledons remain enclosed in the testa for a time. In either case, the **plumule** is well protected from damage while it is being pulled through the soil, because it is enclosed between the cotyledons (Figure 16.31(d)).

Once the cotyledons are above the soil, the hypocotyl straightens up and the leaves of the plumule open out (Figure 16.31(e)). Up to this point, all the food needed for making new cells and producing energy has come from the cotyledons.

The main type of food stored in the cotyledons is starch. Before this can be used by the growing shoot and root, the starch has to be turned into soluble sugar. In this form, it can be transported by the phloem cells. The change from starch to sugar in the cotyledons is brought about by enzymes, which become active as soon as the seed starts to

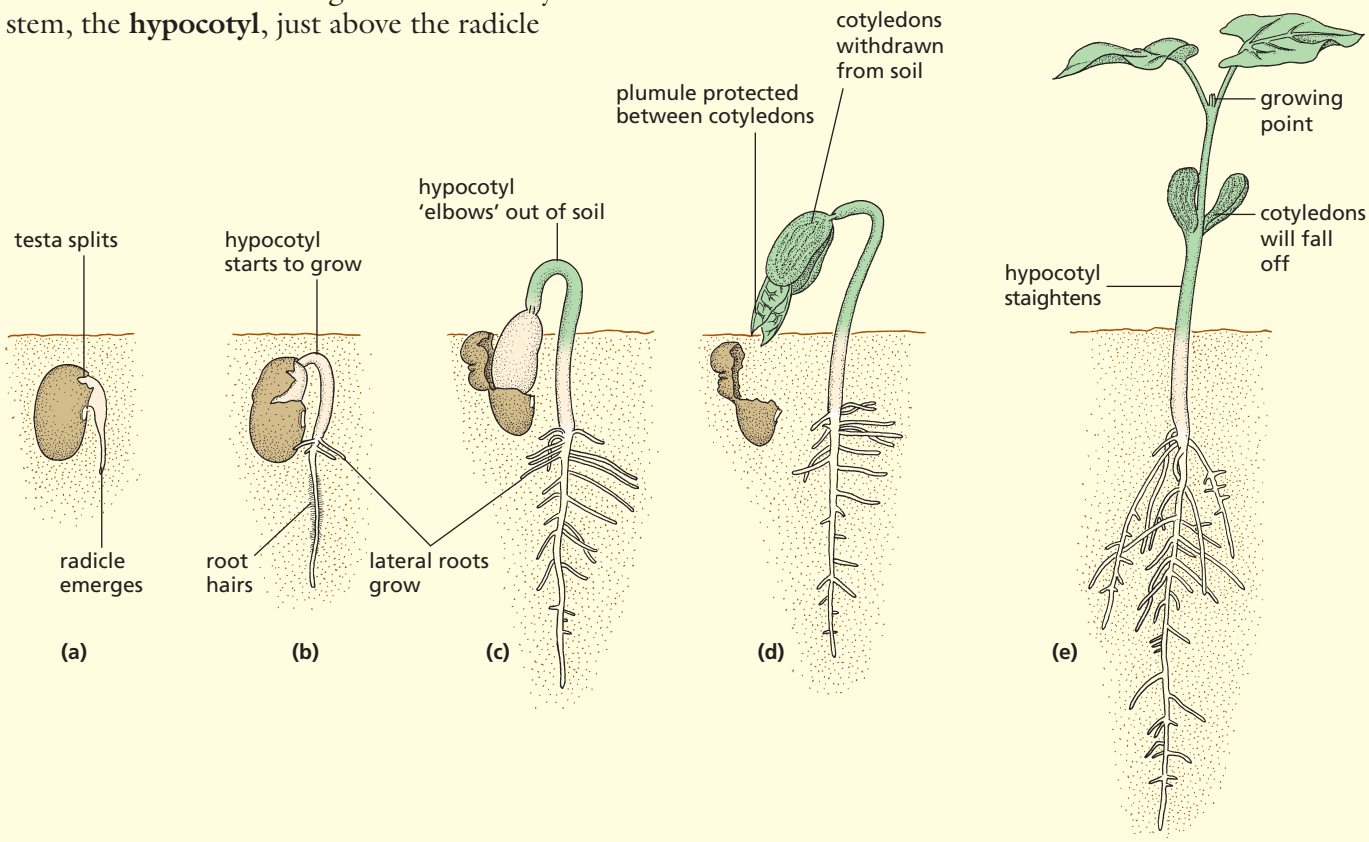



**Figure 16.31** Germination of French bean

germinate. The cotyledons shrivel as their food reserve is used up, and they fall off altogether soon after they have been brought above the soil.

By now the plumule leaves have grown much larger, turned green and started to absorb sunlight and make their own food by photosynthesis (page 66). Between the plumule leaves is a growing point, which continues the upward growth of the stem and the production of new leaves. The embryo has now become an independent plant, absorbing water and mineral salts from the soil, carbon dioxide from the air and making food in its leaves.

## The importance of water, oxygen and temperature in germination

### Use of water in the seedling

Most seeds, when first dispersed, contain very little water. In this dehydrated state, their metabolism is very slow and their food reserves are not used up. The dry seeds can also resist extremes of temperature and desiccation. Before the metabolic changes needed for germination can take place, seeds must absorb water.

Water is absorbed firstly through the micropyle, in some species, and then through the testa as a whole. Once the radicle has emerged, it will absorb water from the soil, particularly through the root hairs. The water that reaches the embryo and cotyledons is used to:

- activate the enzymes in the seed
- help the conversion of stored starch to sugar, and proteins to amino acids
- transport the sugar in solution from the cotyledons to the growing regions
- expand the vacuoles of new cells, causing the root and shoot to grow and the leaves to expand
- maintain the turgor (Chapter 3) of the cells and thus keep the shoot upright and the leaves expanded
- provide the water needed for photosynthesis once the plumule and young leaves are above ground
- transport salts from the soil to the shoot.

### Uses of oxygen

In some seeds the testa is not very permeable to oxygen, and the early stages of germination are probably anaerobic (Chapter 12). The testa when soaked or split open allows oxygen to enter. The oxygen is used in aerobic respiration, which provides the energy for the many chemical changes involved in mobilising the food reserves and making the new cytoplasm and cell walls of the growing seedling.

### Importance of temperature

In Chapter 5 it was explained that a rise in temperature speeds up most chemical reactions, including those taking place in living organisms. Germination, therefore, occurs more rapidly at high temperatures, up to about 40°C. Above 45°C, the enzymes in the cells are denatured and the seedlings would be killed. Below certain temperatures (e.g. 0–4°C) germination may not start at all in some seeds. However, there is considerable variation in the range of temperatures at which seeds of different species will germinate.

# Extension work

## Germination and light

Since a great many cultivated plants are grown from seeds which are planted just below soil level, it seems obvious that light is not necessary for germination. There are some species, however, in which the seeds need some exposure to light before they will germinate, e.g. foxgloves and some varieties of lettuce. In all seedlings, once the shoot is above ground, light is necessary for photosynthesis.

## Dormancy

When plants shed their seeds in summer and autumn, there is usually no shortage of water, oxygen and warmth. Yet, in a great many species, the seeds do not germinate until the following spring. These seeds are said to be **dormant**, i.e. there is some internal control mechanism that prevents immediate germination even though the external conditions are suitable.

If the seeds did germinate in the autumn, the seedlings might be killed by exposure to frost, snow and freezing conditions. Dormancy delays the period of germination so that adverse conditions are avoided.

The controlling mechanisms are very varied and are still the subject of investigation and discussion. The factors known to influence dormancy are plant growth substances (see 'Tropic responses' in Chapter 14), the testa, low temperature and light, or a combination of these.

# Practical work

## Experiments on the conditions for germination

The environmental conditions that might be expected to affect germination are temperature, light intensity and the availability of water and air. The relative importance of some of these conditions can be tested by the experiments that follow.

### 1 The need for water

- Label three containers A, B and C and put dry cotton wool in the bottom of each.
- Place equal numbers of soaked seeds in all three.
- Leave A quite dry; add water to B to make the cotton wool moist; add water to C until all the seeds are completely covered (Figure 16.32).
- Put lids on the containers and leave them all at room temperature for a week.

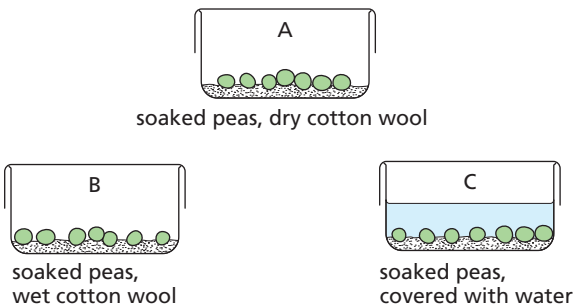



**Figure 16.32** Experiment to show the need for water in germination

**Result**
The seeds in B will germinate normally. Those in A will not germinate. The seeds in C may have started to germinate but will probably not be as advanced as those in B and may have died and started to decay.

**Interpretation**
Although water is necessary for germination, too much of it may prevent germination by cutting down the oxygen supply to the seed.

### 2 The need for oxygen

- Set up the experiment as shown in Figure 16.33.

  **CARE:** Pyrogallic acid and sodium hydroxide is a caustic mixture. Use eye shields, handle the liquids with care and report any spillage at once.
- If the moist cotton wool is rolled in some cress seeds, they will stick to it. The bungs must make an airtight seal in the flask and the cotton wool must not touch the solution. Pyrogallic acid and sodium hydroxide absorb oxygen from the air, so the cress seeds in flask A are deprived of oxygen. Flask B is the control (see 'Aerobic respiration' in Chapter 12). This is to show that germination can take place in these experimental conditions provided oxygen is present.

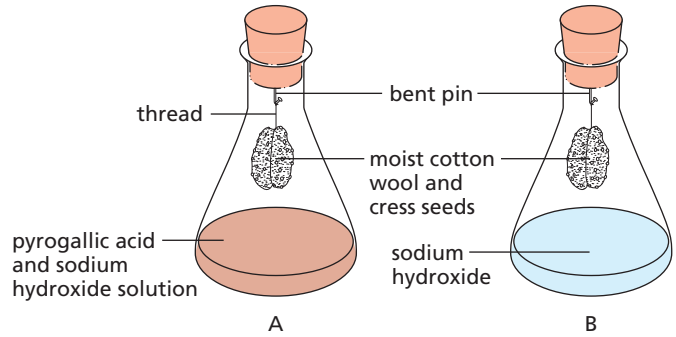



**Figure 16.33** Experiment to show the need for oxygen

- Leave the flasks for a week at room temperature.

**Result**
The seeds in flask B will germinate but there will be little or no germination in flask A.

**Interpretation**
The main difference between flasks A and B is that A lacks oxygen. Since the seeds in this flask have not germinated, it looks as if oxygen is needed for germination.

To show that the chemicals in flask A had not killed the seeds, the cotton wool can be swapped from A to B. The seeds from A will now germinate.

**Note:** Sodium hydroxide absorbs carbon dioxide from the air. The mixture (sodium hydroxide + pyrogallic acid) in flask A, therefore, absorbs both carbon dioxide and oxygen from the air in this flask. In the control flask B, the sodium hydroxide absorbs carbon dioxide but not oxygen. If the seeds in B germinate, it shows that lack of carbon dioxide did not affect them, whereas lack of oxygen did.

### 3 Temperature and germination

- Soak some maize grains for a day and then roll them up in three strips of moist blotting paper as shown in Figure 16.34.
- Put the rolls into plastic bags. Place one in a refrigerator (about 4 °C), leave one upright in the room (about 20 °C) and put the third in a warm place such as over a radiator or, better, in an incubator set to 30 °C.
- Because the seeds in the refrigerator will be in darkness, the other seeds must also be enclosed in a box or a cupboard, to exclude light. Otherwise it could be objected that it was lack of light rather than low temperature that affected germination.
- After a week, examine the seedlings and measure the length of the roots and shoots.

**Result**
The seedlings kept at 30 °C will be more advanced than those at room temperature. The grains in the refrigerator may not have started to germinate at all.

**Interpretation**
Seeds will not germinate below a certain temperature. The higher the temperature, the faster the germination, at least up to 35–40 °C.

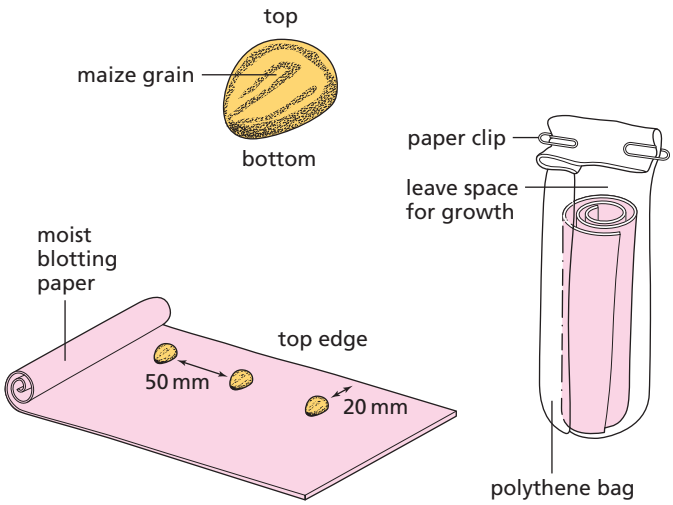



**Figure 16.34** Experiment to show the influence of temperature on germination. Roll the seeds in moist blotting-paper and stand the rolls upright in plastic bags.

## Controlling the variables

These experiments on germination illustrate one of the problems of designing biological experiments. You have to decide what conditions (the '**variables**') could influence the results and then try to change only one condition at a time. The dangers are that: (1) some of the variables might not be controllable, (2) controlling some of the variables might also affect the condition you want to investigate, and (3) there might be a number of important variables you have not thought of.

1 In your germination experiments, you were unable to control the quality of the seeds, but had to assume that the differences between them would be small. If some of the seeds were dead or diseased, they would not germinate in any conditions and this could distort the results. This is one reason for using as large a sample as possible in the experiments.
2 You had to ensure that, when temperature was the variable, the exclusion of light from the seeds in the refrigerator was not an additional variable. This was done by putting all the seeds in darkness.
3 A variable you might not have considered could be the way the seeds were handled. Some seeds can be induced to germinate more successfully by scratching or chipping the testa.

# Self-pollination and cross-pollination

**Key definitions**
**Self-pollination** is the transfer of pollen grains from the anther of a flower to the stigma of the same flower, or a different flower on the same plant.
**Cross-pollination** is the transfer of pollen grains from the anther of a flower to the stigma of a flower on a different plant of the same species.

In **self-pollinating** plants, the pollen that reaches the stigma comes from the same flower or another flower on the same plant. In **cross-pollination**, the pollen is carried from the anthers of one flower to the stigma in a flower of another plant of the same species.

If a bee carried pollen from one of the younger flowers near the middle of a lupin plant (Figure 16.25) to an older flower near the bottom, this would be self-pollination. If, however, the bee visited a separate lupin plant and pollinated its flowers, this would be cross-pollination.

The term 'cross-pollination', strictly speaking, should be applied only if there are genetic differences between the two plants involved. The flowers on a single plant all have the same genetic constitution. The flowers on plants growing from the same rhizome or rootstock (see 'Asexual reproduction' earlier in this chapter) will also have the same genetic constitution. Pollination between such flowers is little different from self-pollination in the same flower.

If a plant relies on self-pollination, the disadvantage will be that variation will not occur in subsequent generations. Those plants may not, therefore, be able to adapt to changing environmental conditions. However, self-pollination can happen even if there are no pollinators, since the flower's own pollen may drop onto its stigma. This means that even if pollinators are scarce (perhaps because of the reckless use of insecticides) the plant can produce seeds and prevent extinction.

Cross-pollination, on the other hand, will guarantee variation and give the plant species a

better chance of adapting to changing conditions. Some plants maintain cross-pollination by producing stamens (male reproductive parts) at a different time to the carpels (female reproductive parts). However, cross-pollinated plants do have a reliance on pollinators to carry the pollen to other plants.

## Fertilisation

The pollen grain absorbs liquid from the stigma and a microscopic **pollen tube** grows out of the grain. This tube grows down the style and into the ovary, where it enters a small hole, the **micropyle**, in an ovule (Figure 16.35). The nucleus of the pollen grain travels down the pollen tube and enters the ovule. Here it combines with the nucleus of the egg cell. Each ovule in an ovary needs to be fertilised by a separate pollen grain.

Although pollination must occur before the ovule can be fertilised, pollination does not necessarily result in fertilisation. A bee may visit many flowers on a Bramley apple tree, transferring pollen from one flower to another. The Bramley, however, is 'self-sterile'; pollination with its own pollen will not result in fertilisation. Pollination with pollen from a different variety of apple tree, for example a Worcester, can result in successful fertilisation and fruit formation.

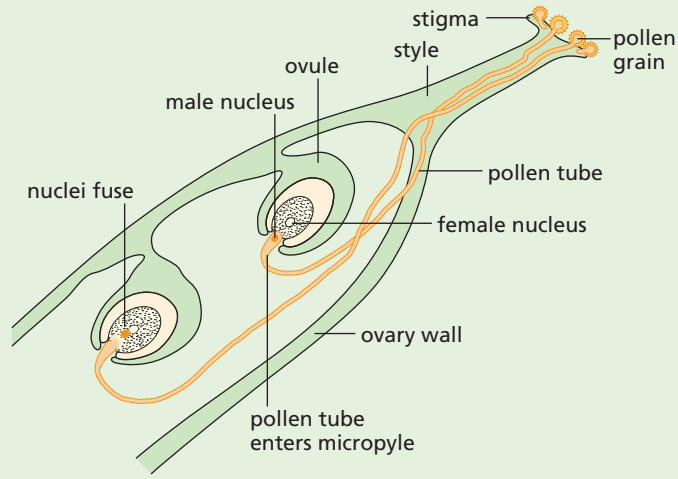



**Figure 16.35** Diagram of fertilisation showing pollen tube

# Extension work

## Fruit and seed formation

After the pollen and the egg nuclei have fused, the egg cell divides many times and produces a miniature plant called an **embryo**. This consists of a tiny root and shoot, with two special leaves called **cotyledons**. In dicot plants (see 'Features of organisms' in Chapter 1) food made in the leaves of the parent plant is carried in the phloem to the cotyledons.

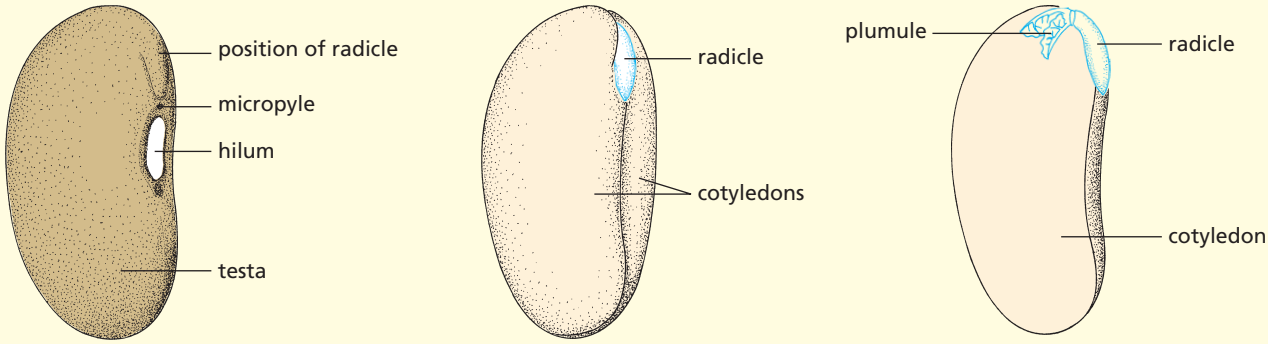
The cotyledons eventually grow so large with this stored food that they completely enclose the embryo (see Figure 16.37). In monocot plants

**(a)** Tomato flowers – the petals of the older flowers are shrivelling

**(b)** After fertilisation – the petals have dropped and the ovary is growing.

**(c)** Ripe fruit – the ovary has grown and ripened. The green sepals remain and the dried stigma is still attached.

**Figure 16.36** Tomato; fruit formation




**(a)** external appearance **(b)** testa removed **(c)** one cotyledon removed

**Figure 16.37** A French bean seed

**Figure 16.38** Lupin flower after fertilisation. The ovary (still with the style and stigma attached) has grown much larger than the flower and the petals have shrivelled.

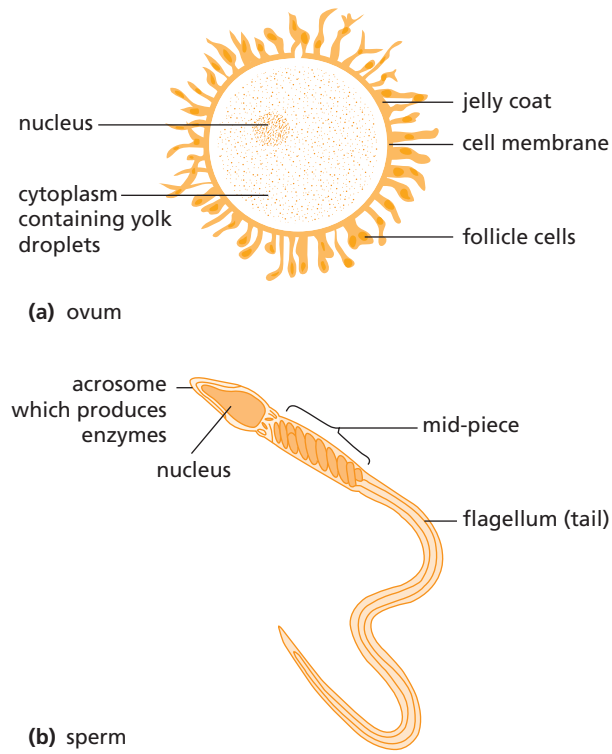
(see 'Features of organisms' in Chapter 1) the food store is laid down in a special tissue called endosperm, which is outside the cotyledons. In both cases the outer wall of the ovule becomes thicker and harder, and forms the seed coat or **testa**.

As the seeds grow, the ovary also becomes much larger and the petals and stamens shrivel and fall off (Figures 16.36(b) and 16.38). The ovary is now called a **fruit** (Figure 16.36). The biological definition of a fruit is a fertilised ovary. It is not necessarily edible – the lupin ovary forms a dry pod.

## Sexual reproduction in humans

Reproduction is the process of producing new individuals. In human reproduction the two sexes, male and female, each produce special types of reproductive cells, called gametes. The male gametes are the **sperm** (or **spermatozoa**) and the female gametes are the **ova** (singular = ovum) or eggs (Figure 16.39).

To produce a new individual, a sperm has to reach an ovum and join with it (fuse with it). The sperm nucleus then passes into the ovum and the two nuclei also fuse. This is fertilisation. The cell formed after the fertilisation of an ovum by a sperm is called a zygote. A zygote will grow by cell division




**(a)** ovum

**(b)** sperm

**Figure 16.39** Human gametes

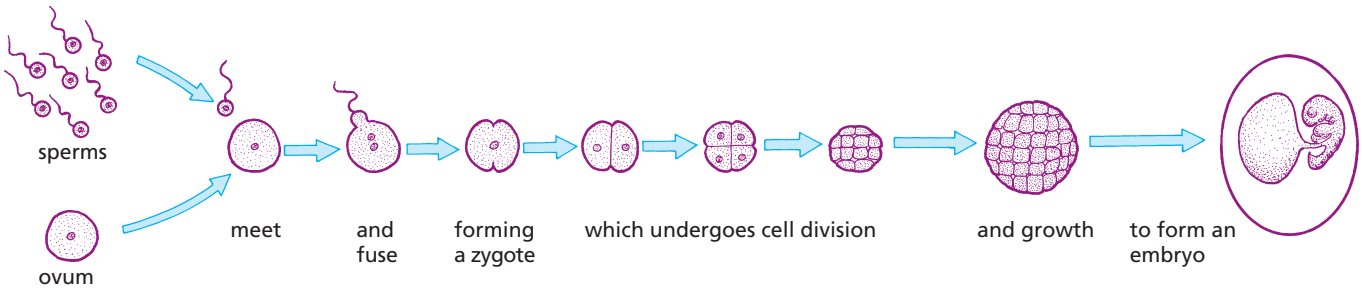



**Figure 16.40** Fertilisation and development

to produce first an **embryo** and then a fully formed animal (Figure 16.40).

In humans, the male produces millions of sperm, while the female produces a smaller number of eggs (usually one a month for about 40 years). Usually only one egg is fertilised at a time; two eggs being fertilised at the same time produces (non-identical) twins.

To bring the sperm close enough to the ova for fertilisation to take place, there is an act of mating or **copulation**. In mammals this act results in sperm from the male animal being injected into the female. The sperm swim inside the female's reproductive system and fertilise any eggs that are present. The zygote then grows into an embryo inside the body of the female.

## The human reproductive system

### Female

Table 16.4 summarises the functions of parts of the female reproductive system. The eggs are produced from the female reproductive organs called **ovaries**. These are two whitish oval bodies, 3–4 cm long. They lie in the lower half of the abdomen, one on each side of the **uterus** (Figure 16.41 and Figure 16.42) Close to each ovary is the expanded, funnel-shaped opening of the **oviduct**, the tube down which the ova pass when released from the ovary. The oviduct is sometimes called the **Fallopian tube**.

The oviducts are narrow tubes that open into a wider tube, the uterus or womb, lower down in the abdomen. When there is no embryo developing in it, the uterus is only about 80 mm long. It leads to the outside through a muscular tube, the **vagina**. The **cervix** is a ring of muscle closing the lower end of the uterus where it joins the vagina. The urethra, from the bladder, opens into the **vulva** just in front of the vagina.

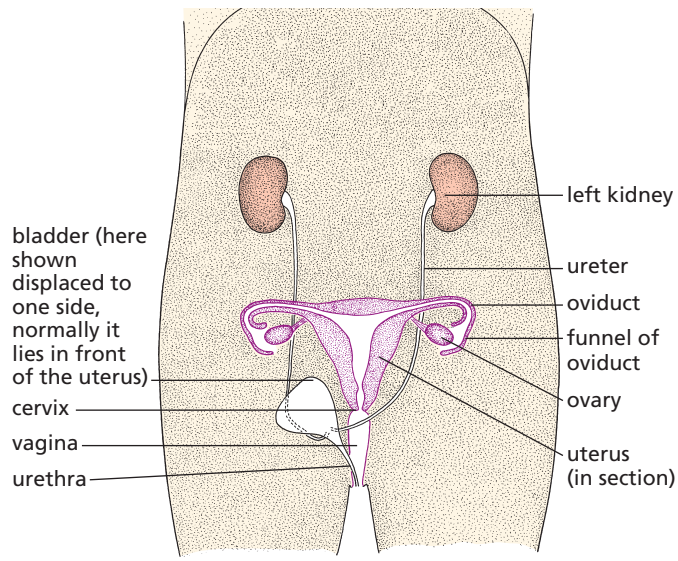



**Figure 16.41** The female reproductive organs; front view

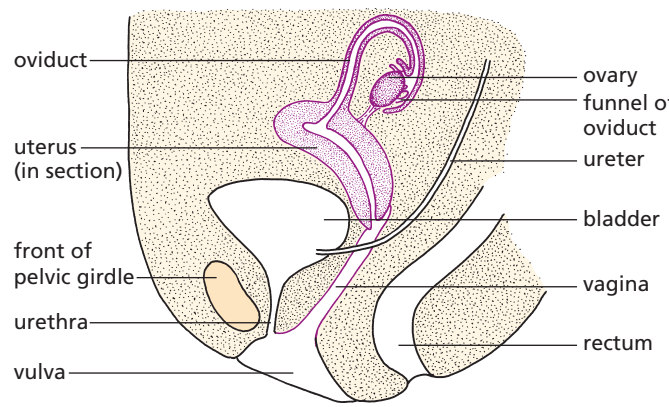



**Figure 16.42** The female reproductive organs; side view

### Male

Table 16.5 summarises the functions of parts of the male reproductive system. Sperm are produced in the male reproductive organs (Figures 16.43 and 16.44), called the **testes** (singular = testis). These lie outside the abdominal cavity in a special sac called the **scrotum**. In this position they are kept at a

**Table 16.4** Functions of parts of the female reproductive system

| Part | Function |
|---|---|
| cervix | a ring of muscle, separating the vagina from the uterus |
| funnel of oviduct | directs an ovum (egg) from the ovary into the oviduct |
| ovary | contains follicles in which ova (eggs) are produced |
| oviduct | carries an ovum to the uterus, with propulsion provided by tiny cilia in the wall; also the site of fertilisation |
| urethra | carries urine from the bladder |
| uterus | where the fetus develops |
| vagina | receives the male penis during sexual intercourse; sperm are deposited here |

temperature slightly below the rest of the body. This is the best temperature for sperm production.

The testes consist of a mass of sperm-producing tubes (Figure 16.44). These tubes join to form ducts leading to the **epididymis**, a coiled tube about 6 metres long on the outside of each testis. The epididymis, in turn, leads into a muscular **sperm duct**.

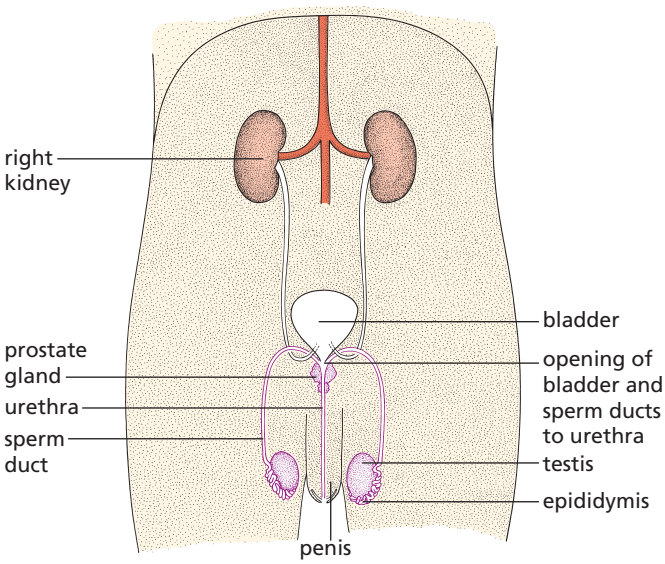



**Figure 16.43** The male reproductive organs; front view

The two sperm ducts, one from each testis, open into the top of the urethra just after it leaves the bladder. A short, coiled tube called the **seminal vesicle** branches from each sperm duct just before it enters the **prostate gland**, which surrounds the urethra at this point.

The urethra passes through the **penis** and may conduct either urine or sperm at different times. The penis consists of connective tissue with many blood spaces in it. This is called **erectile tissue**.

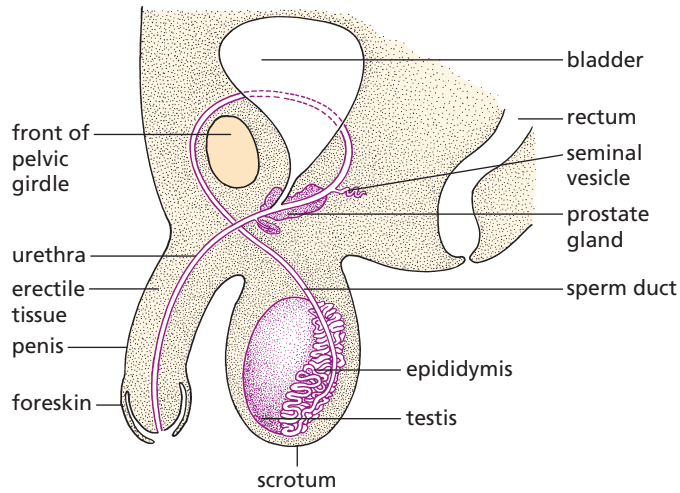



**Figure 16.44** The male reproductive organs; side view

**Table 16.5** Functions of parts of the male reproductive system

| Part | Function |
|---|---|
| epididymis | a mass of tubes in which sperm are stored |
| penis | can become firm, to insert into the vagina of the female during sexual intercourse in order to transfer sperm |
| prostate gland | adds fluid and nutrients to sperm to form semen |
| scrotum | a sac that holds the testes outside the body, keeping them cooler than body temperature |
| seminal vesicle | adds fluid and nutrients to sperm to form semen |
| sperm duct | muscular tube that links the testis to the urethra to allow the passage of semen containing sperm |
| testis | male gonad that produces sperm |
| urethra | passes semen containing sperm through the penis; also carries urine from the bladder |

## Production of gametes

### Sperm production

The lining of the sperm-producing tubules in the testis consists of rapidly dividing cells (Figure 16.45). After a series of cell divisions, the cells grow long tails called flagellae (singular: flagellum) and become sperm (Figure 16.46), which pass into the epididymis.

During copulation, the epididymis and sperm ducts contract and force sperm out through the urethra. The prostate gland and seminal vesicle add fluid to the sperm. This fluid plus the sperm it contains is called **semen**, and the ejection of sperm through the penis is called **ejaculation**.

### Ovulation

The egg cells (ova) are present in the ovary from the time of birth. No more are formed during the female's lifetime, but between the ages of 10 and 14 some of

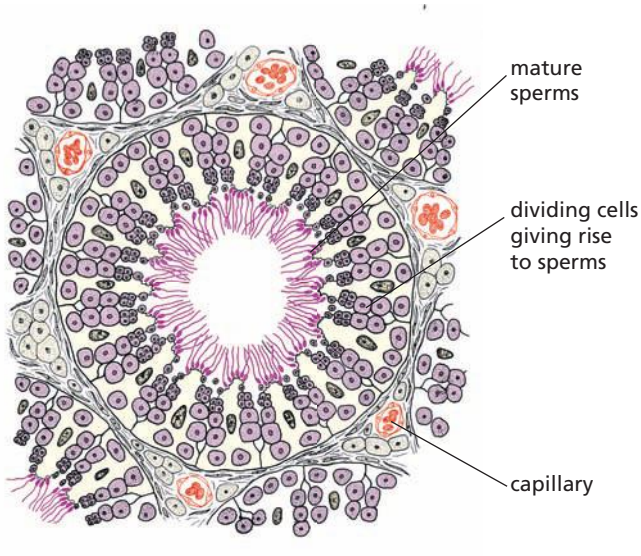



**Figure 16.45** Section through sperm-producing tubules

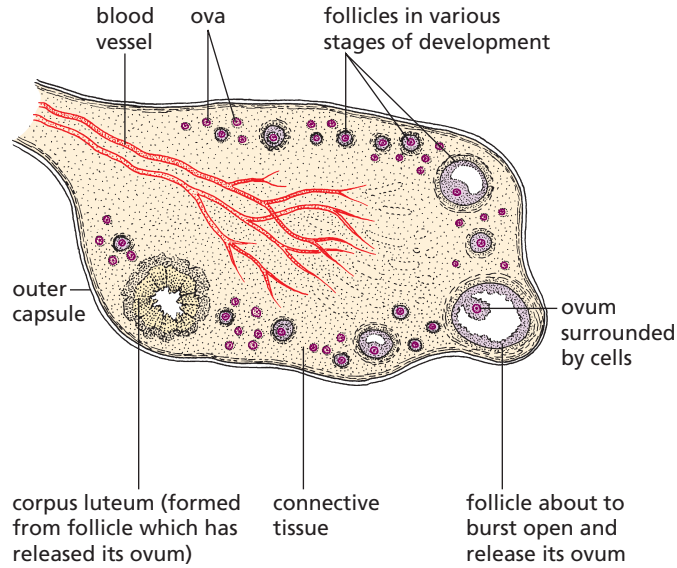



**Figure 16.47** Section through an ovary

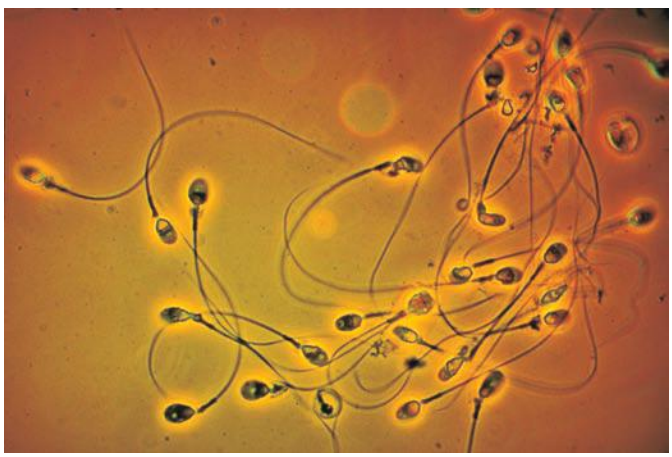


**Figure 16.46** Human sperm (×800). The head of the sperm has a slightly different appearance when seen in 'side' view or in 'top' view.

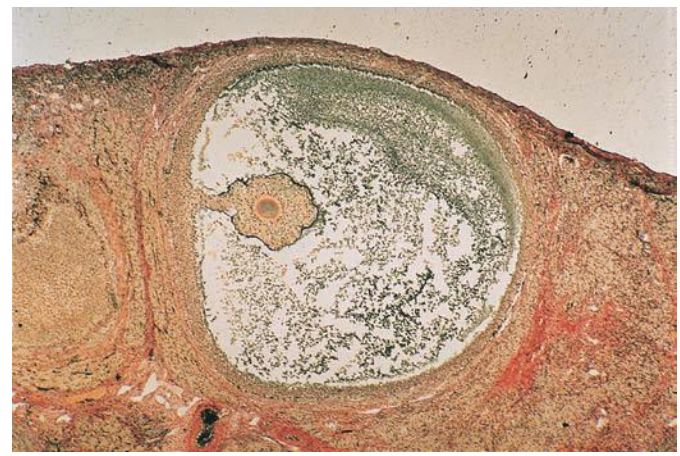


**Figure 16.48** Mature follicle as seen in a section through part of an ovary (×30). The ovum is surrounded by follicle cells. These produce the fluid that occupies much of the space in the follicle.

the egg cells start to mature and are released, one at a time about every 4 weeks from alternate ovaries. As each ovum matures, the cells around it divide rapidly and produce a fluid-filled sac. This sac is called a **follicle** (Figure 16.47) and, when mature, it projects from the surface of the ovary like a small blister (Figure 16.48). Finally, the follicle bursts and releases the ovum with its coating of cells into the funnel of the oviduct. This is called **ovulation**. From here, the ovum is wafted down the oviduct by the action of cilia (see 'Levels of organisation' in Chapter 2) in the lining of the tube. If the ovum meets sperm cells in the oviduct, it may be fertilised by one of them.

