

muscle fibre receives a single connection to the end of a neurone in a region known as the motor end plate. The arrival of an action potential triggers depolarisation that is transmitted along the sarcolemma and into the muscle fibre. Transverse or T tubules conduct action potentials that stimulate opening of voltage-gated Ca^{2+} channels. The Ca^{2+} ions diffuse out of the sarcoplasmic reticulum to the myofibrils to stimulate contraction.

KEY POINTS

motor unit a motor neurone plus the muscle fibres it supplies

neuromuscular junction a synaptic connection between motor nerve and muscle

At the end plate are thousands of T tubules which carry the stimulus through the membrane and cause contraction. But the number of muscle fibres stimulated by a single motor neurone axon varies from a few to many because the axon divides and has many end connections. The combination of a motor neurone axon and all the muscle fibres it stimulates is called a motor unit. (Figure 9.2.13). There are many motor units in a nerve that collectively provide electrical stimuli to a muscle to generate a muscle contraction.

The number of muscle fibres connected to each unit can vary within a particular muscle and from muscle to muscle; the largest muscles have motor units with connection to more muscle fibres, whereas smaller muscles have fewer muscle fibres in each motor unit. For example, thigh muscles can have a thousand fibres connected in each unit, while muscles that control the eye might have ten. Not all motor units are always activated at the same time. The more motor units that are active,

the larger the number of muscle fibres that contract, and the greater the muscle contraction. Muscles which possess more motor units have greater individual motor neurone stimuli and can control the output of force more finely.

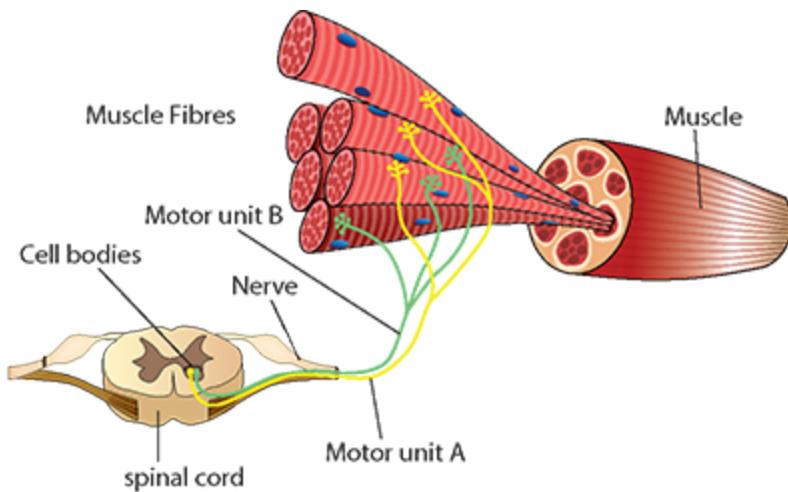


Figure 9.2.13: A motor unit consist of a motor neurone and the muscle cells it supplies

TEST YOUR UNDERSTANDING

- 4** Explain why muscles occur in antagonistic pairs.
- 5** Outline the functions of cartilage and synovial fluid in the elbow joint.
- 6** Compare the movement of a hinge joint and a ball-and-socket joint.
- 7** Explain how actin and myosin filaments produce the striped appearance of skeletal muscle.
- 8** Describe the role of ATP in muscle contraction.

9.2.4 Locomotion

Locomotion is defined as the ability of an organism to move from one place to another. Animals move and change their locations for a variety of reasons, including finding food, seeking out a suitable habitat or avoiding an unsuitable one, escaping predators or pursuing a mate. The structures that animals use for movement include cilia, legs, wings, arms, fins and tails. Vertebrate locomotion results from coordinated patterns of movement involving activation of hundreds of muscles under the control of the spinal cord. Neurones of the brain stem initiate locomotion via the spinal cord and motor neurones linked to muscles carry out the movement.

Locomotion by all animals requires three important factors:

- 1 Propulsion to move the animal in the right direction with sufficient force.
- 2 Stability to ensure that if a limb is lifted from the ground the animal remains sufficiently stable.
- 3 Support to ensure the animal is held up by its body (or other medium) as it moves.



Figure 9.2.14: The satin bowerbird builds an elaborate bower decorated with blue objects to attract females.

Advantages of locomotion

Every type of locomotion uses a lot of energy, but this is balanced by the advantages it gives to animals that can move about. Feeding and searching for food, as well as escaping from predators, are made easier for animals that can move from place to place.

- 1 Searching for and enticing a partner to mate require locomotion. Many fish, such as the three-spined stickleback (*Gasterosteus aculeatus*), perform mating rituals involving specific movements. Stickleback males build a nest and dance erratic, zigzag dances to encourage egg-carrying females to come into the nest where he can fertilise the eggs. Among the birds, the satin bowerbird

(*Ptilonorhynchus violaceus*) has one of the most complex and colourful mating rituals. Male birds build elaborate bowers, which resemble piles of sticks but are carefully decorated exclusively with blue objects (Figure 9.2.14). If a female bird is impressed by a bower and comes to view the male, he must then perform a dance to ensure she will mate with him.



Figure 9.2.15: Dolphins have streamlined bodies to reduce friction as they swim

-
- 2 Some species move huge distances in regular journeys called migrations. This enables them to find the most favourable conditions for feeding or breeding. Swallows migrate a distance of about 5000 km from Europe to spend the summer in South Africa. They take about 10 days for their journey, flying through the day and roosting in huge flocks in reed beds at night. Swallows feed on flying insects on their journey, catching their food as they travel. The

birds arrive at their destination in January, leaving behind the winter in Europe and arriving at their summer feeding areas when the temperature is warm, around 25 °C.

- 3 Foraging means searching for and collecting food resources. Most animals must forage for food and herbivores such as rabbits, horses and may spend most of their active day moving about as they search for and eat plant food. Small birds such as the blue tit will forage for insects and larger birds such as terns and gulls skim the surface of water to seek out fish. All these types of foraging behaviour rely on locomotion on land, sea or in the air.
- 4 Escaping danger – all species need to escape from their predators and there are a huge range of strategies that animals use. Running, jumping, dropping from trees to the ground as well as climbing into trees or flying away are strategies used by mammals all over the world. For all these strategies, locomotion is essential to move away from danger.

Adaptations for movement

Swimming

Fish and aquatic birds and marine mammals swim and are propelled by their fins or flippers. Water supports their bodies and maintains their stability so that for short periods of time these animals can dive or move forwards without moving their limbs (Figure 9.2.15). Movements of fins and flippers propel the animals downward as they dive for food.

Dolphins are aquatic mammals. Their bodies are perfectly adapted for swimming. They have a streamlined shape which makes it easy to move through water. Like all vertebrates their

limbs have a pentadactyl pattern ([Chapter 11](#)) but they are adapted to form flippers. A dolphin's tail has a flattened shape which forms a fluke which moves up and down to propel the animal forward or downward as they dive.

As mammals, dolphins breathe air and must return to the water surface to inhale. They breathe through nostrils, called a blowhole, located on top of their heads. When they come to the surface, the blowhole opens, allowing them to take air into their lungs. When they dive back under water, the blowhole is tightly closed by a layer of muscle. Dolphins cannot take in air through their mouths, they only breathe through their blowholes. In this way, breathing and eating are kept entirely separate so that dolphins can capture prey in their mouths and swallow it without the risk of water entering their lungs.

TEST YOUR UNDERSTANDING

- 9** What is the difference between movement and locomotion?
- 10** Why is locomotion important to animals
- 11** Suggest three adaptations for swimming that marine mammals have for swimming.

Links

- How is energy needed for movement made available? ([Section 3.2](#))
- How have movement and locomotion led to analogous structures in different classes of organisms? ([Chapter 11](#))

SELF-ASSESSMENT CHECKLIST

Think about the topics covered in this chapter. Which parts are you most confident with? Which topics require some extra practice?

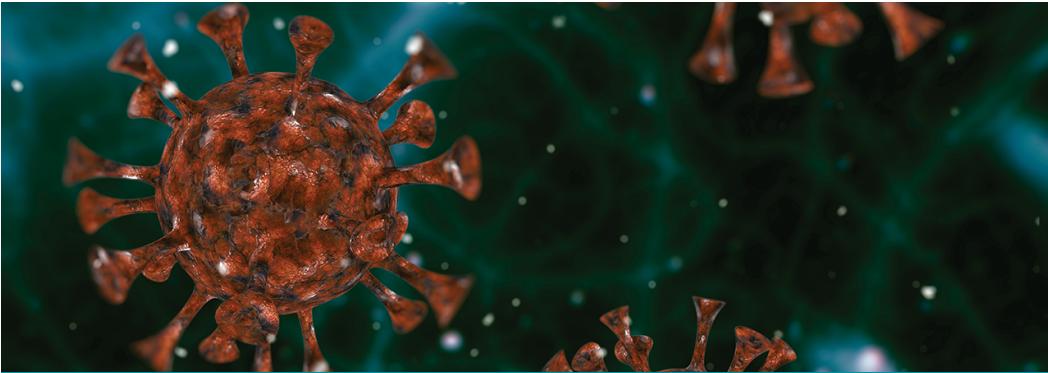
| I can... | Subsection | Needs more work | Nearly there | Confident to move on |
|---|------------|-----------------|--------------|----------------------|
| recall that inputs to the spinal cord and brain are carried by sensory neurones | 9.1.1 | | | |
| understand that muscles are stimulated by outputs from the brain via motor neurones | 9.1.1 | | | |
| recall that a nerve contains bundles of fibres of both sensory and motor neurones | 9.1.1 | | | |
| summarise the stage in a reflex arc | 9.1.1 | | | |
| identify receptors and effectors | 9.1.1 | | | |

| | | | | | |
|--|-------|--|--|--|--|
| understand the roles of the cerebrum and cerebellum in controlling movement | 9.1.1 | | | | |
| distinguish between voluntary and involuntary movement in the digestive system | 9.1.1 | | | | |
| recognise that all living things can move but that some are sedentary | 9.2.1 | | | | |
| outline the functions of a skeleton and the differences between an exoskeleton and an endoskeleton | 9.2.2 | | | | |
| identify the parts of a synovial joint and the range of movements of different joints | 9.2.2 | | | | |
| describe the action of antagonistic | 9.2.3 | | | | |

| | | | | |
|--|-------|--|--|--|
| muscles in breathing | | | | |
| outline the sliding filament theory of muscle action and the importance of the protein titin | 9.2.3 | | | |
| outline the structure of motor units in skeletal muscle | 9.2.3 | | | |
| distinguish between movement and locomotion and summarise reasons for locomotion | 9.2.4 | | | |
| summarise the adaptations of marine mammals that enable locomotion in water. | 9.2.4 | | | |

EXAM-STYLE QUESTIONS

You can find questions in the style of IB exams in the digital coursebook.



› Chapter 10

Defence against disease

C3.2

INTRODUCTION

A pathogen is a living organism or virus that invades the body and causes infectious disease. Most pathogens are bacteria and viruses, but protists, parasitic worms and fungi can also be pathogenic. Living organisms defend themselves against the pathogens that cause infectious diseases.

10.1 Defence against disease

LEARNING OBJECTIVES

In this section you will:

- learn that living organisms defend themselves against pathogens which cause diseases
- distinguish between the innate and adaptive immune systems
- understand that the first lines of defence are the skin and mucous membranes
- recognise that blood clotting is a series of reactions that seals the skin if it is cut
- learn that phagocytes are a type of blood cell that recognise and remove pathogens in a series of stages that result in phagocytosis
- learn that animals have complex immune systems that attack pathogens by ‘challenge and response’
- define antigens as recognition molecules on cell surfaces
- recognise that antigens on red blood cells stimulate antibody production in a person with a different blood group
- learn that lymphocytes are blood cells that produce antibodies in the specific humoral responses to infection

- recognise that some lymphocytes act as memory cells and confer immunity
- understand that cell-mediated response to infection involves cytotoxic T lymphocytes, B lymphocytes and helper T-cells
- learn that activated B-cells form clones of plasma cells and memory cells as part of the humoral response and that memory cells provide immunity if a pathogen is encountered again
- discover that antibiotics can block prokaryotic cell process but some strains of bacteria have evolved resistance to them
- learn that viral diseases cannot be treated with antibiotics
- discover that scientists are seeking new sources of antibiotics to treat bacterial infections
- understand that human immunodeficiency virus (HIV) is a virus that infects the immune system and can lead to AIDS
- understand that pathogens can transfer from one species to another and are called zoonoses
- discover how vaccines stimulate an immune response and how smallpox was eradicated by vaccination
- recognise how epidemics are prevented by herd immunity.

GUIDING QUESTIONS

- How do organisms defend themselves against pathogens that cause disease?
- What prevents animals from destroying their own cells and tissues?