The released ovum is enclosed in a jelly-like coat called the **zona pellucida** and is still surrounded by a layer of follicle cells. Before fertilisation can occur, sperm have to get through this layer of cells and the successful sperm has to penetrate the zona pellucida with the aid of enzymes secreted by the head of the sperm.

## Mating and fertilisation

### Mating

Sexual arousal in the male results in an erection. That is, the penis becomes firm and erect as a result of blood flowing into the erectile tissue. Arousal in the female stimulates the lining of the vagina to produce mucus. This lubricates the vagina and makes it easy for the erect penis to enter.

In the act of copulation, the male inserts the penis into the female's vagina. The sensory stimulus (sensation) that this produces causes a reflex (see 'Nervous control

in humans' in Chapter 14) in the male, which results in the ejaculation of semen into the top of the vagina.

The previous paragraph is a very simple description of a biological event. In humans, however, the sex act has intense psychological and emotional importance. Most people feel a strong sexual drive, which has little to do with the need to reproduce. Sometimes the sex act is simply the meeting of an urgent physical need. Sometimes it is an experience that both man and woman enjoy together. At its 'highest' level it is both of these, and is also an expression of deeply felt affection within a lasting relationship.

## Fertilisation

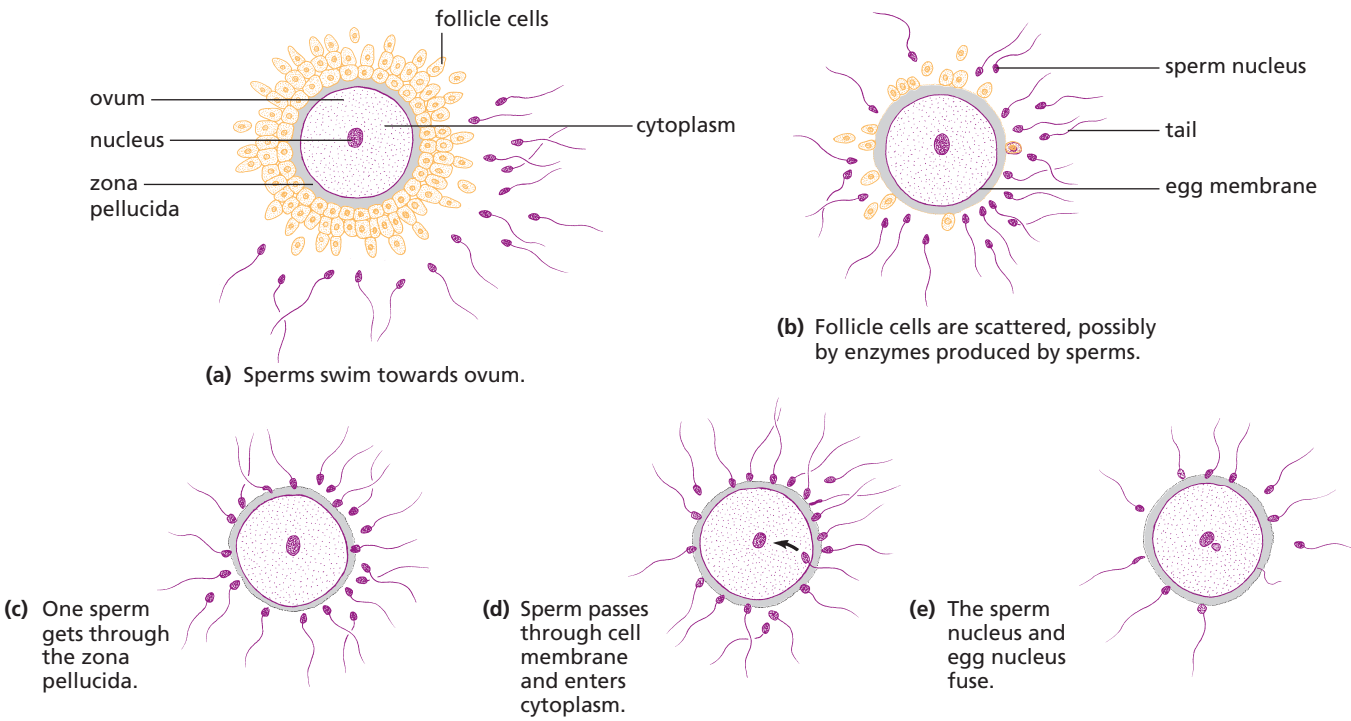
The sperm swim through the cervix and into the uterus by wriggling movements of their tails. They pass through the uterus and enter the oviduct, but the method by which they do this is not known for certain. If there is an ovum in the oviduct, one of the sperm may bump into it and stick to its surface. The acrosome at the head of the sperm secretes enzymes which digest part of the egg membrane. The sperm then enters the cytoplasm of the ovum and the male nucleus of the sperm fuses with the female nucleus. This is the moment of fertilisation and is shown in more detail in Figure 16.49. Although a single ejaculation may contain over three hundred million sperm, only a few hundred will reach the oviduct and only one will fertilise the ovum. The function of the others is not fully understood.

The released ovum is thought to survive for about 24 hours; the sperm might be able to fertilise an ovum for about 2 or 3 days. So there is only a short period of about 4 days each month when fertilisation might occur. If this fertile period can be estimated accurately, it can be used either to achieve or to avoid fertilisation (conception) (see 'Methods of birth control in humans').

The fertilised egg has 23 chromosomes from the mother and 23 from the father, bringing its chromosome number to 46 (the same as other human body cells). It is called a zygote.

## Pregnancy and development

The fertilised ovum (zygote) first divides into two cells. Each of these divides again, so producing four cells. The cells continue to divide in this way to produce a solid ball of cells (Figure 16.50), an early stage in the development of the embryo. This early embryo travels down the oviduct to the uterus. Here it sinks into the lining of the uterus, a process called **implantation** (Figure 16.52(a)). The embryo continues to grow and produces new cells that form tissues and organs (Figure 16.51). After 8 weeks, when all the organs are formed, the embryo is called a **fetus**. One of the first organs to form is the heart, which pumps blood around the body of the embryo.




**(a)** Sperms swim towards ovum.

**(b)** Follicle cells are scattered, possibly by enzymes produced by sperms.

**(c)** One sperm gets through the zona pellucida.

**(d)** Sperm passes through cell membrane and enters cytoplasm.

**(e)** The sperm nucleus and egg nucleus fuse.

**Figure 16.49** Fertilisation of an ovum

As the embryo grows, the uterus enlarges to contain it. Inside the uterus the embryo becomes enclosed in a fluid-filled sac called the **amnion** or water sac, which protects it from damage and prevents unequal pressures from acting on it (Figure 16.52(b) and (c)). The fluid is called **amniotic fluid**. The oxygen and food needed to keep the embryo alive and growing are obtained from the mother's blood by means of a structure called the **placenta**.

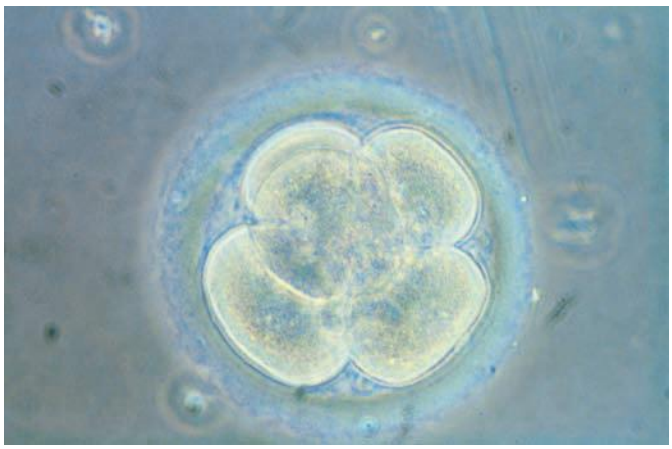
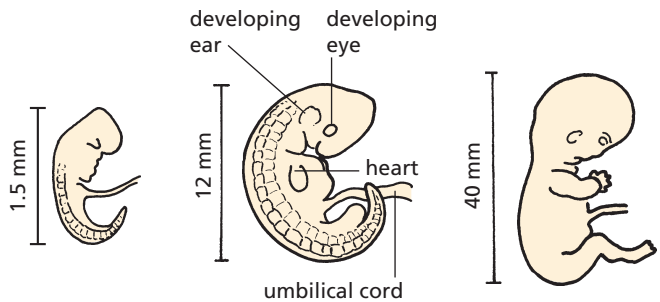


**Figure 16.50** Human embryo at the 8-cell stage (×230) with five of the cells clearly visible. The embryo is surrounded by the zona pellucida.




**(a)** after 2 weeks **(b)** about 5 weeks **(c)** 8 weeks

**Figure 16.51** Human embryo: the first 8 weeks

## Placenta

Soon after the ball of cells reaches the uterus, some of the cells, instead of forming the organs of the embryo, grow into a disc-like structure, the placenta (Figure 16.52(c)). The placenta becomes closely attached to the lining of the uterus and is attached to the embryo by a tube called the **umbilical cord** (Figure 16.52(c)). The nervous system (brain, spinal cord and sense organs) start to develop very quickly. After a few weeks, the embryo's heart has developed and is circulating blood through the umbilical cord and placenta as well as through its own tissues (Figure 16.51(b)). Oxygen and nutrients such as glucose and amino acids pass across the placenta to the embryo's bloodstream. Carbon dioxide passes from the embryo's blood to that of the mother. Blood entering the placenta from the mother does not mix with the embryo's blood.

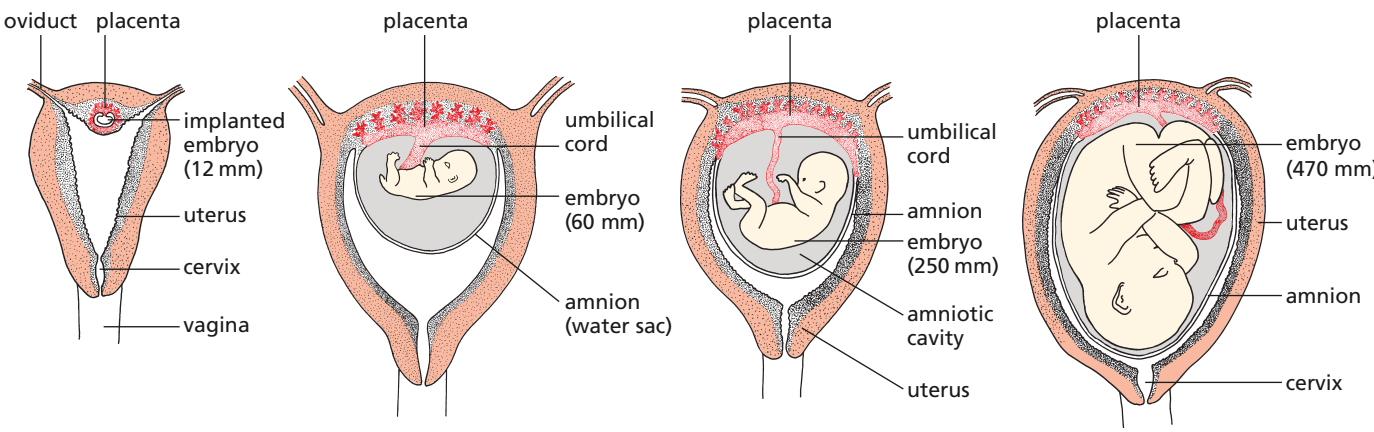
Figure 16.53 shows the human embryo at 7 weeks surrounded by the amnion and placenta.

## Antenatal care

'Antenatal' or 'prenatal' refers to the period before birth. Antenatal care is the way a woman should look after herself during pregnancy, so that the birth will be safe and her baby healthy.

The mother-to-be should make sure that she eats properly, and perhaps takes more iron and folic acid (a vitamin), than she usually does to prevent anaemia. If her job is a light one, she may go on working for the first 6 months of pregnancy. She should not do heavy work, however, or repeated lifting or stooping.

Pregnant women who drink or smoke are more likely to have babies with low birth weights. These babies are more likely to be ill than babies of normal




**(a)** 5 weeks **(b)** 10 weeks **(c)** 5 months **(d)** 35 weeks (a few weeks before birth)

**Figure 16.52** Growth and development in the uterus (not to scale)

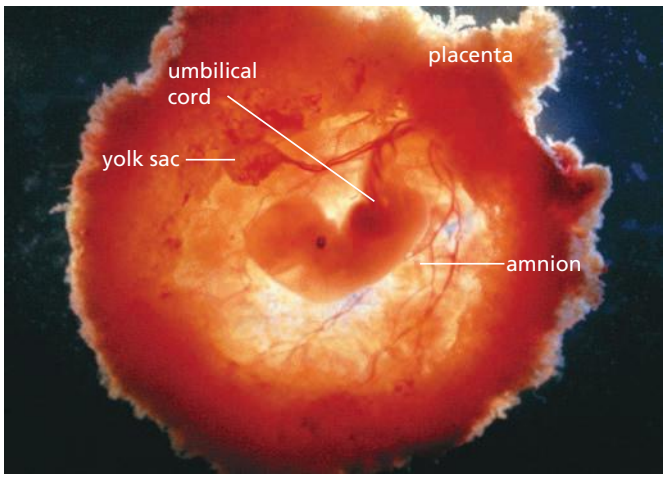



**Figure 16.53** Human embryo, 7 weeks (×1.5). The embryo is enclosed in the amnion. Its limbs, eye and ear-hole are clearly visible. The amnion is surrounded by the placenta; the fluffy-looking structures are the placental villi, which penetrate into the lining of the uterus. The umbilical cord connects the embryo to the placenta.

weight. Smoking may also make a miscarriage more likely. So a woman who smokes should give up smoking during her pregnancy. Alcohol can cross the placenta and damage the fetus. Pregnant women who take as little as one alcoholic drink a day are at risk of having babies with lower than average birth weights. These underweight babies are more likely to become ill.

Heavy drinking during pregnancy, sometimes called 'binge drinking', can lead to deformed babies. This risk is particularly great in the early stages of pregnancy when the brain of the fetus is developing, and can result in a condition called fetal alcohol syndrome (FAS). At that stage the mother may not yet be aware of her pregnancy and continue to drink heavily. A child suffering from FAS can have a range of medical problems, many associated with permanent brain damage. All levels of drinking are thought to increase the risk of miscarriage.

During pregnancy, a woman should not take any drugs unless they are strictly necessary and prescribed by a doctor. In the 1950s, a drug called thalidomide was used to treat the bouts of early morning sickness that often occur in the first 3 months of pregnancy. Although tests had appeared to show the drug to be safe, it had not been tested on pregnant animals. About 20% of pregnant women who took thalidomide had babies with deformed or missing limbs (Figure 16.54).

**Figure 16.54** Children suffering from the effects of thalidomide

If a woman catches **rubella** (German measles) during the first 4 months of pregnancy, there is a danger that the virus may affect the fetus and cause abortion or still-birth. Even if the baby is born alive, the virus may have caused defects of the eyes (cataracts), ears (deafness) or nervous system. All girls should be vaccinated against rubella to make sure that their bodies contain antibodies to the disease (see Chapter 10).

## Twins

Sometimes a woman releases two ova when she ovulates. If both ova are fertilised, they may form twin embryos, each with its own placenta and amnion. Because the twins come from two separate ova, each fertilised by a different sperm, it is possible to have a boy and a girl. Twins formed in this way are called **fraternal twins**. Although they are both born within a few minutes of each other, they are no more alike than other brothers or sisters.

Another cause of twinning is when a single fertilised egg, during an early stage of cell division, forms two separate embryos. Sometimes these may share a placenta and amnion. Twins formed from a single ovum and sperm must be the same sex, because only one sperm (X or Y) fertilised the ovum. These 'one-egg' twins are sometimes called **identical twins** because, unlike fraternal twins, they will closely resemble each other in every respect.

## Birth

The period from fertilisation to birth takes about 38 weeks in humans. This is called the **gestation** period. A few weeks before the birth, the fetus has come to lie head downwards in the uterus, with its head just above the cervix (Figures 16.52(d) and

16.55). When birth starts, the uterus begins to contract rhythmically. This is the beginning of what is called 'labour'. These regular rhythmic contractions become stronger and more frequent. The opening of the cervix gradually widens (dilates) enough to let the baby's head pass through and the contractions of the muscles in the uterus wall are assisted by muscular contractions of the abdomen. The amniotic sac breaks at some stage in labour and the fluid escapes through the vagina. Finally, the muscular contractions of the uterus wall and abdomen push the baby head-first through the widened cervix and vagina (Figure 16.56). The umbilical cord, which still connects the child to the placenta, is tied and cut. Later, the placenta breaks away from the uterus and is pushed out separately as the 'afterbirth'.

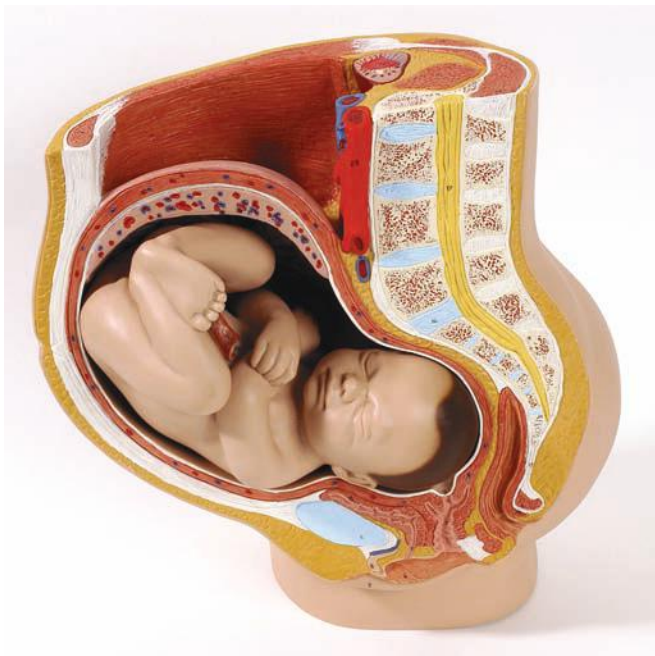


**Figure 16.55** Model of human fetus just before birth. The cervix and vagina seem to provide narrow channels for the baby to pass through but they widen quite naturally during labour and delivery.

The sudden fall in temperature felt by the newly born baby stimulates it to take its first breath and it usually cries. In a few days, the remains of the umbilical cord attached to the baby's abdomen shrivel and fall away, leaving a scar in the abdominal wall, called the navel.

### Induced birth

Sometimes, when a pregnancy has lasted for more than 38 weeks or when examination shows that the placenta is not coping with the demands of the fetus, birth may be induced. This means that it is started artificially.

This is often done by carefully breaking the membrane of the amniotic sac. Another method is to inject a hormone, **oxytocin**, into the mother's veins. Either of these methods brings on the start of labour. Sometimes both are used together.

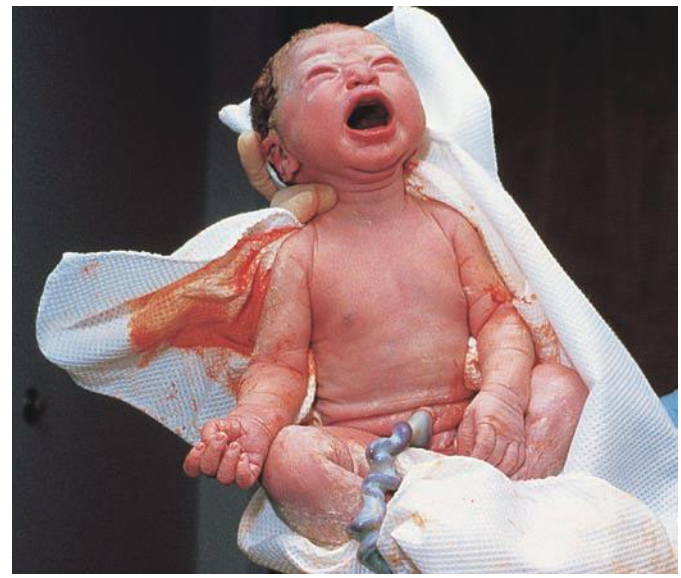


**Figure 16.56** Delivery of a baby. The umbilical cord is still intact.

## Comparing male and female gametes

Figure 2.13(g) shows a sperm cell in detail. Sperm are much smaller than eggs and are produced in much larger numbers (over 300 million in a single ejaculation). The tip of the cell carries an acrosome, which secretes enzymes capable of digesting a path into an egg cell, through the jelly coat, so the sperm nucleus can fuse with the egg nucleus. The cytoplasm of the mid-piece of the sperm contains many mitochondria. They carry out respiration, providing energy to make the tail (flagellum) move and propel the sperm forward.

The egg cell (see Figure 2.13(h)) is much larger than a sperm cell and only one egg is released each month while the woman is fertile. It is surrounded by a jelly coat, which protects the contents of the cell and prevents more than one sperm from entering and fertilising the egg. The egg cell contains a large amount of cytoplasm, which is rich in fats and proteins. The fats act as energy stores. Proteins are available for growth if the egg is fertilised.

## Functions of the placenta and umbilical cord

The blood vessels in the placenta are very close to the blood vessels in the uterus so that oxygen, glucose, amino acids and salts can pass from the mother's blood to the embryo's blood (Figure 16.57(a)). So the blood flowing in the umbilical vein from the placenta carries food and oxygen to be used by the living, growing tissues of the embryo. In a similar way, the carbon dioxide and urea in the embryo's blood escape from the vessels in the placenta and are carried away by the mother's blood in the uterus (Figure 16.57(b)). In this way the embryo gets rid of its excretory products.

There is no direct communication between the mother's blood system and that of the embryo. The exchange of substances takes place across the thin walls of the blood vessels. In this way, the mother's blood pressure cannot damage the delicate vessels of the embryo and it is possible for the placenta to select the substances allowed to pass into the embryo's blood. The placenta can prevent some harmful substances in the mother's blood from reaching the embryo. It cannot prevent all of them, however: alcohol and nicotine can pass to the developing fetus. If the mother is a heroin addict, the baby can be born addicted to the drug.

Some pathogens such as the rubella virus and HIV can pass across the placenta. Rubella (German measles), although a mild infection for the mother, can infect the fetus and results in major health problems, including deafness, congenital heart disease, diabetes and mental retardation. HIV is potentially fatal.

The placenta produces hormones, including oestrogens and progesterone. It is assumed that these hormones play an important part in maintaining the pregnancy and preparing for birth, but their precise function is not known. They may influence the development and activity of the muscle layers in the wall of the uterus and prepare the mammary glands in the breasts for milk production.

## Feeding and parental care

Within the first 24 hours after birth, the baby starts to suck at the breast. During pregnancy the mammary glands (breasts) enlarge as a result of an increase in the number of milk-secreting cells. No milk is secreted during pregnancy, but the hormones that start the birth process also act on the milk-secreting cells of the breasts. The breasts are stimulated to release milk by the baby sucking the nipple. The continued production of milk is under the control of hormones, but the amount of milk produced is related to the quantity taken by the child during suckling.

Milk contains the proteins, fats, sugar, vitamins and salts that babies need for their energy requirements and tissue-building, but there is too little iron present for the manufacture of haemoglobin. All the iron needed for the first weeks or months is stored in the liver of the fetus during gestation.

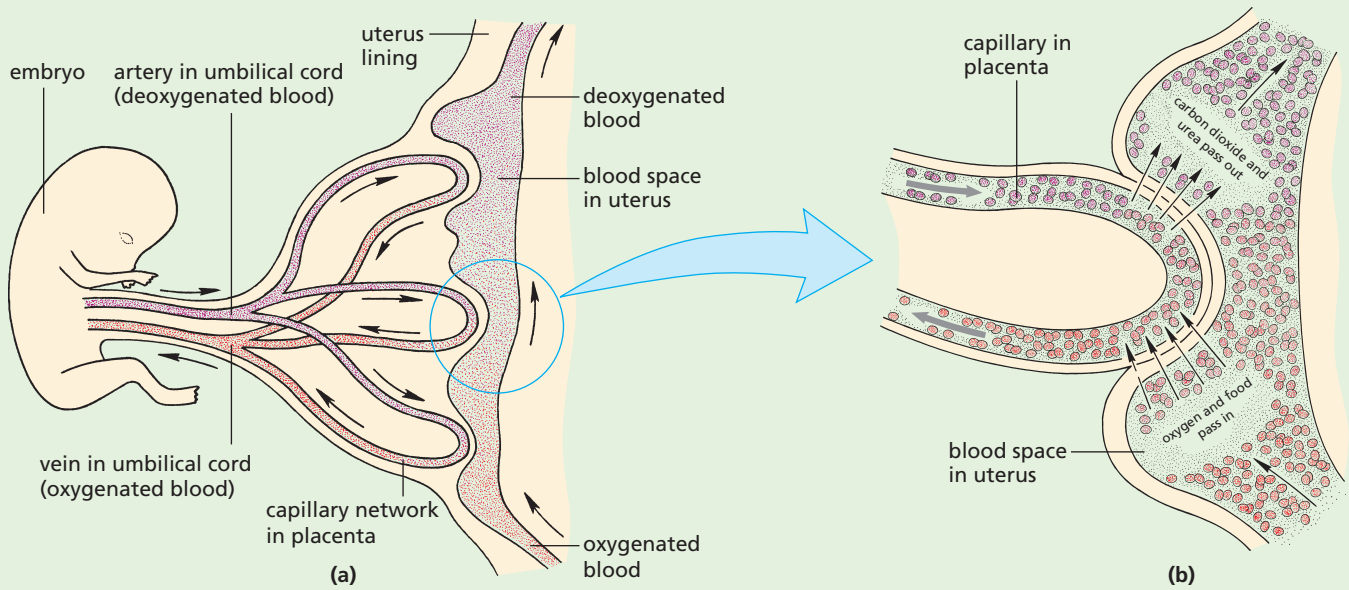



**Figure 16.57** The exchange of substances between the blood of the embryo and the mother

The liquid produced in the first few days is called **colostrum**. It is sticky and yellow, and contains more protein than the milk produced later. It also contains some of the mother's antibodies. This provides passive immunity (see Chapter 10) to infection.

The mother's milk supply increases with the demands of the baby, up to 1 litre per day. It is gradually supplemented and eventually replaced entirely by solid food, a process known as **weaning**.

Cows' milk is not wholly suitable for human babies. It has more protein, sodium and phosphorus, and less sugar, vitamin A and vitamin C, than human milk. It is less easily digested than human milk. Manufacturers modify the components of dried cows' milk to resemble human milk more closely and this makes it more acceptable if the mother cannot breastfeed her baby.

Cows' milk and proprietary dried milk both lack human antibodies, whereas the mother's milk contains antibodies to any diseases from which she has recovered. It also carries white cells that produce antibodies or ingest bacteria. These antibodies are important in defending the baby against infection at a time when its own immune responses are not fully developed. Breastfeeding provides milk free from bacteria, whereas bottle-feeding carries the risk of introducing bacteria that cause intestinal diseases. Breastfeeding also offers emotional and psychological benefits to both mother and baby.

Other advantages of breastfeeding over bottle-feeding include the following:

- There is no risk of an allergic reaction to breast milk.
- Breast milk is produced at the correct temperature.
- There are no additives or preservatives in breast milk.
- Breast milk does not require sterilisation since there are no bacteria present that could cause intestinal disease.
- There is no cost involved in using breast milk.
- Breast milk does not need to be prepared.
- Breastfeeding triggers a reduction in the size of the mother's uterus.

# Sex hormones in humans

## Puberty and the menstrual cycle

### Puberty

Although the ovaries of a young girl contain all the ova she will ever produce, they do not start to be released until she reaches the age of about 10–14 years. This stage in her life is known as **puberty**.

At about the same time as the first ovulation, the ovary also releases female sex hormones into the bloodstream. These hormones are called **oestrogens** and when they circulate around the body, they bring about the development of **secondary sexual characteristics**. In a girl these are the increased growth of the breasts, a widening of the hips and the growth of hair in the pubic region and in the armpits. There is also an increase in the size of the uterus and vagina. Once all these changes are complete, the girl is capable of having a baby.

Puberty in boys occurs at about the same age as in girls. The testes start to produce sperm for the first time and also release a hormone, called **testosterone**, into the bloodstream. The male secondary sexual characteristics, which begin to appear at puberty, are enlargement of the testes and penis, deepening of the voice, growth of hair in the pubic region, armpits, chest and, later on, the face. In both sexes there is a rapid increase in the rate of growth during puberty.

In addition to the physical changes at puberty, there are emotional and psychological changes associated with the transition from being a child to becoming an adult, i.e. the period of **adolescence**. Most people adjust to these changes smoothly and without problems. Sometimes, however, a conflict arises between having the status of a child and the sexuality and feelings of an adult.

### The menstrual cycle

The ovaries release an ovum about every 4 weeks. In preparation for this the lining of the uterus wall thickens, so that an embryo can embed itself if the released ovum is fertilised. If no implantation occurs,

the uterus lining breaks down. The cells, along with blood are passed out of the vagina. This is called a **menstrual period**. The appearance of the first menstrual period is one of the signs of puberty in girls. After menstruation, the uterus lining starts to re-form and another ovum starts to mature.

### Hormones and the menstrual cycle

At the start of the cycle, the lining of the uterus wall has broken down (menstruation). As each follicle in the ovaries develops, the amount of oestrogens produced by the ovary increases. The oestrogens act on the uterus and cause its lining to become thicker and develop more blood vessels. These are changes that help an early embryo to implant.

Two hormones, produced by the **pituitary gland** at the base of the brain, promote ovulation. The hormones are **follicle-stimulating hormone** (**FSH**) and **luteinising hormone**, or **lutropin** (**LH**). They act on a ripe follicle and stimulate maturation and release of the ovum.

Once the ovum has been released, the follicle that produced it develops into a solid body called the **corpus luteum**. This produces a hormone called **progesterone**, which affects the uterus lining in the same way as the oestrogens, making it grow thicker and produce more blood vessels.

If the ovum is fertilised, the corpus luteum continues to release progesterone and so keeps the uterus in a state suitable for implantation. If the ovum is not fertilised, the corpus luteum stops producing progesterone. As a result, the thickened lining of the uterus breaks down and loses blood, which escapes through the cervix and vagina. The events in the menstrual cycle are shown in Figure 16.58.

### Menopause

Between the ages of 40 and 55, the ovaries cease to release ova or produce hormones. As a consequence, menstrual periods cease, the woman can no longer have children, and sexual desire is gradually reduced.

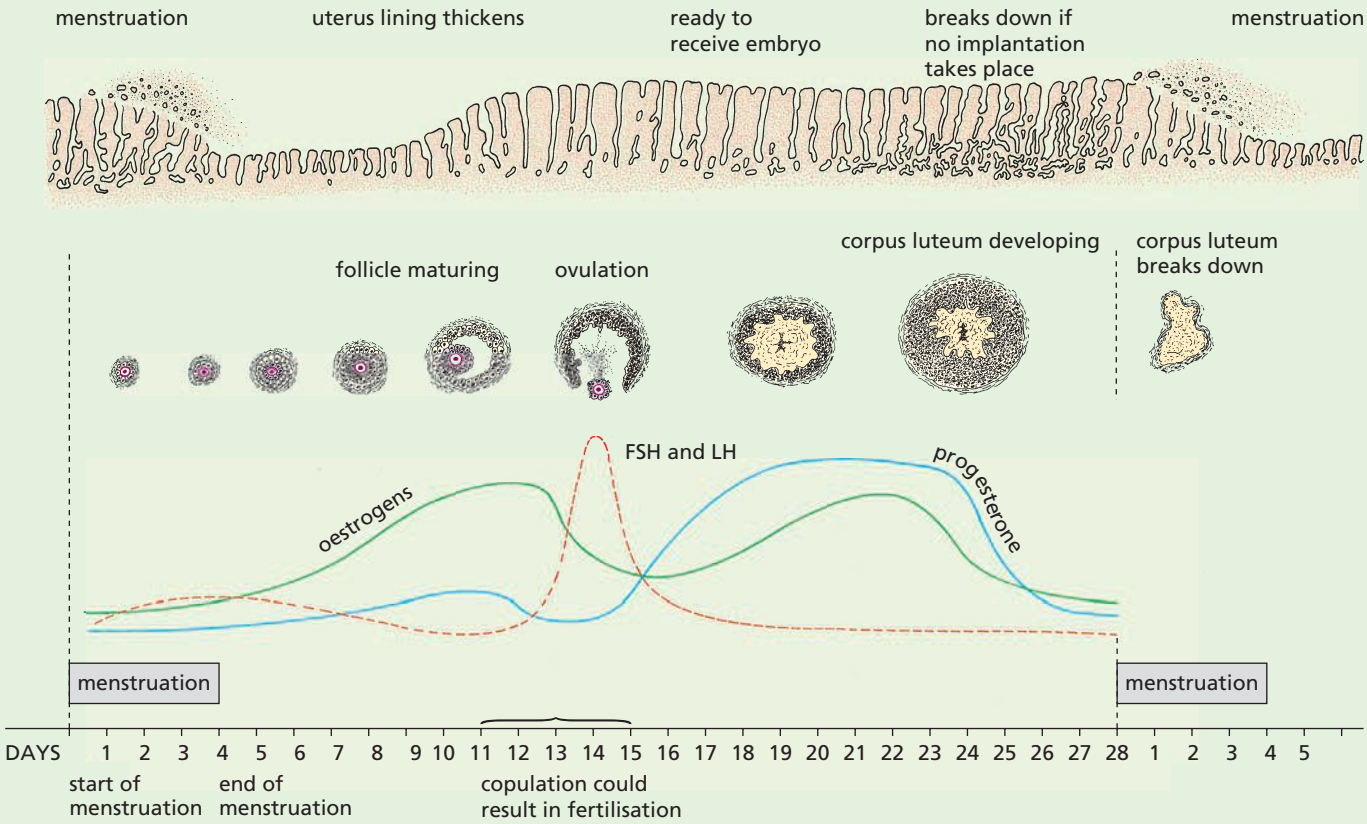



**Figure 16.58** The menstrual cycle

# Methods of birth control in humans

As little as 4 weeks after giving birth, it is possible, though unlikely, that a woman may conceive again. Frequent breastfeeding may reduce the chances of conception. Nevertheless, it would be possible to have children at about 1-year intervals. Most people do not want, or cannot afford, to have as many children as this. All human communities, therefore, practise some form of birth control to space out births and limit the size of the family.

## Natural methods of family planning

### Abstinence

This is the most obvious way of preventing a pregnancy. This involves a couple avoiding sexual intercourse. In this way, sperm cannot come into contact with an egg and fertilisation cannot happen.

### Monitoring body temperature

If it were possible to know exactly when ovulation occurred, intercourse could be avoided for 3–4 days before and 1 day after ovulation. At the moment, however, there is no simple, reliable way to recognise ovulation, though it is usually 12–16 days before the onset of the next menstrual period. By keeping careful records of the intervals between menstrual periods, it is possible to calculate a potentially fertile period of about 10 days in mid-cycle, when sexual intercourse should be avoided if children are not wanted.

On its own, this method is not very reliable but there are some physiological clues that help to make it more accurate. During or soon after ovulation, a woman's temperature rises by about 0.5 °C. It is reasonable to assume that 1 day after the temperature returns to normal, a woman will be infertile.

### Cervical mucus

Another clue comes from the type of mucus secreted by the cervix and lining of the vagina. As the time for ovulation approaches, the mucus becomes more fluid. Women can learn to detect these changes and so calculate their fertile period.

By combining the 'calendar', 'temperature' and 'mucus' methods, it is possible to achieve about 80% 'success', i.e. only 20% unplanned pregnancies. Highly motivated couples may achieve better rates of success and, of course, it is a very helpful way of finding the fertile period for couples who do want to conceive.

## Artificial methods of family planning

### Barrier methods

**Sheath or condom**

A thin rubber sheath is placed on the erect penis before sexual intercourse. The sheath traps the sperm and prevents them from reaching the uterus. It also prevents the transmission of sexually transmitted infections (STIs).

**Diaphragm**

A thin rubber disc, placed in the vagina before intercourse, covers the cervix and stops sperm entering the uterus. Condoms and diaphragms, used in conjunction with chemicals that immobilise sperm, are about 95% effective. However, a diaphragm does not prevent the risk of transmission of STIs.

**Femidom**

This is a female condom. It is a sheath or pouch, made of polyurethane or rubber, with a flexible ring at each end. The ring at the closed end of the sheath is inserted into the vagina to hold the femidom in place. The ring at the open end is placed outside the vagina. During sexual intercourse, semen is trapped inside the femidom. A femidom reduces the risk of infection by STIs.

### Chemical methods

**Spermicides**

Spermicides are chemicals which, though harmless to the tissues, can kill or immobilise sperm. The spermicide, in the form of a cream, gel or foam, is placed in the vagina. On their own, spermicides are not very reliable but, in conjunction with condoms or diaphragms, they are effective.

**Intra-uterine device (IUD)**

A small T-shaped plastic and copper device, also known as a coil, can be inserted by a doctor or nurse into the wall of the uterus, where it probably prevents implantation of a fertilised ovum. It is about 98% effective but there is a small risk of developing uterine infections, and it does not protect against STIs.

**Intra-uterine system (IUS)**

This is similar to an IUD; is T-shaped and releases the hormone progesterone slowly over a long period of time (up to 5 years). The hormone prevents ovulation. An IUS does not protect against STIs.

**Contraceptive pill**

The pill contains chemicals, which have the same effect on the body as the hormones oestrogen and

progesterone. When mixed in suitable proportions these hormones suppress ovulation and so prevent conception. The pills need to be taken each day for the 21 days between menstrual periods.

There are many varieties of contraceptive pill in which the relative proportions of oestrogen- and progesterone-like chemicals vary. They are 99% effective, but long-term use of some types may increase the risk of cancer of the breast and cervix. The pill does not protect against STIs.

**Contraceptive implant**
This is a small plastic tube about 4 cm long, which is inserted under the skin of the upper arm of a woman by a doctor or nurse. Once in place it slowly releases the hormone progesterone, preventing pregnancy. It lasts for about 3 years. It does not protect against STIs, but has more than a 99% success rate in preventing pregnancy.

**Contraceptive injection**
This injection, given to women, contains progesterone and stays effective for between 8 and 12 weeks. It works by thickening the mucus in the cervix, stopping sperm reaching an egg. It also thins the lining of the uterus, making it unsuitable for implantation of an embryo. It does not protect against STIs.

### Surgical methods

**Male sterilisation – vasectomy**
This is a simple and safe surgical operation in which the man's sperm ducts are cut and the ends sealed. This means that his semen contains the secretions of the prostate gland and seminal vesicle but no sperm, so cannot fertilise an ovum. Sexual desire, erection, copulation and ejaculation are quite unaffected.

The testis continues to produce sperm and testosterone. The sperm are removed by white cells as fast as they form. The testosterone ensures that there is no loss of masculinity.

The sperm ducts can be rejoined by surgery but this is not always successful.

**Female sterilisation – laparotomy**
A woman may be sterilised by an operation in which her oviducts are tied, blocked or cut. The ovaries are unaffected. Sexual desire and menstruation continue as before, but sperm can no longer reach the ova. Ova are released, but break down in the upper part of the oviduct.

The operation cannot usually be reversed.

## The use of hormones in fertility and contraception treatments

### Infertility

About 85–90% of couples trying for a baby achieve pregnancy within a year. Those that do not may be sub-fertile or infertile. Female infertility is usually caused by a failure to ovulate or a blockage or distortion of the oviducts. The latter can often be corrected by surgery.

**Using hormones to improve fertility**
Failure to produce ova can be treated with **fertility drugs**. These drugs are similar to hormones and act by increasing the levels of FSH and LH. Administration of the drug is timed to promote ovulation to coincide with copulation.

**Artificial insemination (AI)**
Male infertility is caused by an inadequate quantity of sperm in the semen or by sperm that are insufficiently mobile to reach the oviducts. There are few effective treatments for this condition, but pregnancy may be achieved by **artificial insemination** (**AI**). This involves injecting semen through a tube into the top of the uterus. In some cases, the husband's semen can be used but, more often, the semen is supplied by an anonymous donor.

With AI, the woman has the satisfaction of bearing her child rather than adopting, and 50% of the child's genes are from the mother. It also allows a couple to have a baby that is biologically theirs if the man is infertile.

Apart from religious or moral objections, the disadvantages are that the child can never know his or her father and there may be legal problems about the legitimacy of the child in some countries.

***In vitro* fertilisation**
'*In vitro*' means literally 'in glass' or, in other words, the fertilisation is allowed to take place in laboratory glassware (hence the term 'test-tube babies'). This technique may be employed where surgery cannot be used to repair blocked oviducts.

*In vitro* fertilisation has received considerable publicity since the first 'test-tube' baby was born

in 1978. The woman may be given fertility drugs, which cause her ovaries to release several mature ova simultaneously. These ova are then collected by laparoscopy, i.e. they are sucked up in a fine tube inserted through the abdominal wall. The ova are then mixed with the husband's seminal fluid and watched under the microscope to see if cell division takes place. (Figure 16.50 is a photograph of such an '*in vitro*' fertilised ovum.)

One or more of the dividing zygotes are then introduced to the woman's uterus by means of a tube inserted through the cervix. Usually, only one (or none) of the zygotes develops, though occasionally there are multiple births.

The success rate for *in vitro* fertilisation is between 12 and 40% depending on how many embryos are transplanted. However, new research using time-lapse photography of the developing IVF embryos during the first few days of life could raise the success rate to up to 78%. It could also reduce the cost from between £5000 and £10 000 for each treatment cycle to £750 in Britain. The photographs are used to select the best embryos, based on their early development.

### Using hormones for contraception

Oestrogen and progesterone control important events in the menstrual cycle.

Oestrogen encourages the re-growth of the lining of the uterus wall after a period and prevents the release of FSH. If FSH is blocked, no further ova are matured. The uterus lining needs to be thick to allow successful implantation of an embryo.

Progesterone maintains the thickness of the uterine lining. It also inhibits the secretion of luteinising hormone (LH), which is responsible for ovulation. If LH is suppressed, ovulation cannot happen, so there are no ova to be fertilised.

Because of the roles of oestrogen and progesterone, they are used, singly or in combination, in a range of contraceptive methods.

### Social implications of contraception and fertility treatments

Some religions are against any artificial forms of contraception and actively discourage the use of contraceptives such as the sheath and femidom. However, these are important in the prevention of transmission of STDs in addition to their role as contraceptives.

Fertility treatments such as *in vitro* fertilisation are controversial because of the 'spare' embryos that are created and not returned to the uterus. Some people believe that since these embryos are potential human beings, they should not be destroyed or used for research. In some cases the 'spare' embryos have been frozen and used later if the first transplants did not work.

# Sexually transmitted infections (STIs)

**Key definition**
A **sexually transmitted infection** is an infection that is transmitted via body fluids through sexual contact.

## AIDS and HIV

The initials of AIDS stand for **acquired immune deficiency syndrome**. (A 'syndrome' is a pattern of symptoms associated with a particular disease.) The virus that causes AIDS is the **human immunodeficiency virus** (**HIV**).

After a person has been infected, years may pass before symptoms develop. So people may carry the virus yet not show any symptoms. They can still infect other people, however. It is not known for certain what proportion of HIV carriers will eventually develop AIDS: perhaps 30–50%, or more.

HIV is transmitted by direct infection of the blood. Drug users who share needles contaminated with infected blood run a high risk of the disease. It can also be transmitted sexually, both between men and women and, especially, between homosexual men who practise anal intercourse. Prostitutes, who have many sexual partners, are at risk of being infected if they have sex without using condoms and are, therefore, a potential source of HIV to others.

Haemophiliacs have also fallen victim to AIDS. Haemophiliacs have to inject themselves with a blood product that contains a clotting factor. Before the risks were recognised, infected carriers sometimes donated blood, which was used to produce the clotting factor.

Babies born to HIV carriers may become infected with HIV, either in the uterus or during birth or from the mother's milk. The rate of infection varies from about 40% in parts of Africa to 14% in Europe. If the mother is given drug therapy during labour and the baby within 3 days, this method of transmission is reduced.

There is no evidence to suggest that the disease can be passed on by droplets (Chapter 10), by saliva or by normal everyday contact.

When AIDS first appeared, there were no effective drugs. Today, there is a range of drugs that can be given separately or as a 'cocktail', which slow the progress of the disease. Research to find a vaccine and more effective drugs is ongoing.

There is a range of blood tests designed to detect HIV infection. These tests do not detect the virus but do indicate whether antibodies to the virus are in the blood. If HIV antibodies are present, the person is said to be **HIV positive**. The tests vary in their reliability and some are too expensive for widespread use. The American Food and Drug Administration claims a 99.8% accuracy, but this figure is disputed.

## Control of the spread of STIs

The best way to avoid sexually transmitted infections is to avoid having sexual intercourse with an infected person. However, the symptoms of the disease are often not obvious and it is difficult to recognise an infected individual. So the disease is avoided by not having sexual intercourse with a person who *might* have the disease. Such persons are:

- prostitutes who offer sexual intercourse for money
- people who are known to have had sexual relationships with many others
- casual acquaintances whose background and past sexual activities are not known.

These are good reasons, among many others, for being faithful to one partner.

The risk of catching a sexually transmitted disease can be greatly reduced if the man uses a condom or if a woman uses a femidom. These act as barriers to bacteria or viruses.

If a person suspects that he or she has caught a sexually transmitted disease, treatment must be sought at once. Information about treatment can be obtained by phoning one of the numbers listed under 'Venereal Disease' or 'Health Information Service' in the telephone directory. Treatment is always confidential. The patients must, however, ensure that anyone they have had sexual contact with also gets treatment. There is no point in one partner being cured if the other is still infected.

STIs that are caused by a bacterium, such as syphilis and gonorrhoea, can be treated with antibiotics if the symptoms are recognised early enough. However, HIV is viral so antibiotics are not effective.

## The effects of HIV on the immune system

HIV attacks certain kinds of lymphocyte (see 'Blood' in Chapter 9), so the number of these cells in the body decreases. Lymphocytes produce antibodies against infections. If the body cannot respond to infections through the immune system, it becomes vulnerable to pathogens that might not otherwise be life-threatening. As a result, the patient has little or no resistance to a wide range of diseases such as influenza, pneumonia, blood disorders, skin cancer or damage to the nervous system, which the body cannot resist.

## Questions

Core

1 Plants can often be propagated from stems but rarely from roots. What features of shoots account for this difference?
2 The plants that survive a heath fire are often those that have a rhizome (e.g. ferns). Suggest a reason why this is so.
3 Working from outside to inside, list the parts of a bisexual flower.
4 What features of flowers might attract insects?
5 Which part of a flower becomes:
   a the seed
   b the fruit?
6 Put the following events in the correct order for pollination in a lupin plant:
   A Bee gets dusted with pollen.
   B Pollen is deposited on stigma.
   C Bee visits older flower.
   D Bee visits young flower.
   E Anthers split open.
7 What are the functions in a seed of:
   a the radicle
   b the plumule
   c the cotyledons?

8 During germination of the broad bean, how are the following parts protected from damage as they are forced through the soil:
   a the plumule
   b the radicle?
9 List all the possible purposes for which a growing seedling might use the food stored in its cotyledons.
10 At what stage of development is a seedling able to stop depending on the cotyledons for its food?
11 What do you think are the advantages to a germinating seed of having its radicle growing some time before the shoot starts to grow?
12 a Describe the natural conditions in the soil that would be most favourable for germination.
   b How could a gardener try to create these conditions?
13 How do sperm differ from ova in their structure (see Figure 16.39)?
14 List the structures, in the correct order, through which the sperm must pass from the time they are produced in the testis, to the time they leave the urethra.
15 What structures are shown in Figure 16.44, but are not shown in Figure 16.43?
16 In what ways does a zygote differ from any other cell in the body?
17 If a woman starts ovulating at 13 years old and stops at 50:
   a how many ova are likely to be released from her ovaries
   b about how many of these are likely to be fertilised?
18 List, in the correct order, the parts of the female reproductive system through which sperm must pass before reaching and fertilising an ovum.
19 State exactly what happens at the moment of fertilisation.
20 Is fertilisation likely to occur if mating takes place:
   a 2 days before ovulation
   b 2 days after ovulation?
   Explain your answers.
21 Draw up a table with three columns as shown below. In the first column write:
   male reproductive organs
   female reproductive organs
   male gamete
   female gamete
   place where fertilisation occurs
   zygote grows into
   Now complete the other two columns.

| | Flowering plants | Mammals |
|---|---|---|
| male reproductive organs | | |
| female reproductive organs | | |
| male gamete, etc. | | |

22 In what ways will the composition of the blood in the umbilical vein differ from that in the umbilical artery?
23 An embryo is surrounded with fluid, its lungs are filled with fluid and it cannot breathe. Why doesn't it suffocate?
24 If a mother gives birth to twin boys, does this mean that they are identical twins? Explain.
25 Study Figures 16.51 and 16.52. On each diagram the age and size of the developing embryo are stated.
   a Copy and complete the following table:

| Age/weeks | Size/mm |
|---|---|
| 0 | 0 |
| 2 | |
| 5 | |
| 8 | |
| 10 | |
| 20 | |
| 35 | |

   b Use the data in your table to plot a graph to show the growth of the embryo.

Extended

26 In what ways does asexual reproduction in *Mucor* differ from asexual reproduction in flowering plants?
27 A gardener finds a new and attractive plant produced as a result of a chance mutation. Should she attempt to produce more of the same plant by self-pollination or by vegetative propagation? Explain your reasoning.
28 Which of the following do not play a part in asexual reproduction?
   mitosis, gametes, meiosis, cell division, chromosomes, zygote
29 Revise asexual reproduction and then state how we exploit the process of asexual reproduction in plants.
30 Which structures in a flower produce:
   a the male gametes
   b the female gametes?
31 In not more than two sentences, distinguish between the terms *pollination* and *fertilisation*.
32 In flowering plants:
   a can pollination occur without fertilisation
   b can fertilisation occur without pollination?
33 Which parts of a tomato flower:
   a grow to form the fruit
   b fall off after fertilisation
   c remain attached to the fruit?
34 From the list of changes at puberty in girls, select those that are related to childbearing and say what part you think they play.
35 One of the first signs of pregnancy is that the menstrual periods stop. Explain why you would expect this.

## Checklist

After studying Chapter 16 you should know and understand the following:

### Asexual reproduction

- Asexual reproduction is the process resulting in the production of genetically identical offspring from one parent.
- Asexual reproduction occurs without gametes or fertilisation.
- Fungi can reproduce asexually by single-celled spores.
- Many flowering plants reproduce asexually by vegetative propagation.
- Plants reproduce asexually when some of their buds grow into new plants.
- The stolon of the strawberry plant is a horizontal stem that grows above the ground, takes root at the nodes and produces new plants.
- The couch grass rhizome is a horizontal stem that grows below the ground and sends up shoots from its nodes.
- Bulbs are condensed shoots with circular fleshy leaves. Bulb-forming plants reproduce asexually from lateral buds.
- Rhizomes, corms, bulbs and tap roots may store food, which is used to accelerate early growth.
- A clone is a population of organisms produced asexually from a single parent.
- Whole plants can be produced from single cells or small pieces of tissue.

- Artificial propagation from cuttings or grafts preserves the desirable characteristics of a crop plant.
- Vegetative propagation produces (genetically) identical individuals.
- Asexual reproduction keeps the characteristics of the organism the same from one generation to the next, but does not result in variation to cope with environmental change.

### Sexual reproduction

- Sexual reproduction is the process involving the fusion of the nuclei of two gametes (sex cells) to form a zygote and the production of offspring that are genetically different from each other.
- The male gamete is small and mobile. The female gamete is larger and not often mobile.
- The male gamete of an animal is a sperm. The male gamete of a flowering plant is the pollen nucleus.
- The female gamete of an animal is an ovum. The female gamete of a flowering plant is an egg cell in an ovule.
- Fertilisation is the fusion of gamete nuclei.

- The nuclei of gametes are haploid and the nucleus of the zygote is diploid.
- There are advantages and disadvantages of sexual reproduction to a species.
- There are advantages and disadvantages of sexual reproduction in crop production.

### Sexual reproduction in plants

- Flowers contain the reproductive organs of plants.
- The stamens are the male organs. They produce pollen grains, which contain the male gamete.
- The carpels are the female organs. They produce ovules, which contain the female gamete and will form the seeds.
- The flowers of most plant species contain male and female organs. A few species have unisexual flowers.
- Brightly coloured petals attract insects, which pollinate the flower.
- Pollination is the transfer of pollen from the anthers of one flower to the stigma of a flower on the same or another plant.
- Pollination may be carried out by insects or by the wind.
- Flowers that are pollinated by insects are usually brightly coloured and have nectar.
- Flowers that are pollinated by the wind are usually small and green. Their stigmas and anthers hang outside the flower where they are exposed to air movements.
- Fertilisation occurs when a pollen tube grows from a pollen grain into the ovary and up to an ovule. The pollen nucleus passes down the tube and fuses with the ovule nucleus.
- After fertilisation, the ovary grows rapidly to become a fruit and the ovules become seeds.
- Germination is influenced by temperature and the amount of water and oxygen available.

- Self-pollination is the transfer of pollen grains from the anther of a flower to the stigma of the same flower.
- Cross-pollination is transfer of pollen grains from the anther of a flower to the stigma of a flower on a different plant of the same species.
- Self-pollination and cross-pollination have implications to a species.

### Sexual reproduction in humans

- The male reproductive cells (gametes) are sperm. They are produced in the testes and expelled through the urethra and penis during mating.
- The female reproductive cells (gametes) are ova (eggs). They are produced in the ovaries. One is released each month. If sperm are present, the ovum may be fertilised as it passes down the oviduct to the uterus.
- Fertilisation happens when a sperm enters an ovum and the sperm and egg nuclei join up (fuse).
- The fertilised ovum (zygote) divides into many cells and becomes embedded in the lining of the uterus. Here it grows into an embryo.
- The embryo gets its food and oxygen from its mother.
- The embryo's blood is pumped through blood vessels in the umbilical cord to the placenta, which is attached to the uterus lining. The embryo's blood comes very close to the mother's blood so that food and oxygen can be picked up and carbon dioxide and nitrogenous waste can be got rid of.

- Good ante-natal care, in the form of special dietary needs and maintaining good health, is needed to support the mother and her fetus.
- When the embryo is fully grown, it is pushed out of the uterus through the vagina by contractions of the uterus and abdomen.
- Twins may result from two ova being fertilised at the same time or from a zygote forming two embryos.

- Eggs and sperm are different in size, structure, mobility and numbers produced.
- Sperm and eggs have special features to adapt them for their functions.
- The placenta and umbilical cord are involved in exchange of materials between the mother and fetus. Some toxins and viruses can also be passed across and affect the fetus.
- Human milk and breastfeeding are best for babies.

**Sex hormones in humans**

- At puberty, the testes and ovaries start to produce mature gametes and the secondary sexual characteristics develop.
- Each month, the uterus lining thickens up in readiness to receive a fertilised ovum. If an ovum is not fertilised, the lining and some blood are lost through the vagina. This is menstruation.

- Oestrogen and progesterone are secreted by endocrine glands.
- The release of ova and the development of an embryo are under the control of hormones like oestrogen, progesterone, follicle-stimulating hormone and luteinising hormone.

**Methods of birth control in humans**

- There are effective ways of spacing births and limiting the size of a family. These include natural, chemical, barrier and surgical methods.

- Hormones can be used to control fertility, including contraception and promoting egg-cell development.
- Female infertility may be relieved by surgery, fertility drugs or *in vitro* fertilisation.
- Male infertility can be by-passed by artificial insemination.
- There are social implications of using hormones in contraception and for increasing the chances of pregnancy.

**Sexually transmitted infections (STIs)**

- A sexually transmitted infection is an infection transmitted via bodily fluids through sexual contact.
- HIV is an example of an STI.
- HIV can be transmitted in a number of ways.
- The spread of HIV can be controlled.
- HIV infection may lead to AIDS.

- HIV affects the immune system by reducing the number of lymphocytes and decreasing the ability to produce antibodies.

# 17 Inheritance

**Inheritance**
Define inheritance

**Chromosomes, genes and proteins**
Define chromosome and gene
Inheritance of sex in humans

Genetic code for proteins
Role of DNA in cell function
How a protein is made
Gene expression
Define haploid nucleus, diploid nucleus
Diploid cells

**Mitosis**
Define mitosis
Role of mitosis
Duplication and separation of chromosomes

**Meiosis**
Define meiosis
Role of meiosis

The process of mitosis
The function of chromosomes
Stem cells
Gamete production and chromosomes
Meiosis

**Monohybrid inheritance**
Define allele, genotype, phenotype, homozygous, heterozygous, dominant, recessive
Use of genetic diagrams and Punnett squares

Use of test crosses
Co-dominance and incomplete dominance
Define sex-linked characteristic
Colour blindness
Genetic crosses involving co-dominance and sex linkage

## Inheritance

**Key definition**
**Inheritance** is the transmission of genetic information from generation to generation.

We often talk about people inheriting certain characteristics: 'Nathan has inherited his father's curly hair', or 'Fatima has inherited her mother's brown eyes'. We expect tall parents to have tall children. The inheritance of such characteristics is called **heredity** and the branch of biology that studies how heredity works is called **genetics**.

## Chromosomes, genes and proteins

**Key definitions**
A **chromosome** is a thread of DNA, made up of a string of genes.
A **gene** is a length of DNA that codes for a protein.

Inside a nucleus are thread-like structures called **chromosomes** which can be seen most clearly at the time when the cell is dividing. Each chromosome has certain characteristics when ready to divide: there are two **chromatids**, joined at one point called a **centromere** (Figure 17.1). Each chromatid is a string of **genes**, coding for the person's characteristics. The other chromatid carries the same genes in the same order.

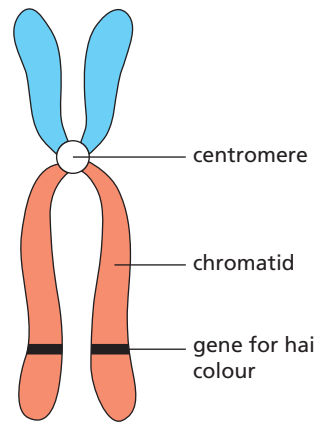



**Figure 17.1** Structure of a chromosome

A human body (**somatic**) cell nucleus contains 46 chromosomes. These are difficult to distinguish when packed inside the nucleus, so scientists separate them and arrange them according to size and appearance. The outcome is called a **karyotype** (Figure 17.2). There are pairs of chromosomes. The only pair that do not necessarily match is chromosome pair 23: the 'sex chromosomes'. The Y chromosome is much smaller than the X chromosome.

### The inheritance of sex

Whether you are a male or female depends on the pair of chromosomes called the 'sex chromosomes'. In females, the two sex chromosomes, called the X chromosomes, are the same size as each other. In males, the two sex chromosomes are of different sizes. One corresponds to the female sex

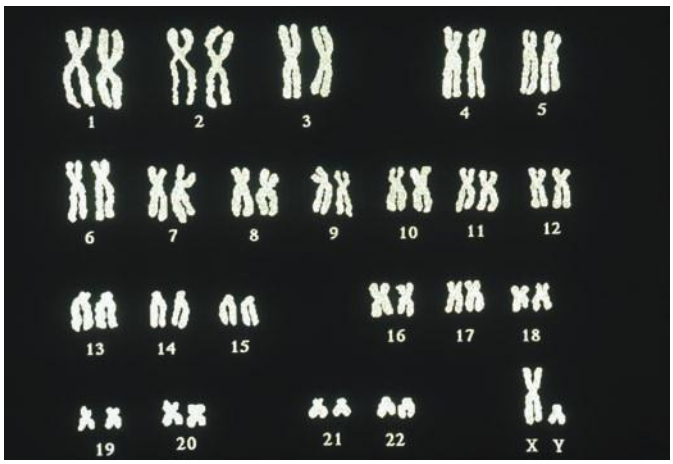



**Figure 17.2** Human karyotype

chromosomes and is called the X chromosome. The other is smaller and is called the Y chromosome. So the female cells contain **XX** and male cells contain **XY**.

A process called **meiosis** takes place in the female's ovary. It makes gametes: sex cells, which have half the normal number of chromosomes. During the process, each ovum receives one of the X chromosomes, so all the ova are the same for this. Meiosis in the male's testes results in 50% of the sperms getting an X chromosome and 50% getting a Y chromosome (Figure 17.3). If an X sperm fertilises the ovum, the zygote will be XX and will grow into a girl. If a Y sperm fertilises the ovum, the zygote will be XY and will develop into a boy. There is an equal chance of an X or Y chromosome fertilising an ovum, so the numbers of girl and boy babies are more or less the same.

Figure 17.4 shows how sex is inherited.

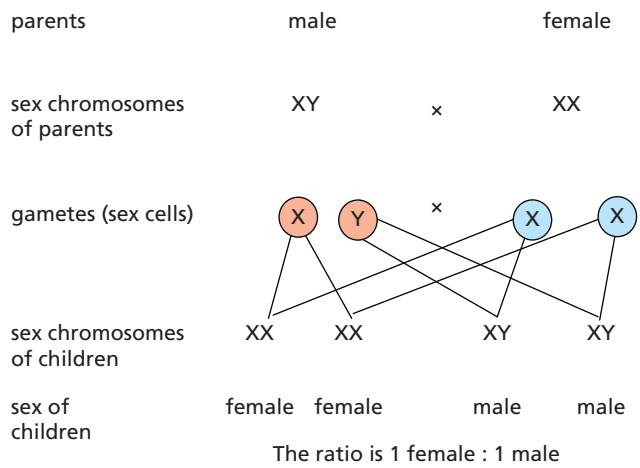



**Figure 17.4** Determination of sex

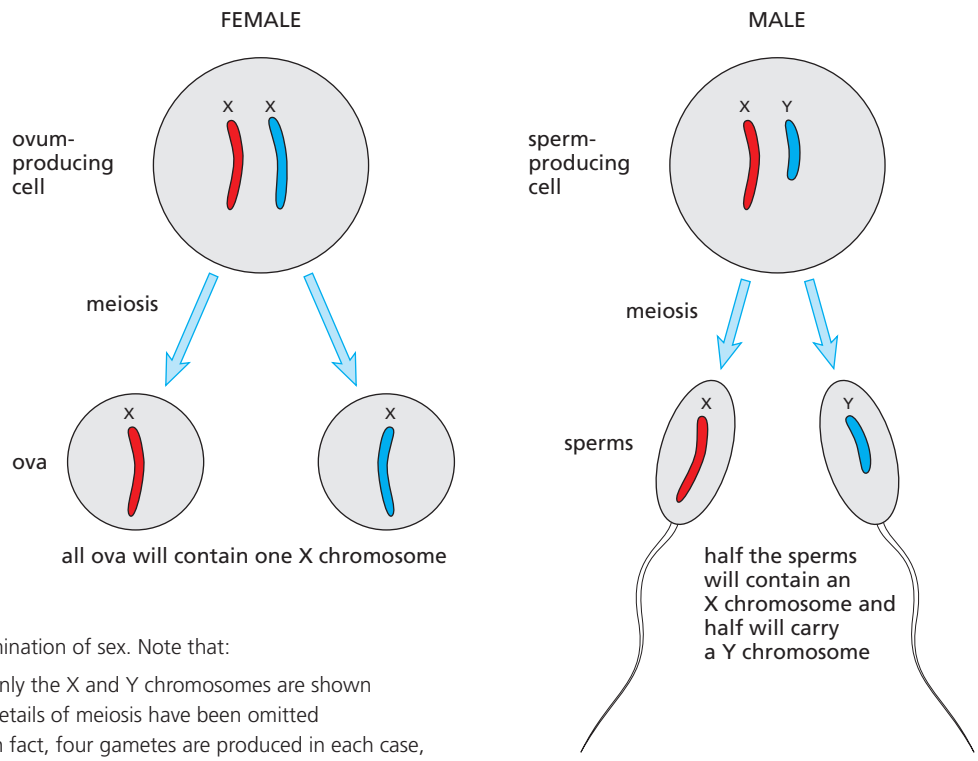



**Figure 17.3** Determination of sex. Note that:

- **(i)** only the X and Y chromosomes are shown
- **(ii)** details of meiosis have been omitted
- **(iii)** in fact, four gametes are produced in each case, but two are sufficient to show the distribution of X and Y chromosomes

## The genetic code

The structure of DNA has already been described in Chapter 4.

Each nucleotide carries one of four bases (A, T, C or G). A string of nucleotides therefore holds a sequence of bases. This sequence forms a code, which instructs the cell to make particular proteins. Proteins are made from amino acids linked together (Chapter 4). The type and sequence of the amino acids joined together will determine the kind of protein formed. For example, one protein molecule may start with the sequence *alanine–glycine–glycine* .... A different protein may start *glycine–serine–alanine* ....

It is the sequence of bases in the DNA molecule that decides which amino acids are used and in which order they are joined. Each group of three bases stands for one amino acid, e.g. the triplet of bases CGA specifies the amino acid *alanine*, the base triplet CAT specifies the amino acid *valine*, and the triplet CCA stands for *glycine*. The tri-peptide *valine–glycine–alanine* is specified by the DNA code CAT–CCA–CGA (Figure 17.5).

A gene, then, is a sequence of triplets of the four bases, which specifies an entire protein. Insulin is a small protein with only 51 amino acids. A sequence of 153 (i.e. 3 × 51) bases in the DNA molecule would constitute the gene that makes an islet cell in the pancreas produce insulin. Most proteins are much larger than this and most genes contain a thousand or more bases.

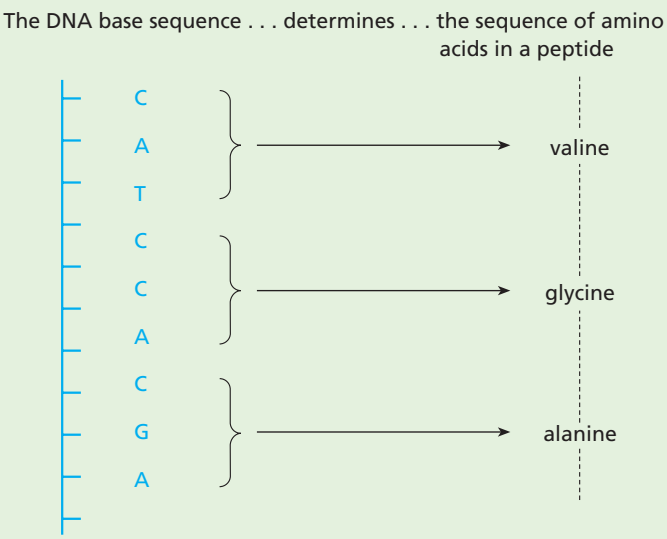



**Figure 17.5** The genetic code (triplet code)

The chemical reactions that take place in a cell determine what sort of a cell it is and what its functions are. These chemical reactions are, in turn, controlled by enzymes. Enzymes are proteins. It follows, therefore, that the **genetic code** of DNA, in determining which proteins, particularly enzymes, are produced in a cell, also determines the cell's structure and function. In this way, the genes also determine the structure and function of the whole organism.

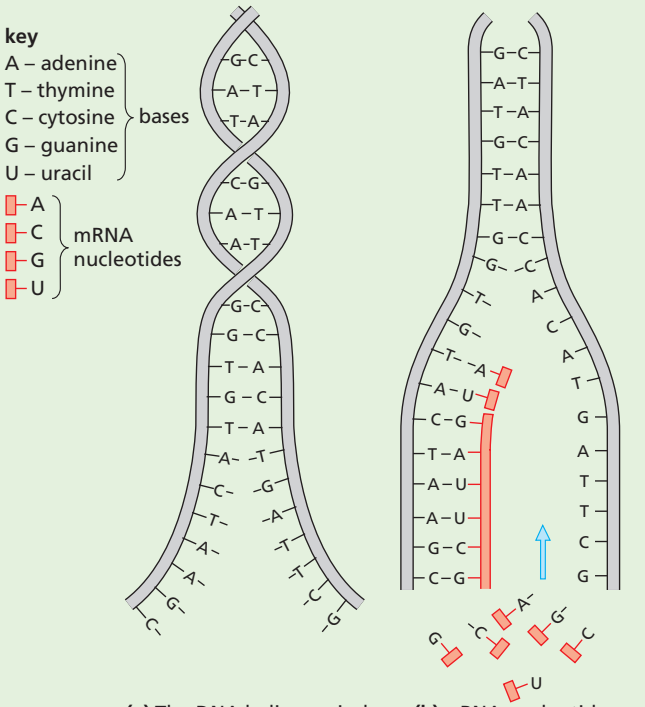
Other proteins coded for in DNA include antibodies and the receptors for neurotransmitters (see details of synapses in Chapter 14).

## The manufacture of proteins in cells

DNA molecules remain in the nucleus, but the proteins they carry the codes for are needed elsewhere in the cell. A molecule called messenger RNA (**mRNA**) is used to transfer the information from the nucleus. It is much smaller than a DNA molecule and is made up of only one strand. Another difference is that mRNA molecules contain slightly different bases (A, C, G and U). Base U is **uracil**. It attaches to the DNA base A.

To pass on the protein code, the double helix of DNA (see Figure 4.12) unwinds to expose the chain of bases. One strand acts as template. A messenger RNA molecule is formed along part of this strand, made up of a chain of nucleotides with complementary bases to a section of the DNA strand (Figure 17.6). The mRNA molecule carrying the protein code then passes out of the nucleus, through a nuclear pore in the membrane. Once in the cytoplasm it attaches itself to a **ribosome**. Ribosomes make proteins. The mRNA molecule instructs the ribosome to put together a chain of amino acids in a specific sequence, thus making a protein. Other mRNA molecules will carry codes for different proteins.

Some proteins are made up of a relatively small number of amino acids. As stated, insulin is a chain of 51 amino acids. On the mRNA molecule each amino acid is coded by a sequence of three bases (a triplet), so the mRNA molecule coding for insulin will contain 153 bases. Other protein molecules are much bigger: haemoglobin in red blood cells is made of 574 amino acids.




**(a)** The DNA helix unwinds: the strands separate, exposing the bases.

**(b)** mRNA nucleotides attach to the exposed DNA bases to form a mRNA molecule.

**Figure 17.6** Formation of messenger RNA

## Gene expression

Body cells do not all have the same requirements for proteins. For example, the function of some cells in the stomach is to make the protein pepsin (see 'Chemical digestion' in Chapter 7). Bone marrow cells make the protein haemoglobin, but do not need digestive enzymes. Specialised cells all contain the same genes in their nuclei, but only the genes needed to code for specific proteins are switched on (**expressed**). This enables the cell to make only the proteins it needs to fulfil its function.

**Key definitions**

A **haploid nucleus** is a nucleus containing a single set of unpaired chromosomes present, for example, in sperm and egg cells.

A **diploid nucleus** is a nucleus containing two sets of chromosomes present, for example, in body cells.

## Number of chromosomes

Figure 17.2 is a karyotype of a human body cell because there are 23 pairs of chromosomes present (they come from a diploid cell). Because the chromosomes are in pairs, the diploid number is always an even number. The karyotype of a sperm cell would show 23 single chromosomes (they come from a **haploid** cell). The sex chromosome would be either X or Y. The chromosomes have different shapes and sizes and can be recognised by a trained observer.

There is a fixed number of chromosomes in each species. Human body cells each contain 46 chromosomes, mouse cells contain 40 and garden pea cells 14 (see also Figure 17.7).

The number of chromosomes in a species is the same in all of its body cells. There are 46 chromosomes in each of your liver cells, in every nerve cell, skin cell and so on.

The chromosomes are always in pairs (Figure 17.7), e.g. two long ones, two short ones, two medium ones. This is because when the zygote is formed, one of each pair comes from the male gamete and one from the female gamete. Your 46 chromosomes consist of 23 from your mother and 23 from your father.

The chromosomes of each pair are called **homologous** chromosomes. In Figure 17.18(b), the two long chromosomes form one homologous pair and the two short chromosomes form another.

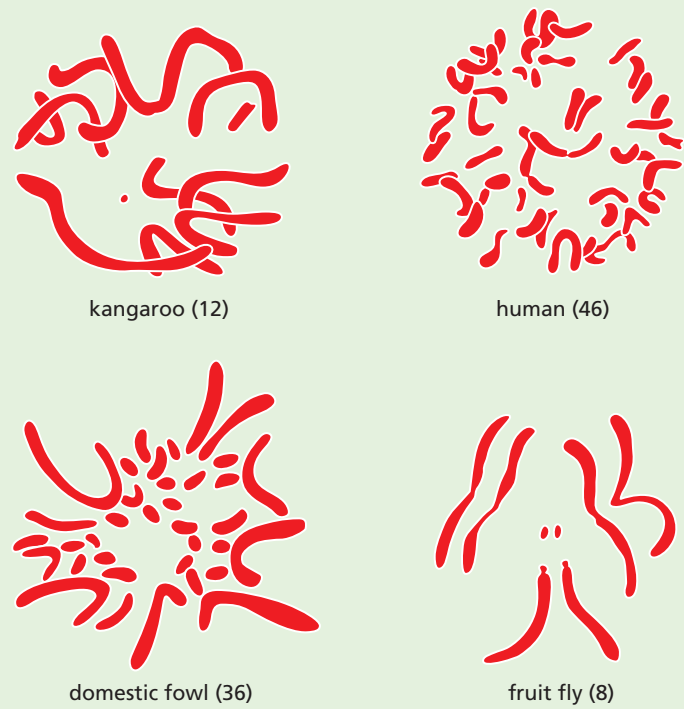



**Figure 17.7** Chromosomes of different species. Note that the chromosomes are always in pairs.

# Mitosis

**Key definitions**
**Mitosis** is nuclear division giving rise to genetically identical cells.

Genetics is the study of inheritance. It can be used to forecast what sorts of offspring are likely to be produced when plants or animals reproduce sexually. What will be the eye colour of children whose mother has blue eyes and whose father has brown eyes? Will a mating between a black mouse and a white mouse produce grey mice, black-and-white mice or some black and some white mice?

To understand the method of inheritance, we need to look once again at the process of sexual reproduction and fertilisation. In sexual reproduction, a new organism starts life as a single cell called a zygote (Chapter 16). This means that you started from a single cell. Although you were supplied with oxygen and food in the uterus, all your tissues and organs were produced by cell division from this one cell. So, the 'instructions' that dictated which cells were to become liver or muscle or bone must all have been present in this first cell. The instructions that decided that you should be tall or short, dark or fair, male or female must also have been present in the zygote.

The process of **mitosis** is important in growth. We all started off as a single cell (a zygote). That cell divided into two cells, then four and so on, to create the organism we are now, made up of millions of cells. Cells have a finite life: they wear out or become damaged, so they need to be replaced constantly. The processes of **growth**, **repair** and **replacement** of cells all rely on mitosis. Organisms that reproduce asexually (see Chapter 16) also use mitosis to create more cells.

## Cell division

When plants and animals grow, their cells increase in number by dividing. Typical growing regions are the ends of bones, layers of cells in the skin, root tips and buds (Figure 17.11). Each cell divides to produce two daughter cells. Both daughter cells may divide again, but usually one of the cells grows and changes its shape and structure and becomes adapted to do one particular job – in other words, it becomes **specialised** (Figure 17.8). At the same time it loses its ability to divide any more. The other cell is still able to divide and so continue the growth of the tissue. Growth is, therefore, the result of cell division, followed by cell enlargement and, in many cases, cell specialisation.