KEY POINTS

bacteria are prokaryotic microorganisms some of which can cause disease.

infectious diseases are caused by pathogens, such as bacteria, viruses, parasites or fungi that can be spread from one person to another.

pathogens are biological agents that can cause infectious disease.

clotting factors are proteins found in blood that work with platelets to help the blood clot if a blood vessel is broken.

KEY POINTS

leucocytes are immune cells that circulate in the blood and in the lymphatic system. There are five types of leucocyte.

mucous membranes line cavities in the body and cover the surface of internal organs.

platelets are cell fragments in the blood that release clotting factors.

10.1.1 Infection and response

In our daily lives we are exposed to many different disease-causing agents. Any organism or virus that can cause disease is known as a pathogen. Many different organisms can infect the human body and cause infectious disease; these include bacteria, viruses, fungi and protocists (microscopic single-celled organisms such as *amoebae*). Relatively few bacteria and fungi are pathogens: most are free-living and useful in the environment ([Chapter 12](#)) but some cause serious illness and even death. Cholera, leprosy, tuberculosis and syphilis are all caused by bacterial infection. Fungal infections cause athlete's foot, ringworm and yeast infections such as thrush. Most protocist diseases in humans are caused by protozoa, which are human parasites. *Trypanosoma* protozoa cause Chagas disease and sleeping sickness, *Giardia* protozoa cause giardiasis and *Plasmodium* protozoa cause malaria.

All viruses have the potential to be pathogenic, because no virus can function outside the cell of its host organism. A virus takes over the mechanisms of its host's cells and directs them to make more viruses ([Section 5.3](#)). Examples of viral infections include measles, rubella, chickenpox, shingles, influenza and COVID-19.

The body's first line of defence

Despite the fact that we come into contact with many pathogens every day, we are not often ill. This is due to our effective immune system, which both prevents pathogens entering the body and also deals with any that do. The body has a series of responses to disease-causing organisms.

The first line of defence against infection is our skin. Skin acts as a physical and chemical barrier to pathogens. Unbroken skin is a tough barrier to any potential invaders. It is waterproof and its secretions repel bacteria. Sebum from sebaceous glands has antibacterial properties and sweat, which is slightly acidic, also inhibits bacterial growth. Openings in the skin, such as eyes and nose, can provide entry points for pathogens but these are protected by mucous membranes, which line the respiratory, urinary, reproductive and intestinal tracts. Secretions such as tears, mucus and saliva contain the enzymes lysozyme and phospholipase. Lysozymes kill bacteria by catalysing the hydrolysis of bonds in their cell walls, while phospholipases destroy phospholipids in bacterial membranes. In addition, if pathogens are swallowed in food or water, the acidic environment of the stomach helps to kill them.

Blood clotting

If the protective layer of our skin is broken or cut and blood vessels are broken, pathogens have a route into the bloodstream. To prevent blood loss and the entry of pathogens, any blood that escapes from a damaged vessel quickly forms a clot, which plugs the gap.

Platelets, erythrocytes (red blood cells) and leucocytes (a type of white blood cell) are all important in the clotting process. Platelets are small cell fragments that form in the bone marrow and circulate in the bloodstream. Also important are two plasma proteins, which are present in the blood in their inactive forms until they are activated when needed (Figure 10.1.1). These two inactive proteins are **prothrombin**, a glycoprotein, and **fibrinogen**, a plasma protein produced by the liver.

If a small blood vessel is damaged, injured cells or platelets release clotting factors, which cause platelets to stick to the area. These factors activate prothrombin, which is converted to its active form, thrombin. Thrombin in turn activates the soluble protein fibrinogen, converting it to active fibrin, which is insoluble and forms long threads. This cascade of reactions ensures a speedy response to any damage. Fibrin forms a mesh of fibres that covers the damaged area and traps passing blood cells, forming a soft clot (Figure 10.1.2). If a clot is exposed to air, it dries and forms a scab, which will protect the area until the tissue beneath has been repaired.

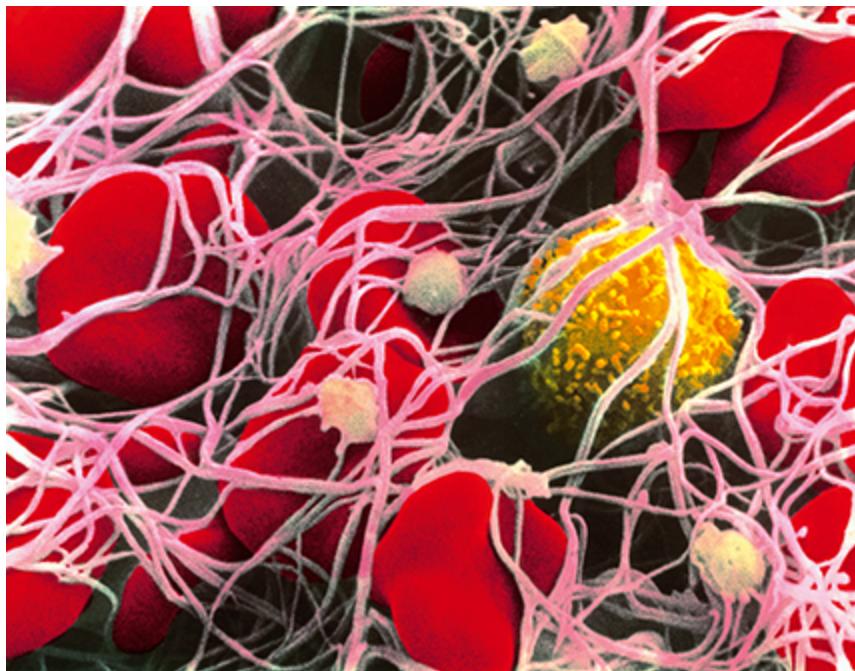


Figure 10.1.1: False-colour transmission electron micrograph showing red blood cells and threads of fibrin forming a clot ($\times 3600$).

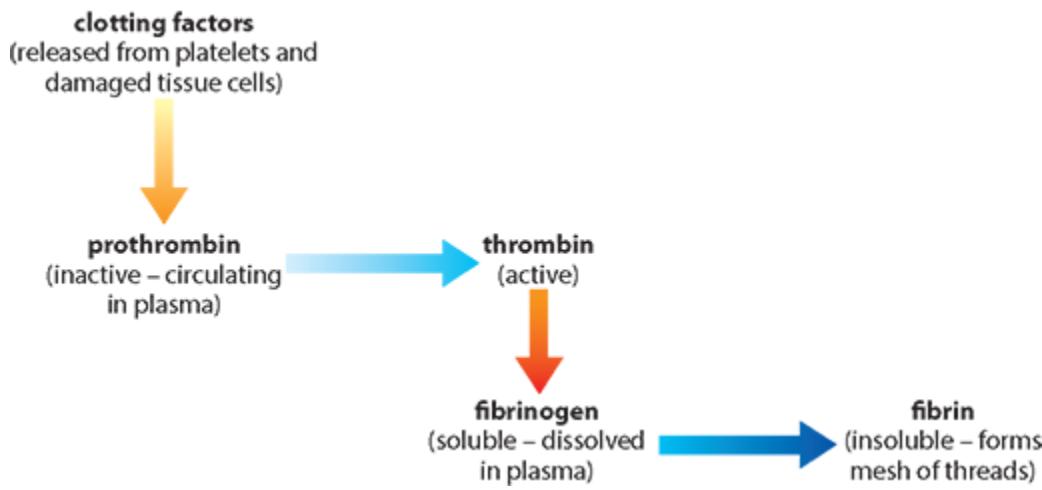


Figure 10.1.2: The sequence of reactions in the blood-clotting cascade.

KEY POINTS

an antigen is a substance that stimulates the production of antibody.

non-specific immunity refers to response of the body to any pathogen.

phagocytes blood cells are capable of engulfing bacteria and other small cells by phagocytosis.

phagocytosis is the process of modifying the shape of a phagocytic cell so that it can engulf bacteria or other particles.

Innate immune responses and adaptive immunity

The **innate immune system** is the body's first line of defence against pathogens that enter the body. It responds in the same way to all invaders and foreign substances. It is often called the non-specific immune system. It acts quickly so that if pathogens enter the skin through a small wound, they will be detected and

destroyed within hours. But the innate immune system has limited ability to prevent pathogens spreading.

The innate immune system consists of:

- protection by the skin and mucous membranes
- protection by phagocytes and proteins.

The innate immune system does not change during an organism's lifetime.

The **adaptive immune system** takes over if the innate immune system is unable to destroy a pathogen. It is very specific to the pathogen that is causing an infection. The response is slower than the innate immune system because the pathogen must be identified before a response can occur. After this the adaptive immune system is more accurate and specific in its response. It can also remember pathogens, so that if the same pathogen enters the body again, the adaptive immune system can respond faster.

This memory is also the reason why the body can become immune to certain infections. It may take a few days for the adaptive immune system to respond the first time, but the next time the body encounters the pathogen it can react immediately. The second infection is likely to be milder.

The adaptive immune system is made up of:

- T lymphocytes in the tissue between the body's cells
- B lymphocytes, also found in the tissue between the body's cells
- antibodies in the blood and other bodily fluids.

Non-specific innate immunity

Pathogens that do enter the body are soon recognised by phagocytic leucocytes, which form a vital part of the body's innate immune system. These specialised white blood cells circulate in the blood system and, because they are easily able to change their shape, can also squeeze in and out of capillaries. Phagocytic leucocytes respond to invaders by engulfing and destroying them in a process called phagocytosis (Figure 10.1.3).

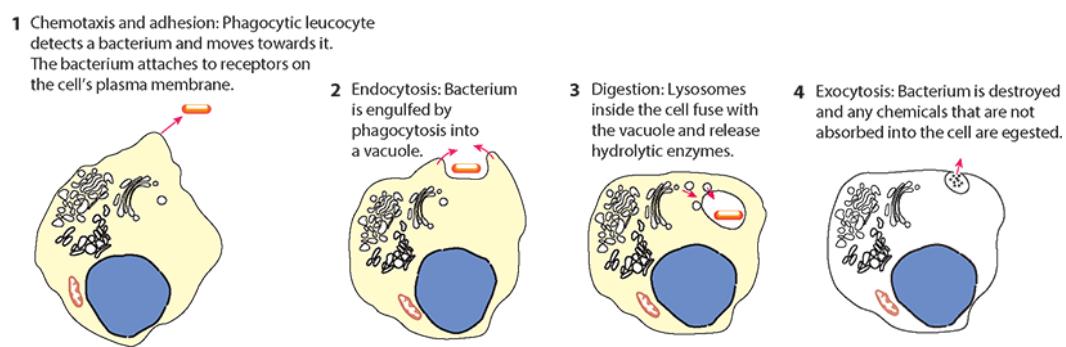


Figure 10.1.3: Phagocytosis of a pathogen.

This type of response provides non-specific immunity, which is so called because the phagocytes respond in the same way no matter what pathogen they meet. Phagocytes are able to move by amoeboid action, changing the shape of their cells to propel themselves along to where they are needed. Phagocytes are able to distinguish between invaders, foreign bodies that are not part of the individual's own body (non-self), and those which form part of the body (self). When phagocytes come into contact with bacteria, the receptors on the phagocyte's surface will bind to them. If the body is infected, chemical signals attract phagocytes to places where the pathogen has invaded the body in a process known as chemotaxis. These signals may come from pathogens or from other phagocytes already in the area. As Figure 10.1.3 shows, the phagocyte adheres to the pathogen, engulfs it by endocytosis and once the pathogen is inside the phagocyte, releases hydrolytic enzymes that destroy it. Any waste products

leave the phagocyte by exocytosis. Phagocytes do not attack the body's own cells and tissues but they may remove dead tissues that result from apoptosis.

KEY POINTS

an antibody is one of millions of blood proteins produced by plasma cells in response to specific antigens, which are then neutralised or destroyed.

immunity is resistance to the onset of a disease after infection by the agent causing the disease.

lymphocyte is a type of leucocyte that produces antibodies. Some act as memory cells.

memory cells are lymphocytes that enable the body to respond quickly to an antigen it has already encountered.

Adaptive (specific) immunity and antibody production

Many animals have complex immune systems that attack different pathogens in very specific ways known as challenge and response. This response can be summarised as follows:

- If the body is challenged by a pathogen it responds with both non-specific and specific immune reactions.
- All the body's own cells have molecular markers on their cell plasma membranes that identify each cell as 'self' and belonging to the body. The body can recognise invading pathogens because they do not have these markers on their surface.
- Non-specific immune cells (macrophages) ingest and put the foreign antigens on their surface membranes. The

macrophages present these antigens to lymphocytes as examples of ‘non-self’.

- Lymphocytes can then respond with the production of specific antibodies to destroy the non-self invaders. This process is known as the humoral response.

Antigens (antibody-generating substances) are glycoproteins and proteins found embedded in the plasma membranes or cell walls of bacteria or in the protein coat of a virus. These antigens enable the body to recognise a pathogen as being ‘not self’ – that is, not a part of the body – and they give a clear signal to switch on the immune response, with the rapid production of antibodies.