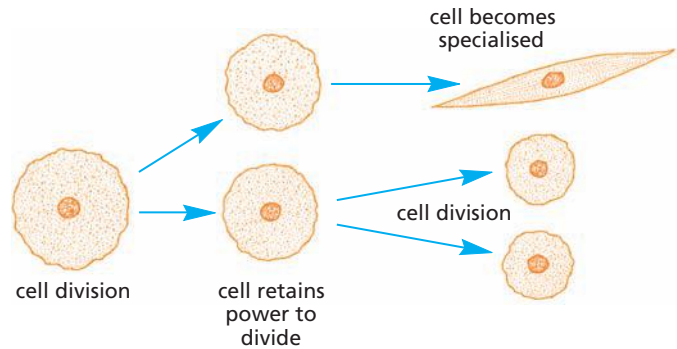
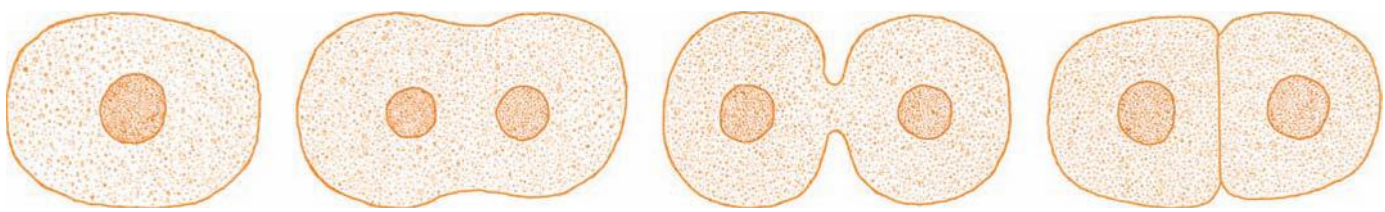



**Figure 17.8** Cell division and specialisation. Cells that retain the ability to divide are sometimes called **stem cells.**

The process of cell division in an animal cell is shown in Figure 17.9. The events in a plant cell are shown in Figures 17.10 and 17.11. Because of the cell wall, the cytoplasm cannot simply pinch off in the middle, and a new wall has to be laid down between the two daughter cells. Also a new vacuole has to form.

Organelles such as mitochondria and chloroplasts are able to divide and are shared more or less equally between the daughter cells at cell division.



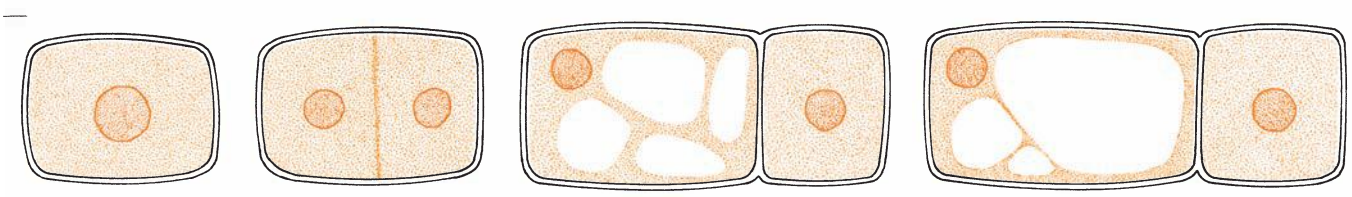
**(a)** Animal cell about to divide.

**(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 17.9** Cell division in an animal cell



**(a)** A plant cell about to divide has a large nucleus and no vacuole.

**(b)** The nucleus divides first. A new cell wall develops and separates the two cells.

**(c)** The cytoplasm adds layers of cellulose on each side of the new cell wall. Vacuoles form in the cytoplasm of one cell.

**(d)** The vacuoles join up to form one vacuole. This takes in water and makes the cell bigger. The other cell will divide again.

**Figure 17.10** Cell division in a plant cell

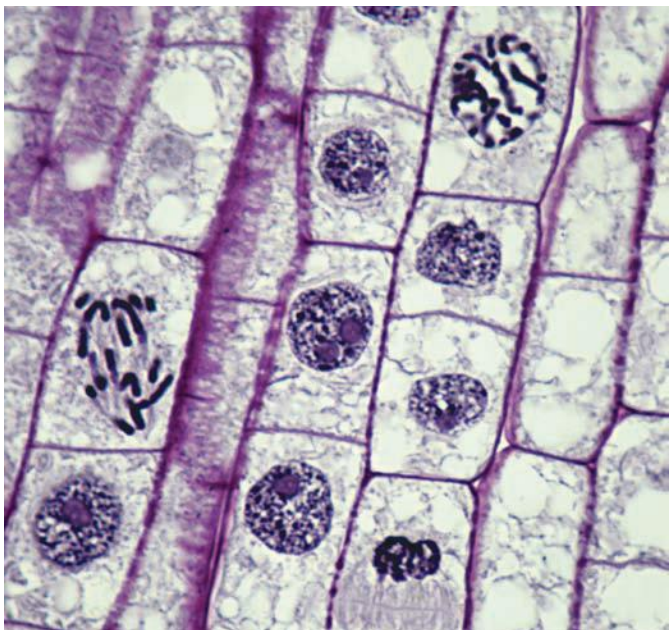


**Figure 17.11** Cell division in an onion root tip (×250). The nuclei are stained blue. Most of the cells have just completed cell division.

## Practical work

### Squash preparation of chromosomes using acetic orcein

#### Preparation of root tips

- Support *Allium cepa* (onion) root tips over beakers or jars of water.
- Keep the onions in darkness for several days until the roots growing into the water are 2–3 cm long.
- Cut off about 5 mm of the root tips and place them in a watch glass.
- Cover the root tips with nine drops acetic orcein and one drop molar hydrochloric acid.
- Heat the watch glass gently over a very small Bunsen flame till the steam rises from the stain, but do not boil.
- Leave the watch glass covered for at least 5 minutes.
- Place one of the root tips on a clean slide, cover with 45% ethanoic (acetic) acid and cut away all but the terminal 1 mm.
- Cover this root tip with a clean coverslip and make a squash preparation as described next.

#### Making the squash preparation

- Squash the softened, stained root tips by lightly tapping on the coverslip with a pencil: hold the pencil vertically and let it slip through the fingers to strike the coverslip (Figure 17.12).
- The root tip will spread out as a pink mass on the slide; the cells will separate and the nuclei, many of them with chromosomes in various stages of mitosis (because the root tip is a region of rapid cell division), can be seen under the high power of the microscope (×400).

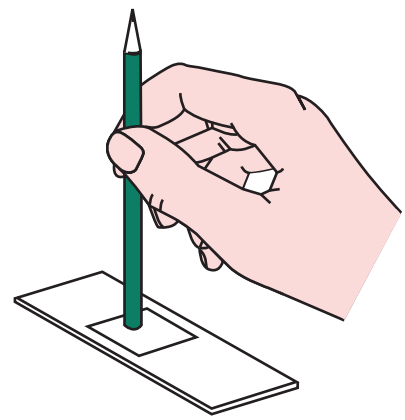


**Figure 17.12** Tap the coverslip gently to squash the tissue

## Meiosis

**Key definitions**

**Meiosis** is nuclear division, which gives rise to cells that are genetically different.

The process of meiosis takes place in the **gonads** of animals (e.g. the testes and ovaries of mammals, and the anthers and ovules of flowering plants). The cells formed are **gametes** (sperm and egg cells in mammals; egg cells and pollen grain nuclei in flowering plants). Gametes are different from other cells because they have half the normal number of chromosomes (they are **haploid**).

## The process of mitosis

To understand how the 'instructions' are passed from cell to cell, we need to look in more detail at what happens when the zygote divides and produces an organism consisting of thousands of cells. This type of cell division is called mitosis. It takes place not only in a zygote but in all growing tissues.

When a cell is not dividing, there is very little detailed structure to be seen in the nucleus even if it is treated with special dyes called stains. Just before cell division, however, a number of long, thread-like structures appear in the nucleus and show up very clearly when the nucleus is stained (Figures 17.13 and 17.14). These thread-like structures are called chromosomes. Although they are present in the nucleus all the time, they show up clearly only at cell division because at this time they get shorter and thicker.

Each chromosome duplicates itself and is seen to be made up of two parallel strands, called chromatids (Figure 17.1). When the nucleus divides into two, one chromatid from each chromosome goes into each daughter nucleus. The chromatids in each nucleus now become chromosomes and later they will make copies of themselves ready for the next cell division. The process of copying is called **replication** because each chromosome makes a replica (an exact copy) of itself. As Figure 17.13 is a simplified diagram of mitosis, only two chromosomes are shown, but there are always more than this. Human cells contain 46 chromosomes.

Mitosis will be taking place in any part of a plant or animal that is producing new cells for growth or replacement. Bone marrow produces new blood cells by mitosis; the epidermal cells of the skin are replaced by mitotic divisions in the basal layer; new epithelial cells lining the alimentary canal are produced by mitosis; growth of muscle or bone in animals, and root, leaf, stem or fruit in plants, results from mitotic cell divisions.

An exception to this occurs in the final stages of gamete production in the reproductive organs of plants and animals. The cell divisions that give rise to gametes are not mitotic but meiotic.

Cells that are not involved in the production of gametes are called **somatic cells**. Mitosis takes place only in somatic cells.

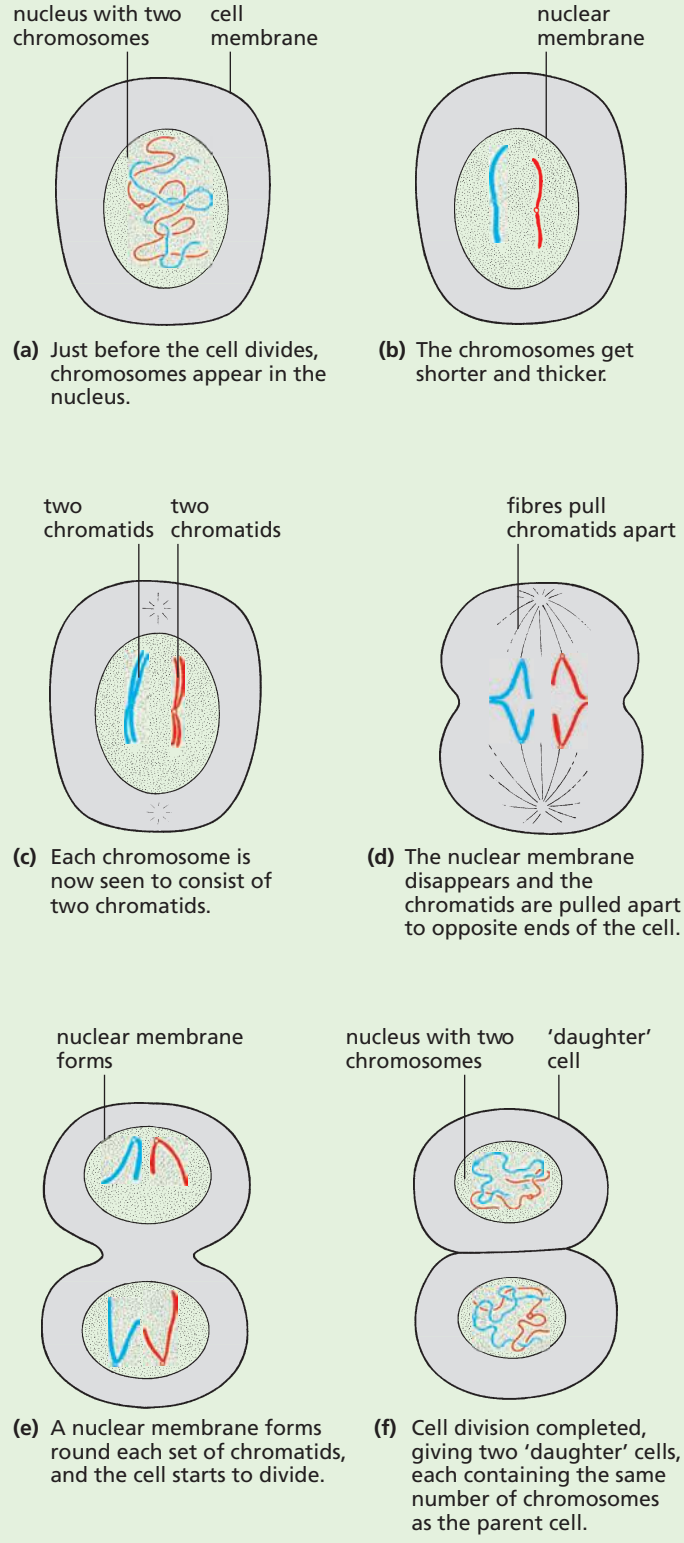



**Figure 17.13** Mitosis. Only two chromosomes are shown. Three of the stages described here are shown in Figure 17.14.

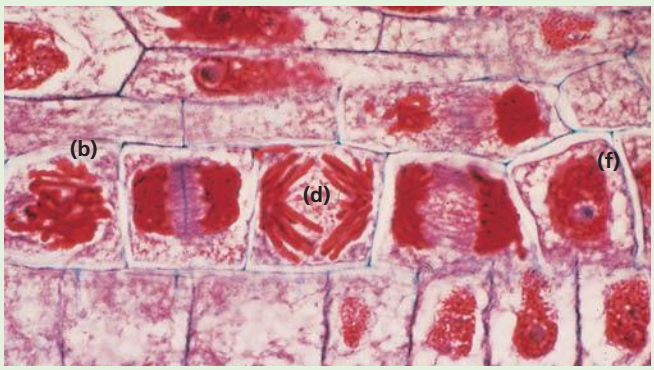
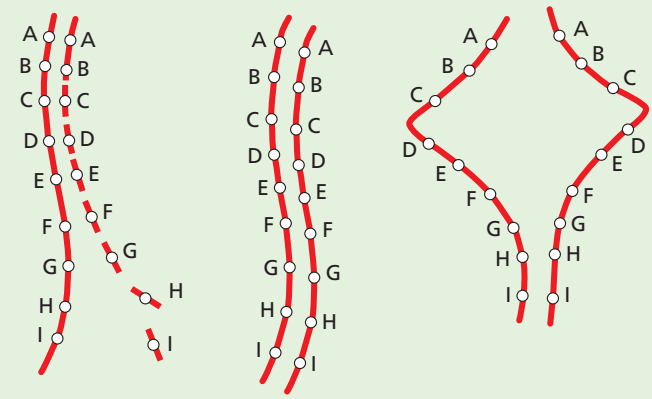



**Figure 17.14** Mitosis in a root tip (×500). The letters refer to the stages described in Figure 17.13. (The tissue has been squashed to separate the cells.)

## The function of chromosomes

When a cell is not dividing, its chromosomes become very long and thin. Along the length of the chromosome is a series of chemical structures called genes (Figure 17.15). The chemical that forms the genes is called DNA (which is short for deoxyribonucleic acid, Chapter 4). Each gene controls some part of the chemistry of the cell. It is these genes that provide the 'instructions' mentioned at the beginning of the chapter. For example, one gene may 'instruct' the cell to make the pigment that is formed in the iris of brown eyes. On one chromosome there will be a gene that causes the cells of the stomach to make the enzyme pepsin. When the chromosome replicates, it builds an exact replica of itself, gene by gene (Figure 17.16). When the chromatids separate at mitosis, each cell will receive a full set of genes. In this way, the chemical instructions in the zygote are passed on to all cells of the body. All the chromosomes, all the genes and, therefore, all the instructions are faithfully reproduced by mitosis and passed on complete to all the cells.


**Figure 17.15** Relationship between chromosomes and genes. The drawing does not represent real genes or a real chromosome. There are probably thousands of genes on a chromosome.



**(a)** A chromosome builds upa replica of itself.

**(b)** When the cell divides, the original and the replica are called chromatids.

**(c)** Mitosis separates the chromatids. Each new cell getsa full set of genes.

**Figure 17.16** Replication. (A, B, C, etc. represent genes.)

Which of the instructions are used depends on where a cell finally ends up. The gene that causes brown eyes will have no effect in a stomach cell and the gene for making pepsin will not function in the cells of the eye. So a gene's chemical instructions are carried out only in the correct situation.

The genes that produce a specific effect in a cell (or whole organism) are said to be **expressed**. In the stomach lining, the gene for pepsin is expressed. The gene for melanin (the pigment in brown eyes) is not expressed.

## Stem cells

Recent developments in tissue culture have involved **stem cells**. Stem cells are those cells in the body that have retained their power of division. Examples are the basal cells of the skin ('Homeostasis' in Chapter 14), which keep dividing to make new skin cells, and cells in the red bone marrow, which constantly divide to produce the whole range of blood cells ('Blood' in Chapter 9).

In normal circumstances this type of stem cell can produce only one type of tissue: epidermis, blood, muscle, nerves, etc. Even so, culture of these stem cells could lead to effective therapies by introducing healthy stem cells into the body to take over the function of diseased or defective cells.

Cells taken from early embryos (**embryonic stem cells**) can be induced to develop into almost any kind of cell, but there are ethical objections to using human embryos for this purpose. However, it has recently been shown that, given the right

conditions, brain stem cells can become muscle or blood cells, and liver cells have been cultured from blood stem cells. Scientists have also succeeded in reprogramming skin cells to develop into other types of cell, such as nerve cells. Bone marrow cells are used routinely to treat patients with leukaemia (cancer of white blood cells). The use of adult stem cells does not have the ethical problems of embryonic stem cells, since cells that could become whole organisms are not being destroyed.

## Gamete production and chromosomes

The genes on the chromosomes carry the instructions that turn a single-cell zygote into a bird or a rabbit or an oak tree. The zygote is formed at fertilisation, when a male gamete fuses with a female gamete. Each gamete brings a set of chromosomes to the zygote. The gametes, therefore, must each contain only half the diploid number of chromosomes, otherwise the chromosome number would double each time an organism reproduced sexually. Each human sperm cell contains 23 chromosomes and each human ovum has 23 chromosomes. When the sperm and ovum fuse at fertilisation (Chapter 16), the diploid number of 46 (23 + 23) chromosomes is produced (Figure 17.17).

The process of cell division that gives rise to gametes is different from mitosis because it results in the cells containing only half the diploid number of chromosomes. This number is called the haploid number and the process of cell division that gives rise to gametes is called **meiosis**.

Meiosis takes place only in reproductive organs.

## Meiosis

In a diploid cell that is going to divide and produce gametes, the chromosomes shorten and thicken as in mitosis. The pairs of homologous chromosomes, e.g. the two long ones and the two short ones in Figure 17.18(b), lie alongside each other and, when the nucleus divides for the first time, it is the chromosomes and not the chromatids that are separated. This results in only half the total number of chromosomes going to each daughter cell. In Figure 17.18(c), the diploid number of four chromosomes is being reduced to two chromosomes prior to the first cell division.

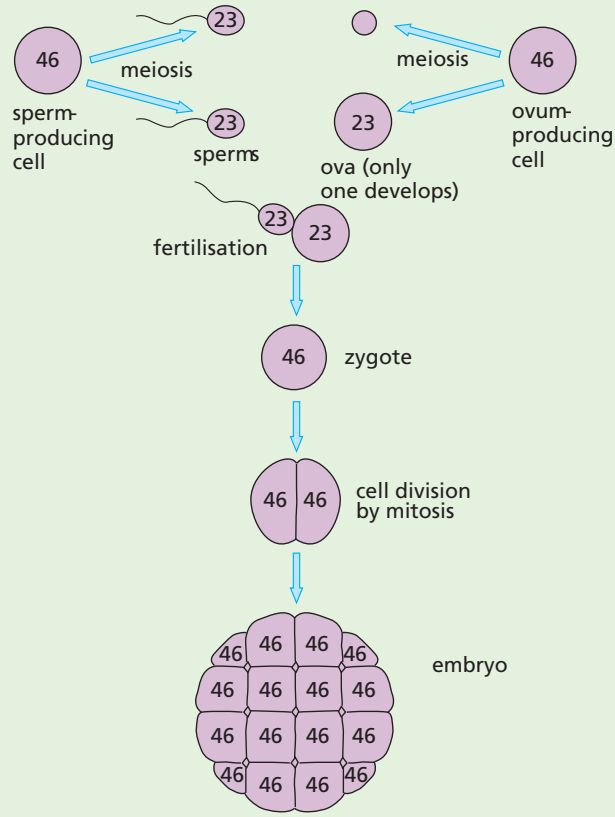



**Figure 17.17** Chromosomes in gamete production and fertilisation

By now (Figure 17.18(d)), each chromosome is seen to consist of two chromatids and there is a second division of the nucleus (Figure 17.18(e)), which separates the chromatids into four distinct nuclei (Figure 17.18(f)).

This gives rise to four gametes, each with the haploid number of chromosomes. In the anther of a plant (Chapter 16), four haploid pollen grains are produced when a pollen mother cell divides by meiosis (Figure 17.19). In the testis of an animal, meiosis of each sperm-producing cell forms four sperm. In the cells of the ovule of a flowering plant or the ovary of a mammal, meiosis gives rise to only one mature female gamete. Four gametes may be produced initially, but only one of them turns into an egg cell that can be fertilised.

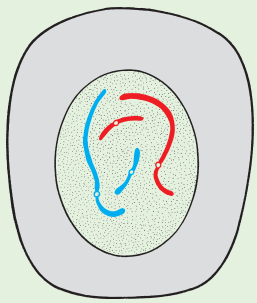
As a result of meiosis and fertilisation, the maternal and paternal chromosomes meet in different combinations in the zygotes. Consequently, the offspring will differ from their parents and from each other in a variety of ways.

Asexually produced organisms (Chapter 16) show no such variation because they are produced by mitosis and all their cells are identical to those of their single parent.

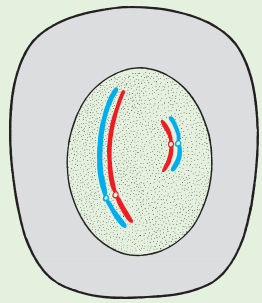
Table 17.1 compares meiosis and mitosis.

**Table 17.1** Mitosis and meiosis compared

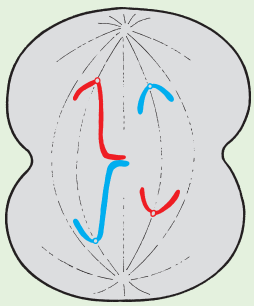
| Meiosis | Mitosis |
|---|---|
| occurs in the final stages of cell division leading to production of gametes | occurs during cell division of somatic cells |
| only half the chromosomes are passed on to the daughter cells, i.e. the haploid number of chromosomes | a full set of chromosomes is passed on to each daughter cell; this is the diploid number of chromosomes |
| homologous chromosomes and their genes are randomly assorted between the gametes | the chromosomes and genes in each daughter cell are identical |
| new organisms produced by meiosis in sexual reproduction will show variations from each other and from their parents | if new organisms are produced by mitosis in asexual reproduction (e.g. bulbs, Chapter 16) they will all resemble each other and their parents; they are said to be 'clones' |



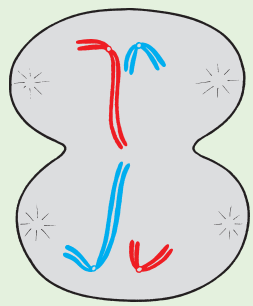
**(a)** The chromosomes appear. Those in red are from the organism's mother; the blue ones are from the father.



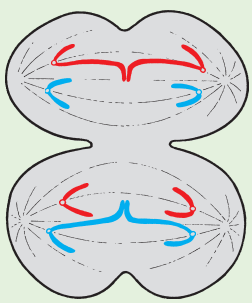
**(b)** Homologous chromosomes lie alongside each other.



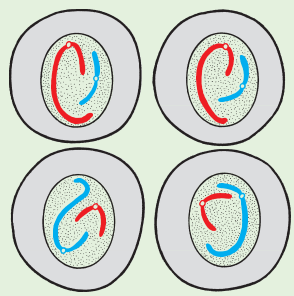
**(c)** The nuclear membrane disappears and corresponding chromosomes move apart to opposite ends of the cell.



**(d)** By now each chromosome has become two chromatids.



**(e)** A second division takes place to separate the chromatids.



**(f)** Four gametes are formed. Each contains only half the original number of chromosomes.

**Figure 17.18** Meiosis

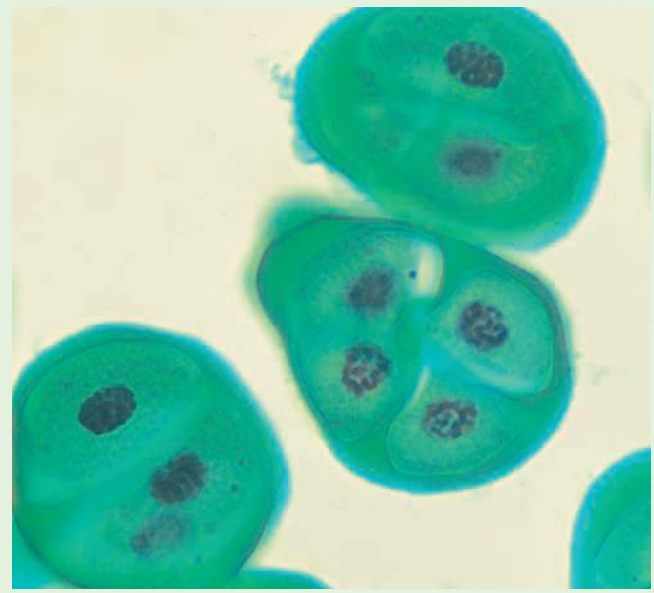


**Figure 17.19** Meiosis in an anther (×1000). The last division of meiosis in the anther of a flower produces four pollen grains.

# Monohybrid inheritance

**Key definitions**

An **allele** is a version of a gene.

**Genotype** is the genetic make-up of an organism in terms of the alleles present.

**Phenotype** is the features of an organism.

**Homozygous** means having two identical alleles of a particular gene e.g. **TT**, where **T** is tall. Note that two identical homozygous individuals that breed together will be pure-breeding.

**Heterozygous** means having two different alleles of a particular gene e.g. **Tt**. Note that a heterozygous individual will not be pure breeding.

An allele that is expressed if it is present is **dominant**.

An allele that is only expressed when there is no dominant allele of the gene present is **recessive**.

## Alleles

The genes that occupy corresponding positions on homologous chromosomes and control the same characteristic are called **allelomorphic genes**, or **alleles**. The word 'allelomorph ' means 'alternative form'. For example, there are two alternative forms of a gene for eye colour. One allele produces brown eyes and one allele produces blue eyes.

There are often more than two alleles of a gene. The human ABO blood groups are controlled by three alleles, though only two of these can be present in one genotype.

## Patterns of inheritance

A knowledge of mitosis and meiosis allows us to explain, at least to some extent, how heredity works. The allele in a mother's body cells that causes her to have brown eyes may be present on one of the chromosomes in each ovum she produces. If the father's sperm cell contains an allele for brown eyes on the corresponding chromosome, the zygote will receive an allele for brown eyes from each parent. These alleles will be reproduced by mitosis in all the embryo's body cells and when the embryo's eyes develop, the alleles will make the cells of the iris produce brown pigment (melanin) and the child will have brown eyes. In a similar way, the child may receive alleles for curly hair.

Figure 17.20 shows this happening, but it does not, of course, show all the other chromosomes with thousands of genes for producing the enzymes, making different types of cell and all the other processes that control the development of the organism.

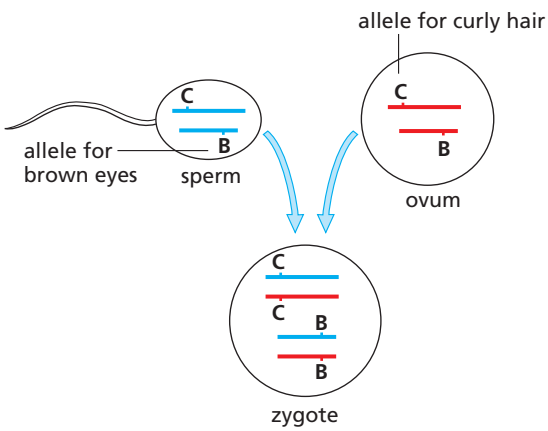



**Figure 17.20** Fertilisation. Fertilisation restores the diploid number of chromosomes and combines the alleles from the mother and father.

## Single-factor inheritance

Because it is impossible to follow the inheritance of the thousands of characteristics controlled by genes, it is usual to start with the study of a single gene that controls one characteristic. We have used eye colour as an example so far. Probably more than one allele pair is involved, but the simplified example will serve our purpose. It has already been explained how an allele for brown eyes from each parent results in the child having brown eyes. Suppose, however, that the mother has blue eyes and the father brown eyes. The child might receive an allele for blue eyes from its mother and an allele for brown eyes from its father (Figure 17.21). If this happens, the child will, in fact, have brown eyes. The allele for brown eyes is said to be **dominant** to the allele for blue eyes. Although the allele for blue eyes is present in all the child's cells, it is not expressed. It is said to be **recessive** to brown.

Eye colour is a useful 'model' for explaining inheritance but it is not wholly reliable because 'blue' eyes vary in colour and sometimes contain small amounts of brown pigment.

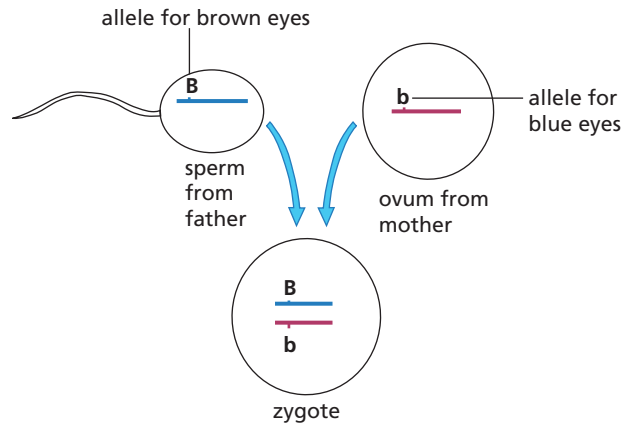



**Figure 17.21** Combination of alleles in the zygote (only one chromosome is shown). The zygote has both alleles for eye colour; the child will have brown eyes.

This example illustrates the following important points:

- There is a pair of alleles for each characteristic, one allele from each parent.
- Although the allele pairs control the same characteristic, e.g. eye colour, they may have different effects. One tries to produce blue eyes, the other tries to produce brown eyes.
- Often one allele is dominant over the other.

- The alleles of each pair are on corresponding chromosomes and occupy corresponding positions. For example, in Figure 17.20 the alleles for eye colour are shown in the corresponding position on the two short chromosomes and the alleles for hair curliness are in corresponding positions on the two long chromosomes. In diagrams and explanations of heredity:
  - alleles are represented by letters
  - alleles controlling the same characteristic are given the same letter, and
  - the dominant allele is given the capital letter.

For example, in rabbits, the dominant allele for black fur is labelled **B**. The recessive allele for white fur is labelled **b** to show that it corresponds to **B** for black fur. If it were labelled **w**, we would not see any connection between **B** and **w**. **B** and **b** are obvious partners. In the same way **L** could represent the allele for long fur and **l** the allele for short fur.

## Breeding true

A white rabbit must have both the recessive alleles **b** and **b**. If it had **B** and **b**, the dominant allele for black (**B**) would override the allele for white (**b**) and produce a black rabbit. A black rabbit, on the other hand, could be either **BB** or **Bb** and, by just looking at the rabbit, you could not tell the difference. When a male black rabbit **BB** produces sperm, each one of the pair of chromosomes carrying the **B** alleles will end up in different sperm cells. Since the alleles are the same, all the sperm will have the **B** allele for black fur (Figure 17.22(a)).

A black rabbit **BB** is called a true-breeding black and is said to be **homozygous** for black coat colour ('homo-' means 'the same'). If this rabbit mates with another black (**BB**) rabbit, all the babies will be black because all will receive a dominant allele for black fur. When all the offspring have the same characteristic as the parents, this is called '**breeding true**' for this characteristic.

When a **Bb** black rabbit produces gametes by meiosis, the chromosomes with the **B** allele and the chromosomes with the **b** allele will end up in different gametes. So 50% of the sperm cells will carry **B** alleles and 50% will carry **b** alleles (Figure 17.22(b)). Similarly, in the female, 50% of the ova will have a **B** allele and 50% will have a **b** allele. If a **b** sperm fertilises a **b** ovum, the offspring, with two **b** alleles (**bb**), will be white. The black **Bb** rabbits are not true-breeding because they may produce some white babies as well as black ones. The **Bb** rabbits are called **heterozygous** ('hetero-' means 'different').

The black **BB** rabbits are homozygous dominant. The white **bb** rabbits are homozygous recessive.

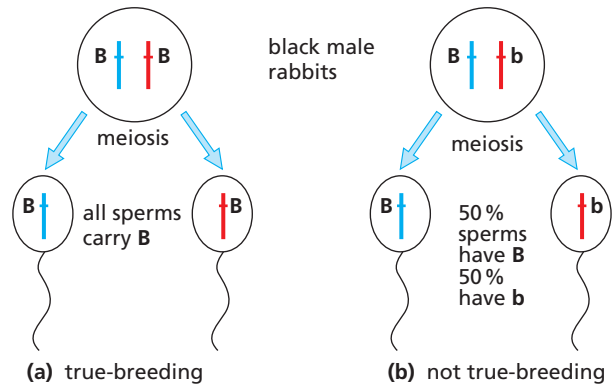



**Figure 17.22** Breeding true

## Genotype and phenotype

The two kinds of black rabbit **BB** and **Bb** are said to have the same **phenotype**. This is because their coat colours look exactly the same. However, because they have different allele pairs for coat colour they are said to have different **genotypes**, i.e. different combinations of alleles. One genotype is **BB** and the other is **Bb**.

You and your brother might both be brown-eyed phenotypes but your genotype could be **BB** and his could be **Bb**. You would be homozygous dominant for brown eyes; he would be heterozygous for eye colour.

## The three to one ratio

The result of a mating between a true-breeding (homozygous) black mouse (**BB**) and a true-breeding (homozygous) brown mouse (**bb**) is shown in Figure 17.23(a). The illustration is greatly simplified because it shows only one pair of the 20 pairs of mouse chromosomes and only one pair of alleles on the chromosomes.

Because black is dominant to brown, all the offspring from this mating will be black phenotypes, because they all receive the dominant allele for black fur from the father. Their genotypes, however, will be **Bb** because they all receive the recessive **b** allele from the mother. They are heterozygous for coat colour. The offspring resulting from this first mating are called the **$F_1$ generation**.

Figure 17.23(b) shows what happens when these heterozygous, $F_1$ black mice are mated together to produce what is called the $F_2$ generation. Each sperm or ovum produced by meiosis can contain only one of the alleles for coat colour, either **B** or **b**. So there are two kinds of sperm cell, one kind with the **B** allele and one kind with the **b** allele. There are also two kinds of ovum, with either **B** or **b** alleles. When fertilisation occurs, there is no way of telling whether a **b** or a **B** sperm will fertilise a **B** or a **b** ovum, so we have to look at all the possible combinations as follows:

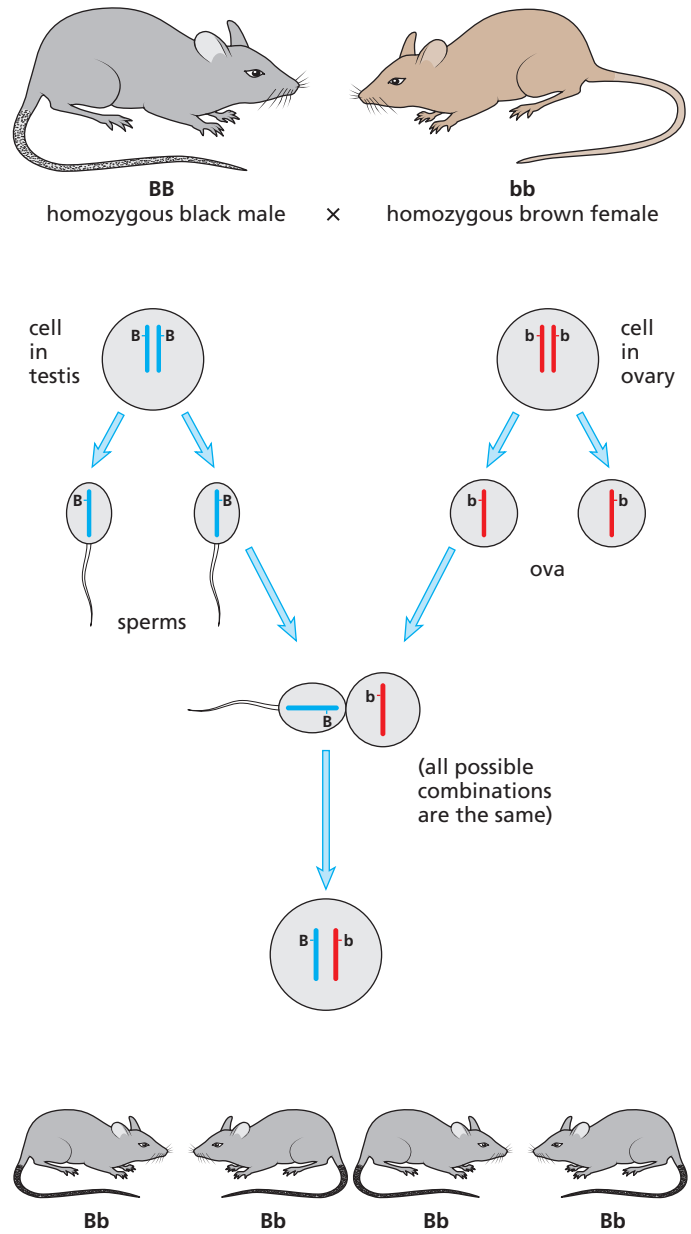
- A **b** sperm fertilises a **B** ovum. Result: **bB** zygote.
- A **b** sperm fertilises a **b** ovum. Result: **bb** zygote.
- A **B** sperm fertilises a **B** ovum. Result: **BB** zygote.
- A **B** sperm fertilises a **b** ovum. Result: **Bb** zygote.

There is no difference between **bB** and **Bb**, so there are three possible genotypes in the offspring – **BB**, **Bb** and **bb**. There are only two phenotypes – black (**BB** or **Bb**) and brown (**bb**). So, according to the laws of chance, we would expect three black baby mice and one brown. Mice usually have more than four offspring and what we really expect is that the **ratio** (proportion) of black to brown will be close to 3:1.

If the mouse had 13 babies, you might expect nine black and four brown, or eight black and five brown. Even if she had 16 babies you would not expect to find exactly 12 black and four brown because whether a **B** or **b** sperm fertilises a **B** or **b** ovum is a matter of chance. If you spun ten coins, you would not expect to get exactly five heads and five tails. You would not be surprised at six heads and four tails or even seven heads and three tails. In the same way, we would not be surprised at 14 black and two brown mice in a litter of 16.

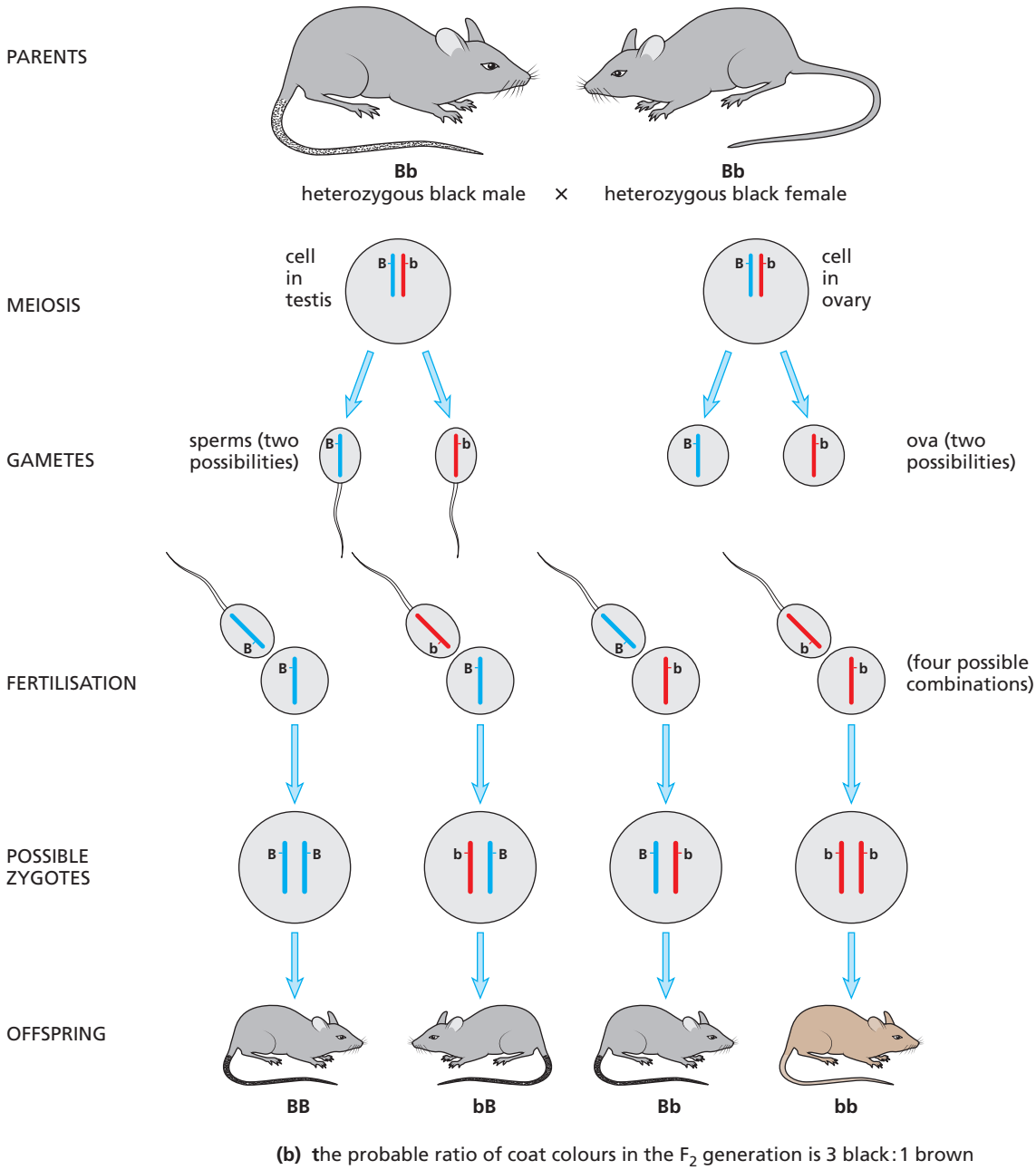
To decide whether there really is a 3:1 ratio, we need a lot of results. These may come either from breeding the same pair of mice together for a year or so to produce many litters, or from mating 20 black and 20 brown mice, crossing the offspring and adding up the number of black and brown babies in the $F_2$ families (see also Figure 17.24).

When working out the results of a genetic cross, it is useful to display the outcomes in a '**Punnett square**' (Figure 17.25). This a box divided into four compartments. The two boxes along the top are labelled with the genotypes of the gametes of one parent. The genotypes are circled to show they are gametes. The parent's genotype is written above the gametes. The boxes down the left-hand side are labelled with the genotypes of the gametes of the other parent. The parent's genotype is written to the left. The genotypes of the offspring can then be predicted by completing the four boxes, as shown. In this example, two heterozygous tall organisms (**Tt**) are the parents. The genotypes of the offspring are **TT**, **Tt**, **Tt** and **tt**. We know that the allele **T** is dominant because the parents are tall, although they carry both tall and dwarf alleles. So, the phenotypes of the offspring will be three tall to one dwarf.




**(a)** all the $F_1$ generation are heterozygous black

**Figure 17.23** Inheritance of coat colour in mice




**(b)** the probable ratio of coat colours in the $F_2$ generation is 3 black : 1 brown

**Figure 17.23** Inheritance of coat colour in mice *(continued)*

**Figure 17.24** $F_2$ hybrids in maize. In the two left-hand cobs, the grain colour phenotypes appear in a 3:1 ratio (try counting single rows in the lighter cob). What was the colour of the parental grains for each of these cobs?

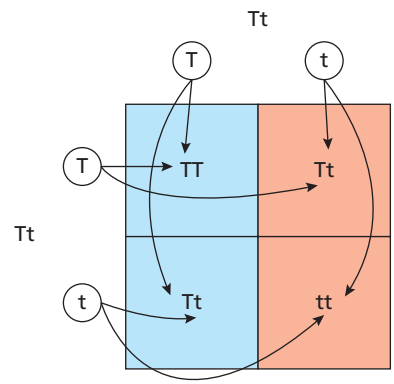



**Figure 17.25** Using a Punnett square to predict the outcomes of a genetic cross

## The recessive test-cross (back-cross)

A black mouse could have either the **BB** or the **Bb** genotype. One way to find out which is to cross the black mouse with a known homozygous recessive mouse, **bb**. The **bb** mouse will produce gametes with only the recessive **b** allele. A black homozygote, **BB**, will produce only **B** gametes. Thus, if the black mouse is **BB**, all the offspring from the cross will be black heterozygotes, **Bb**.

Half the gametes from a black **Bb** mouse would carry the **B** allele and half would have the **b** allele. So, if the black mouse is **Bb**, half of the offspring from the cross will, on average, be brown homozygotes, **bb**, and half will be black heterozygotes, **Bb**.

The term 'back-cross' refers to the fact that, in effect, the black, mystery mouse is being crossed with the same genotype as its brown grandparent, the **bb** mouse in Figure 17.23(a). Mouse ethics and speed of reproduction make the use of the actual grandparent quite feasible!

## Co-dominance and incomplete dominance

### Co-dominance

If both genes of an allelomorphic pair produce their effects in an individual (i.e. neither allele is dominant to the other) the alleles are said to be **co-dominant**.

The inheritance of the human ABO blood groups provides an example of co-dominance. In the ABO system, there are four phenotypic blood groups, A, B, AB and O. The alleles for groups A and B are co-dominant. If a person inherits alleles for group A and group B, his or her red cells will carry both antigen A and antigen B.

However, the alleles for groups A and B are both completely dominant to the allele for group O. (Group O people have neither A nor B antigens on their red cells.)

Table 17.2 shows the genotypes and phenotypes for the ABO blood groups. (Note that the allele for group O is sometimes represented as $I^o$ and sometimes as i.)

**Table 17.2** The ABO blood groups

| Genotype | Blood group (phenotype) |
|---|---|
| $I^AI^A$ or $I^AI^o$ | A |
| $I^BI^B$ or $I^BI^o$ | B |
| $I^AI^B$ | AB |
| $I^oI^o$ | O |

Since the alleles for groups A and B are dominant to that for group O, a group A person could have the genotype $I^AI^A$ or $I^AI^o$. Similarly a group B person could be $I^BI^B$ or $I^BI^o$. There are no alternative genotypes for groups AB and O.

### Inheritance of blood group O

Blood group O can be inherited, even though neither parent shows this phenotype.

Two parents have the groups A and B. The father is $I^AI^o$ and the mother is $I^BI^o$ (Figure 17.26).

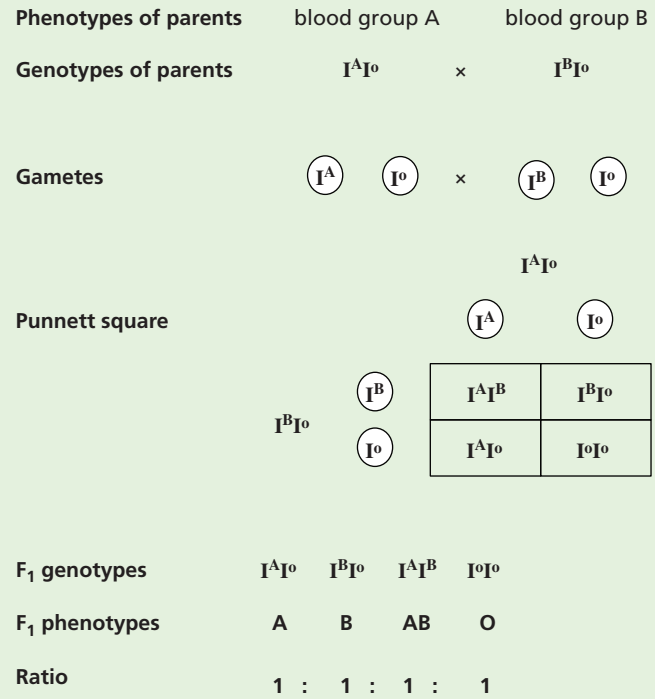



**Figure 17.26** Inheritance of blood group O

Some plants show co-dominance with regard to petal colour. For example, with the gene for flower colour in the geranium, the alleles are $C^R$ (red) and $C^W$ (white). The capital letter '**C**' has been chosen to represent colour. Pure breeding (homozygous) flowers may be red ($C^RC^R$) or white ($C^WC^W$). If these are cross-pollinated, all the first filial ($F_1$) generation will be heterozygous ($C^RC^W$) and they are pink because both alleles have an effect on the phenotype.

Self-pollinating the pink ($F_1$) plants results in an unusual ratio in the next ($F_2$) generation of 1 red : 2 pink : 1 white.

**Incomplete dominance**

This term is sometimes taken to mean the same as 'co-dominance' but, strictly, it applies to a case where the effect of the recessive allele is not completely masked by the dominant allele.

An example occurs with sickle-cell anaemia (see 'Variation' in Chapter 18). If a person inherits both recessive alleles ($Hb^SHb^S$) for sickle-cell haemoglobin, then he or she will exhibit signs of the disease, i.e. distortion of the red cells leading to severe bouts of anaemia.

A heterozygote ($Hb^AHb^S$), however, will have a condition called 'sickle-cell trait'. Although there may be mild symptoms of anaemia the condition is not serious or life-threatening. In this case, the normal haemoglobin allele ($Hb^A$) is not completely dominant over the recessive ($Hb^S$) allele.

## Sex linkage

**Key definitions**

A **sex-linked characteristic** is one in which the gene responsible is located on a sex chromosome, which makes it more common in one sex than the other.

The sex chromosomes, X and Y, carry genes that control sexual development. In addition they carry genes that control other characteristics. These tend to be on the X chromosome, which has longer arms to the chromatids. Even if the allele is recessive, because there is no corresponding allele on the Y chromosome, it is bound to be expressed in a male (XY). There is less chance of a recessive allele being expressed in a female (XX) because the other X chromosome may carry the dominant form of the allele.

One example of this is a form of colour blindness (Figure 17.27). In the following case, the mother is a carrier of colour blindness ($X^CX^c$). This means she shows no symptoms of colour blindness, but the recessive allele causing colour blindness is present on one of her X chromosomes. The father has normal colour vision ($X^CY$).

| | | | | |
|---|---|---|---|---|
| **Phenotypes of parents** | mother: normal vision | | father: normal vision | |
| **Genotypes of parents** | $X^CX^c$ | × | $X^CY$ | |
| **Gametes** | $X^C$ $X^c$ | × | $X^C$ | $Y$ |

**Punnett square**

| | | $X^C$ | $X^c$ |
|---|---|---|---|
| $X^CY$ | $X^C$ | $X^CX^C$ | $X^CX^c$ |
| | $Y$ | $X^CY$ | $X^cY$ |

| | |
|---|---|
| **$F_1$ genotypes** | $X^CX^C$ $X^CX^c$ $X^CY$ $X^cY$ |
| **$F_1$ phenotypes** | 2 females with normal vision; 2 males, one with normal vision, one with colour blindness |

**Figure 17.27** Inheritance of colour blindness

If the gene responsible for a particular condition is present only on the Y chromosome, only males can suffer from the condition because females do not possess the Y chromosome.

# Extension work

## Ideas about heredity: Gregor Mendel (1822–84)

Mendel was an Augustinian monk from the town of Brünn (now Brno) in Czechoslovakia (now the Czech Republic). He studied maths and science at the University of Vienna in order to teach at a local school.

He was the first scientist to make a systematic study of patterns of inheritance involving single characteristics. This he did by using varieties of the pea plant, *Pisum sativum*, which he grew in the monastery garden. He chose pea plants because they were self-pollinating (Chapter 16). Pollen from the anthers reached the stigma of the same flower even before the flower bud opened.

Mendel selected varieties of pea plant that bore distinctive and contrasting characteristics, such as green seeds vs yellow seeds, dwarf vs tall, round seeds vs wrinkled (Figure 17.28). He used only plants that bred true.

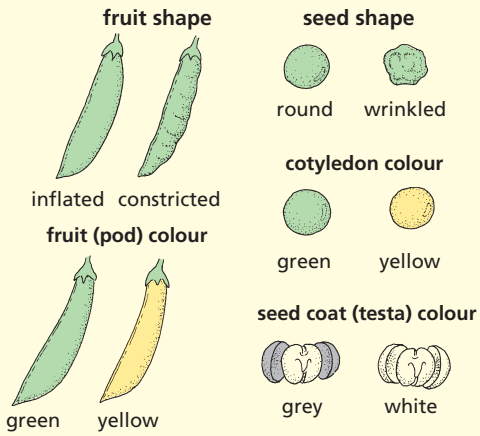



**Figure 17.28** Some of the characteristics investigated by Mendel

He then crossed pairs of the contrasting varieties. To do this he had to open the flower buds, remove the stamens and use them to dust pollen on the stigmas of the contrasting variety. The offspring of this cross he called the 'first filial' generation, or $F_1$.

The first thing he noticed was that all the offspring of the $F_1$ cross showed the characteristic of only one of the parents. For example, tall plants crossed with dwarf plants produced only tall plants in the first generation.

Next he allowed the plants of the $F_1$ generation to self-pollinate and so produce a second filial generation, or $F_2$. Surprisingly, the dwarf characteristic that had, seemingly, disappeared in the $F_1$ reappeared in the $F_2$. This characteristic had not, in fact, been lost but merely concealed or suppressed in the $F_1$ to re-emerge in the $F_2$. Mendel called the repressed feature 'recessive' and the expressed feature 'dominant'.

Also, it must be noted, the plants were all either tall or dwarf; there were no intermediates, as might be expected if the characteristics blended.

Mendel noticed that pollen from tall plants, transferred to the stigmas of short plants, produced the same result as transferring pollen from short plants to the stigmas of tall plants. This meant that male and female gametes contributed equally to the observed characteristic.

When Mendel counted the number of contrasting offspring in the $F_2$, he found that they occurred in the ratio of three dominant to one recessive. For example, of 1064 $F_2$ plants from the tall × dwarf cross, 787 were tall and 277 dwarf, a ratio of 2.84:1. This $F_2$ ratio occurred in all Mendel's crosses, for example:

- round vs wrinkled seeds 5474:1850 = 2.96:1
- yellow vs green seeds 6022:2001 = 3.01:1
- green vs yellow pods 428:152 = 2.82:1

Two-thirds of the dominant tall $F_2$ plants did not breed true when self-pollinated but produced the 3:1 ratio of tall : dwarf. They were therefore similar to the plants of the $F_1$ generation.

It is not clear whether Mendel speculated on how the characteristics were represented in the gametes or how they achieved their effects. At one point he wrote of 'the differentiating elements of the egg and pollen cells', but it is questionable whether he envisaged actual structures being responsible.

Similarly, when Mendel wrote 'exactly similar factors must be at work', he meant that there must be similar processes taking place. He does not use the term 'factor' to imply particles or any entities that control heritable characteristics.

His symbols **A**, **Ab** and **b** seem to be shorthand for the types of plants he studied: **A** = true-breeding dominant, **b** = true-breeding recessive and **Ab** = the non-true-breeding 'hybrid'. The letters represented the visible characteristics, whereas today they represent the alleles responsible for producing the characteristic. For example, Mendel never refers to **AA** or **bb** so he probably did not appreciate that each characteristic is represented twice in the somatic cells but only once in the gametes.

When Mendel crossed plants, each carrying two contrasting characteristics, he found that the characteristics turned up in the offspring independently of each other. For example, in a cross between a tall plant with green seeds and a dwarf plant with yellow seeds, some of the offspring were tall with yellow seeds and some dwarf with green seeds.

So, Mendel's work was descriptive and mathematical rather than explanatory. He showed that certain characteristics were inherited in a predictable way, that the gametes were the vehicles, that these characteristics did not blend but retained their identity and could be inherited independently of each other. He also recognised dominant and recessive characteristics and, by 'hybridisation', that in the presence of the dominant characteristic the recessive characteristic, though not expressed, did not 'disappear'.

Mendel published his results in 1866 in '*Transactions of the Brünn Natural History Society*', which, understandably, did not have a

wide circulation. Only when Mendel's work was rediscovered in 1900 was the importance and significance of his findings appreciated.

Mendel's observations are sometimes summarised in the form of 'Mendel's laws', but Mendel did not formulate any laws and these are the product of modern knowledge of genetics.

- The first 'law' (the law of segregation) is expressed as 'of a pair of contrasted characters only one can be represented in the gamete'.
- The second 'law' (the law of independent assortment) is given as 'each of a pair of contrasting characters may be combined with either of another pair'.

## Questions

### Core

1 A married couple has four girl children but no boys. This does not mean that the husband produces only X sperms. Explain why not.
2 Which sex chromosome determines the sex of a baby? Explain your answer.
3 Some plants occur in one of two sizes, tall or dwarf. This characteristic is controlled by one pair of genes. Tallness is dominant to shortness. Choose suitable letters for the gene pair.
4 Why are there two types of gene controlling one characteristic? Do the two types affect the characteristic in the same way as each other?
5 The allele for red hair is recessive to the allele for black hair. What colour hair will a person have if he inherits an allele for red hair from his mother and an allele for black hair from his father?
6 a Read Question 5 again. Choose letters for the alleles for red hair and black hair and write down the allele combination for having red hair.
  b Would you expect a red-haired couple to breed true?
  c Could a black-haired couple have a red-haired baby?
7 Use the words 'homozygous', 'heterozygous', 'dominant' and 'recessive' (where suitable) to describe the following allele combinations: **Aa**, **AA**, **aa**.
8 A plant has two varieties, one with red petals and one with white petals. When these two varieties are cross-pollinated, all the offspring have red petals. Which allele is dominant? Choose suitable letters to represent the two alleles.
9 Look at Figure 17.23(a). Why is there no possibility of getting a **BB** or a **bb** combination in the offspring?
10 In Figure 17.23(b) what proportion of the $F_2$ black mice are true-breeding?
11 Two black guinea-pigs are mated together on several occasions and their offspring are invariably black. However, when their black offspring are mated with white guinea-pigs, half of the matings result in all black litters and the other half produce litters containing equal numbers of black and white babies. From these results, deduce the genotypes of the parents and explain the results of the various matings, assuming that colour in this case is determined by a single pair of alleles.

### Extended

12 How many bases will there be in an mRNA molecule coding for haemoglobin?
13 How many chromosomes would there be in the nucleus of:
  a a human muscle cell
  b a mouse kidney cell
  c a human skin cell that has just been produced by mitosis
  d a kangaroo sperm cell?
14 What is the diploid number in humans?
15 Suggest why sperm could be described as *male sperm* and *female sperm*.
16 a What are gametes?
  b What are the male and female gametes of
    i plants and
    ii animals called, and where are they produced?
  c What happens at fertilisation?
  d What is a zygote and what does it develop into?
17 How many chromatids will there be in the nucleus of a human cell just before cell division?
18 Why can chromosomes not be seen when a cell is not dividing?
19 In which human tissues would you expect mitosis to be going on, in:
  a a 5-year-old child
  b an adult?
20 What is the haploid number for:
  a a human
  b a fruit fly?
21 Which of the following cells would be haploid and which diploid: white blood cell, male cell in pollen grain, guard cell, root hair, ovum, sperm, skin cell, egg cell in ovule?
22 Where in the body of the following organisms would you expect meiosis to be taking place?
  a a human male
  b a human female
  c a flowering plant
23 How many chromosomes would be present in:
  a a mouse sperm cell
  b a mouse ovum?
24 Why are organisms that are produced by asexual reproduction identical to each other?
25 Two black rabbits thought to be homozygous for coat colour were mated and produced a litter that contained all black babies. The $F_2$, however, resulted in some white babies, which meant that one of the grandparents was heterozygous for coat colour. How would you find out which grandparent was heterozygous?
26 What combinations of blood groups can result in a child being born with blood group O? Use Punnett squares to show your reasoning.

27 A woman of blood group A claims that a man of blood group AB is the father of her child. A blood test reveals that the child's blood group is O.
   a Is it possible that the woman's claim is correct?
   b Could the father have been a group B man?
   Explain your reasoning.
28 A red cow has a pair of alleles for red hairs. A white bull has a pair of alleles for white hairs. If a red cow and a white bull are mated, the offspring are all 'roan', i.e. they have red and white hairs equally distributed over their body.
   a Is this an example of co-dominance or incomplete dominance?
   b What coat colours would you expect among the offspring of a mating between two roan cattle?
29 Predict the ratio of children with colour blindness resulting from a mother who is a carrier for colour blindness having children with a father who is colour blind.

## Checklist

After studying Chapter 17 you should know and understand the following:

- Inheritance is the transmission of genetic information from generation to generation.

### Chromosomes, genes and proteins

- A chromosome is a thread of DNA, made up of a string of genes.
- A gene is a length of DNA that codes for a protein.
- An allele is a version of a gene.
- Chromosomes are found as thread-like structures in the nuclei of all cells.
- Chromosomes are in pairs; one of each pair comes from the male and one from the female parent.
- Sex, in mammals, is determined by the X and Y chromosomes. Males are XY; females are XX.

- The DNA molecule is coiled along the length of the chromosome.
- A DNA molecule is made up of a double chain of nucleotides in the form of a helix.
- The nucleotide bases in the helix pair up A–T and C–G.
- Triplets of bases control production of the specific amino acids that make up a protein.
- Genes consist of specific lengths of DNA.
- Most genes control the type of enzyme that a cell will make.
- When proteins are made:
  - the DNA with the genetic code for the protein remains in the nucleus
  - mRNA molecules carry a copy of the genetic code to the cytoplasm
  - the mRNA passes through ribosomes in the cytoplasm and the ribosome puts together amino acids to form protein molecules.
- The specific order of amino acids is decided by the sequence of bases in the mRNA.
- All body cells in an organism contain the same genes, but many genes in a particular cell are not expressed because the cell only makes the specific proteins it needs.
- A haploid nucleus is a nucleus containing a single set of unpaired chromosomes (e.g. in sperm and egg cells).
- A diploid nucleus is a nucleus containing two sets of chromosomes (e.g. in body cells).
- In a diploid cell, there is a pair of each type of chromosome; in a human diploid cell there are 23 pairs.

### Mitosis

- Mitosis is nuclear division giving rise to genetically identical cells.
- Mitosis is important in growth, repair of damaged tissues, replacement of cells and in asexual reproduction.

- Before mitosis, the exact duplication of chromosomes occurs.
- Each species of plant or animal has a fixed number of chromosomes in its cells.
- When cells divide by mitosis, the chromosomes and genes are copied exactly and each new cell gets a full set.
- Stem cells are unspecialised cells that divide by mitosis to produce daughter cells that can become specialised for specific purposes.

### Meiosis

- Meiosis is reduction division in which the chromosome number is halved from diploid to haploid resulting in genetically different cells.
- Gametes are the result of meiosis.
- At meiosis, only one chromosome of each pair goes into the gamete.
- Meiosis produces variation by forming new combinations of maternal and paternal chromosomes.

### Monohybrid inheritance

- The genotype of an organism is its genetic make-up.
- The phenotype of an organism is its features.
- Homozygous means having two identical alleles of a particular gene. Two identical homozygous individuals that breed together will be pure-breeding.
- Heterozygous means having two different alleles of a particular gene. A heterozygous individual will therefore not be pure-breeding.
- A dominant allele is one that is expressed if it is present.

- A recessive allele is one that is only expressed when there is no dominant allele of the gene present.
- Genetic diagrams are used to predict the results of monohybrid crosses and calculate phenotypic ratios.
- Punnett squares can be used in crosses to work out and show the possible different genotypes.

- A test-cross is used to identify an unknown genotype, for instance to find out if it is pure breeding or heterozygous.
- In some cases, neither one of a pair of alleles is fully dominant over the other. This is called co-dominance.
- The inheritance of ABO blood groups is an example of co-dominance.
- The phenotypes are A, B, AB and O blood groups.
- The genotypes are $I^A$, $I^B$ and $I^o$.
- A sex-linked characteristic is a characteristic in which the gene responsible is located on a sex chromosome. This makes it more common in one sex than in the other.
- Colour blindness is an example of sex linkage.
- Genetic diagrams can be used to predict the results of monohybrid crosses involving co-dominance and sex linkage.

# 18 Variation and selection

**Variation**
Define variation
Discontinuous and continuous variation
Define mutation
Causes of mutations

Causes of discontinuous and continuous variation
Define gene mutation
Sickle-cell anaemia
Down's syndrome
Mutations in bacteria

**Adaptive features**
Define adaptive feature
Describe adaptive features of organisms

Define adaptive feature, fitness
Adaptive features of hydrophytes and xerophytes

**Selection**
Natural selection
Artificial selection
Selective breeding

Define the process of adaptation
Evolution
Development of strains of resistant bacteria
Use of selective breeding
Compare natural and artificial selection

## Variation

**Key definition**
**Variation** is the differences between individuals of the same species.

The term '**variation**' refers to observable differences within a species. All domestic cats belong to the same species, i.e. they can all interbreed, but there are many variations of size, coat colour, eye colour, fur length, etc. Those variations that can be inherited are determined by genes. They are **genetic variations**. **Phenotypic variations** may be brought about by genes, but can also be caused by the environment, or a combination of both genes and the environment.

So, there are variations that are not heritable, but determined by factors in the environment. A kitten that gets insufficient food will not grow to the same size as its litter mates. A cat with a skin disease may have bald patches in its coat. These conditions are not heritable. They are caused by environmental effects. Similarly, a fair-skinned person may be able to change the colour of his or her skin by exposing it to the Sun, so getting a tan. The tan is an **acquired characteristic**. You cannot inherit a suntan. Black skin, on the other hand, is an **inherited characteristic**.

Many features in plants and animals are a mixture of acquired and inherited characteristics (Figure 18.1). For example, some fair-skinned people never go brown in the Sun, they only become sunburned. They have not inherited the genes for producing the extra brown pigment in their skin. A fair-skinned person with the genes for producing pigment will only go brown if he or she exposes themselves to sunlight. So the tan is a result of both inherited and acquired characteristics.


**Figure 18.1** Acquired characteristics. These apples have all been picked from different parts of the same tree. All the apples have similar genotypes, so the differences in size must have been caused by environmental effects.

### Discontinuous variation

In **discontinuous variation**, the variations take the form of distinct, alternative phenotypes with no intermediates (Figures 18.2 and 18.4). The mice in Figure 17.23 are either black or brown; there are no intermediates. You are either male or female. Apart from a small number of abnormalities, sex is inherited in a discontinuous way. Some people can roll their tongue into a tube. Others are unable to do it. They

are known as non-tongue rollers. Again, there are no intermediates (Figure 18.2).

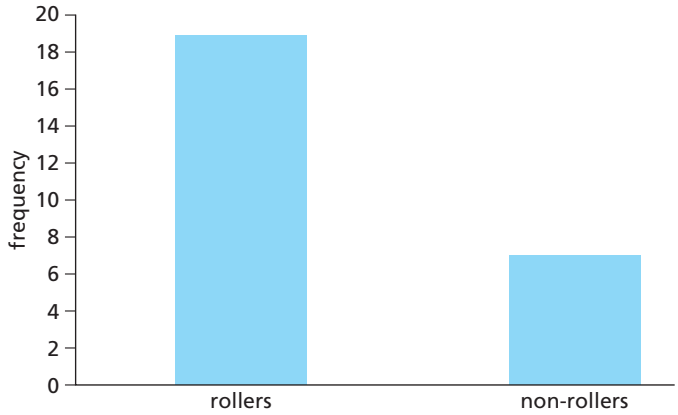



**Figure 18.2** Discontinuous variation. Tongue rollers and non-rollers in a class

Discontinuous variation cannot usually be altered by the environment. You cannot change your eye colour by altering your diet. A genetic dwarf cannot grow taller by eating more food. You cannot learn how to roll your tongue.

## Continuous variation

An example of **continuous variation** is height. There are no distinct categories of height; people are not either tall or short. There are all possible intermediates between very short and very tall (Figure 18.3).

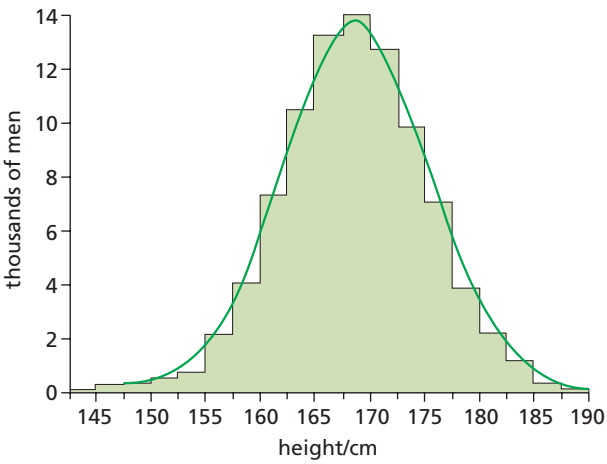



**Figure 18.3** Continuous variation. Heights of 90 000 army recruits. The apparent 'steps' in the distribution are the result of arbitrarily chosen categories, differing in height by 1 cm. But heights do not differ by exactly 1 cm. If measurements could be made accurately to the nearest millimetre there would be a smooth curve like the one shown in colour.

There are many characteristics that are difficult to classify as either wholly continuous or discontinuous variations. Human eye colour has already been mentioned. People can be classified roughly as having blue eyes or brown eyes, but there are also categories described as grey, hazel or green. It is likely that there are a small number of genes for eye colour and a dominant gene for brown eyes, which overrides all the others when it is present. Similarly, red hair is a discontinuous variation but it is masked by genes for other colours and there is a continuous range of hair colour from blond to black.

## Mutations

**Key definition**
A **mutation** is a spontaneous genetic change. Mutation is the way new alleles are formed.

Many of the cat coat variations mentioned overleaf may have arisen, in the first place, as mutations in a wild stock of cats. A recent variant produced by a mutation is the 'rex' variety, in which the coat has curly hairs.

Many of our high-yielding crop plants have arisen as a result of mutations in which the whole chromosome set has been doubled.

Exposure to **mutagens**, namely certain chemicals and radiation, is known to increase the rate of mutation. Some of the substances in tobacco smoke, such as tar, are mutagens, which can cause cancer.

Ionising radiation from X-rays and radioactive compounds, and ultraviolet radiation from sunlight, can both increase the mutation rate. It is uncertain whether there is a minimum dose of radiation below which there is negligible risk. It is possible that repeated exposure to low doses of radiation is as harmful as one exposure to a high dose. It has become clear in recent years that, in light-skinned people, unprotected exposure to ultraviolet radiation from the Sun can cause a form of skin cancer.

Generally speaking, however, exposure to natural and medical sources of radiation carries less risk than smoking cigarettes or driving a car, but it is sensible to keep exposure to a minimum.

Genetic variation may be the result of new combinations of genes in the zygote, or mutations.

## Discontinuous variation

Discontinuous variation is under the control of a single pair of alleles or a small number of genes. An example is human blood groups. These were discussed in Chapter 17.

A person is one of four blood groups: A, B, AB or O. There are no groups in between.

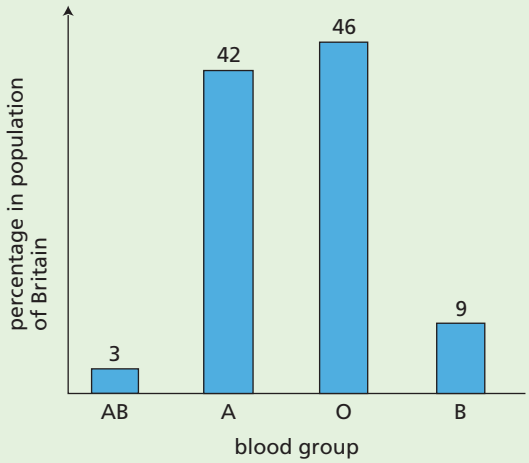



**Figure 18.4** Discontinuous variation. Frequencies of ABO blood groups in Britain. The figures could not be adjusted to fit a smooth curve because there are no intermediates.

## Continuous variation

Continuous variation is influenced by a combination of both genetic and environmental factors. Continuously variable characteristics are usually controlled by several pairs of alleles. There might be five pairs of alleles for height – (**Hh**), (**Tt**), (**Ll**), (**Ee**) and (**Gg**) – each dominant allele adding 4 cm to your height. If you inherited all ten dominant genes (**HH**, **TT**, etc.) you could be 40 cm taller than a person who inherited all ten recessive genes (**hh**, **tt**, etc.).

The actual number of genes that control height, intelligence, and even the colour of hair and skin, is not known.

Continuously variable characteristics are greatly influenced by the environment. A person may inherit genes for tallness and yet not get enough food to grow tall. A plant may have the genes for large fruits but not get enough water, minerals or sunlight to produce large fruits. Continuous variations in human populations, such as height, physique and intelligence, are always the result of interaction between the genotype and the environment.

## New combinations of genes

If a grey cat with long fur is mated with a black cat with short fur, the kittens will all be black with short fur. If these offspring are mated together, in due course the litters may include four varieties: black–short, black–long, grey–short and grey–long. Two of these are different from either of the parents.

## Mutation

**Key definition**
A **gene mutation** is a change in the base sequence in DNA.

A mutation may occur in a gene or a chromosome. In a gene mutation it may be that one or more genes are not replicated correctly. A chromosome mutation may result from damage to or loss of part of a chromosome during mitosis or meiosis, or even the gain of an extra chromosome, as in Down's syndrome (see page 273).

An abrupt change in a gene or chromosome is likely to result in a defective enzyme and will usually disrupt the complex reactions in the cells. Most mutations, therefore, are harmful to the organism.

Surprisingly, only about 3% of human DNA consists of genes. The rest consists of repeated sequences of nucleotides that do not code for proteins. This is sometimes called '**junk DNA**', but that term only means that we do not know its function. If mutations occur in these non-coding sequences they are unlikely to have any effect on the organism and are, therefore, described as 'neutral'.

Rarely, a gene or chromosome mutation produces a beneficial effect and this may contribute to the success of the organism (see 'Selection' later in this chapter).

If a mutation occurs in a gamete, it will affect all the cells of the individual that develops from the zygote. Thus the whole organism will be affected. If the mutation occurs in a somatic cell (body cell), it will affect only those cells produced, by mitosis, from the affected cell.

Thus, a mutation in a gamete may result in a genetic disorder, e.g. haemophilia or cystic fibrosis. Mutations in somatic cells may give rise to cancers by promoting uncontrolled cell division in the

affected tissue. For example, skin cancer results from uncontrolled cell division in the basal layer of the skin.

A mutation may be as small as the substitution of one organic base for another in the DNA molecule, or as large as the breakage, loss or gain of a chromosome.

### Sickle-cell anaemia

This condition has already been mentioned in Chapter 17. A person with sickle-cell disease has inherited both recessive alleles ($Hb^SHb^S$) for defective haemoglobin. The distortion and destruction of the red cells, which occurs in low oxygen concentrations, leads to bouts of severe anaemia (Figure 18.5). In many African countries, sufferers have a reduced chance of reaching reproductive age and having a family. There is thus a selection pressure, which tends to remove the homozygous recessives from the population. In such a case, you might expect the harmful $Hb^S$ allele to be selected out of the population altogether. However, the heterozygotes ($Hb^AHb^S$) have virtually no symptoms of anaemia but do have the advantage that they are more resistant to malaria than the homozygotes $Hb^AHb^A$. It appears that the malaria parasite is unable to invade and reproduce in the sickle cells.

The selection pressure of malaria, therefore, favours the heterozygotes over the homozygotes and the potentially harmful $Hb^S$ allele is kept in the population (Figure 18.6).

When Africans migrate to countries where malaria does not occur, the selective advantage of the $Hb^S$ allele is lost and the frequency of this allele in the population diminishes.