Antibodies are protein molecules that are produced by lymphocytes, a type of leucocyte found in the blood and lymph nodes, in response to any antigen that enters the body. There are millions of different antibodies and each one is specific to an antigen. For example, the antibodies that lymphocytes produce in response to infection by an influenza virus are quite different from those produced by different lymphocytes in response to a tuberculosis bacterium. Even fragments of pathogens, or their toxins, can stimulate the release of antibodies. After an infection has passed, some of the lymphocytes giving rise to antibodies specific to the infecting antigen remain in the bloodstream as memory cells. This means that the immune system can respond quickly if the same antigen enters the body again later, by producing antibodies and preventing a widespread infection. The person is said to have acquired immunity to the antigen. Figure 10.1.4 explains how antibodies are made.

Each antibody molecule has a basic Y shape but the arrangement of molecules at the top of the Y shape forms specific binding sites that give every antibody its own unique properties (Figure

10.1.5). These specific binding sites attach to the corresponding antigen site on the surface of the pathogen or its toxin. Once an antibody has bound to an antigen, it can destroy it in one of a number of ways. Some cause bacterial cells to clump together, making the job of phagocytes easier. Others cause cell walls to rupture, deactivate toxins or act as recognition signals for phagocytes, giving a clear indication that action is needed (Figure 10.1.5).

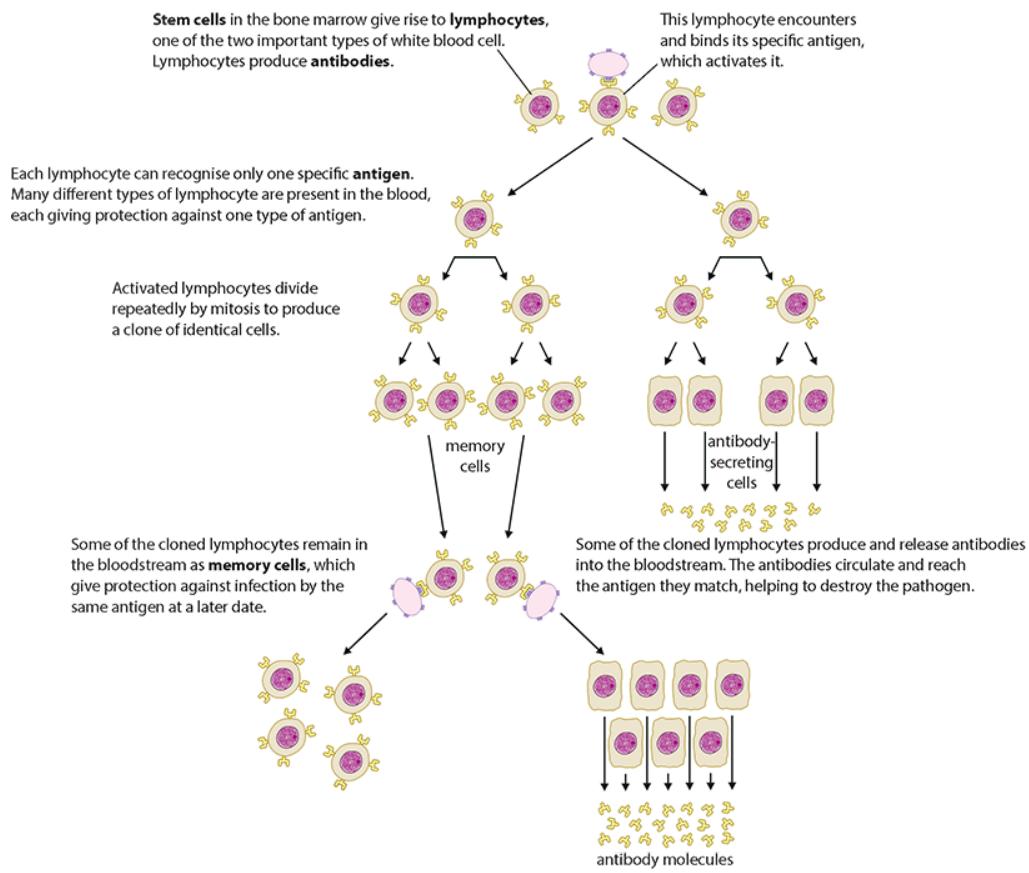


Figure 10.1.4: Antibody production involves a series of stages that also result in memory cells being produced.

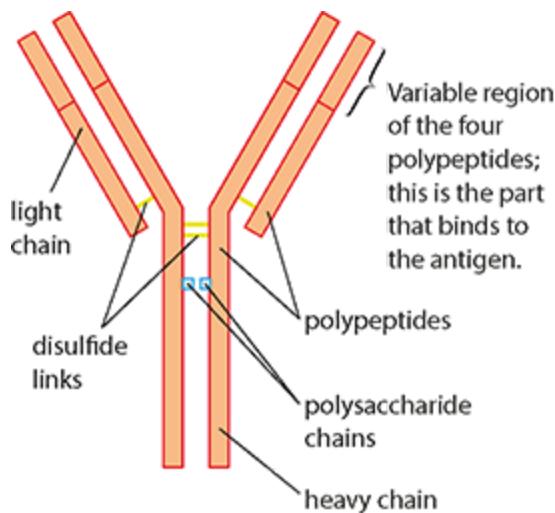


Figure 10.1.5: The basic structure of an antibody molecule.

A vaccination protects us from a specific disease by stimulating our immune system to produce antibodies against antigens carried by the disease-causing agent. Memory cells then remain in our bloodstream, so that if the actual disease-causing agent is encountered later, antibodies can be released quickly and an infection avoided. (You can read more about vaccination in the Higher Level section of this chapter.)

The importance of antigens in blood groups and antigens

There are four main human blood groups and these are classified by the ABO system according to the antigens that red blood cells have on their surfaces and the antibodies found in blood plasma (Section 4.6).

Antigens are protein molecules found on the surface of red blood cells.

- blood group A – has A antigens on the red blood cells with anti-B antibodies in the plasma

- blood group B – has B antigens with anti-A antibodies in the plasma
- blood group O – has no antigens, but both anti-A and anti-B antibodies in the plasma
- blood group AB – has both A and B antigens, but no antibodies.

Blood transfusions are given in medical procedures or to save the life of a person who has lost a lot of blood, but receiving blood from the wrong group can be life-threatening. For example, if a person with group B blood is given group A blood, their anti-A antibodies will attack the group A cells and destroy them. So group A blood must never be given to someone who has group B blood and vice versa. As group O red blood cells do not have any A or B antigens, group O blood can safely be given to a person who has any other blood group.

10.1.2 Cell-mediated and humoral responses

Immunity: challenge and response

Resistance to an infection is known as immunity. Immunity is acquired from infancy onwards as the body is exposed to, and learns to recognise, many different types of pathogen that have the potential to cause disease. We become able to distinguish between cells that are our own ‘self’ and those that are ‘non-self’ and are therefore likely to be pathogens or cause harm. Cells are recognised by the proteins on their plasma membranes.

Certain leucocytes (a type of white blood cell) are able to recognise ‘non-self’ proteins, or antigens. Antigens may be on the surface of a pathogen, or may be part of a toxin secreted by a pathogen. Antigens are also likely to be present on the cell surfaces of transplanted tissues or organs and on the surfaces of some cancer cells.

If a pathogen enters the body, the immune system is stimulated to respond. As it is ‘challenged’ by the pathogen, it ‘responds’ by setting in motion processes that will destroy it. The first line of defence is phagocytic leucocytes (macrophages). These cells respond in a non-specific way and will consume bacteria, viruses and other pathogens, as well as dead cells and cell fragments.

Our second line of defence is a specific response to antigens. Healthy cells have ‘self-antigens’ on the surface of their membranes. If a cell is infected with a virus, it has pieces of viral antigens on its surface. This is a signal for the immune system that lets it know this is a cell that must be destroyed.

One important group of cells involved in destroying both pathogens and cancer cells are cytotoxic T lymphocytes or killer T-cells. Killer T-cells find and destroy infected or mutated cells. To do this they recognise the difference between the infected cells and healthy cells from the antigen markers on their surface membranes. Killer T-cells are able to find cancerous cells or cells that contain viruses and destroy them.

The second line of defence also involves the production of antibodies.

There are two main parts of our immune system that allow us to protect ourselves from disease by producing antibodies. They are the cell-mediated response and the humoral response. These systems work together and separately. The cell-mediated response involves the production of specialised lymphocytes called T-cells, while the humoral response is associated with the blood serum (the non-cellular part of the blood) and involves antibodies secreted by B-cell lymphocytes.

KEY POINTS

cell-mediated response production of specialised T-cells in the immune system.

humoral response a series of immune reactions in the blood that lead to the production of antibodies, specifically the action of B-cells in the non-cellular (serum) part of the blood.

Antibody proteins are vital to the body's immune response, and producing them effectively requires interaction between three types of cell:

1 macrophages

- 2** B lymphocytes (B-cells)
- 3** helper T lymphocytes (T-cells).

The immune response takes several days to become fully active and in the meantime we may become ill. Sometimes symptoms are mild, such as with the common cold, but sometimes they are severe, leading to permanent disability or even death.

Clonal selection: humoral response

B-cells are antibody-producing lymphocytes, but each B-cell can only produce one particular type of antibody. Since the antibody–antigen response is highly specific, there must be a great many types of B-cell to be able to respond to all the possible types of antigen. At any time, there can only be a few of each type of B-cell in the bloodstream because most of the blood volume is taken up with red cells.

B-cells recognise and bind antigens, including bacteria, viruses and toxins (free antigens) outside body cells, and each B-cell recognises one specific antigen. When a pathogen enters the bloodstream, its surface antigen molecules are exposed to the antibodies attached to different B-cells in the blood. If there is a match between an antigen and an antibody, the B-cell with the matching antibody becomes ‘selected’, while all the other B-cells are rejected. The selected B-cell is stimulated to divide and produces a clone of antibody-secreting cells, in a process known as clonal selection.

It is likely that any pathogen will have many different antigenic molecules on its surface so several different types of B-cell will probably be selected. Each of these will result in clone of antibody-secreting B-cells. This is therefore called a polyclonal response and it will result in a more efficient destruction of the

pathogen as the antibodies neutralise or inactivate the antigens. B-cells are also important in the cell-mediated response.

Antibody production and the cell-mediated response

The response to pathogens is more complex than simple clonal selection and it involves two types of lymphocyte: B-cells and T-cells. There are several different types of T-cells that respond to antigen molecules that have been processed and presented by infected cells or phagocytic cells in the cell-mediated response.

The stages of antibody production are:

- 1 When a pathogen enters the bloodstream it is consumed by a macrophage, partly digested and antigen proteins from it are placed on the outer surface of the macrophage. This is called antigen presentation because the proteins are being ‘presented’ to other cells.
- 2 Helper T-cells with receptors matching the presented antigens bind to the macrophages and are activated.
- 3 Activated helper T-cells then start dividing into two types of clones of cells. One clone type is active helper T-cells, which are required for the next step in the process, and the other clone type is memory cells, which will be used if the same pathogen ever invades the body again.
- 4 B-cells with the matching antibody also take in and process antigen proteins from the pathogen and place them on their outer surface.
- 5 Active helper T-cells bind to these B-cells and, in turn, activate them.

- 6 Just like the T-cells, the B-cells now divide into two clones of cells. One is made up of active B-cells, or plasma cells, which secrete huge quantities of antibodies into the bloodstream. The second clone is made up of memory cells.

KEY POINT

clonal selection exposure to antigen results in activation of selected T-cell or B-cell clones, producing an immune response.

- 7 Antibodies in the bloodstream destroy pathogens and also help the macrophages to detect and consume more pathogens.