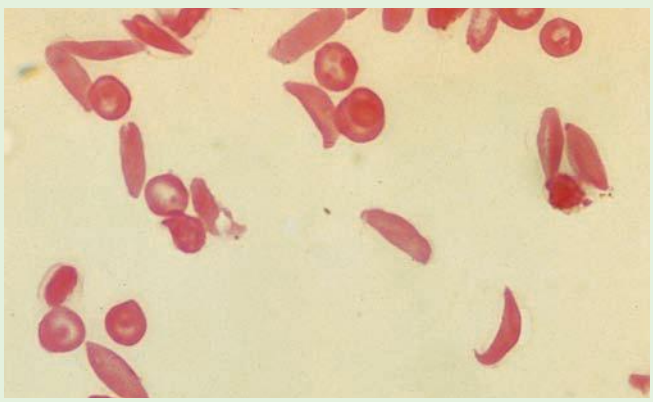


**Figure 18.5** Sickle-cell anaemia (×800). At low oxygen concentration the red cells become distorted.

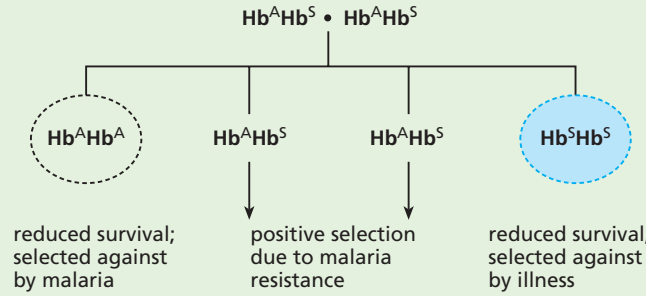



**Figure 18.6** Selection in sickle-cell disease

With **sickle-cell anaemia**, the defective haemoglobin molecule differs from normal haemoglobin by only one amino acid (represented by a sequence of three bases), i.e. *valine* replaces *glutamic acid*. This could be the result of faulty replication at meiosis. When the relevant parental chromosome replicated at gamete formation, the DNA could have produced the triplet –CAT– (which specifies *valine*) instead of –CTT– (which specifies *glutamic acid*). In this case, a change of just one base (from A to T) makes a significant difference to the characteristics of the protein (haemoglobin).

### Down's syndrome

Down's syndrome is a form of mental and physical disability, which results from a chromosome mutation. During the process of meiosis which produces an ovum, one of the chromosomes (chromosome 21) fails to separate from its homologous partner, a process known as **non-disjunction**. As a result, the ovum carries 24 chromosomes instead of 23, and the resulting zygote has 47 instead of the normal 46 chromosomes. The risk of having a baby with Down's syndrome increases as the mother gets older.

### Mutations in bacteria

Mutations in bacteria often produce resistance to drugs. Bacterial cells reproduce very rapidly, perhaps as often as once every 20 minutes. Thus a mutation, even if it occurs only rarely, is likely to appear in a large population of bacteria. If a population of bacteria containing one or two drug-resistant mutants is subjected to that particular drug, the non-resistant bacteria will be killed but the drug-resistant mutants survive (see Figure 15.1). Mutant genes are inherited in the same way as normal genes, so when the surviving mutant bacteria reproduce, all their offspring will be resistant to the drug.

Mutations are comparatively rare events; perhaps only one in every 100 000 replications results in a mutation. Nevertheless they do occur naturally all the time.

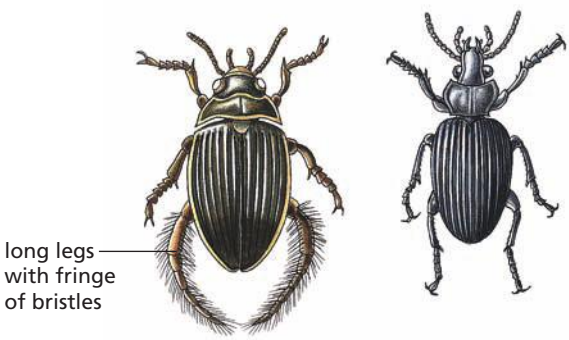
# Adaptive features

**Key definition**
An **adaptive feature** is an inherited feature that helps an organism to survive and reproduce in its environment.

## Adaptation

When biologists say that a plant or animal is *adapted* to its habitat they usually mean that, in the course of evolution, changes have occurred in the organism, which make it more successful in exploiting its habitat, e.g. animals finding and digesting food, selecting nest sites or hiding places, or plants exploiting limited mineral resources or tolerating salinity or drought. It is tempting to assume that because we find a plant or animal in a particular habitat it must be adapted to its habitat. There is some logic in this; if an organism was not adapted to its habitat, presumably it would be eliminated by natural selection. However, it is best to look for positive evidence of **adaptation**.

Sometimes, just by looking at an organism and comparing it with related species, it is possible to make reasoned guesses about adaptation. For example, there seems little doubt that the long, hair-fringed hind legs of a water beetle are adaptations to locomotion in water when compared with the corresponding legs of a land-living relative (Figure 18.7).

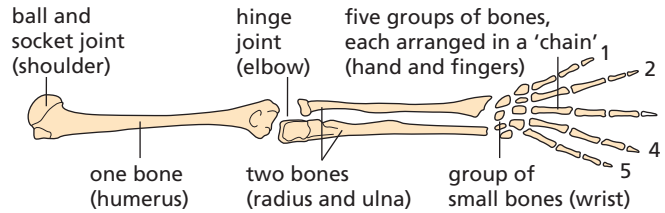



**(a)** water beetle **(b)** ground beetle

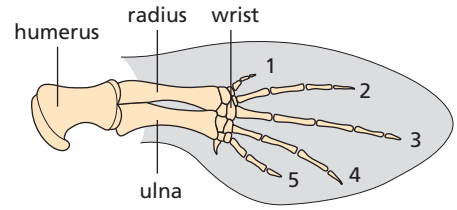
**Figure 18.7** Adaptation to locomotion in water and on land

Similarly, in Figure 18.8 it seems reasonable to suppose that, compared with the generalised mammalian limb, the forelimbs of whales are adapted for locomotion in water.

By studying animals which live in extreme habitats, it is possible to suggest ways in which they might be adapted to these habitats especially if the observations are supported by physiological evidence.




**(a)** pattern of bones in human forelimb




**(b)** whale

**Figure 18.8** Skeletons of the forelimbs of human and whale

## The camel

Camels are adapted to survive in a hot, dry and sandy environment. Adaptive physical features are closable nostrils and long eyelashes, which help keep out wind-blown sand (Figure 18.9). Their feet are broad and splay out under pressure, so reducing the tendency to sink into the sand. Thick fur insulates the body against heat gain in the intense sunlight.

Physiologically, a camel is able to survive without water for 6–8 days. Its stomach has a large water-holding capacity, though it drinks to replace water lost by evaporation rather than in anticipation of water deprivation.

The body temperature of a 'thirsty' camel rises to as much as 40 °C during the day and falls to about 35 °C at night. The elevated daytime temperature reduces the heat gradient between the body and the surroundings, so less heat is absorbed. A camel is able to tolerate water loss equivalent to 25% of its body weight, compared with humans for whom a 12% loss may be fatal. The blood volume and concentration are maintained by withdrawing water from the body tissues.

The nasal passages are lined with mucus. During exhalation, the dry mucus absorbs water vapour. During inhalation the now moist mucus adds water vapour to the inhaled air. In this way, water is conserved.

The role of the camel's humps in water conservation is more complex. The humps contain fat and are therefore an important reserve of energy-giving food. However, when the fat is metabolised during respiration, carbon dioxide and water

**Figure 18.9** Protection against wind-blown sand. The nostrils are slit-like and can be closed. The long eyelashes protect the eyes

**Figure 18.11** The heavy coat and small ears also help the polar bear to reduce heat losses.

(metabolic water) are produced. The water enters the blood circulation and would normally be lost by evaporation from the lungs, but the water-conserving nasal mucus will trap at least a proportion of it.

## The polar bear

Polar bears live in the Arctic, spending much of their time on snow and ice. Several physical features contribute to their adaptation to this cold environment.

It is a very large bear (Figure 18.10), which means that the ratio of its surface area to its volume is relatively small. The relatively small surface area means that the polar bear loses proportionately less heat than its more southerly relatives. Also its ears are small, another feature that reduces heat loss (Figure 18.11).

It has a thick coat with long, loosely packed coarse hairs (guard hairs) and a denser layer of shorter woolly hairs forming an insulating layer. The long hairs are oily and water-repellent and enable the bear to shake off water when it emerges from a spell of swimming.

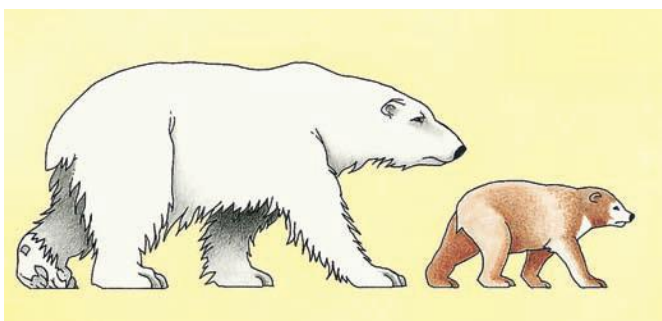


**Figure 18.10** The polar bear and the sun bear (from SE Asia). The smaller surface area/volume ratio in the polar bear helps conserve heat.

The principal thermal insulation comes from a 10 cm layer of fat (blubber) beneath the skin. The thermal conductivity of fat is little different from any other tissue but it has a limited blood supply. This means that very little warm blood circulates close to the skin surface.

The hollow hairs of the white fur are thought to transmit the Sun's heat to the black skin below. Black is an efficient colour for absorbing heat. The white colour is also probably an effective camouflage when hunting its prey, mainly seals.

A specific adaptation to walking on snow and ice is the heat-exchange arrangement in the limbs. The arteries supplying the feet run very close to the veins returning blood to the heart. Heat from the arteries is transferred to the veins before the blood reaches the feet (Figure 18.12). So, little heat is lost from the feet but their temperature is maintained above freezing point, preventing frost-bite.

Polar bears breed in winter when temperatures fall well below zero. However, the pregnant female excavates a den in the snow in which to give birth and rear her two cubs. In this way the cubs are protected from the extreme cold.

The female remains in the den for about 140 days, suckling her young on the rich milk, which is formed from her fat reserves.

## Venus flytrap

Many plants show adaptions as well as animals. Insectivorous plants such as the Venus flytrap (Figure 18.13) live in habitats where there is often a shortage of nitrates for growth. They have developed pairs of leaves with tooth-like edges. The leaves have

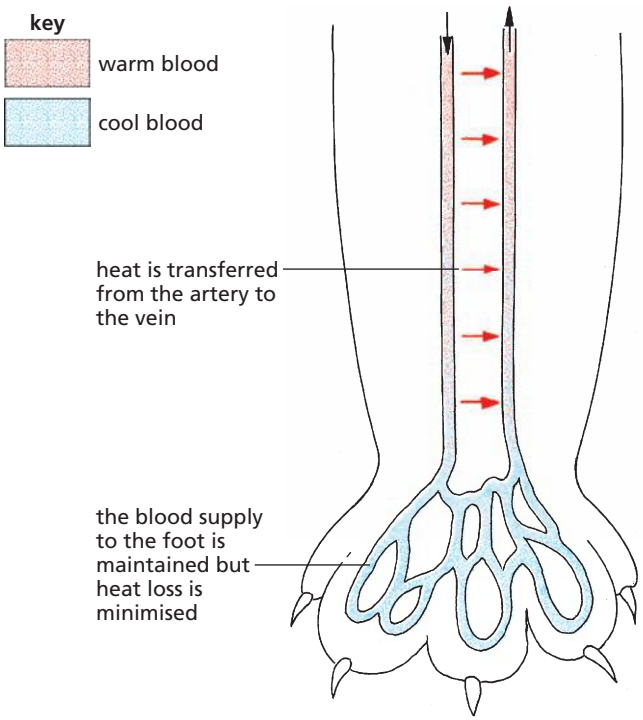



**Figure 18.12** The heat-exchange mechanism in the polar bear's limb

sensitive hairs on their surface. When an insect walks inside the leaves, the hairs are triggered, causing the leaves to close very rapidly – trapping the animal. The leaves then secrete protease enzymes, which digest the insect's protein and produce soluble amino acids. These are absorbed by the leaf and used to build new proteins. It is unusual for a photosynthetic plant to show such rapid movement or to gain nourishment other than by photosynthesis.

**Figure 18.13** Venus flytrap with trapped insect, which will eventually be digested

## Other adaptations

Adaptive features of the long-eared bat and the hare are illustrated in Figures 18.14 and 18.15.

**Figure 18.14** Long-eared bat. The bat gives out high-pitched sounds, which are reflected back from its prey and from obstacles, to its ears and sensitive patches on its face. By timing these echoes the bat can judge its distance from the obstacle or prey. This allows it to fly and feed in the dark. Its body is covered in fur for insulation. Its forearms are covered by a membrane of skin to form a wing. The fingers are very long to stretch out the membrane to increase the surface area of the wing.

**Figure 18.15** Hare. This animal is a herbivore and is hunted by predators such as foxes. Its fur is a good insulator and its colour provides excellent camouflage. The long ears help to pick up and locate sound vibrations. The eyes at the side of the head give the hare good all around vision. The hind legs are very long to enable the animal to run away from predators and its kick is a good defence mechanism. Some species of hare change the colour of their fur in winter from brown to white to provide better camouflage in snow.

**Key definitions**

**Adaptive features** are the inherited functional features of an organism that increase its fitness.

**Fitness** is the probability of that organism surviving and reproducing in the environment in which it is found.

## Adaptations to arid conditions

In both hot and cold climates, plants may suffer from water shortage. High temperatures accelerate evaporation from leaves. At very low temperatures the soil water becomes frozen and therefore unavailable to the roots of plants. Plants modified to cope with lack of water are called **xerophytes**.

It is thought that the autumn leaf-fall of deciduous trees and shrubs is an essential adaptation to winter 'drought'. Loss of leaves removes virtually all evaporating surfaces at a time when water may become unavailable. Without leaves, however, the plants cannot make food by photosynthesis and so they enter a dormant condition in which metabolic activity is at a low level.

### Pine tree

The pine tree (*Pinus*) (Figure 18.16) is an evergreen tree that survives in cold climates. It has small, compact, needle-like leaves. The small surface area of such leaves offers little resistance to high winds. This helps to resist wind damage and can reduce the amount of water lost in transpiration. However, photosynthesis can continue whenever water is available. Sunken stomata create high humidity and reduce transpiration. A thick waxy cuticle is present on the epidermis to prevent evaporation from the surface of the leaf.

**Figure 18.16** Pine leaves, reduced to needles to lower the rate of transpiration

Some plants live in very sandy soil, which does not retain moisture well. Often this is combined with very low rainfall, making access to water difficult. Only plants with special adaptations, such as desert and sand dune species, can survive.

### Cacti

Cacti are adapted to hot, dry conditions in several ways. Often they have no leaves, or the leaves are reduced to spines. This reduces the surface area for transpiration and also acts as a defence against herbivores. Photosynthesis is carried out by a thick green stem, which offers only a small surface area for evaporation. Cacti are succulent, i.e. they store water in their fleshy tissues and draw on this store for photosynthesis (Figure 18.17).

**Figure 18.17** A cactus (succulent) growing in desert conditions in Arizona

The stomata of many cacti are closed during the day when temperatures are high, and open at night when evaporation is at a minimum. This strategy requires a slightly different form of photosynthesis. At night, carbon dioxide diffuses in through the open stomata and is 'fixed' (i.e. incorporated) into an organic acid. Little water vapour is lost at night. In the daytime the stomata are closed but the organic acid breaks down to yield carbon dioxide, which is then built into sugars by photosynthesis. Closure of the stomata in the daytime greatly reduces water loss.

**Marram grass**

Marram grass (*Ammophila*) lives on sand dunes (Figure 18.18), where water drains away very quickly. It has very long roots to search for water deep down in the sand. Its leaves roll up into straw-like tubes in dry weather due to the presence of hinge cells, which become flaccid as they lose water (Figure 18.19). Leaf rolling, along with the fact that the stomata are sunken, helps to increase humidity around the stomata, reducing transpiration. The presence of fine hairs around the stomata reduces air movement so humidity builds up and transpiration is reduced.

**Figure 18.18** Marram grass growing on a sand dune

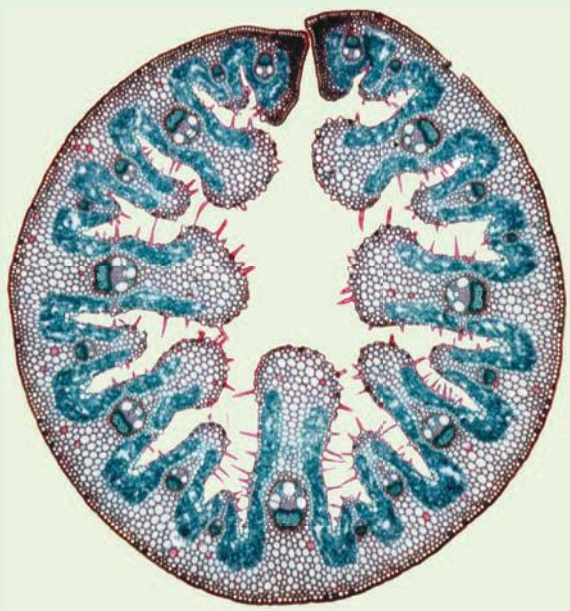


**Figure 18.19** Transverse section of rolled up Marram grass leaf

## Adaptations to living in water

Plants adapted to living in water are called **hydrophytes**. An example is the water lily (*Nymphaea*) (Figure 18.20). The leaves contain large air spaces to make them buoyant, so they float on or near the surface (Figure 18.21). This enables them to gain light for photosynthesis. The lower epidermis lacks stomata to prevent water entering the air spaces, while stomata are present on the upper epidermis for gas exchange. With land plants, most stomata are usually on the lower epidermis.

The roots of hydrophytes, which can be poorly developed, also contain air spaces. This is because the mud they grow in is poorly oxygenated and the root cells need oxygen for respiration. Stems lack much support as the water they are surrounded by provides buoyancy for the plant.

**Figure 18.20** Water lily (*Nymphaea*)

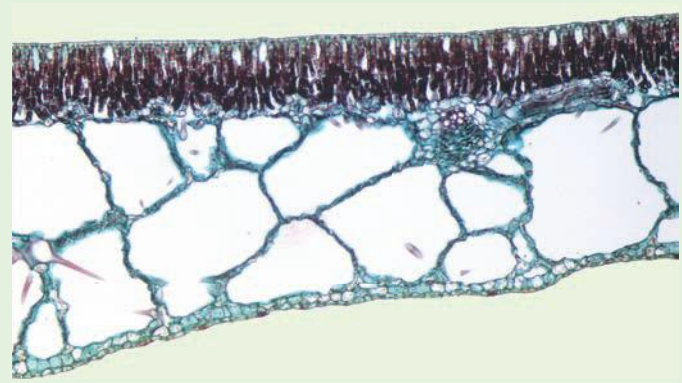


**Figure 18.21** Section through water lily leaf

# Selection

## Natural selection

Theories of evolution have been put forward in various forms for hundreds of years. In 1858, Charles Darwin and Alfred Russel Wallace published a theory of evolution by natural selection, which is still an acceptable theory today.

The theory of evolution by natural selection is as follows:

- Individuals within a species are all slightly different from each other (Figure 18.22). These differences are called variations.
- If the climate or food supply changes, individuals possessing some of these variations may be better able to survive than others. For example, a variety of animal that could eat the leaves of shrubs as well as grass would be more likely to survive a drought than one that fed only on grass.
- If one variety lives longer than others, it is also likely to leave behind more offspring. A mouse that lives for 12 months may have ten litters of five babies (50 in all). A mouse that lives for 6 months may have only five litters of five babies (25 in all).
- If some of the offspring inherit alleles responsible for the variation that helped the parent survive better, they too will live longer and have more offspring.
- In time, this particular variety will outnumber and finally replace the original variety.

This is sometimes called 'the survival of the fittest'. However, 'fitness', in this case, does not mean good health but implies that the organism is well fitted to the conditions in which it lives.

Thomas Malthus, in 1798, suggested that the increase in the size of the human population would outstrip the rate of food production. He predicted that the number of people would eventually be regulated by famine, disease and war. When Darwin read the Malthus essay, he applied its principles to other populations of living organisms.

He observed that animals and plants produce vastly more offspring than can possibly survive to maturity and he reasoned that, therefore, there must be a 'struggle for survival'.

For example, if a pair of rabbits had eight offspring that grew up and formed four pairs, eventually having eight offspring per pair, in four generations the number of rabbits stemming from the original pair would be 512 (i.e. $2 \rightarrow 8 \rightarrow 32 \rightarrow 128 \rightarrow 512$). The population of rabbits, however, remains more or less constant. Many of the offspring in each generation must, therefore, have failed to survive to reproductive age.

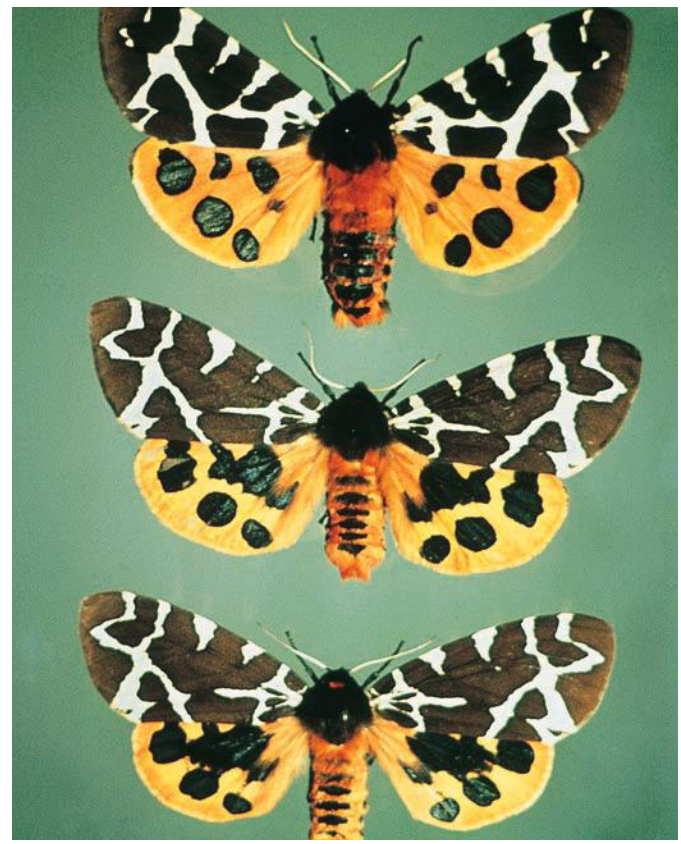


**Figure 18.22** Variation. The garden tiger moths in this picture are all from the same family. There is a lot of variation in the pattern on the wings.

## Competition and selection

There will be **competition** between members of the rabbit population for food, burrows and mates. If food is scarce, space is short and the number of potential mates limited, then only the healthiest, most vigorous, most fertile and otherwise well-adapted rabbits will survive and breed.

The competition does not necessarily involve direct conflict. The best adapted rabbits may be able to run faster from predators, digest their food more efficiently, have larger litters or grow coats that camouflage them better or more effectively reduce heat losses. These rabbits will survive longer and leave more offspring. If the offspring inherit the advantageous characteristics of their parents, they may give rise to a new race of faster, different coloured,

thicker furred and more fertile rabbits, which gradually replace the original, less well-adapted varieties. The new variations are said to have **survival value**.

This is natural selection; the better adapted varieties are 'selected' by the pressures of the environment (**selection pressures**).

For natural selection to be effective, the variations have to be heritable. Variations that are not heritable are of no value in natural selection. Training may give athletes more efficient muscles, but this characteristic will not be passed on to their children.

### The peppered moth

A possible example of natural selection is provided by a species of moth called the peppered moth, found in Great Britain. The common form is speckled but there is also a variety that is black. The black variety was rare in 1850, but by 1895 in the Manchester area of England its numbers had risen to 98% of the population of peppered moths. Observation showed that the light variety was concealed better than the dark variety when they rested on tree-trunks covered with lichens (Figure 18.23). In the Manchester area of England, pollution had caused the death of the lichens and the darkening of the tree-trunks with soot. In this industrial area the dark variety was the better camouflaged (hidden) of the two and was not picked off so often by birds. So the dark variety survived better, left more offspring and nearly replaced the light form.

The selection pressure, in this case, was presumed to be mainly predation by birds. The adaptive variation that produced the selective advantage was the dark colour.

Although this is an attractive and plausible hypothesis of how natural selection could occur, some of the evidence does not support the hypothesis or has been called into question.

For example, the moths settle most frequently on the underside of branches rather than conspicuously on tree trunks, as in Figure 18.23. Also, in several unpolluted areas the dark form is quite abundant, for example 80% in East Anglia in England. Research is continuing in order to test the hypothesis.

## Selective breeding

The process of selective breeding involves humans selecting individuals with desirable features. These individuals are then cross-bred to produce the next generation. Offspring with the most desirable features are chosen to continue the breeding programme and the process is repeated over a number of generations.

Human communities practise this form of selection when they breed plants and animals for specific characteristics. The many varieties of cat that you see today have been produced by selecting individuals with pointed ears, particular fur colour or length, or even no tail, etc. One of the kittens in a litter might vary from the others by having distinctly pointed ears. This individual, when mature, is allowed to breed. From the offspring, another very pointed-eared variant is selected for the next breeding stock, and so on, until the desired or 'fashionable' ear shape is established in a true-breeding population (Figure 18.24).

More important are the breeding programmes to improve agricultural livestock or crop plants. Animal-breeders will select cows for their high milk yield and

(a) (b) (c) (d)

**Figure 18.23** Selection for varieties of the peppered moth

sheep for their wool quality. Plant-breeders will select varieties for their high yield and resistance to fungus diseases (Figure 18.25).

**Figure 18.24** Selective breeding. The Siamese cat, produced by artificial selection over many years

**Figure 18.25** Selective breeding in tomatoes. Different breeding programmes have selected genes for fruit size, colour and shape. Similar processes have given rise to most of our cultivated plants and domesticated animals.

## Evolution

**Key definitions**

**Adaptation** is the process, resulting from natural selection, by which populations become more suited to their environment over many generations.

**Evolution** can be described as the change in adaptive features of a population over time as a result of natural selection.

Most biologists believe that natural selection, among other processes, contributes to the evolution of new species and that the great variety of living organisms on the Earth is the product of millions of years of evolution involving natural selection.

### Antibiotic-resistant bacteria

Antibiotics are drugs used to treat infections caused by bacteria (see 'Medicinal drugs' in Chapter 15). Bacterial cells reproduce very rapidly, perhaps as often as once every 20 minutes. Thus a mutation, even if it occurs only rarely, is likely to appear in a large population of bacteria. If a population of bacteria containing one or two drug-resistant mutants is subjected to that particular drug, the non-resistant bacteria will be killed but the drug-resistant mutants survive (Figure 15.1). Mutant genes are inherited in the same way as normal genes, so when the surviving mutant bacteria reproduce, all their offspring will be resistant to the drug.

## Selective breeding

An important part of any breeding programme is the selection of the desired varieties. The largest fruit on a tomato plant might be picked and its seeds planted next year. In the next generation, once again only seeds from the largest tomatoes are planted. Eventually it is possible to produce a true-breeding variety of tomato plant that forms large fruits. Figure 18.25 shows the result of such selective breeding. The same technique can be used for selecting other desirable qualities, such as flavour and disease resistance.

Similar principles can be applied to farm animals. Desirable characteristics, such as high milk yield and resistance to disease, may be combined. Stock-breeders will select calves from cows that give large quantities of milk. These calves will be used as breeding stock to build a herd of high yielders. A characteristic such as milk yield is probably under the control of many genes. At each stage of selective breeding the farmer, in effect, is keeping the beneficial genes and discarding the less useful genes from his or her animals.

Selective breeding in farm stock can be slow and expensive because the animals often have small numbers of offspring and breed only once a year.

By producing new combinations of genes, selective breeding achieves the same objectives as

genetic engineering but it takes much longer and is less predictable.

In selective breeding, the transfer of genes takes place between individuals of the same or closely related species. Genetic engineering involves transfer between unrelated species.

Selective breeding and genetic engineering both endeavour to produce new and beneficial combinations of genes. Selective breeding, however, is much slower and less precise than genetic engineering. On the other hand, cross-breeding techniques have been around for a very long time and are widely accepted.

One of the drawbacks of selective breeding is that the whole set of genes is transferred. As well as the desirable genes, there may be genes that, in a homozygous condition, would be harmful. It is known that artificial selection repeated over a large number of generations tends to reduce the fitness of the new variety.

A long-term disadvantage of selective breeding is the loss of variability. By eliminating all the offspring that do not bear the desired characteristics, many genes are lost from the population. At some future date, when new combinations of genes are sought, some of the potentially useful ones may no longer be available.

In attempting to introduce, in plants, characteristics such as salt tolerance or resistance to disease or drought, the geneticist goes back to wild varieties, as shown in Figure 18.26. However, with the current rate of extinction, this source of genetic material is diminishing.

In the natural world, reduction of variability could lead to local extinction if the population was unable to adapt, by natural selection, to changing conditions.

## Comparing natural and artificial selection

Natural selection occurs in groups of living organisms through the passing on of genes to the next generation by the best adapted organisms, without human interference. Those with genes that provide an advantage, to cope with changes in environmental conditions for example, are more likely to survive, while others die before they can breed and pass on their genes. However, variation within the population remains.

Artificial selection is used by humans to produce varieties of animals and plants that have an increased economic importance. It is considered a safe way of developing new strains of organisms, compared with genetic engineering, and is a much faster process than natural selection. However, artificial selection removes variation from a population, leaving it susceptible to disease and unable to cope with changes in environmental conditions. Potentially, therefore, artificial selection puts a species at risk of extinction.

(a) (b) (c) (d) (e)

**Figure 18.26** The genetics of bread wheat. A primitive wheat (a) was crossed with a wild grass (b) to produce a better-yielding hybrid wheat (c). The hybrid wheat (c) was crossed with another wild grass (d) to produce one of the varieties of wheat (e) which is used for making flour and bread.

## Questions

Core

1 Study the following photographs and captions, then make a list of the adaptations of each animal.
   a long-eared bat (Figure 18.14)
   b hare (Figure 18.15)
   b polar bear (Figure 18.11) (See also details in the text.)
2 What features of a bird's appearance and behaviour do you think might help it compete for a mate?
3 What selection pressures do you think might be operating on the plants in a lawn?

Extended

4 Suggest some good characteristics that an animal-breeder might try to combine in sheep by mating different varieties together.
5 A variety of barley has a good ear of seed but has a long stalk and is easily blown over. Another variety has a short, sturdy stalk but a poor ear of seed.
Suggest a breeding programme to obtain and select a new variety that combines both of the useful characteristics.
Choose letters to represent the genes and show the genotypes of the parent plants and their offspring.

## Checklist

After studying Chapter 18 you should know and understand the following:

### Variation

- Variation is the differences between individuals of the same species.
- Variations within a species may be inherited or acquired.
- Continuous variation results in a range of phenotypes between two extremes, e.g. height in humans.
- Discontinuous variation results in a limited number of phenotypes with no intermediates, e.g. tongue rolling.
- Mutation is the way in which new alleles are formed.
- Increases in the rate of mutation can be caused by ionising radiation and some chemicals.

- Discontinuous variation results, usually, from the effects of a single pair of alleles, and produces distinct and consistent differences between individuals.
- Blood groups are an example of discontinuous variation.
- Discontinuous variations cannot be changed by the environment.
- Phenotypic (continuous) variations are usually controlled by a number of genes affecting the same characteristic and can be influenced by the environment.
- A gene mutation is a change in the base sequence of DNA.
- Sickle-cell anaemia is caused by a change in the base sequence of the gene for haemoglobin. This results in abnormal haemoglobin, which changes shape when oxygen levels are low.
- The inheritance of sickle-cell anaemia can be predicted using genetic diagrams.
- People who are heterozygous for the sickle-cell allele have a resistance to malaria.

### Adaptive features

- An adaptive feature is an inherited feature that helps an organism to survive and reproduce in its environment.
- Adaptive features of a species can be recognised from its image in a drawing or photograph.

- An adaptive feature is the inherited functional features of an organism that increase its fitness.
- Fitness is the probability of that organism surviving and reproducing in the environment in which it is found.
- Hydrophytes are plants that have adaptive features to live in a watery environment.
- Xerophytes are plants that have adaptive features to live in very dry environments.

### Selection

- Some members of a species may have variations that enable them to compete more effectively.
- These variants will live longer and leave more offspring.
- If the beneficial variations are inherited, the offspring will also survive longer.
- The new varieties may gradually replace the older varieties.
- Natural selection involves the elimination of less well-adapted varieties by environmental pressures.
- Selective breeding is used to improve commercially useful plants and animals.

- Adaptation is the process, resulting from natural selection, by which populations become more suited to their environment over many generations.
- The development of strains of antibiotic-resistant bacteria is an example of natural selection.
- Selective breeding by artificial selection is carried out over many generations to improve crop plants and domesticated animals.
- Evolution is the change in adaptive features of a population over time as the result of natural selection.

# 19 Organisms and their environment

**Energy flow**
Sun as source of energy

Flow of energy through organisms

**Food chains and food webs**
Define food chain, food web, producer, consumer, herbivore, carnivore, decomposer
Interpret food chains, food webs and pyramids of number
Impact of over-harvesting and introduction of foreign species on food chains and webs

Transfer of energy between trophic levels
Define trophic level
Loss of energy between levels
Efficiency of supplying green plants as human food
Identify levels in food chains, webs, pyramids of number and biomass
Describe and interpret pyramids of biomass
Advantages of using pyramids of biomass
Recycling

**Nutrient cycles**
Carbon cycle
Water cycle

Nitrogen cycle
Roles of micro-organisms in nitrogen cycle

**Population size**
Define population
Factors affecting rate of population growth
Human population growth

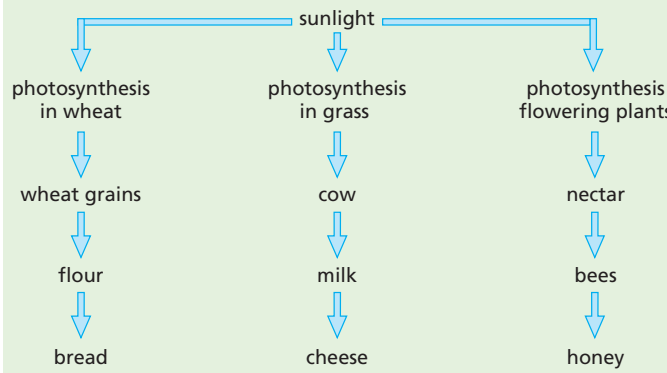
Define community, ecosystem
Factors affecting the increase in size of the human population
Identify and explain phases on a sigmoid population growth curve

## Energy flow

Nearly all living things depend on the Sun to provide energy. This is harnessed by photosynthesising plants and the energy is then passed through food chains.

### Dependence on sunlight

With the exception of atomic energy and tidal power, all the energy released on Earth is derived from sunlight. The energy released by animals comes, ultimately, from plants that they or their prey eat and the plants depend on sunlight for making their food. Photosynthesis is a process in which light energy is trapped by plants and converted into chemical energy (stored in molecules such as carbohydrates, fats and proteins). Since all animals depend, in the end, on plants for their food, they therefore depend indirectly on sunlight. A few examples of our own dependence on photosynthesis are given below.




Nearly all the energy released on the Earth can be traced back to sunlight. Coal comes from tree-like plants, buried millions of years ago. These plants absorbed sunlight for their photosynthesis when they were alive. Petroleum was formed, also millions of years ago, probably from the partly decayed bodies of microscopic algae that lived in the sea. These, too, had absorbed sunlight for photosynthesis.

Today it is possible to use mirrors and solar panels to collect energy from the Sun directly, but the best way, so far, of trapping and storing energy from sunlight is to grow plants and make use of their products, such as starch, sugar, oil, alcohol and wood, for food or as energy sources. For example, sugar from sugar-cane can be fermented to alcohol, and used as a motor fuel instead of petrol.

Eventually, through one process or another, all the chemical energy in organisms is transferred to the environment. However, it is not a cyclical process like those described later in this chapter.

# Food chains and food webs

**Key definitions**

A **food chain** shows the transfer of energy from one organism to the next, beginning with a producer.
A **food web** is a network of interconnected food chains.
A **producer** is an organism that makes its own organic nutrients, usually using energy from sunlight, through photosynthesis.
A **consumer** is an organism that gets its energy from feeding on other organisms.
A **herbivore** is an animal that gets its energy by eating plants.
A **carnivore** is an animal that gets its energy by eating other animals.
A **decomposer** is an organism that gets its energy from dead or waste organic material.

'Interdependence' means the way in which living organisms depend on each other in order to remain alive, grow and reproduce. For example, bees depend for their food on pollen and nectar from flowers. Flowers depend on bees for pollination (Chapter 16). Bees and flowers are, therefore, interdependent.

## Food chains

One important way in which organisms depend on each other is for their food. Many animals, such as rabbits, feed on plants. Such animals are called **herbivores**. Animals that eat other animals are called **carnivores**. A **predator** is a carnivore that kills and eats other animals. A fox is a predator that preys on rabbits. **Scavengers** are carnivores that eat the dead remains of animals killed by predators. These are not hard and fast definitions. Predators will sometimes scavenge for their food and scavengers may occasionally kill living animals. Animals obtain their energy by ingestion.

Basically, all animals depend on plants for their food. Foxes may eat rabbits, but rabbits feed on grass. A hawk eats a lizard, the lizard has just eaten a grasshopper but the grasshopper was feeding on a grass blade. This relationship is called a food chain (Figure 19.1).

The organisms at the beginning of a food chain are usually very numerous while the animals at the end of the chain are often large and few in number. The **food pyramids** in Figure 19.2 show this relationship. There will be millions of microscopic, single-celled algae in a pond (Figure 19.3(a)). These will be eaten by the larger but less numerous water fleas and other crustacea (Figure 19.3(b)), which in turn will become the food of small fish such as minnow and stickleback. The hundreds of small fish may be able to provide enough food for only four or five large carnivores, like pike or perch.