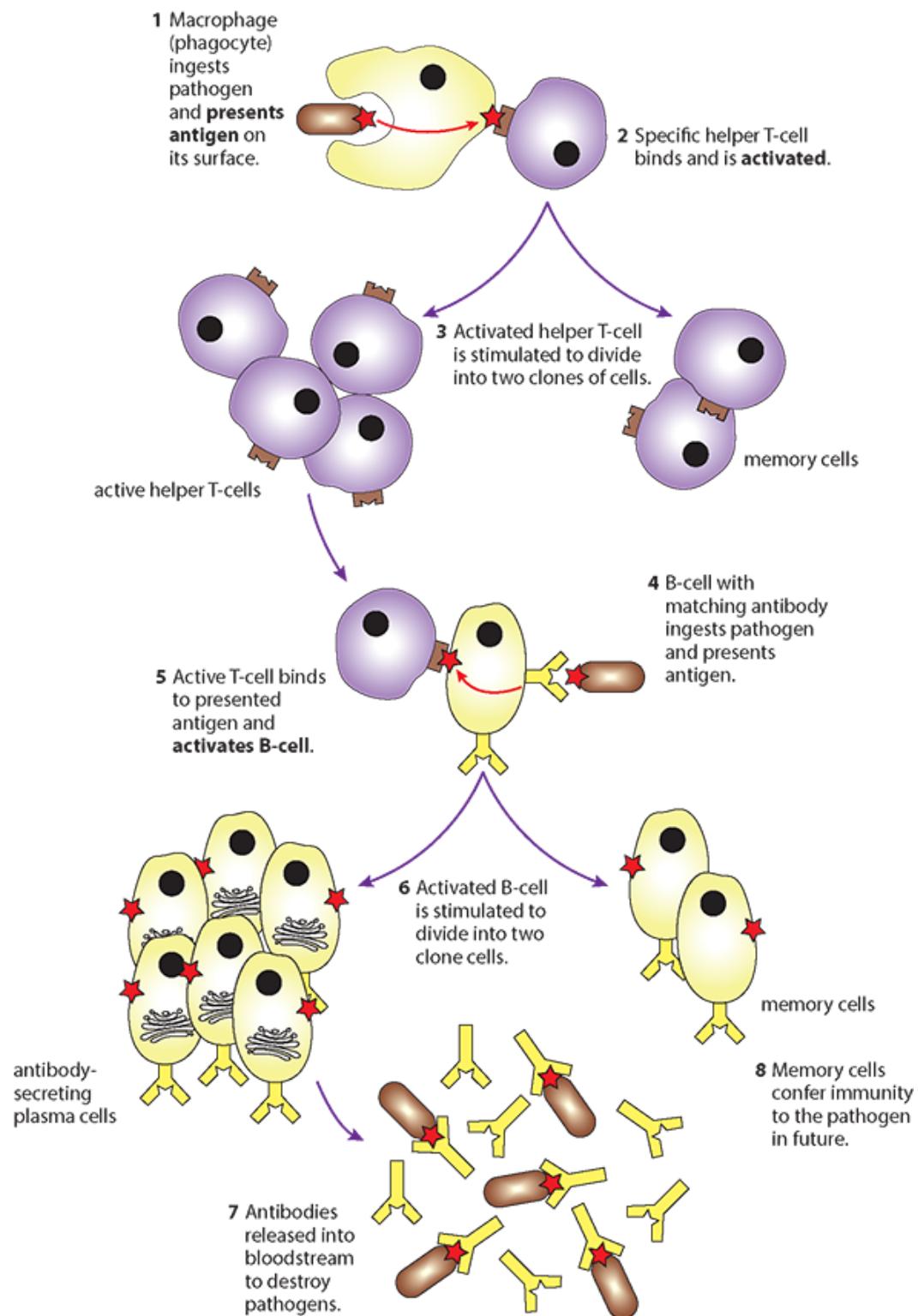


Figure 10.1.6: Summary of the process of antibody production in the cell-mediated response.

| Type of cell | Function of cell |
|---|--|
| macrophages (phagocytic leucocytes) | engulf any pathogen or dead cells and present their antigens on their cell surface membrane |
| cytotoxic T lymphocytes (killer T-cells) | destroy cells that are ‘non-self’ and have antigen on their surface membrane |
| B lymphocyte (B-cells) | B-cells are cloned to become activated plasma cells to produce antibodies, or to become memory cells in the humoral response |
| T lymphocytes (T-cells), helper T-cells | bind to macrophages and become activated; T-cells are cloned to produce more activated T-cells and memory cells |
| plasma cells | antibody-producing cells derived from T-cells and B-cells; part of the humoral response |
| memory cells | cells produced by B-cells and T-cells which remain in the bloodstream after infection to prolong resistance to the antigen |

Table 10.1: Cells involved in the immune response.

- 8 Memory cells remain and allow the body to make a large and rapid response should the same pathogen invade again. It is the persistence of memory cells that gives the organism immunity to that pathogen in the future.

Figure 10.1.6 The production of antibodies in the cell-mediated response involves macrophages, helper T-cells and B-cells.

Plasma cells contain large amounts of rough endoplasmic reticulum to synthesise antibodies.

Table 10.1 summarises the types of cell involved in the immune response.

10.1.3 HIV and AIDS

Human immunodeficiency virus (HIV; Figure 10.1.7), first identified in the early 1980s, causes the series of symptoms together known as acquired immune deficiency syndrome, or AIDS. HIV infects only the helper T-cells, a type of lymphocyte that is important in maintaining communication between cells of the immune system. After a latent period of months or years, helper T-cells are gradually destroyed and, as their numbers fall, so does the body's ability to fight infection. Helper T-cells instruct other lymphocytes to clone and generate antibodies, and without them an infected person can no longer fight off pathogens. Secondary infections result and the person is said to be suffering from AIDS.

HIV is a retrovirus, which means it can insert its DNA into that of a host cell using a protein called reverse transcriptase. Even if all the viruses in the body could be removed, the infected T-cells would continue to make new viruses.

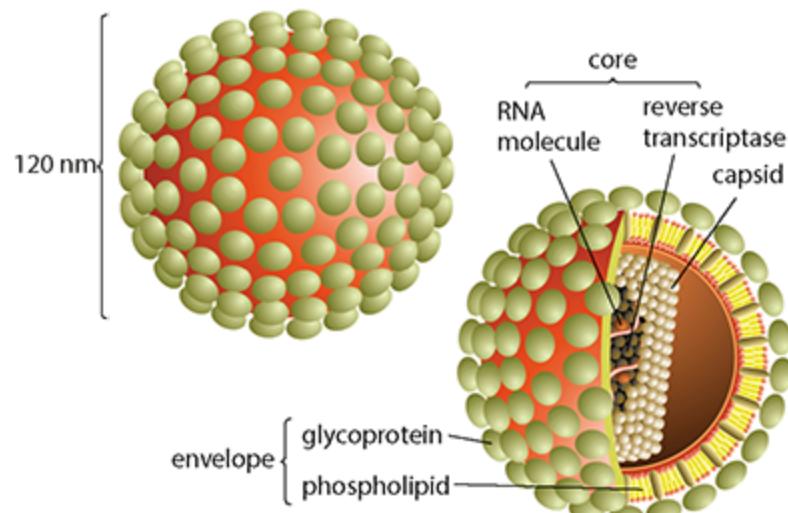


Figure 10.1.7: HIV viruses consist of a spherical glycoprotein and lipid coat enclosing two strands of RNA. The virus is 60 times smaller than a red blood cell.

Cause and consequences of AIDS

HIV is transmitted in blood, vaginal secretions, semen, breast milk and sometimes across the placenta. In some countries, HIV has been transmitted in blood transfusions, but in most places with medical care facilities, blood for transfusion is now screened for the virus. The virus is most frequently passed from person to person in bodily fluids during sex and also when non-sterile syringe needles are used to administer either legal or illegal drugs.

AIDS is the end stage of an HIV infection. It is caused by a severe failure of the immune system as the HIV virus selectively infects helper T-cells. Some infected individuals have no symptoms in the early stages of the disease while others may be slightly unwell when first infected. Symptoms of AIDS develop as the number of active helper T-cells decreases. The symptoms occur as a result of secondary infections caused by bacteria, fungi and viruses. The body is unable to resist these infections due to its compromised immune system (Figure 10.1.8).

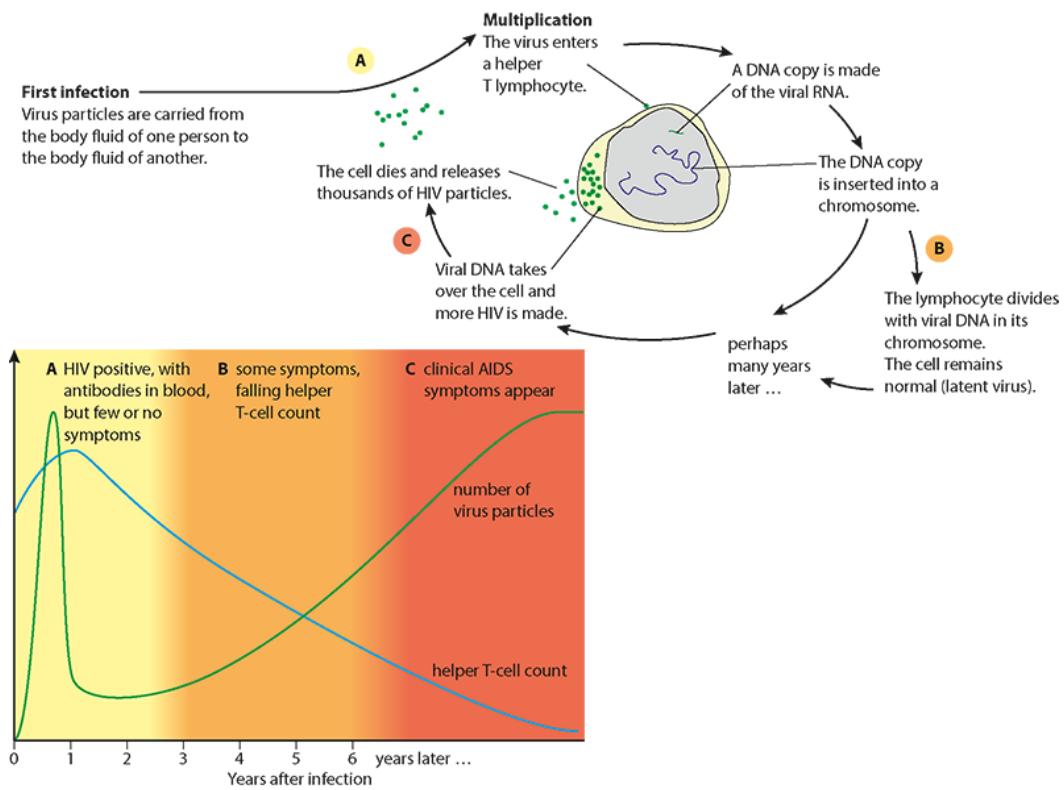


Figure 10.1.8: HIV infection proceeds through three stages: **A** HIV-positive with few symptoms, **B** some symptoms and low helper T-cell count and **C** clinical AIDS with associated symptoms.

10.1.4 Antibiotics

If the body's natural defences are unable to deal with an infection, medical intervention may be needed. Most bacterial infections can be treated with **antibiotics**. Antibiotics are natural substances that slow the growth of bacteria. Since the discovery of penicillin in 1928, many antibiotics have been isolated and about 50 are now manufactured for medical use. These antibiotics work in different ways but are effective because prokaryotic and eukaryotic cells have different metabolic pathways. So, eukaryotic cells are not affected by antibiotics. Some antibiotics block the protein synthesis mechanism in bacteria while not affecting the process in human cells (Figure 10.1.9). Others interfere with the formation of the bacterial cell wall and prevent bacteria growing and dividing.

Viruses are not living and have no metabolic pathways of their own. Since they use their human host's metabolism to build new viruses, antibiotics have no effect against viral infections.

INTERNATIONAL MINDEDNESS

International aspects of disease

AIDS is a worldwide pandemic but some regions and some age groups are more seriously affected than others. There were approximately 38 million people across the world with HIV/AIDS in 2019. Of these, 36.2 million were adults and 1.8 million were children under the age of 15 years. The vast majority of people with HIV are in low-income and middle-income countries. In 2019, there were 20 million people with HIV in eastern and southern Africa, 5 million in western and

central Africa, 6 million in Asia and the Pacific and 2 million in Western and Central Europe and North America.

Nevertheless, education campaigns and new treatments have improved the situation and there has been a decline in new HIV infections of almost 25% since 2010.

In 2019 nearly 70% of people infected with HIV (about 25 million) were receiving antiretroviral therapy (ART). People who know they have HIV and take ART can remain healthy and are unlikely to pass the virus on. In addition, 85% of pregnant people with HIV received ART to prevent transmission of HIV to their babies during pregnancy and childbirth. AIDS-related deaths have been reduced significantly since the peak in 2004. In 2019, around 690 000 people died from AIDS-related illnesses worldwide, compared to 1.1 million in 2010.

The spread of the HIV virus, and other pathogens such as avian influenza (bird flu) and SARS (COVID-19) are problems for the whole world. International travel means that pathogens can travel further and faster than ever before. Governments and health authorities must work together to co-ordinate their responses.

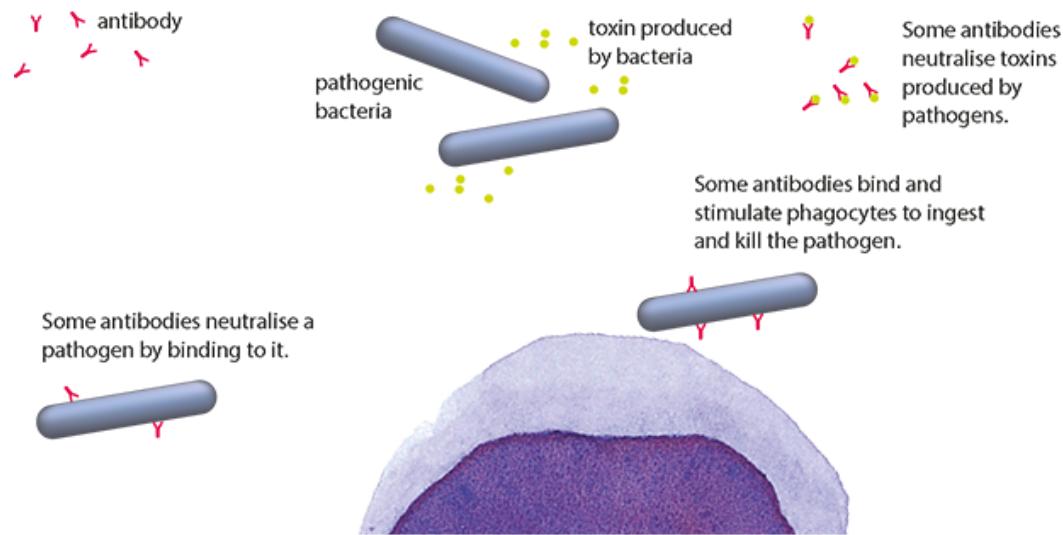


Figure 10.1.9: The various ways in which different antibodies can destroy bacteria or their toxins.

Antibiotic resistance

Antibiotics kill or block the growth of bacteria but not all bacteria are susceptible to them. In any population of bacteria some individuals will have a natural resistance to the antibiotic used to kill them. This resistance may arise spontaneously by mutations. Resistant strains multiply along with susceptible strains but, if antibiotics are used, only the sensitive bacteria will be killed while the resistant ones survive. Resistant bacteria are also able to pass on their resistance to other bacteria via their plasmids. Plasmids are loops of DNA, separate from the bacterial chromosome, that can be passed from one bacterium to another. Treating a disease caused by resistant strains of bacteria becomes very difficult. Doctors may have to prescribe stronger doses of antibiotic or try different antibiotics to kill the resistant bacteria.

NATURE OF SCIENCE

Assessing risk in science: collaboration, safety and new medicines

The discovery of antibiotics began by accident. On 3 September 1928, Alexander Fleming was examining a batch of culture plates on which he had grown *Staphylococcus* bacteria. He noticed that one of the plates had a green mould growing on it. The mould was *Penicillium notatum*. The mould growth was circular in shape, and the area around it seemed to be free of *Staphylococcus*. On other areas of the plate, the bacteria were continuing to grow well. Fleming deduced that the bacteria around the circular mould had been killed by a substance produced by the mould.

Fleming discovered that the mould could kill other bacteria and that it could be given to small animals without any harmful effects. However, he then moved on to other research and it was not until 10 years later that Howard Florey and Ernst Chain, working at Oxford University, isolated the bacteria-killing substance, penicillin, produced by the mould. Chain was a German chemist and Florey an Australian pathologist. It was Chain who isolated and purified penicillin and Florey who tested its safety to use on animals and humans. The first tests the team carried out on mice in 1940 would not have met the stringent standards for testing on animals today. Eight mice were given lethal doses of *Streptococcus* bacteria. Half the mice were then given injections of penicillin. The following day all the untreated mice were found to be dead but those that had been given penicillin survived.

One of the first uses of penicillin was in 1941, when Dr Charles Fletcher gave it to patient at a hospital in Oxford who was near to death as a result of bacterial infection in a wound.

Fletcher used some penicillin on the patient and the wound made a spectacular recovery. Unfortunately, Fletcher did not have sufficient penicillin to clear the patient's body of bacteria and he died a few weeks later as the pathogen regained a hold.



Figure 10.1.10: The discovery of penicillin is commemorated with a plaque on the wall of St Mary's Hospital in London where Alexander Fleming carried out his work.

An American brewing company began mass production of penicillin and soon sufficient quantities were available to treat all the bacterial infections among the troops fighting in World War II. Penicillin was nicknamed 'the wonder drug' and in 1945 Fleming, Chain and Florey shared the Nobel Prize in Physiology or Medicine for its isolation and development.

To consider:

- 1 Why did the discovery of penicillin have such a profound effect on people at the time?

- 2** Why was the collaboration of three scientists vital to the discovery of penicillin?
- 3** What are the ethical issues involved in using a new drug for the first time? Was Fletcher right to use penicillin on his patient?
- 4** The test on the safety of penicillin used by Florey would not be accepted today. What are the risks associated with the development of new medicines?

The more often antibiotics are used, and the more different types that are used, the greater the risk that resistance will develop. So, over-use and the improper use of antibiotics are thought to have contributed to the development of resistance. Bacteriologists are concerned that some diseases will become untreatable with currently available antibiotics. The so-called superbug meticillin-resistant *Staphylococcus aureus* (MRSA) now has multiple resistance to many antibiotics and recently strains of the bacteria that cause tuberculosis and the sexually transmitted disease gonorrhoea have been found to be resistant to *all* the antibiotics that have been used to treat them.

SCIENCE IN CONTEXT

Sources of new antibiotics

Bacterial diseases cause social and economic problems for countries all over the world and modern travel has enabled infections to spread rapidly. The problem of drug-resistant bacteria is serious and growing and is likely to become one of the biggest threats to human and animal health in the 21st century. Most people are aware of the ‘superbugs’, such as MRSA and *Clostridium difficile*, which are a leading cause of

infections in hospitals. But there are other resistant bacteria, such as drug-resistant *Mycobacterium tuberculosis*, the organism that causes tuberculosis, which is resistant to several antibiotics and can take up to 2 years to treat.

There have been few significant discoveries of new antibiotics for many years. Existing antibiotics are becoming less effective because some of the bacteria that are not killed by current antibiotics pass on antibiotic resistance to other species of bacteria. Traditional sources of antibiotics are fungi and bacteria which produce them to defend themselves against bacteria. Penicillin (described in the section on Assessing risk in science: collaboration, safety and new medicines) is one example of an antibiotic derived from a fungus. Scientists continue to seek potential new sources of antibiotics in the natural world in the soil, in plants and animals such as corals.

There are thousands of species of bacteria present in the soil but they are hard to grow and study in the laboratory. In the early 21st century a team of scientists from several countries worked together and devised a new method to find those that have antibiotic properties. The team designed a device called an ichip (isolation chip) which cultures different species of bacteria in their soil environment and has enabled the researchers to study many new microorganisms. They discovered that the soil bacterium *Eleftheria terrae* produces an antibiotic called teixobactin that has been shown to be effective against many drug-resistant strains. Teixobactin was discovered using the ichip in 2015. Tests revealed teixobactin was effective against Gram-positive bacteria including MRSA and the bacteria that cause tuberculosis. However, it was not effective against Gram-negative bacteria such as *Escherichia coli*. Gram-negative bacteria have an outer lipid layer, which Gram-positive bacteria do not.

Teixobactin inhibits bacteria in a way in which cells are unlikely to develop resistance. Penicillin inhibits the production of new cell walls, but teixobactin does the opposite. It prevents cell walls being broken down. For cells to grow and then divide their walls must be able to expand. If cell breakdown is blocked the cell is trapped and cannot expand or grow and so it will die.

Another new method in antibiotic research has been used at the Massachusetts Institute of Technology in the USA. Researchers used a machine-learning algorithm to seek and identify new antibiotics. The researchers designed a system to look for chemical features that make molecules effective at killing *E. coli*. They trained a computer to check 2500 molecules, including about 1700 already approved drugs and 800 natural substances with a wide range of different structures and biological activities. The computer identified a substance which the team called halicin after the fictional computer Hal in the film *2001: A Space Odyssey*. Halicin was tested against different resistant bacterial strains grown in the laboratory and others isolated from patients. It was able to kill many of them, including *C. difficile* and *M. tuberculosis*. With further development, halicin may become an antibiotic of the future.

TEST YOUR UNDERSTANDING

- 1** Define the term ‘pathogen’.
- 2** Describe what is meant by the term ‘antigen’.
- 3** State why antibiotics are not effective in treating viral diseases.

4 Distinguish between the roles of a ‘phagocyte’ and a ‘lymphocyte’.

10.1.5 Zoonoses - pathogens and species specificity

Pathogens that cause disease in one species do not always affect other species. For example, the pathogens responsible for syphilis, gonorrhoea, measles and polio infect humans, whereas canine distemper virus does not. *Shigella*, a bacterium that causes dysentery in humans and baboons, does not affect chimpanzees. The exact reasons for these differences are not fully understood, but it may be that cells in non-susceptible species do not have suitable receptors on their plasma membranes for the pathogens to bind to them. The temperature of the host organism may also be important: birds cannot be infected with mammalian tuberculosis that affects humans, deer, goats, pigs, cats, dogs and badgers because the bacteria that cause the disease cannot survive at the higher core temperatures of birds' bodies. Similarly, frogs are unaffected by anthrax-causing bacteria because their body temperatures are too low.

Occasionally, however, a disease does cross the species barrier, and a disease that does this is called a zoonosis. Zoonotic pathogens may be bacterial, viral or parasitic and can spread to humans through direct contact or through food, water or the environment. The malaria parasite is one example of a parasite that can infect humans but also infects birds, bats and lizards. It is transmitted via a mosquito that carries the juvenile stages of the parasite. Other zoonotic diseases include influenza, which has many variants that affect different species and is transmitted through the air from one species to another. Examples are: rabies caused by a virus which affects dogs, skunks, bats and foxes and is transmitted in the saliva when an infected animal bites another; anthrax, which affects hooved animals such as deer, goats and

cattle as well as humans and is transmitted by contact with infected animals; and avian or bird flu, which affects wild and domestic birds and mammals who may become infected by saliva, mucus or feces of infected birds. Bird flu infections among people are very rare, but can happen if sufficient numbers of virus particles enter the eyes, nose, or mouth. Another serious zoonotic disease is Japanese encephalitis, a viral brain infection that is spread to humans through mosquito bites. It is very rare in humans, but the virus is found in pigs and birds in south east Asia. It is passed to mosquitoes when they bite an infected animal. All these diseases have serious social and economic consequences and cause loss of life and income.

KEY POINT

zoonosis is a disease that can cross species barriers and affect a different species.

Most newly emerging diseases that have crossed the barrier from animal to human are caused by viruses. Crossing to a new species is a rare occurrence, but viruses that do so can cause severe outbreaks of disease, especially if they develop the ability to pass from human to human, rather than just from animal to human. The spread of the COVID-19 virus through human populations has shown us how a virus can spread rapidly all over the world and how international travel and trade increase the spread of this, and other viruses.

For a virus to infect a new species, genetic adaptations must occur within the virus. Avian flu arose in this way. The expansion of both human and farm populations has made close interaction between birds and humans more common and enabled the virus to transfer from infected birds to humans via a

bird's saliva, feces or nasal secretions. Many strains of bird flu have emerged, but one of the most widely publicised is the H5N1 influenza virus, a highly pathogenic Asian strain that caused a pandemic in birds in 2003. This virus can cause severe illness in humans who are infected by direct contact with infected birds and it has a high mortality rate. It does not appear that H5N1 can be spread by human-to-human contact at present. However, because viruses can adapt and change quickly, it may evolve this ability at some point and would then have the potential to cause a human pandemic. Health agencies have begun the preparation of vaccines in case this should happen.

INTERNATIONAL MINDEDNESS

COVID-19

Coronavirus disease 2019 (COVID-19) is a contagious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The virus is thought to have originated in bats, but this has not been confirmed conclusively. Coronaviruses are not rare in nature and previously caused the human epidemic of SARS that began in 2003. The first known case of COVID-19 was identified in Wuhan, China, in December 2019 where the virus was isolated from three people with pneumonia. It is a new variant of the SARS-CoV-2 coronavirus and since it was identified many new variants have developed. All structural features of the new virus occur in related coronaviruses in nature, but mutations of this virus made it highly infectious to humans. COVID-19 disease was declared a pandemic by the World Health Organization on 11 March 2020, mainly due to the speed and scale of the transmission of the disease. The virus is a single-stranded RNA virus, and its genome encodes for 29 proteins involved in the infection, replication and virus

assembly process. Like other coronaviruses it has crown-like spikes on its surface. In less than one year, with international collaboration among the scientific community, the virus genome was sequenced, methods of transmission were identified, treatments were investigated and new vaccines were developed to combat it. The pandemic has caused loss of life and damage to economies throughout the world. It is possible that other viruses will do the same in the future.



Figure 10.1.11: Newspaper headlines around the world summarised the seriousness of the COVID-19 pandemic.

To consider:

- 1 How did the COVID-19 pandemic affect life where you live?
 - 2 As the pandemic developed, new variants of the COVID-19 appeared. Research how these variants arose and how they affected the spread of the virus.