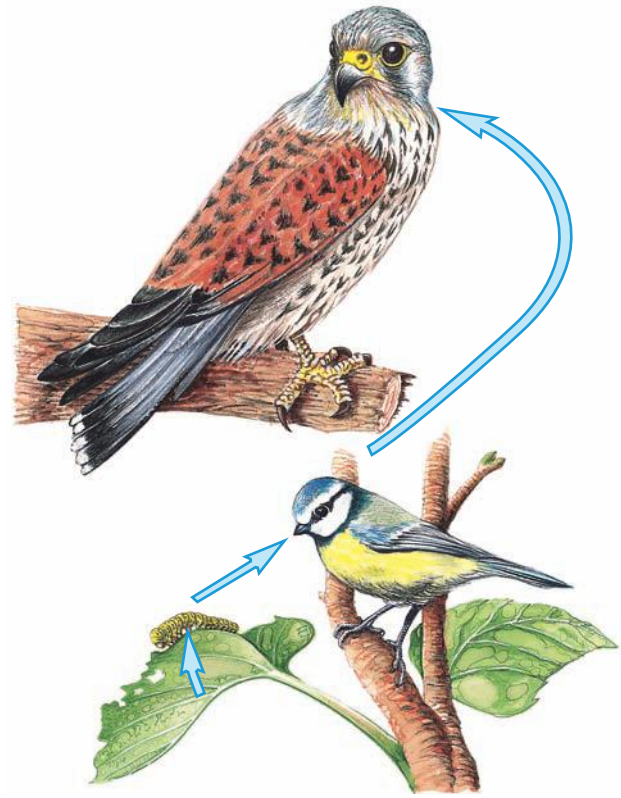


**Figure 19.1** A food chain. The caterpillar eats the leaf; the blue tit eats the caterpillar but may fall prey to the kestrel.

The organisms at the base of the food pyramids in Figure 19.2 are plants. Plants produce food from carbon dioxide, water and salts (see 'Photosynthesis', Chapter 6), and are, therefore, called **producers**. The animals that eat the plants are called **primary consumers**, e.g. grasshoppers. Animals that prey on the plant-eaters are called **secondary consumers**, e.g. shrews, and these may be eaten by **tertiary consumers**, e.g. weasels or kestrels (Figure 19.4).

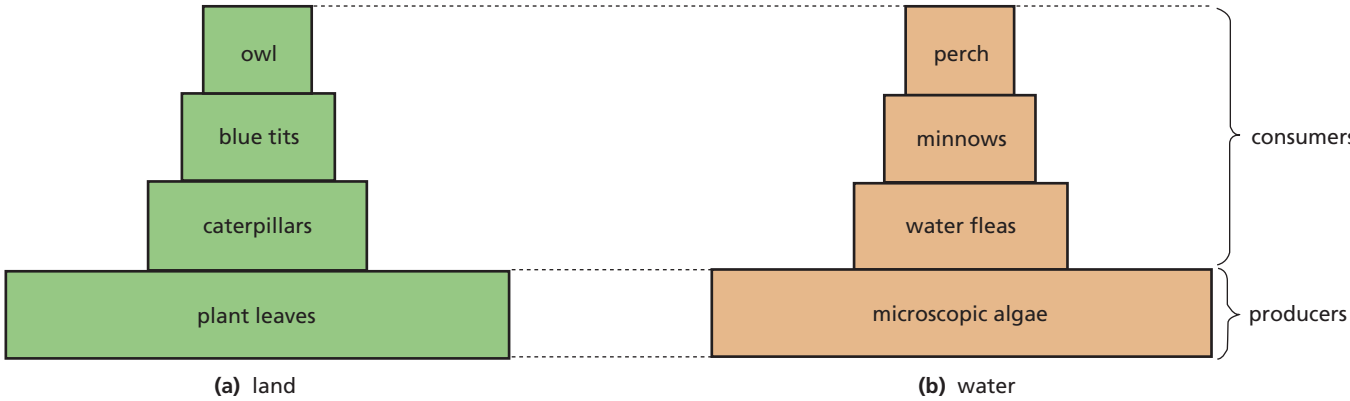
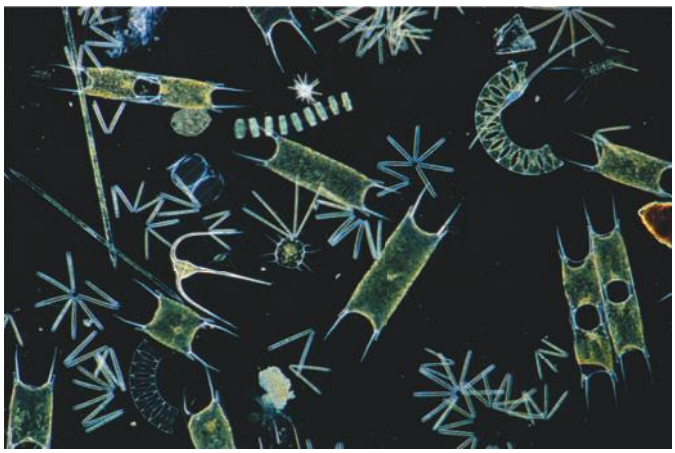



**Figure 19.2** Examples of food pyramids (pyramids of numbers)



**(a)** phytoplankton (×100) These microscopic algae form the basis of a food pyramid in the water.

**(b)** zooplankton (×20) These crustacea will eat microscopic algae.

**Figure 19.3** Plankton. The microscopic organisms that live in the surface waters of the sea or fresh water are called, collectively, plankton. The single-celled algae (see Chapter 1) are the phytoplankton. They are surrounded by water, salts and dissolved carbon dioxide. Their chloroplasts absorb sunlight and use its energy for making food by photosynthesis. Phytoplankton is eaten by small animals in the zooplankton, mainly crustacea (see Chapter 1). Small fish will eat the crustacea.

**Figure 19.4** The kestrel, a secondary or tertiary consumer

## Pyramids of numbers

The width of the bands in Figure 19.2 is meant to represent the relative number of organisms at each trophic level. So the diagrams are sometimes called **pyramids of numbers**.

However, you can probably think of situations where a pyramid of numbers would not show the same effect. For example, a single sycamore tree may provide food for thousands of greenfly. One oak tree may feed hundreds of caterpillars. In these cases the pyramid of numbers is upside-down, as shown in Figure 19.5.

## Food webs

Food chains are not really as straightforward as described above, because most animals eat more than one type of food. A fox, for example, does not feed entirely on rabbits but takes beetles, rats and voles in

its diet. To show these relationships more accurately, a **food web** can be drawn up (Figure 19.6).

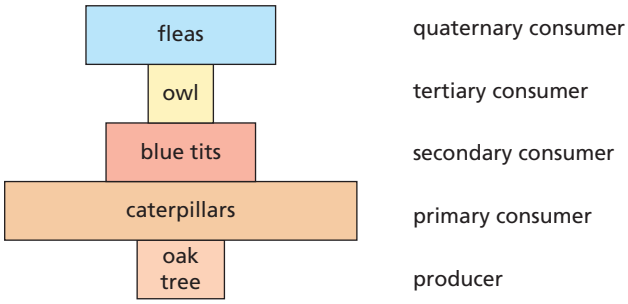



**Figure 19.5** An inverted pyramid of numbers

The food webs for land, sea and fresh water, or for ponds, rivers and streams, will all be different. Food webs will also change with the seasons when the food supply changes.

If some event interferes with a food web, all the organisms in it are affected in some way. For example, if the rabbits in Figure 19.6 were to die out, the foxes, owls and stoats would eat more beetles and rats. Something like this happened in 1954 when the disease myxomatosis wiped out nearly all the rabbits in England. Foxes ate more voles, beetles and blackberries, and attacks on lambs and chickens increased. Even the vegetation was affected because the tree seedlings that the rabbits used to nibble on were able to grow. As a result, woody scrubland started to develop on what had been grassy downs. A similar effect is shown in Figure 19.7.

## The effects of over-harvesting

Over-harvesting causes the reduction in numbers of a species to the point where it is endangered or made extinct. As a result biodiversity is affected. The species may be harvested for food, or for body parts such as tusks (elephants), horns (rhinos – Figure 19.8), bones and fur (tigers) or for selling as pets (reptiles, birds and fish, etc.). In parts of Africa, bush meat is used widely as a source of food. Bush meat is the flesh of primates, such as monkeys. However, hunting these animals is not always regulated or controlled and rare species can be threatened as a result of indiscriminate killing. (See also 'Habitat destruction' in Chapter 21.)

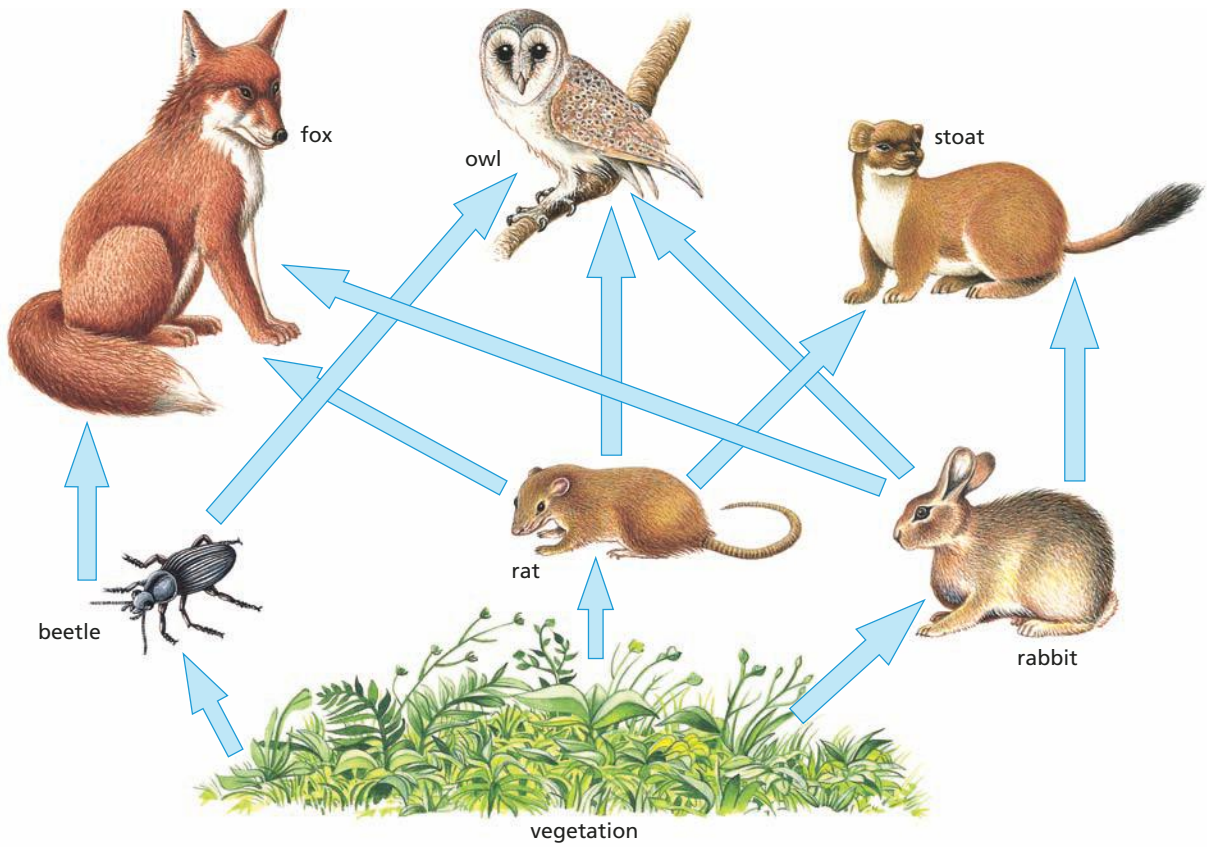



**Figure 19.6** A food web

**(a)** Sheep have eaten any seedlings that grew under the trees

**(b)** Ten years later, the fence has kept the sheep off and the tree seedlings have grown

**Figure 19.7** Effect of grazing

**Figure 19.8** The rhinoceros is endangered because some people believe, mistakenly, that powdered rhino horn (Cornu Rhinoceri Asiatici) has medicinal properties, and others greatly prize rhino horn handles for their daggers.

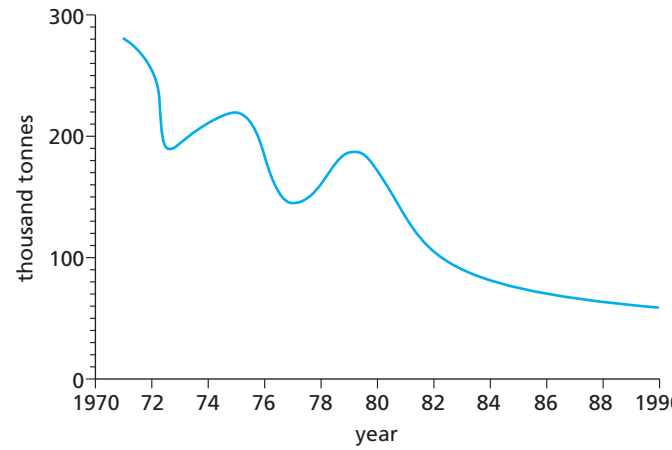



**Figure 19.9** Landings of North Sea cod from 1970 to 1990

## Overfishing

Small populations of humans, taking fish from lakes or oceans and using fairly basic methods of capture, had little effect on fish numbers. At present, however, commercial fishing has intensified to the point where some fish stocks are threatened or can no longer sustain fishing. In the past 100 years, fishing fleets have increased and the catching methods have become more sophisticated.

If the number of fish removed from a population exceeds the number of young fish reaching maturity, then the population will decline (Figure 19.9).

At first, the catch size remains the same but it takes longer to catch it. Then the catch starts to contain a greater number of small fish so that the return per day at sea goes down even more. Eventually the stocks are so depleted that it is no longer economical to exploit them. The costs of the boats, the fuel and the wages of the crew exceed the value of the catch. Men are laid off, boats lie rusting in the harbour and the economy of the fishing community and those who depend on it is destroyed. Overfishing has severely reduced stocks of many fish species: herring in the North Sea, halibut in the Pacific and anchovies off the Peruvian coast, for example. In 1965, 1.3 million tonnes of herring were caught in the North Sea. By 1977 the catch had diminished to 44 000 tonnes, i.e. about 3% of the 1965 catch.

Similarly, whaling has reduced the population of many whale species to levels that give cause for concern. Whales were the first marine organisms to face extinction through overfishing. This happened

in the early 1800s when they were killed for their **blubber** (a thick fat layer around the body of the mammal) for use as lamp oil. The blue whale's numbers have been reduced from about 2 000 000 to 6000 as a result of intensive hunting.

Overfishing can reduce the populations of fish species and can also do great damage to the environment where they live. For example, the use of heavy nets dragged along the sea floor to catch the fish can wreck coral reefs, destroying the habitats of many other animal species. Even if the reef is not damaged, fishing for the top predators such as grouper fish has a direct effect on the food chain: fish lower down the chain increase in numbers, and overgraze on the reef. This process is happening on the Great Barrier Reef in Australia. Grouper fish are very slow growing and take a long time to become sexually mature, so the chances of them recovering from overfishing are low and they are becoming endangered.

## Introducing foreign species to a habitat

One of the earliest examples of this process was the accidental introduction of rats to the Galapagos Islands by pirates or whalers in the 17th or 18th centuries. The rats had no natural predators and food was plentiful: they fed on the eggs of birds, reptiles and tortoises, along with young animals. The Galapagos Islands provide a habitat for many rare species, which became endangered as a result of the presence of the rats. A programme of rat extermination is now being carried out on the islands to protect their unique biodiversity.

The prickly pear cactus, *Opuntia*, was introduced to Australia in 1839 for use as a living fence to control the movement of cattle, but its growth got out of control because of the lack of herbivores that eat it. Millions of acres of land became unusable. A moth, *Cactoblastis cactorum*, whose young feed on the cactus, was successfully introduced from Argentina and helped to control the spread of the cactus. Other places with similar problems, for example the island of Nevis in the West Indies, followed Australia's example, but with less successful results. The moth had no natural predators and ate other native cactus species as well as the prickly pear, bringing them to the brink of extinction. The moth is now spreading to parts of the United States of America and poses a threat to other cactus species.

Food chains and webs can also be disrupted by the use of pesticides and other poisons, sometimes released accidentally during human activities. More details can be found in Chapter 21.

## Energy transfer

Study Figure 19.1. When an herbivorous animal eats a plant (the caterpillar feeding on a leaf), the chemical energy stored in that plant leaf is transferred to the herbivore. Similarly, when a carnivore (the blue tit) eats the herbivore, the carnivore gains the energy stored in the herbivore. If the carnivore is eaten by another carnivore (the kestrel), the energy is transferred again.

### Use of sunlight

To try and estimate just how much life the Earth can support it is necessary to examine how efficiently the Sun's energy is used. The amount of energy from the Sun reaching the Earth's surface in 1 year ranges from 2 million to 8 million kilojoules per $m^2$ ($2–8 \times 10^9 J\,m^{-2}\,yr^{-1}$) depending on the latitude. When this energy falls onto grassland, about 20% is reflected by the vegetation, 39% is used in evaporating water from the leaves (transpiration), 40% warms up the plants, the soil and the air, leaving only about 1% to be used in photosynthesis for making new organic matter in the leaves of the plants (Figure 19.10).

This figure of 1% will vary with the type of vegetation being considered and with climatic factors, such as availability of water and the soil temperature. Sugar-cane grown in ideal conditions can convert 3% of the Sun's energy into photosynthetic products; sugar-beet at the height of its growth has nearly a 9% efficiency. Tropical forests and swamps are far more productive than grassland but it is difficult, and, in some cases undesirable, to harvest and utilise their products.

In order to allow crop plants to approach their maximum efficiency they must be provided with sufficient water and mineral salts. This can be achieved by irrigation and the application of fertiliser.

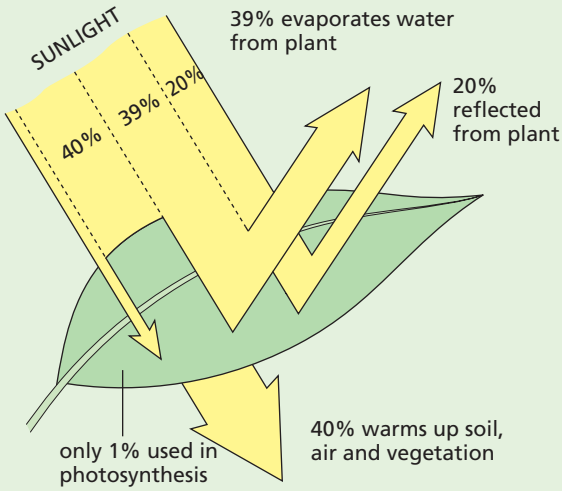



**Figure 19.10** Absorption of Sun's energy by plants

## Energy transfer between organisms

Having considered the energy conversion from sunlight to plant products, the next step is to study the efficiency of transmission of energy from plant products to primary consumers. On land, primary consumers eat only a small proportion of the available vegetation. In a deciduous forest only about 2% is eaten; in grazing land, 40% of the grass may be eaten by cows. In open water, however, where the producers are microscopic plants (phytoplankton, see Figure 19.3(a)) and are swallowed whole by the primary consumers in the zooplankton (see Figure 19.3(b)), 90% or more may be eaten. In the land communities, the parts of the vegetation not eaten by the primary consumers will eventually die and be used as a source of energy by the decomposers.

A cow is a primary consumer; over 60% of the grass it eats passes through its alimentary canal (Chapter 7) without being digested. Another 30% is used in the cow's respiration to provide energy for its movement and other life processes. Less than 10% of the plant material is converted into new animal tissue to contribute to growth (Figure 19.11). This figure will vary with the diet and the age of the animal. In a fully grown animal all the digested food will be used for energy and replacement and none will contribute to growth. Economically it is desirable to harvest the primary consumers before their rate of growth starts to fall off.

The transfer of energy from primary to secondary consumers is probably more efficient, since a greater proportion of the animal food is digested and absorbed than is the case with plant material. The transfer of energy at each stage in a food chain may

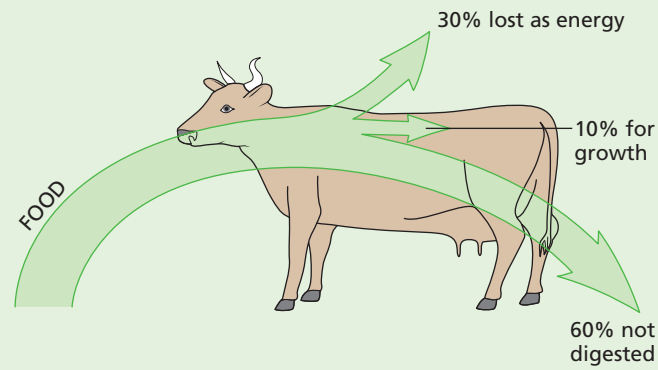



**Figure 19.11** Energy transfer from plants to animals

be represented by classifying the organisms in a community as producers, or primary, secondary or tertiary consumers, and showing their relative masses in a pyramid such as the one shown in Figure 19.2 but on a more accurate scale. In Figure 19.12 the width of the horizontal bands is proportional to the masses (dry weight) of the organisms in a shallow pond.

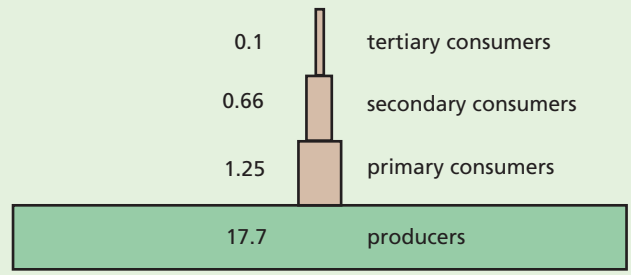



**Figure 19.12** Biomass (dry weight) of living organisms in a shallow pond (grams per square metre)

**Key definitions**

The **trophic level** of an organism is its position in a food chain, food web or pyramid of numbers or biomass.

It is very unusual for food chains to have more than five trophic levels because, on average, about 90% of the energy is lost at each level. Consequently, very little of the energy entering the chain through the producer is available to the top consumer. The food chain below shows how the energy reduces through the chain. It is based on grass obtaining 100 units of energy.

| grass | → | locust | → | lizard | → | snake | → | mongoose |
|---|---|---|---|---|---|---|---|---|
| 100 units | | 10 units | | 1 unit | | 0.1 unit | | 0.01 unit |

## Energy transfer in agriculture

In human communities, the use of plant products to feed animals that provide meat, eggs and dairy products is wasteful, because only 10% of the plant

material is converted to animal products. It is more economical to eat bread made from the wheat than to feed the wheat to hens and then eat the eggs and chicken meat. This is because eating the wheat as bread avoids using any part of its energy to keep the chickens alive and active. Energy losses can be reduced by keeping hens indoors in small cages, where they lose little heat to the atmosphere and cannot use much energy in movement (Figure 19.13). The same principles can be applied in 'intensive' methods of rearing calves. However, many people feel that these methods are less than humane, and the saving of energy is far less than if the plant products were eaten directly by humans, as is the case in vegetarians.

**Figure 19.13** Battery chickens. The hens are well fed but kept in crowded and cramped conditions with no opportunity to move about or scratch in the soil as they would normally do.

Consideration of the energy flow of a modern agricultural system reveals other sources of inefficiency. To produce 1 tonne of nitrogenous fertiliser takes energy equivalent to burning 5 tonnes of coal. Calculations show that if the energy needed to produce the fertiliser is added to the energy used to produce a tractor and to power it, the energy derived from the food so produced is less than that expended in producing it.

### Pyramids of biomass

As stated earlier, displaying food chains using pyramids of number, such as those shown in Figure 19.5, can produce inverted pyramids. This is because the top consumers may be represented by large numbers of very small organisms, for example, fleas feeding on an owl. The way around this problem is to consider not the single tree, but the mass of the leaves that it produces in the growing season, and the mass of the insects that can live on them. **Biomass** is the term used when the mass of living organisms is being considered, and pyramids of biomass can be constructed as in Figure 19.12. A pyramid of biomass is nearly always the correct pyramid shape.

An alternative is to calculate the energy available in a year's supply of leaves and compare this with the energy needed to maintain the population of insects that feed on the leaves. This would produce a **pyramid of energy**, with the producers at the bottom having the greatest amount of energy. Each successive trophic level would show a reduced amount of energy.

The elements that make up living organisms are recycled, i.e. they are used over and over again (see next section). This is not the case with energy, which flows from producers to consumers and is eventually lost to the atmosphere as heat.

## Recycling

There are a number of organisms that have not been fitted into the food webs or food chains described so far. Among these are the **decomposers**. Decomposers do not obtain their food by photosynthesis, nor do they kill and eat living animals or plants. Instead they feed on dead and decaying matter such as dead leaves in the soil or rotting tree-trunks (Figure 19.14). The most numerous examples are the fungi, such as mushrooms, toadstools or moulds, and the bacteria, particularly those that live in the soil. They produce extracellular enzymes that digest the decaying matter and then they absorb the soluble products back into their cells. In so doing, they remove the dead remains of plants and animals, which would otherwise collect on the Earth's surface. They also break these remains down into substances that can be used by other organisms. Some bacteria, for example, break down the protein of dead plants and animals and release nitrates, which are taken up by

**Figure 19.14** Decomposers. These toadstools are getting their food from the rotting log.

plant roots and are built into new amino acids and proteins. This use and reuse of materials in the living world is called **recycling**.

The general idea of recycling is illustrated in Figure 19.15. The green plants are the producers, and the animals that eat the plants and each other are the consumers. The bacteria and fungi, especially those in the soil, are called the decomposers because they break down the dead remains and release the chemicals for the plants to use again. Three examples of recycling, for water, carbon and nitrogen, are described in the next section.

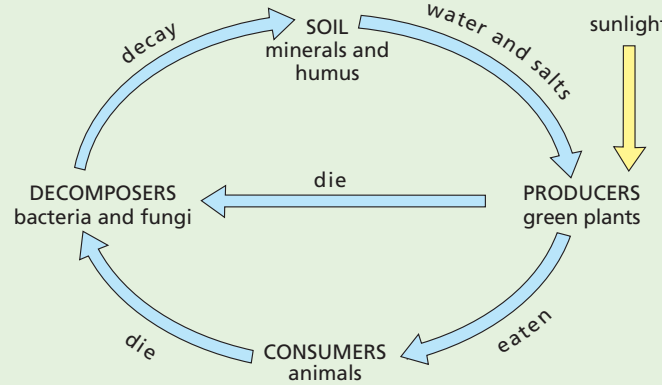



**Figure 19.15** Recycling in an ecosystem

# Nutrient cycles

## The carbon cycle

Carbon is an element that occurs in all the compounds which make up living organisms. Plants get their carbon from carbon dioxide in the atmosphere and animals get their carbon from plants. The carbon cycle, therefore, is mainly concerned with what happens to carbon dioxide (Figure 19.16).

### Removal of carbon dioxide from the atmosphere

#### Photosynthesis

Green plants remove carbon dioxide from the atmosphere as a result of their photosynthesis. The carbon from the carbon dioxide is built first into a carbohydrate such as sugar. Some of this is changed into starch or the cellulose of cell walls, and the proteins, pigments and other compounds of a plant. When the plants are eaten by animals, the organic plant material is digested, absorbed and built into the compounds making up the animals' tissues. Thus the carbon atoms from the plant become part of the animal.

#### Fossilisation

Any environment that prevents rapid decay may produce **fossils**. The carbon in the dead organisms becomes trapped and compressed and can remain there for millions of years. The carbon may form **fossil fuels** such as coal, oil and natural gas. Some animals make shells or exoskeletons containing carbon and these can become fossils.

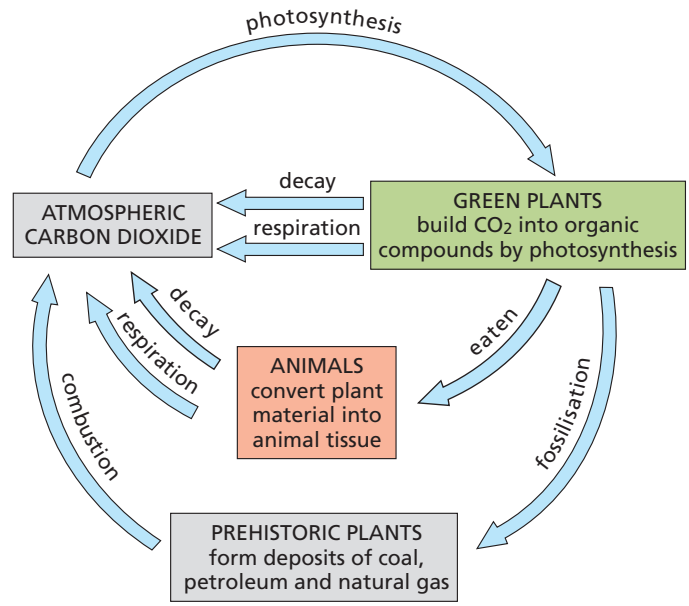



**Figure 19.16** The carbon cycle

## Addition of carbon dioxide to the atmosphere

### Respiration

Plants and animals obtain energy by oxidising carbohydrates in their cells to carbon dioxide and water (Chapter 12). The carbon dioxide and water are excreted so the carbon dioxide returns once again to the atmosphere.

### Decomposition

A crucial factor in carbon recycling is the process of decomposition, or decay. If it were not for decay, essential materials would not be released from dead organisms. When an organism dies, the enzymes in its cells, freed from normal controls, start to digest its own tissues (auto-digestion). Soon, scavengers appear on the scene and eat much of the remains; blowfly larvae devour carcases, earthworms consume dead leaves.

Finally the decomposers, fungi and bacteria (collectively called **micro-organisms**), arrive and invade the remaining tissues (Figure 19.17). These saprophytes secrete extracellular enzymes (Chapter 5) into the tissues and reabsorb the liquid products of digestion. When the micro-organisms themselves die, auto-digestion takes place, releasing the products such as nitrates, sulfates, phosphates, etc. into the soil or the surrounding water to be taken up again by the producers in the ecosystem.

**Figure 19.17** Mould fungus growing on over-ripe oranges

The speed of decay depends on the abundance of micro-organisms, temperature, the presence of water and, in many cases, oxygen. High temperatures speed up decay because they speed up respiration of the micro-organisms. Water is necessary for all living processes and oxygen is needed for aerobic respiration of the bacteria and fungi. Decay can take place in anaerobic conditions but it is slow and incomplete, as in the waterlogged conditions of peat bogs.

### Combustion (burning)

When carbon-containing fuels such as wood, coal, petroleum and natural gas are burned, the carbon is oxidised to carbon dioxide ($C + O_2 \rightarrow CO_2$). The hydrocarbon fuels, such as coal and petroleum, come from ancient plants, which have only partly decomposed over the millions of years since they were buried.

So, an atom of carbon which today is in a molecule of carbon dioxide in the air may tomorrow be in a molecule of cellulose in the cell wall of a blade of grass. When the grass is eaten by a cow, the carbon atom may become part of a glucose molecule in the cow's bloodstream. When the glucose molecule is used for respiration, the carbon atom will be breathed out into the air once again as carbon dioxide.

The same kind of cycling applies to nearly all the elements of the Earth. No new matter is created, but it is repeatedly rearranged. A great proportion of the atoms of which you are composed will, at one time, have been part of other organisms.

### The effects of the combustion of fossil fuels

If you look back at the carbon cycle, you will see that the natural processes of photosynthesis, respiration and decomposition would be expected to keep the $CO_2$ concentration at a steady level. However, since the Industrial Revolution, we have been burning the fossil fuels such as coal and petroleum and releasing extra $CO_2$ into the atmosphere. As a result, the concentration of $CO_2$ has increased from 0.029% to 0.035% since 1860. It is likely to go on increasing as we burn more and more fossil fuel.

Although it is not possible to prove beyond all reasonable doubt that production of $CO_2$ and other 'greenhouse gases' is causing a rise in the Earth's temperature, i.e. global warming, the majority of scientists and climatologists agree that it is happening now and will get worse unless we take drastic action to reduce the output of these gases (see 'Pollution' in Chapter 21 for further details of the greenhouse effect and global warming).

Another factor contributing to the increase in atmospheric $CO_2$ is **deforestation**. Trees are responsible for removing gaseous $CO_2$ and trapping the carbon in organic molecules (carbohydrates, proteins and fats – see Chapter 4). When they are cut down the amount of photosynthesis globally is reduced. Often deforestation is achieved by a process called 'slash and burn', where the felled trees are burned to provide land for agriculture (see 'Habitat destruction' in Chapter 21) and this releases even more atmospheric $CO_2$.

## The water cycle

The **water cycle** (Figure 19.18) is somewhat different from other cycles because only a tiny proportion of the water that is recycled passes through living organisms.

Animals lose water by **evaporation** (Chapter 14), defecation (Chapter 7), urination (Chapter 13) and exhalation (Chapter 11). They gain water from their food and drink. Plants take up water from the soil and lose it by **transpiration** (Chapter 8). Millions of tonnes of water are transpired, but only a tiny fraction of this has taken part in the reactions of respiration (Chapter 12) or photosynthesis (Chapter 6).

The great proportion of water is recycled without the intervention of animals or plants. The Sun shining and the wind blowing over the oceans **evaporate** water from their vast, exposed surfaces. The water vapour produced in this way enters the atmosphere and eventually **condenses** to form clouds. The clouds release their water in the form of rain or snow (**precipitation**). The rain collects in streams, rivers and lakes and ultimately finds its way back to the oceans. The human population diverts some of this water for drinking, washing, cooking, irrigation, hydroelectric schemes and other industrial purposes, before allowing it to return to the sea.

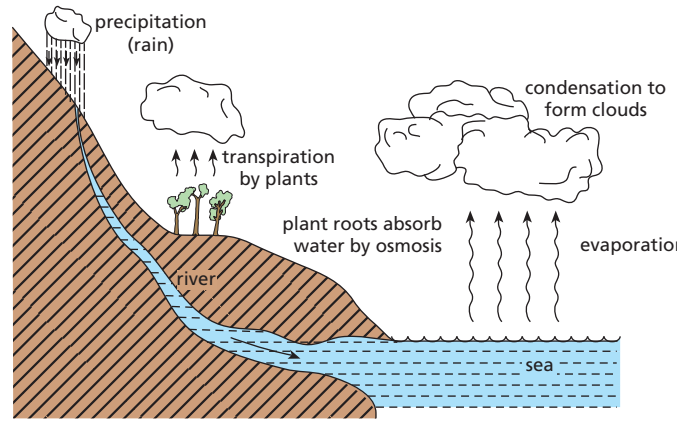



**Figure 19.18** The water cycle

## The nitrogen cycle

When a plant or animal dies, its tissues **decompose**, partly as a result of the action of saprotrophic bacteria. One of the important products of the decay of animal and plant protein is ammonia ($NH_3$, a compound of nitrogen), which is washed into the soil (Figure 19.20). It dissolves readily in water to form ammonium ions ($NH_4^+$).

The excretory products of animals contain nitrogenous waste products such as ammonia, urea and uric acid (Chapter 13). Urea is formed in the liver of humans as a result of **deamination**. The organic matter in animal droppings is also decomposed by soil bacteria.

### Processes that add nitrates to soil

#### Nitrifying bacteria

These are bacteria living in the soil, which use the ammonia from excretory products and decaying organisms as a source of energy (as we use glucose in respiration). In the process of getting energy from ammonia, called **nitrification**, the bacteria produce **nitrates**.

- The 'nitrite' bacteria oxidise ammonium compounds to nitrites ($NH_4^+ \rightarrow NO_2^-$).
- 'Nitrate' bacteria oxidise nitrites to nitrates ($NO_2^- \rightarrow NO_3^-$).

Although plant roots can take up ammonia in the form of its compounds, they take up nitrates more readily, so the nitrifying bacteria increase the fertility of the soil by making nitrates available to the plants.

#### Nitrogen-fixing bacteria

This is a special group of nitrifying bacteria that can absorb nitrogen as a gas from the air spaces in the soil, and build it into compounds of ammonia. Nitrogen gas cannot itself be used by plants. When it has been made into a compound of ammonia, however, it can easily be changed to nitrates by other nitrifying bacteria. The process of building the gas, nitrogen, into compounds of ammonia is called **nitrogen fixation**. Some of the nitrogen-fixing bacteria live freely in the soil. Others live in the roots of **leguminous plants** (peas, beans, clover), where they cause swellings called **root nodules** (Figure 19.19). These leguminous plants are able to thrive in soils where nitrates are scarce, because the nitrogen-fixing bacteria in their nodules make compounds of nitrogen available for them. Leguminous plants are also included in crop rotations to increase the nitrate content of the soil.

### Lightning

The high temperature of lightning discharge causes some of the nitrogen and oxygen in the air to combine and form oxides of nitrogen. These dissolve in the rain and are washed into the soil as weak acids, where they form nitrates. Although several million tonnes of nitrate may reach the Earth's surface in this way each year, this forms only a small fraction of the total nitrogen being recycled.

## Processes that remove nitrates from the soil

### Uptake by plants

Plant roots absorb nitrates from the soil and combine them with carbohydrates to make amino acids, which are built up into proteins (Chapter 6). These proteins are then available to animals, which feed on the plants and digest the proteins in them.

### Leaching

Nitrates are very soluble (i.e. dissolve easily in water), and as rainwater passes through the soil it dissolves the nitrates and carries them away in the run-off or to deeper layers of the soil. This is called **leaching**. (See Chapter 21 for some of the implications of leaching.)

### Denitrifying bacteria

These are bacteria that obtain their energy by breaking down nitrates to nitrogen gas, which then escapes from the soil into the atmosphere.

All of these processes are summed up in Figure 19.20.