SCIENCE IN CONTEXT

Allergic responses

Sometimes when microorganisms enter the body, or if the skin is injured, the immune system may trigger an inflammatory response. Inflammation is either a general response to an injury or a reaction that occurs in an area where phagocytes are destroying pathogens. The inflammatory response is brought about by two types of cell. These are basophils, which are a type of leucocyte (white blood cell), and mast cells, found beneath the skin and around blood vessels. Both types of cell can be stimulated to release a substance known as histamine into the affected area. Histamine relaxes the muscle in the walls of arterioles so that blood flow to the affected area is increased and it also loosens the cells in the capillary walls so that they become ‘leaky’. Plasma can then escape from capillaries into the surrounding tissue causing swelling (known as oedema) as well as a slight increase in temperature. Histamine also stimulates sensory neurons leading to pain or itching (Figure 10.1.12).

In some cases, histamine release can lead to an excessive immune response known as an allergy. An allergy is an immune response to an antigen (known as an allergen) to which most people show no reaction. Asthma, eczema and hayfever are common allergic disorders. Allergens include substances such as pollen grains, animal fur, house dust and certain foods. These substances have proteins on their surfaces which act as antigens and stimulate plasma cells to produce antibodies called reagins. Unlike normal antibodies, reagins circulate in the blood and bind to cells that contain histamine, especially the mast cells in the skin and mucus

membranes in the respiratory system. (These tissues are said to be hypersensitive.) Reagins cause the mast cells to release histamine, which binds to receptors on cells nearby and leads to inflammation and other symptoms of an allergy (Figure 10.1.12). In the bronchi, inflammation can lead to constriction and breathing difficulties as well as the secretion of excess mucus.

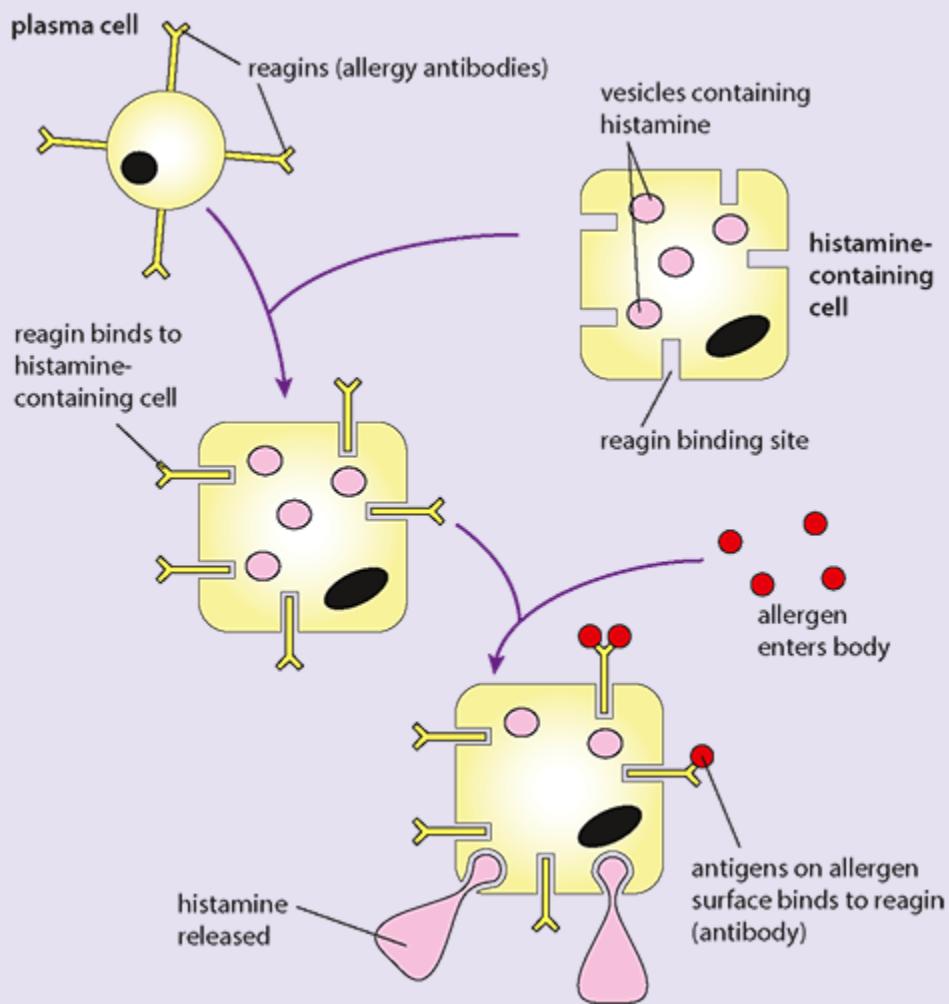


Figure 10.1.12: An allergic reaction occurs when plasma cells release antibodies against an allergen, which leads to the release of histamine.

KEY POINTS

allergy is an excessive immune response to an antigen.

histamine is a chemical produced by some white blood cells (leucocytes) that causes inflammation.

inflammatory response (inflammation) occurs when tissues are injured by bacteria or toxins, causing the release of histamine and other chemicals that leak into tissues, which leads to heat and swelling.

10.1.6 Vaccines and immunisation

Immunity develops when a person has been exposed to a pathogen. For most mild illnesses, such as the common cold or tonsillitis, this happens naturally as a person comes into contact with the viruses or bacteria that cause them. But some pathogens cause diseases that have dangerous or life-threatening symptoms. For these diseases, which include tetanus, tuberculosis, cholera, poliomyelitis, measles and COVID-19, vaccines have been developed to provide a safe first exposure so that a vaccinated person will develop immunity but not the disease.

KEY POINT

vaccine is a modified form of a disease-causing pathogen or their antigens that stimulate immunity without causing illness.

Vaccines are modified forms of the disease-causing pathogens. A vaccine may contain either weakened (attenuated) or dead pathogens carrying antigens, or their toxins. These vaccines are often produced by treating pathogens with heat or chemicals. The newest vaccines use sections of viral mRNA or viral vectors to stimulate an immune response.

Most vaccines are injected into a person's body, although some, such as polio vaccine, can be taken orally. Antigens produced as a result of vaccination stimulate the immune response and the formation of sufficient memory cells to produce antibodies very quickly if the person is infected with the real pathogen later on.

A first vaccination produces a primary response but many vaccinations are followed up with another some time later. The second or 'booster' dose of vaccine causes a greater and faster

production of antibodies and memory cells, known as a secondary response (Figure 10.1.13), and provides long-term protection. The length of time that antibodies and memory cells persist depends on the disease. Rubella vaccination can provide protection for up to 20 years, while vaccinations for tetanus should be repeated every 10 years. Vaccines do not prevent infection by pathogens but they do enable the body to respond quickly to them and prevent serious illness.

KEY POINT

secondary response refers to response to the second exposure to an antigen in a vaccine (or to the same pathogen) that causes a more rapid production of antibodies due to the presence of memory cells.

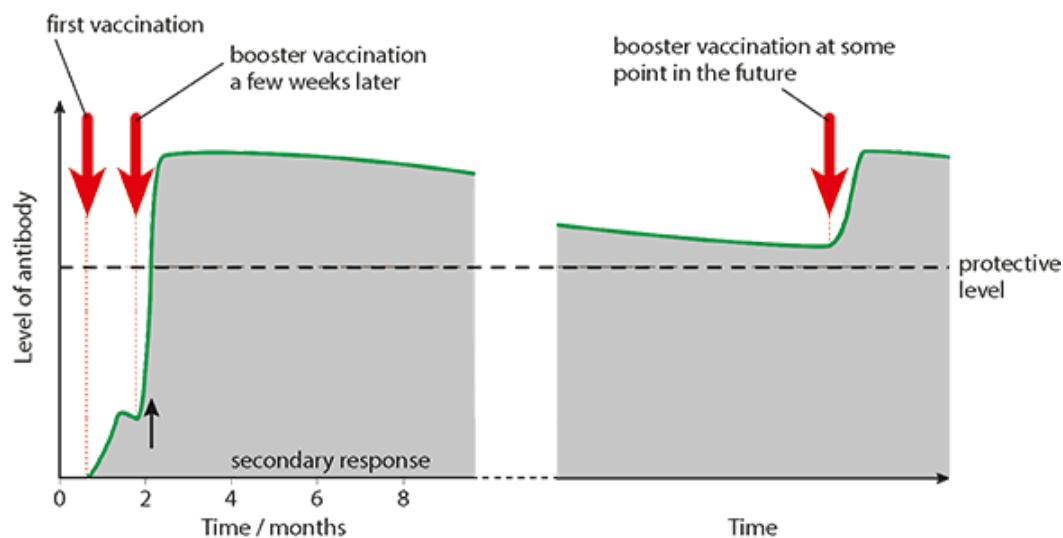


Figure 10.1.13: Antibody levels after vaccination. The persistence of antibodies varies and depends on the vaccine used.

SCIENCE IN CONTEXT

Vaccines against COVID-19

mRNA vaccines are a new type of vaccine to protect against infectious diseases and they have been developed rapidly to vaccinate people against COVID-19. An RNA vaccine consists of an mRNA strand that codes for a disease-specific antigen. Once the mRNA strand in the vaccine is inside the body's cells, the cells use the genetic information to produce the antigen. This antigen is then displayed on the cell surface, where it is recognised by the immune system, which responds by producing antibodies.

Viral vector vaccines use a modified version of a different virus (not the pathogen) to enter our cells and deliver instructions them. The vector virus stimulates them to produce a spike protein from surface of the COVID-19 virus. This protein triggers the production of antibodies and leads to immunity.

NATURE OF SCIENCE

Assessing ethics in science: the case of smallpox

Smallpox was a serious disease caused by the variola virus that killed thousands of people every year. It was transmitted by droplet infection. Edward Jenner (1749–1823) was a British scientist who developed a vaccine to protect people against the disease. He knew that dairymaids who had suffered from a similar but mild disease, called cowpox, were protected against smallpox. In 1796, Jenner isolated pus from the lesions of a dairymaid with cowpox, and applied it to a cut in the skin of an 8 year old boy, James Phipps. The boy caught cowpox and recovered. Next, Jenner inoculated the boy with smallpox viruses and discovered that James had developed immunity to the disease after his exposure to cowpox. Jenner

also tested his ideas on himself and his family. He named the procedure ‘vaccination’ from the Latin word *vacca* (cow).

Jenner was criticised and ridiculed for his ideas but Louis Pasteur (1822–1895) later supported him and went on to investigate the use of vaccines for other diseases.

In the 20th century, smallpox became the first infectious disease of humans to have been eradicated by vaccination. A campaign to eradicate it was started by the World Health Organization in 1977. Ten years later there were no new cases of the disease in the world. The WHO is now working on a programme to eradicate polio worldwide.

To consider:

- 1 Why do you think Jenner was criticised for his ideas and experiments?
- 2 What obstacles today are likely to delay a world vaccination programme like the one that was carried out on smallpox?

SCIENCE IN CONTEXT

Producing and testing new vaccines

Experiments like the ones that Jenner carried out would not be possible now. Today national and international laws require that all new medicines and vaccines are tested on animals before they can be used for humans. Vaccines cannot be tested on humans until ‘preclinical trials’ have been carried out. Preclinical trials are conducted to ensure the vaccine is safe and effective. These are first carried out using cells and tissue cultures in the laboratory (*in vitro*), and then the vaccine is

studied in more detail using animals, often mice, to confirm that they are effective in living organisms. Mice are important model organisms because, on average, the protein-coding regions of mouse and human genomes are 85% identical and some mouse genes are 99% similar to those in the human genome. But there are many uncertainties involved in using animals to test vaccines. There is considerable variety in the immune responses between different species, even those that are closely related. Also many viruses are species specific, which means that using non-human species for testing may not produce the same results.

Preclinical trials are used to understand the toxicity of the vaccine, which means how well it does its job without causing harm to other tissues. Next, testing in animals helps researchers understand the type of immune response that will be generated by a vaccine, and if it is likely be enough to protect a person from developing the disease.

Following this, the vaccine moves on to its first human trials, known as Phase I clinical trials. Small numbers of healthy, human volunteers are vaccinated to see if the vaccine acts in the same way in humans and to work out the most effective dose. Next, Phase II trials check that the vaccine works consistently in a much larger group of adults and researchers check for any side effects. Later a Phase III trial is carried out on a much larger number of people, usually several thousands, so that statistical data can be collected to check that the vaccine is reliable and produces a level of immunity that would prevent disease, and reduce the number of cases of disease. Only after this can an application be made to license a new vaccine.

Herd immunity and preventing epidemics

Herd immunity occurs when a large portion of a population becomes immune to a disease, either because they have had the disease or been vaccinated against it. The spread of disease from person to person becomes less likely when herd immunity is achieved because the disease-causing pathogen has few people to infect. As a result, the whole population, not just those who are immune, becomes protected to some extent as transmission of infection is greatly reduced.

When a high percentage of the population is vaccinated, it is difficult for infectious diseases to spread, because there are not many people who can be infected. For example, if someone with measles is part of a community of people who are vaccinated against measles, the disease cannot easily be passed on to anyone, and it will quickly disappear. This type of herd immunity (also called community immunity) gives protection to vulnerable members of the community such as newborn babies, elderly people and those who are too sick to be vaccinated for example people undergoing chemotherapy treatment or others with weakened immune systems.

Herd immunity does not protect against all diseases that can be prevented by vaccines, only diseases that are transmitted from person to person. One example of this is tetanus, which is caught from bacteria in the environment, not from other people who have the disease. Even if everyone around you is vaccinated against tetanus you will not be protected unless you are vaccinated too.

Herd immunity only works if a sufficient percentage of people in a population are vaccinated; for example, 19 out of every 20 people need to be vaccinated against measles to protect people

who are not vaccinated. Unlike vaccination, herd immunity does not give a high level of individual protection, and so it is not a good alternative to having a vaccination.

INTERNATIONAL MINDEDNESS

The World Health Organization (WHO)

Vaccination gives protection against many bacterial and viral diseases. Bacterial infections can be treated with antibiotics but virus diseases cannot. This means that vaccination against viral infection is very important. The WHO began a worldwide programme to vaccinate people against smallpox in 1967. They monitored outbreaks of the disease and contained them with vaccinations in many countries.

Smallpox only affects humans and other animals do not carry it. With high rates of vaccination it is difficult for a disease to spread as there are few people for the virus to infect. The last known case of smallpox was in Somalia in 1977 and the world was declared free of smallpox.

The WHO is now working on a new challenge to eradicate polio, a disease that can cause paralysis and seriously affects children. In 2020, the WHO was able to certify its African region as free of polio after 4 years without a case. This achievement meant that over 90% of the world's population are now free of the wild poliovirus, and the WHO moved closer to its target of eradicating polio everywhere. Only two countries, Pakistan and Afghanistan, still have poliovirus transmission.

The Director General of the WHO at that time, Dr Tedros Adhanom Ghebreyesus, said, "Ending wild polio virus in Africa is one of the greatest public health achievements of our

time and provides powerful inspiration for all of us to finish the job of eradicating polio globally.”

He attributed the success of the vaccination programme to strong leadership and innovation in the region, along with successful co-ordination of effort between countries in Africa. Major challenges in immunising the region’s children included high levels of population movement, conflict and insecurity that restricted access to health services, as well as the ability of the virus to spread quickly and cross national borders.

EXTENSION

Model organisms

A model organism is a species used by researchers to study specific processes in biology, especially in investigations in genetics, developmental biology and human disease.

Organisms chosen as models are non-human species that can show us how the biological processes of humans or other organisms work.

Ideal characteristics of model organisms include having a short life span, producing a large number of offspring, being easy to observe and having a genome which has been sequenced and is understood. A relatively small number of species are used as models and different organisms are used in different areas of research. Some examples are included in this book. They include the yeast (*Saccharomyces cerevisiae*) used in the study of the cell cycle, the fruit fly (*Drosophila melanogaster*) used to study genetics because it has only four pairs of chromosomes, breeds readily and matures very quickly, and the mouse (*Mus musculus*) used in studies of the

immune system. Mice share many human diseases because they have lived near people for thousands of years.

When studying disease, or testing vaccines, mice are usually chosen because of their similarity to humans in their genetics, anatomy and physiology. But, although all vertebrates share a common ancestor, and have similar developmental and metabolic pathways, information from studies of model organisms must be considered carefully, as there may be important differences as well as similarities.

TEST YOUR UNDERSTANDING

- 5** Define the term zoonosis and give an example.
- 6** Why can a person who has blood group O donate blood to any other person?
- 7** Summarise the importance of memory cells in the immune response.

Links

- How are pathogens classified? ([Chapter 11](#))
- How have some bacteria become resistant to many antibiotics? ([Chapter 11](#))
- How do animals protect themselves from other threats such as predators? ([Chapter 12](#))

SELF-ASSESSMENT CHECKLIST

Think about the topics covered in this chapter. Which parts are you most confident with? Which topics require some extra practice?

| I can... | Subsection | Needs more work | Nearly there | Confident to move on |
|---|------------|-----------------|--------------|----------------------|
| define a pathogen and give examples of organisms that are pathogenic | 10.1.1 | | | |
| summarise the properties of parts of the body that make up the first line of defence | 10.1.1 | | | |
| describe the process of blood clotting | 10.1.1 | | | |
| outline the process of phagocytosis | 10.1.1 | | | |
| describe the humoral immune response including role of lymphocytes and production of antibodies | 10.1.1 | | | |

| | | | | |
|---|--------|--|--|--|
| summarise the effects of HIV on the body's immune system | 10.1.3 | | | |
| outline how antibiotics kill bacteria and why they are ineffective against viruses | 10.1.4 | | | |
| describe how bacteria can become resistant to antibiotics | 10.1.4 | | | |
| define a zoonosis and give some examples of diseases and their transmission | 10.1.5 | | | |
| outline the differences in antibodies on red blood cells and the categorisation of ABO blood groups | 10.1.1 | | | |
| describe the cell-mediated response and the humoral response | 10.1.2 | | | |
| | | | | |

| | | | | |
|---|--------|--|--|--|
| summarise the roles of cytotoxic T-cells, B-cells and T-cells in the immune response | 10.1.2 | | | |
| describe the importance of memory cells | 10.1.2 | | | |
| outline the action of vaccines and recall that smallpox was eradicated by vaccination | 10.1.6 | | | |
| describe what is meant by herd immunity and how it can prevent epidemics. | 10.1.6 | | | |

REFLECTION

Reflect on how your knowledge of this subject is important to real-world situations and problems.

EXAM-STYLE QUESTIONS

You can find questions in the style of IB exams in the digital coursebook.

> Unit 4

Organisation in ecosystems

INTRODUCTION

In any ecosystem living organisms interact and depend on one another in many different ways. All living things need a place to live, a source of food and resources for reproduction. Some species become food for others, some provide a home for others and some co-operate with members of their own species or different species. If an ecosystem is undisturbed it will reach a balance or equilibrium where species that live there coexist in a sustainable way.

To study ecosystems we classify organisms into different groups and observe their adaptations and interactions. We can measure the ways in which energy is transferred from one organism to another as they feed and how the ecological relationships we see in food chains and webs make different systems resilient to change. Over thousands of years, evolution has occurred as different organisms have become adapted to live in different conditions. In a new or changing environment the best adapted will survive to reproduce and occupy new niches.



› Chapter 11

Evolution, speciation and ecosystems

A3.1, A3.2, A4.1, B4.1, B4.2,
D4.1

INTRODUCTION

Over long periods of time and many generations, species change as they become adapted to new surroundings or altered conditions. One result of these changes may be the evolution of new varieties and species. There is strong evidence for the evolution of life on Earth, both from the fossil record and from organisms that are alive today. Natural biological classification attempts to arrange living organisms into groups that enable

them to be identified and studied easily. In this way we can monitor diversity and show evolutionary links between different groups.

11.1 Classification

LEARNING OBJECTIVES

In this section you will:

- Learn that organisms have binomial names consisting of their genus and species
 - understand that natural classification helps identify and predict characteristics of species in a group
 - learn that taxonomists classify organisms using a hierarchy of eight taxa: domain, kingdom, phylum, class, order, family, genus and species but this does not always reflect divergence caused by evolution
 - define a clade as a group that contains all the organisms that have evolved from a common ancestor
 - learn that organisms are now classified into three domains based on rRNA evidence
 - draw clades as branches on phylogenetic diagrams
 - understand that modern cladistics uses genetic sequencing and amino acids to group organisms whereas traditional evidence was drawn from appearance
 - learn that sequence differences accumulate gradually and that there is a positive correlation between the

number of differences between two species and their divergence from a common ancestor.

GUIDING QUESTIONS

- Why does classification help scientists organise the diverse life on Earth?
- How can similarities and differences be used to identify or classify organisms?

11.1.1 The binomial system of classification

Natural classification (also called biological classification) attempts to arrange living organisms into groups so that we can identify them easily and show the evolutionary links between the groups. The system of classification we use today has its origins in a method devised by the Swedish scientist Carolus Linnaeus (1707–1778).

KEY POINT

natural classification is classification according to relationships based on descent from a common ancestor.

The classification of living organisms is simply a method of organising them into groups to show similarities and differences between them. More than 2000 years ago, the Greek philosopher Aristotle (384–322 BCE) classified organisms into two groups: plants and animals. This was useful as a starting point, but as the two main groups were subdivided, problems started to appear. At that time, organisms were seen to be unchanging, so there was no understanding of evolutionary relationships. Many organisms discovered later did not fit into the scheme very well.



Figure 11.1.1: Carolus Linnaeus, also known as Carl Linnaeus, was a Swedish botanist, physician and zoologist, who laid the foundations for the modern scheme of binomial nomenclature.

KEY POINTS

homology is the similarity due to shared ancestry between a pair of structures in different taxonomic groups.

taxon (plural taxa) is a group of one or more populations of an organism or organisms identified by taxonomists as forming a rank such as family or species.

taxonomy is the science of identifying, naming and grouping organisms.

Birds were separated into a group defined as ‘Feathered animals that can fly’ so no place could be found for the flightless cormorant, a bird that does not fly. Bacteria, which were unknown at the time, were not included at all.

In 1735, Carolus Linnaeus (Figure 11.1.1) adapted Aristotle's work, and his system forms the foundation of modern taxonomy. Taxonomy is the science of identifying, naming and grouping organisms.

Linnaeus gave each organism a Latin name, made up of two words. The first part of the name is a **genus** name and the second part is a **species** name. Thus the binomial, or two-part, name for the American grizzly bear is *Ursus americanus* whereas a polar bear is *Ursus maritimus*. Linnaeus used Latin for his names.

Latin has long been the language of medicine and science, and it is unchanging. If *Ursus maritimus* is mentioned anywhere in the world, scientists will know that polar bears are being discussed.

- The genus part of the name indicates a group of species that are very closely related and share a common ancestor.
- The species is usually defined as a group of individuals that are capable of interbreeding to produce fertile offspring.

Linnaeus developed structure in his classification system. For example, he grouped birds into birds of prey, wading birds and perching birds.

Although it is possible to group living things in many different ways, over the last 200 years a hierarchical classification system has emerged through agreement at many scientific meetings.

This system is now used by biologists everywhere. Modern taxonomists all over the world classify species using a hierarchy of groups called taxa (singular: taxon). There are eight levels to the hierarchy:

- 1 domain
- 2 kingdom

3 phylum (plural: phyla)

4 class

5 order

6 family

7 genus (plural: genera)

8 species.

Two examples of how species are classified are shown in Table 11.1.1.

| | Polar bear | Lemon tree |
|---------|-------------------|-------------------|
| Domain | Eukarya | Eukarya |
| Kingdom | Animalia | Plantae |
| Phylum | Chordata | Angiospermata |
| Class | Mammalia | Dicotyledoneae |
| Order | Carnivora | Geriales |
| Family | Ursidae | Rutaceae |
| Genus | <i>Ursus</i> | <i>Citrus</i> |
| Species | <i>maritimus</i> | <i>limon</i> |

Table 11.1.1: The taxonomic hierarchy for a plant species and for an animal species.

NATURE OF SCIENCE

By convention, the genus name starts with a capital letter, while the species does not. Both are written in italic or

underlined. Once an organism has been referred to by its full Latin name in a piece of text, further references abbreviate the genus to the first letter only – for example, *U. maritimus* (Table 11.1.1). Organisms from the same genus can be referred to with the genus name followed by sp. For example, one bear whose species we do not know could be *Ursus* sp. while several bears from the same genus would be written as *Ursus* spp.

Aristotle's original grouping of organisms into just two kingdoms has also been refined. Today the most widely accepted method of classification uses three Domains:

- Archaea – cells which do not contain a nucleus but have a different cell wall from bacteria
- Eubacteria – cells which do not have a nucleus
- Eukarya – organisms whose cells do contain a nucleus.

The Three Domain System was proposed in 1977. It is based on differences in the sequences of nucleotides in a cell's ribosomal RNAs (rRNA), as well as the organisms' membrane structure and sensitivity to antibiotics. Comparing rRNA structure is used because rRNA molecules in all living things have the same function and their structure has remained constant over time. This means that similarities and differences in rRNA nucleotide sequences are a good indicator of how closely related different organisms are.

It is generally thought that all cells came from a common ancestor cell termed the last universal common ancestor (LUCA). These LUCA eventually evolved into three different cell types, each representing a domain. (You can read more about LUCA in [Chapter 6](#)).

- Archaea:
 - 1 Kingdom Archaebacteria (ancient bacteria) – methanogens, halophiles and thermoacidophiles
- Eubacteria:
 - 2 Kingdom Eubacteria (true bacteria) – bacteria and cyanobacteria
- Eukarya:
 - 3 Kingdom Plantae – plants
 - 4 Kingdom Animalia – animals
 - 5 Kingdom Fungi – fungi
 - 6 Kingdom Protista – red algae and dinoflagellates

The problems of classifying asexual organisms

Scientists have devised classification schemes to identify species in an evolutionary or phylogenetic way. This is very difficult for bacteria and other microorganisms which reproduce asexually. The classic definition of a species as a group of organisms that can interbreed and produce fertile offspring cannot be used.