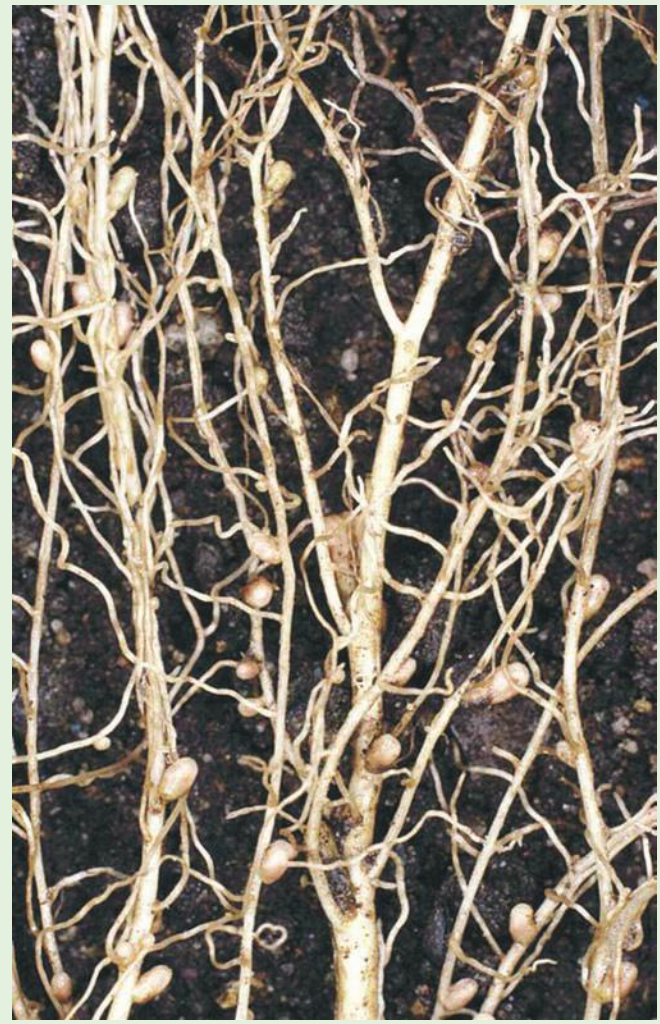


**Figure 19.19** Root nodules of white clover – a leguminous plant

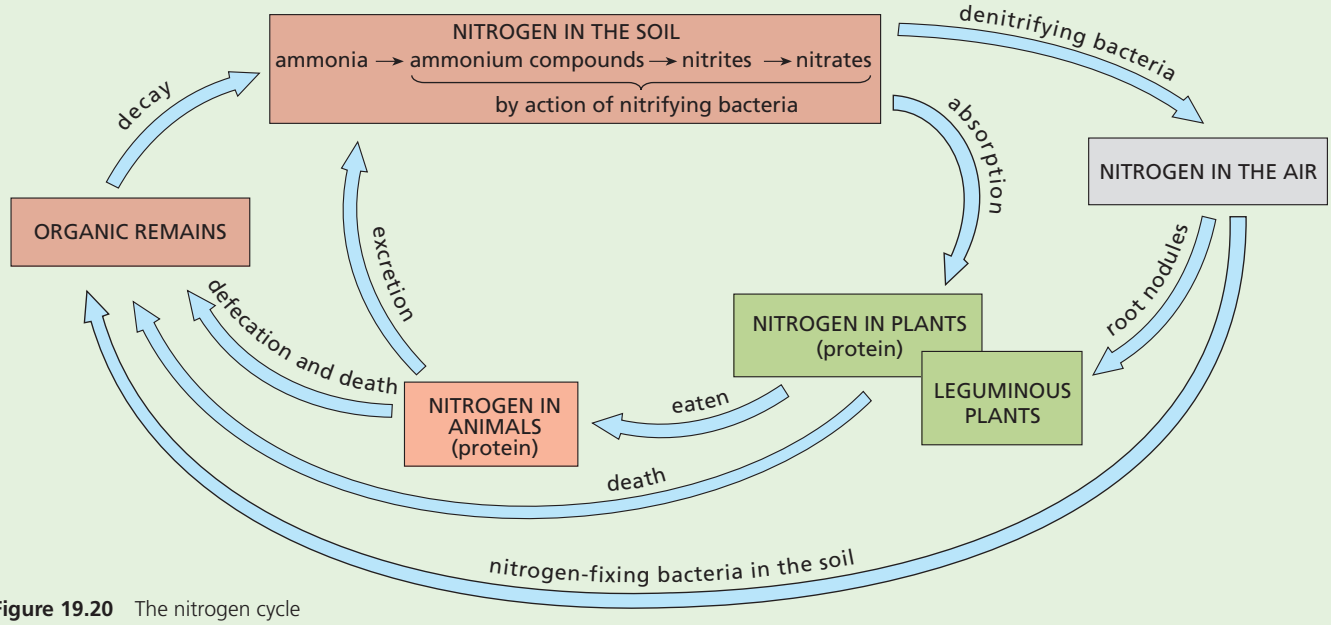



**Figure 19.20** The nitrogen cycle

# Population size

**Key definition**
A **population** is a group of organisms of one species, living and interacting in the same area at the same time.

In biology, the term population always refers to a single species. A biologist might refer to the population of sparrows in a farmyard or the population of carp in a lake. In each case this would mean the total numbers of sparrows or the total numbers of carp in the stated area.

## Population changes

If conditions are ideal, a population can increase in size. For this to happen there needs to be a good **food supply**. This will enable organisms to breed more successfully to produce more offspring; shortage of food can result in starvation, leading to death, or force emigration, reducing the population. The food shortage may be because the food source has all been eaten, or died out, or completed its growing season, or there is competition for it with other species in the same habitat.

In a habitat there are likely to be predators. If heavy **predation** of a population happens, the rate of breeding may be unable to produce enough organisms to replace those eaten, so the population will drop in numbers. There tends to be a time lag in population size change for predators and their prey: as predator numbers increase, prey numbers drop and as predator numbers drop, prey numbers rise again (unless there are other factors that prevent this happening) (see 'Predator–prey relationships' later in this chapter).

**Disease** can be a particular problem in large populations because it can spread easily from one individual to another. Epidemics can reduce population sizes very rapidly. An example was given in the section on food webs: the disease myxomatosis is caused by a virus. It wiped out nearly all the rabbits in England in 1954 and then spread to other parts of Europe, carried by fleas. It was first discovered in 1896 in Uruguay and was deliberately introduced to Australia in 1951 in an attempt to control its large rabbit populations.

When a disease spreads globally it is called a **pandemic**. One of the worst cases experienced by humans was known as Spanish flu. This virus killed between 40 and 50 million people in 1918.

The World Health Organization (WHO) estimates that there were 660 000 malaria deaths in 2010 and there were about 219 million cases of the disease. Malaria (Chapter 10) is caused by a single-celled parasite, spread by mosquitos. It is a treatable disease and drugs are gradually becoming more widely available to prevent it being fatal.

## Human population

In AD 1000, the world population was probably about 300 million. In the early 19th century it rose to 1000 million (1 billion), and by 1984 it had reached 4.7 billion. In 2000 it reached about 6 billion and rose to 7.2 billion in 2014. The United Nations predicts that the global population will decline steadily by 2050, quoting predictions of between 8.3 and 10.9 billion people by that date. The graph in Figure 19.21 shows that the greatest population surge has taken place in the last 300 years.

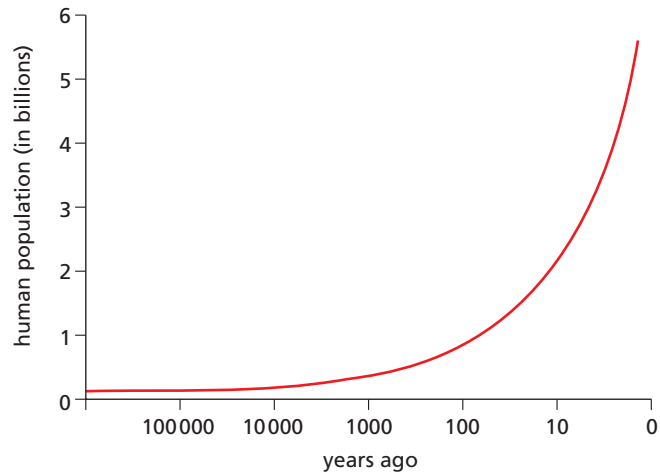



**Figure 19.21** World population growth. The time scale (horizontal axis) is logarithmic. The right-hand space (0–10) represents only 10 years, but the left-hand space (100 000–1 million) represents 900 000 years. The greatest population growth has taken place in the last 300 years.

### Population growth

About 20 years ago, the human population was increasing at the rate of 2% a year. This may not sound very much, but it means that the world population was doubling every 35 years. This doubles the demand for food, water, space and other resources. Recently, the growth rate has slowed to 1%. However, it is not the same everywhere. Nigeria's population is growing by 2.9% each year, but Western Europe's grows at only 0.1%.

Traditionally, it is assumed that population growth is limited by famine, disease or war. These factors are

affecting local populations in some parts of the world today but they are unlikely to have a limiting effect on the rate of overall population growth.

Diseases such as malaria (see Chapter 10) and sleeping sickness (spread by tsetse flies) have for many years limited the spread of people into areas where these insects carry the infections.

Diseases such as bubonic plague and influenza have checked population growth from time to time, and the current AIDS epidemic in sub-Saharan Africa is having significant effects on population growth and life expectancy.

### Factors affecting population growth

If a population is to grow, the birth rate must be higher than the death rate. Suppose a population of 1000 people produces 100 babies each year but only 50 people die each year. This means that 50 new individuals are added to the population each year and the population will double in 20 years (or less if the new individuals start reproducing at 16) (Figure 19.22).

One of the factors affecting population growth is **infant mortality**, i.e. the death rate for children less than 1 year old. Populations in the developing world are growing, not because of an increase in the number of babies born per family, but because more babies are surviving to reach reproductive age. Infant mortality is falling and more people are living longer. That is, **life expectancy** is increasing.

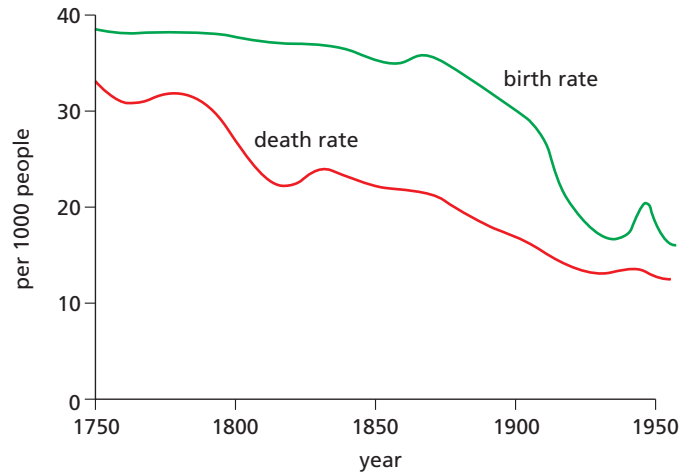



**Figure 19.22** Birth and death rates in England and Wales from 1750 to 1950. Although the birth rate fell during this period, so did the death rate. As a result, the population continued to grow. Note the 'baby boom' after the Second World War. (Used by permission of Carolina Biological Supply Company.)

**Key definition**

A **community** is all of the populations of different species in an ecosystem.

An **ecosystem** is a unit containing the community of organisms and their environment, interacting together. Examples include a decomposing log or a lake.

## Communities

A **community** is made up of all the plants and animals living in an ecosystem. In the soil there is a community of organisms, which includes earthworms, springtails and other insects, mites, fungi and bacteria. In a lake, the animal community will include fish, insects, crustacea, molluscs and protoctista.

The plant community will consist of rooted plants with submerged leaves, rooted plants with floating leaves, reed-like plants growing at the lake margin, plants floating freely on the surface, filamentous algae and single-celled algae in the surface waters.

## Ecosystems

The community of organisms in a habitat, plus the non-living part of the environment (air, water, soil, light, etc.) make up an **ecosystem**. A lake is an ecosystem, which consists of the plant and animal communities mentioned above, and the water, minerals, dissolved oxygen, soil and sunlight on which they depend. An ecosystem is self-supporting (Figure 19.23).

individuals of the same species = POPULATION

POPULATION + populations of other species = COMMUNITY

COMMUNITY + non-living part of environment = ECOSYSTEM

In a woodland ecosystem, the plants absorb light and rainwater for photosynthesis, the animals feed on the plants and on each other. The dead remains of animals and plants, acted upon by fungi and bacteria, return nutrients to the soil.

Lakes and ponds are clear examples of ecosystems. Sunlight, water and minerals allow the plants to grow and support animal life. The recycling of materials from the dead organisms maintains the supply of nutrients.

So, a *population* of carp forms part of the animal *community* living in a *habitat* called a lake. The communities in this habitat, together with their watery *environment*, make up a self-supporting *ecosystem*.

**Figure 19.23** An 'ecosphere'. The 5-inch globe contains seawater, bacteria, algae, snails and a few Pacific shrimps. Given a source of light it is a self-supporting system and survives for several years (at least). The shrimps live for up to 7 years but few reproduce.

A carp is a *secondary consumer* at the top of a *food chain*, where it is in *competition* with other species of fish for food and with other carp for food and mates.

The whole of that part of the Earth's surface which contains living organisms (called the **biosphere**) may be regarded as one vast ecosystem.

No new material (in significant amounts) enters the Earth's ecosystem from space and there is no significant loss of materials. The whole system depends on a constant input of energy from the Sun and recycling of the chemical elements.

### Distribution in an ecosystem

All ecosystems contain producers, consumers and decomposers. The organisms are not distributed uniformly throughout the ecosystem but occupy habitats that suit their way of life.

For example, fish may range freely within an aquatic ecosystem but most of them will have preferred habitats in which they feed and spend most of their time. Plaice, sole and flounders feed on molluscs and worms on the sea floor, whereas herring and mackerel feed on plankton in the surface waters. In a pond, the snails do not range much beyond the plants where they feed. On a rocky coast, limpets and barnacles can withstand exposure between the tides and colonise the rocks. Sea anemones, on the other hand, are restricted mainly to the rocky pools left at low tide.

## Factors affecting the increase in size of the human population

### Increase in life expectancy

The life expectancy is the average age to which a newborn baby can be expected to live. In Europe between 1830 and 1900 the life expectancy was 40–50 years. Between 1900 and 1950 it rose to 65 and now stands at 73–74 years. In sub-Saharan Africa, life expectancy was rising to 58 years until the AIDS epidemic reduced it to about 45 years.

These figures are averages. They do not mean, for example, that everyone in the developing world will live to the age of 58. In the developing world, 40% of the deaths are of children younger than 5 years and only 25–30% are deaths of people over 60. In Europe, only 5–20% of deaths are those of children below the age of 5, but 70–80% are of people over 60.

An increase in the number of people over the age of 60 does not change the rate of population growth much, because these people are past child-bearing age. On the other hand, if the death rate among children falls and the extra children survive to reproduce, the population will continue to grow. This is the main reason for the rapid population growth in the developing world since 1950.

### Causes of the reduction in death rate

The causes are not always easy to identify and vary from one community to the next. In 19th century Europe, agricultural development and economic expansion led to improvements in nutrition, housing and sanitation, and to clean water supplies. These improvements reduced the incidence of infectious diseases in the general population, and better-fed children could resist these infections when they did meet them. The drop in deaths from infectious diseases probably accounted for three-quarters of the total fall in deaths.

The social changes probably affected the population growth more than did the discovery of new drugs or improved medical techniques. Because of these techniques – particularly immunisation – diphtheria, tuberculosis and polio are now rare (Figure 19.24), and by 1977 smallpox had been wiped out by the World Health Organization's vaccination campaign.

In the developing world, sanitation, clean water supplies and nutrition are improving slowly. The surge in the population since 1950 is likely to be at least 50% due to modern drugs, vaccines and insecticides.

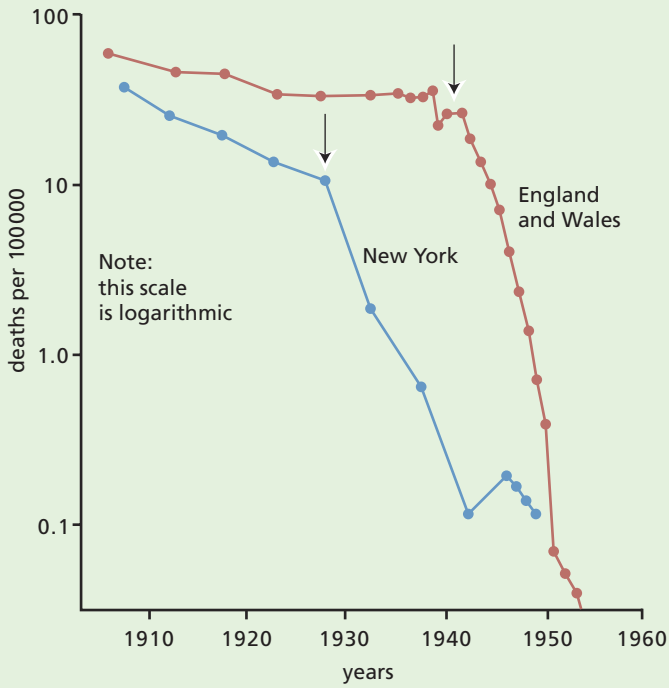



**Figure 19.24** Fall in death rate from diphtheria as a result of immunisation. The arrows show when 50% or more of children were vaccinated. Note that the rate was already falling but was greatly increased by immunisation.

## Stability and growth

Up to 300 years ago, the world population was relatively stable. Fertility (the birth rate) was high and so was the mortality rate (death rate). Probably less than half the children born lived to have children of their own. Many died in their first year (infant mortality), and many mothers died during childbirth.

No one saw any point in reducing the birth rate. If you had a lot of children, you had more help on your land and a better chance that some of them would live long enough to care for you in your old age.

In the past 300 years, the mortality rate has fallen but the birth rate has not gone down to the same extent. As a result the population has expanded rapidly.

In 18th century Europe, the **fertility rate** was about 5. This means that, on average, each woman would have five children. When the death rate fell, the fertility rate lagged behind so that the population increased. However, the fertility rate has now fallen to somewhere between 1.4 and 2.6 and the European population is more or less stable.

A fall in the fertility rate means that young people will form a smaller proportion of the population. There will also be an increasing proportion of old people for the younger generation to look after. In Britain it is estimated that, between 1981 and 1991, the number of people aged 75–84 increased by 16%. The number of those over 85 increased by about 46% (Figure 19.25).

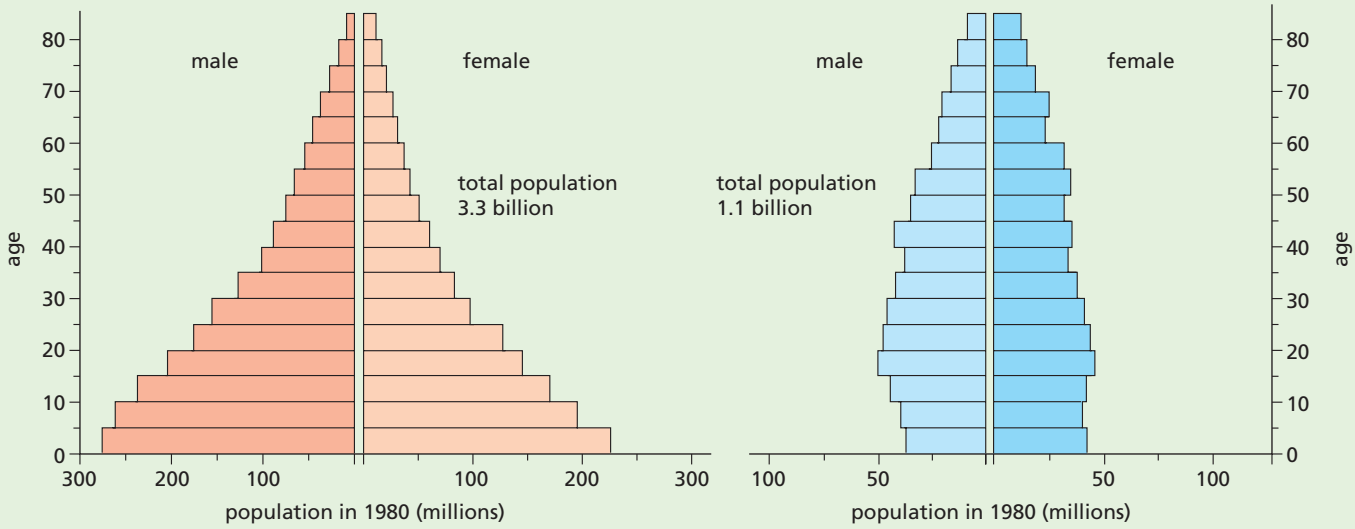
In the developing world, the fertility rate has dropped from about 6.2 to 3.0. This is still higher than the mortality rate. An average fertility rate of 2.1 is necessary to keep the population stable.

As a community grows wealthier, the birth rate goes down. There are believed to be four reasons:

- **Longer and better education:** Marriage is postponed and a better-educated couple will have learned about methods of family limitation.
- **Better living conditions:** Once people realise that half their offspring are not going to die from disease or malnutrition, family sizes fall.
- **Agriculture and cities:** Modern agriculture is no longer labour intensive. Farmers do not need large families to help out on the land. City dwellers do not depend on their offspring to help raise crops or herd animals.
- **Application of family planning methods:** Either natural methods of birth control or the use of contraceptives is much more common.

It takes many years for social improvements to produce a fall in the birth rate. Some countries are trying to speed up the process by encouraging couples to limit their family size (Figure 19.26), or by penalising families who have too many children.

Meanwhile the population goes on growing. The United Nations expect that the birth rate and death rate will not be in balance until the year 2100.




**(a)** The developing regions. The tapering pattern is characteristic of a population with a high birth rate and low average life expectancy. The bulk of the population is under 25.

**(b)** The developed regions. The almost rectangular pattern is characteristic of an industrialised society, with a steady birth rate and a life expectancy of about 70. (The horizontal scale is not the same as in **a**.)

**Figure 19.25** Age distribution of population in 1980

By that time the world population may have reached 10 billion, assuming that the world supply of food will be able to feed this population.

In the past few decades, the world has produced enough food to feed, in theory, all the extra people. But the extra food and the extra people are not always in the same place. As a result, 72% of the world's population has a diet that lacks energy, as well as other nutrients.

Every year between 1965 and 1975, food production in the developed nations rose by 2.8%, while the population rose by 0.7%. In the developing nations during the same period, food production rose by only 1.5% each year, while the annual population rise was 2.4%.

The Western world can produce more food than its people can consume. Meanwhile people in the drier regions of Africa face famine due to drought and population pressure on the environment. Even if the food could be taken to the developing world, people there are often too poor to buy it. Ideally, each region needs to grow more food or reduce its population until the community is self-supporting. Some countries grow tobacco, cotton, tea and coffee (cash crops) in order to obtain foreign currency for imports from the Western world. This is fine, so long as they can also feed their people. But when food is scarce, people cannot live on the cash crops.

**Figure 19.26** Family planning. A health worker in Bangladesh explains the use of a condom.

## Population pressures

More people, more agriculture and more industrialisation will put still more pressure on the environment unless we are very watchful. If we damage the ozone layer, increase atmospheric carbon dioxide, release radioactive products or allow farmland to erode, we may meet with additional limits to population growth.

## Sigmoid population growth curves

### Population growth

A population will not necessarily be evenly spread throughout its habitat, nor will its numbers remain steady. The population will also be made up of a wide variety of individuals: adults (male and female), juveniles, larvae, eggs or seeds, for example. In studying populations, these variables often have to be simplified.

In the simplest case, where a single species is allowed to grow in laboratory conditions, the population develops more or less as shown in Figure 19.27.

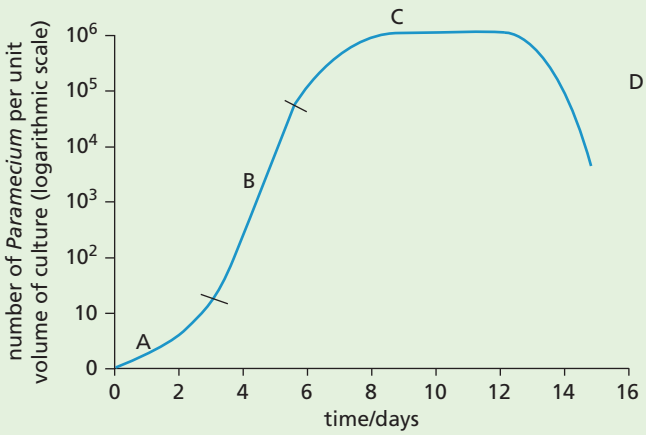



**Figure 19.27** The sigmoid curve (*Paramecium caudatum*). This is the characteristic growth pattern of a population when food is abundant at first.

The population might be of yeast cells growing in a sugar solution, flour beetles in wholemeal flour or weevils in a grain store. The curve shown in Figure 19.27 was obtained using a single-celled organism called *Paramecium* (see Chapter 1), which reproduces by dividing into two (binary fission). The **sigmoid** (S-shaped) form of the graph can be explained as follows:

- **A: Lag phase**. The population is small. Although the numbers double at each generation, this does not result in a large increase.
- **B: Exponential phase (log phase)**. Continued doubling of the population at each generation produces a logarithmic growth rate (e.g. 64 – 128 – 256 – 512 – 1024). When a population of four doubles, it is not likely to strain the resources of the habitat, but when a population of 1024 doubles there is likely to be considerable competition for food and space and the growth rate starts to slow down.
- **C: Stationary phase**. The resources will no longer support an increasing population. At this stage, limiting factors come into play. The food supply may limit further expansion of the population, diseases may start to spread through the dense population and overcrowding may lead to a fall in reproduction rate. Now the mortality rate (death rate) equals the reproduction rate, so the population numbers stay the same.
- **D: Death phase**. The mortality rate (death rate) is now greater than the reproduction rate, so the population numbers begin to drop. Fewer offspring will live long enough to reproduce. The decline in population numbers can happen because the food supply is insufficient, waste products contaminate the habitat or disease spreads through the population.

### Limits to population growth

The sigmoid curve is a very simplified model of population growth. Few organisms occupy a habitat on their own, and the conditions in a natural habitat will be changing all the time. The steady state of the population in part C of the sigmoid curve is rarely reached in nature. In fact, the population is unlikely to reach its maximum theoretical level because of the many factors limiting its growth. These are called **limiting factors**.

#### Competition

If, in the laboratory, two species of *Paramecium* (*P. aurelia* and *P. caudatum*) are placed in an aquarium tank, the population growth of *P. aurelia* follows the sigmoid curve but the population of *P. caudatum* soon declines to zero because *P. aurelia* takes up food more rapidly than *P. caudatum* (Figure 19.28).

This example of competition for food is only one of many factors in a natural environment that will limit a population or cause it to change.

#### Abiotic and biotic limiting factors

Plant populations will be affected by **abiotic** (non-biological) factors such as rainfall, temperature and light intensity. The population of small annual plants may be greatly reduced by a period of drought; a severe winter can affect the numbers of more hardy perennial plants. **Biotic** (biological) factors affecting plants include their leaves being eaten by browsing and grazing animals or by caterpillars and other insects, and the spread of fungus diseases.

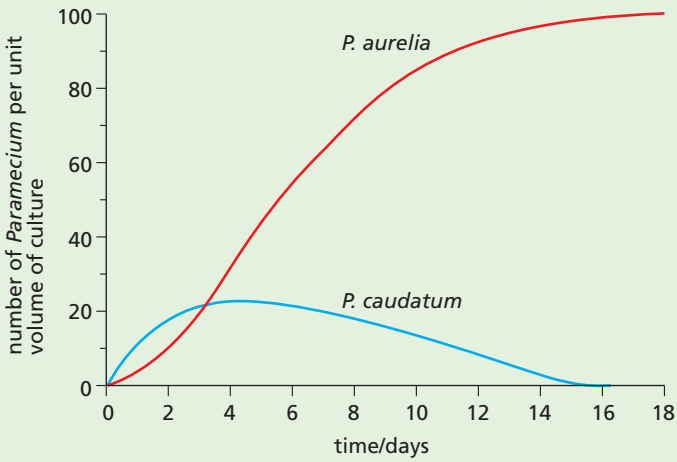



**Figure 19.28** The effect of competition. *Paramecium aurelia* and *P. caudatum* eat the same food but *P. aurelia* can capture and ingest it faster than *P. caudatum*.

**Figure 19.29** A colony of nesting gannets. Availability of suitable nest sites is one of the factors that limits the population.

Animal populations, too, will be limited by abiotic factors such as seasonal changes. A cold winter can severely reduce the populations of small birds. However, animal populations are also greatly affected by biotic factors such as the availability of food, competition for nest sites (Figure 19.29), predation (i.e. being eaten by other animals), parasitism and diseases.

The size of an animal population will also be affected by the numbers of animals entering from other localities (immigration) or leaving the population (emigration).

In a natural environment, it is rarely possible to say whether the fluctuations observed in a population are mainly due to one particular factor because there are so many factors at work. In some cases, however, the key factors can be identified as mainly responsible for limiting the population.

### Predator–prey relationships

A classic example of predator–prey relationships comes from an analysis of the fluctuating populations of lynxes and snowshoe hares in Canada. The figures are derived from the numbers of skins sold by trappers to the Hudson's Bay Company between 1845 and 1945.

The lynx preys on the snowshoe hare, and the most likely explanation of the graph in Figure 19.30 is that an increase in the hare population allowed the predators to increase. Eventually the increasing numbers of lynxes caused a reduction in the hare population.

However, seasonal or other changes affecting one or both of the animals could not be ruled out.

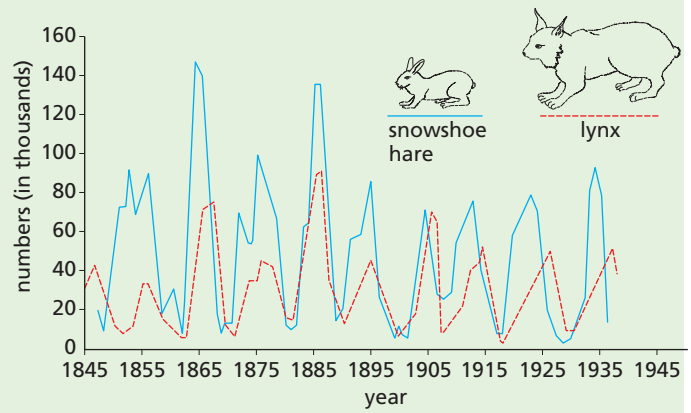



**Figure 19.30** Prey–predator relationships: fluctuations in the numbers of pelts received by the Hudson's Bay Company for lynx (predator) and snowshoe hare (prey) over a 100-year period.

## Questions

### Core

1 Construct a simple food web using the following:
sparrow, fox, wheat seeds, cat, kestrel, mouse.

2 Describe briefly all the possible ways in which the following might depend on each other:
grass, earthworm, blackbird, oak tree, soil.

3 Explain how the following foodstuffs are produced as a result of photosynthesis:
wine, butter, eggs, beans.

4 An electric motor, a car engine and a race horse can all produce energy.
   a Show how this energy could come, originally, from sunlight.
   b What forms of energy on the Earth are *not* derived from sunlight?

5 How do you think evidence is obtained in order to place animals such as a fox and a pigeon in a food web?

6 When humans colonised islands they often introduced their domestic animals, such as goats or cats. This usually had a devastating effect on the natural food webs. Suggest reasons for this.

7 a Why do living organisms need a supply of carbon?
   b Give three examples of carbon-containing compounds that occur in living organisms (see Chapter 4).
   c Where do these organisms get their carbon from?
      i animals
      ii plants

8 Write three chemical equations:
   a to illustrate that respiration produces carbon dioxide (see Chapter 12)
   b to show that burning produces carbon dioxide
   c to show that photosynthesis uses up carbon dioxide (see Chapter 6).

9 Outline the events that might happen to a carbon atom in a molecule of carbon dioxide, which entered the stoma in the leaf of a potato plant and became part of a starch molecule in a potato tuber, which was then eaten by a man. Finally the carbon atom is breathed out again in a molecule of carbon dioxide.

10 Look at the graph in Figure 19.22.
   a When did the post-war 'baby-boom' occur?
   b What was the growth rate of the population in 1800?

11 Which of the following causes of death are likely to have most effect on the growth rate of a population: smallpox, tuberculosis, heart disease, polio, strokes, measles?
Give reasons for your answer.

12 Suggest some reasons why the birth rate tends to fall as a country becomes wealthier.

13 a Give examples of the kind of demands that an increasing population makes on the environment.
   b In what ways can these demands lead to environmental damage?

14 If there are 12 000 live births in a population of 400 000 in 1 year, what is the birth rate?

15 Try to explain why, on average, couples need to have just over two children if the population is to remain stable.

16 Study Figure 19.25 and then comment on:
   a the relative number of boy and girl babies
   b the relative number of men and women of reproductive age (20–40)
   c the relative numbers of the over-70s.

17 In Figure 19.24, what might be the reasons for the fall in death rate from diphtheria even before 50% immunisation was achieved?

### Extended

18 It can be claimed that the Sun's energy is used indirectly to produce a muscle contraction in your arm. Trace the steps in the transfer of energy that would justify this claim.

19 Discuss the advantages and disadvantages of human attempts to exploit a food chain nearer to its source, e.g. the plankton in Figure 19.3.

20 On a lawn growing on nitrate-deficient soil, the patches of clover often stand out as dark green and healthy against a background of pale green grass. Suggest a reason for this contrast.

21 Very briefly explain the difference between nitrifying, nitrogen-fixing and denitrifying bacteria.

22 Study Figure 19.27.
   a How many days does it take for the mortality rate to equal the replacement rate?
   b What is the approximate increase in the population of *Paramecium*:
      i between day 0 and day 2
      ii between day 2 and day 4
      iii between day 8 and day 10?
   c In section B of the graph, what is the approximate reproduction rate of *Paramecium* (i.e. the number of new individuals per day)?

23 In 1937, two male and six female pheasants were introduced to an island off the NW coast of America. There were no other pheasants and no natural predators. The population for the next 6 years increased as follows:

| Year | Population |
|---|---|
| 1937 | 24 |
| 1938 | 65 |
| 1939 | 253 |
| 1940 | 563 |
| 1941 | 1122 |
| 1942 | 1611 |

Plot a graph of these figures and say whether it corresponds to any part of the sigmoid curve.

24 In Figure 19.28, which part of the curve approximately represents the exponential growth of the *P. aurelia* population? Give the answer in days.

25 What forms of competition might limit the population of sticklebacks in a pond?

26 Suggest some factors that might prevent an increase in the population of sparrows in a farmyard:
   a abiotic factors
   b biotic factors

## Checklist

After studying Chapter 19 you should know and understand the following:

### Energy flow

- The Sun is the principal source of energy input to biological systems.

- Energy from the Sun flows through living organisms.
- First, light energy is converted into chemical energy in photosynthetic organisms. Then they are eaten by herbivores. Carnivores eat herbivores.
- As organisms die, the energy is transferred to the environment.

### Food chains and food webs

- A food chain shows the transfer of energy from one organism to the next, beginning with a producer.
- A food web is a network of interconnected food chains.
- Producers are organisms that make their own organic nutrients, usually using energy from sunlight, through photosynthesis.
- Consumers are organisms that get their energy from feeding on other organisms.
- A herbivore is an animal that gets its energy by eating plants.
- A carnivore is an animal that gets its energy by eating other animals.
- All animals depend, ultimately, on plants for their source of food.
- Plants are the producers in a food web; animals may be primary, secondary or tertiary consumers.
- A pyramid of numbers has levels which represent the number of each species in a food chain. There are usually fewer consumers than producers, forming a pyramid shape.
- Over-harvesting unbalances food chains and webs, as does the introduction of foreign species to a habitat.

- Energy is transferred between trophic levels through feeding.
- The trophic level of an organism is its position in a food chain.
- The transfer of energy from one trophic level to another is inefficient.
- Only about 1% of the Sun's energy that reaches the Earth's surface is trapped by plants during photosynthesis.
- At each step in a food chain, only a small proportion of the food is used for growth. The rest is used for energy to keep the organism alive.
- Food chains usually have fewer than five trophic levels.
- Feeding crop plants to animals uses up a lot of energy and makes the process inefficient.
- There is an increased efficiency in supplying green plants as human food.
- A decomposer is an organism that gets its energy from dead or waste organic material.
- A pyramid of biomass is more useful than a pyramid of numbers in representing a food chain.

### Nutrient cycles

- The materials that make up living organisms are constantly recycled.
- Plants take up carbon dioxide during photosynthesis; all living organisms give out carbon dioxide during respiration; the burning of carbon-containing fuels produces carbon dioxide.
- The uptake of carbon dioxide by plants balances the production of carbon dioxide from respiration and combustion.
- The water cycle involves evaporation, transpiration, condensation and precipitation (rain).

- The combustion of fossil fuels and the cutting down of forests increases the carbon dioxide concentrations in the atmosphere.
- Soil nitrates are derived naturally from the excretory products of animals and the dead remains of living organisms.
- Nitrifying bacteria turn these products into nitrates, which are taken up by plants.
- Nitrogen-fixing bacteria can make nitrogenous compounds from gaseous nitrogen.
- Plants make amino acids and proteins.
- Animals eat the proteins.
- Proteins are broken down to remove the nitrogen by the process of deamination.
- Micro-organisms play an important part in the nitrogen cycle. They are involved in decomposition, nitrification, nitrogen fixation and denitrification.

### Population size

- A population is a group of organisms of one species, living and interacting in the same area at the same time.
- The factors affecting the rate of population growth for a population of an organism include food supply, predation and disease.
- The human population has increased in size rapidly over the past 250 years.
- The world population is growing at the rate of 1.7% each year. At this rate, the population more than doubles every 50 years.
- The rate of increase is slowing down and the population may stabilise at 10 billion by the year 2100.
- A population grows when the birth rate exceeds the death rate, provided the offspring live to reproduce.

- A community is all of the populations of different species in an ecosystem.
- An ecosystem is a unit containing the community of organisms and their environment, interacting together.
- A sigmoid population growth curve for a population growing in an environment with limited resources has lag, exponential (log), stationary and death phases.
- In the developed countries, the birth rate and the death rate are now about the same.
- In the developing countries, the birth rate exceeds the death rate and their populations are growing. This is not because more babies are born, but because more of them survive.
- The increased survival rate may be due to improved social conditions, such as clean water, efficient sewage disposal, better nutrition and better housing.
- It is also the result of vaccination, new drugs and improved medical services.
- As a population becomes wealthier, its birth rate tends to fall.