KEY POINTS

homologous structures are anatomical features showing similarities in shape, though not necessarily in function, in different organisms.

phylogenetic classification is the classification system based on evolutionary relationships.

Bacteria are organised into five groups according to their basic shapes: spherical (cocci), rod (bacilli), spiral (spirilla), comma (vibrios) or corkscrew (spirochaetes)([Chapter 10](#)). They do also have many biochemical differences in both their metabolism and cell structure, and this has been useful in classifying some groups.

Why is classification important?

Natural classifications group together organisms that share many of the same characteristics. This means that natural classifications are predictive, so that by studying the characteristics of an organism it is possible to predict the natural group it belongs to.

Phylogenetic classifications are natural classifications that attempt to identify the evolutionary history of species. The role of taxonomy is to group species that are related by common ancestry.

A natural classification such as the one devised by Linnaeus is based on identification of homologous structures that indicate a common evolutionary history. A homology is similarity in structures that are found in different taxonomic groups and which are due to shared (common) ancestry.

If homologies, such as the arrangement of bones in vertebrate limbs, described in [Section 11.4](#) Niches and adaptation, are shared by organisms, then it is likely that those organisms are related. So the binomial system can be both a natural and a phylogenetic classification.

In summary, there are four main reasons why organisms need to be classified:

- 1 to impose order and organisation on our knowledge

- 2 to give each species a unique and universal name, because the local names that people use for the same organism vary from place to place around the world
- 3 to identify evolutionary relationships; if two organisms share particular characteristics then it is likely that they are related to each other, and the more characteristics they share then the closer the relationship
- 4 to predict characteristics; if members of a particular group share characteristics then it is likely that other, newly discovered members of that group will have at least some of those same characteristics.

Classifications change

New species are being found and new discoveries are being made about existing species all the time. Such discoveries may force us to rethink the way we classify living things. For example, in the past, the name ‘bacteria’ was given to all microscopic single-celled prokaryotes. But recent molecular studies have shown that prokaryotes can be divided into two separate domains, the Eubacteria and the Archaea, which evolved independently from a common ancestor. Molecular biology, the study of DNA, RNA and protein sequences and studies of cell ultrastructure have shown that the Archaea and Eukarya (eukaryotes) are in fact more closely related to one another than either is to the Eubacteria. Similar principles are applied to all levels of classification. Taxonomists reclassify organisms when new evidence shows that they have evolved from different ancestral species.

11.1.2 Using a dichotomous key

A dichotomous key is a series of steps, each involving a decision (Figure 11.1.2), which can be used to identify unknown organisms. The key prompts us to decide, through careful observation, whether or not organisms we are studying have particular visible features. The key allows us to distinguish between different organisms on this basis.

When a key is made to identify organisms such as those shown in Figure 11.1.3, each specimen is examined carefully, and a characteristic is chosen that is present in about half of the individuals and absent in the others.

KEY POINT

dichotomous key a key in which organisms are separated into pairs of smaller and smaller groups by observation of their characteristics.

For example, in this key for invertebrates, the presence of wings is the first distinguishing characteristic, which divides the specimens into two smaller groups.

Now, for each group, another diagnostic feature is chosen to divide the specimens into two further groups, and so on. The branching tree diagram shown in Figure 11.1.3 progressively divides the specimens into smaller and smaller groups, until at the end of each branch a single individual is identified.

| | |
|--------------------|---------|
| 1 Wings present | go to 2 |
|--------------------|---------|

| | |
|----------|---------|
| No wings | go to 5 |
|----------|---------|

| | | |
|---|---|------------------|
| 2 | Two pairs of wings | go to 3 |
| | One pair of wings | fly |
| 3 | Legs all approximately the same length | go to 4 |
| | Hind pair of legs much longer than front two pairs | locust |
| 4 | Wings covered in scales | butterfly |
| | Wings transparent, not covered in scales | dragonfly |
| 5 | Four pairs of legs | spider |
| | More than four pairs of legs | go to 6 |
| 6 | Pair of claws present | crab |
| | No claws | go to 7 |
| 7 | Body clearly divided into equal-sized segments | centipede |
| | Body in two regions, segments only clear on hind region | prawn |

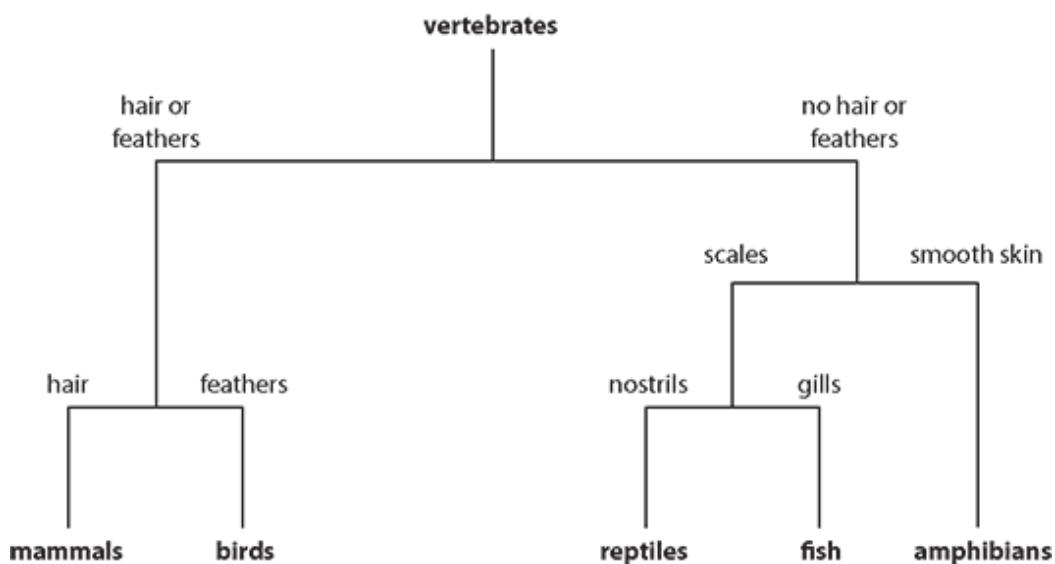


Figure 11.1.2: A simple key like this can be used to identify the vertebrate groups.

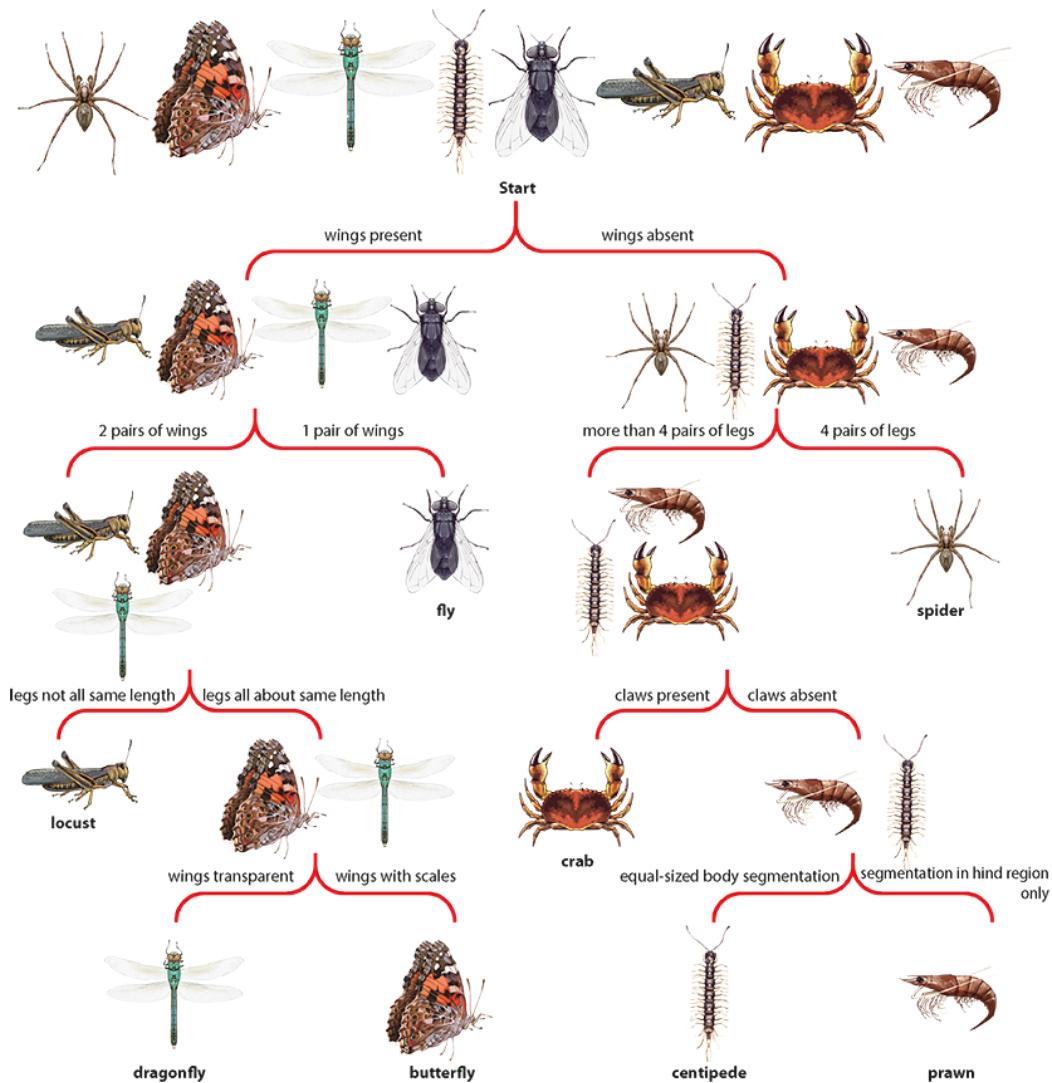


Figure 11.1.3: A dichotomous tree diagram distinguishing eight organisms.

The tree diagram can be ‘translated’ into a written key so that the branch points in the diagram are instead expressed as alternative statements. Each alternative either names the identified specimen or leads to another pair of statements, until an identification is reached. A well written key is composed of a

series of questions or steps, such that an organism that is being studied can only be placed in one of two groups.

NATURE OF SCIENCE

Cooperation and collaboration: an international naming system

Local names for different species can cause confusion. People in different parts of the world or even different parts of the same country use different common names for the same species. What do you think is being described here: armadillo bug, cafner, wood bug, butchy boy, gamersow, chiggle pig, sow bug, chuggypig and pill bug?

All these terms are local names for the woodlouse *Porcellio scaber*, or its relative *Armadillidium vulgare*, and are used in different parts of Europe and North America.

Cooperation and collaboration between international scientists provided an agreed binomial name for the woodlouse so that wherever they are studied, information about them can be attributed to the correct species.

TEST YOUR UNDERSTANDING

- 1** List, in order, the levels in the hierarchy of taxa.
- 2** State the two names from the hierarchy of taxa that are used in the binomial system.
- 3** If you were making a dichotomous key to identify leaves, explain why the question ‘Is the leaf large?’ would not be useful.

11.1.3 Cladistics

The universality of DNA and protein structures

Despite the incredible complexity of life, the building components of living organisms are not only simple in structure but are also universal.

- All living organisms use DNA built from the same four bases to store their genetic information and most use the same triplet code during translation. The few exceptions include mitochondria, chloroplasts and a group of bacteria which all have slight variations in the triplet code they contain.
- Proteins are built up from amino acids and living organisms all make use of the same 20 amino acids. In most cases, if a gene from one organism is transferred into another, it will produce the same polypeptide (if the introns have been removed from it; see [Chapter 3](#)).

These facts indicate a common origin of life and provide evidence to support the view that all organisms have evolved from a common ancestor. Study of the genetic code and amino acids of an organism can provide evidence that links it to its close relatives. This enables us to build up diagrams called cladograms, which show how species are related to one another in clades.

Clades and cladistics

Cladistics is a method of classification that groups organisms together according to the characteristics that have evolved most

recently. Diagrams called cladograms divide groups into separate branches known as clades (Figure 11.1.4 and 11.1.6).

Each branch ends in a group that has characteristics the other group does not share. A clade contains the most recent common ancestor of the group and its descendants, so a clade contains all the organisms that have evolved from a common ancestor.

Figure 11.1.4 shows five organisms forming part of an evolutionary tree.

KEY POINTS

clade a group of organisms, both living and extinct, that includes an ancestor and all the descendants of that ancestor.

cladistics a method of classifying organisms using cladograms to analyse a range of their characteristics.

cladogram a diagram that shows species' evolutionary relationships to one another.

root the ancestral population from which all other species originate

a branching point from the ancestral population is a node

the end of each branch, labelled with name of the taxonomic group is called a terminal branch

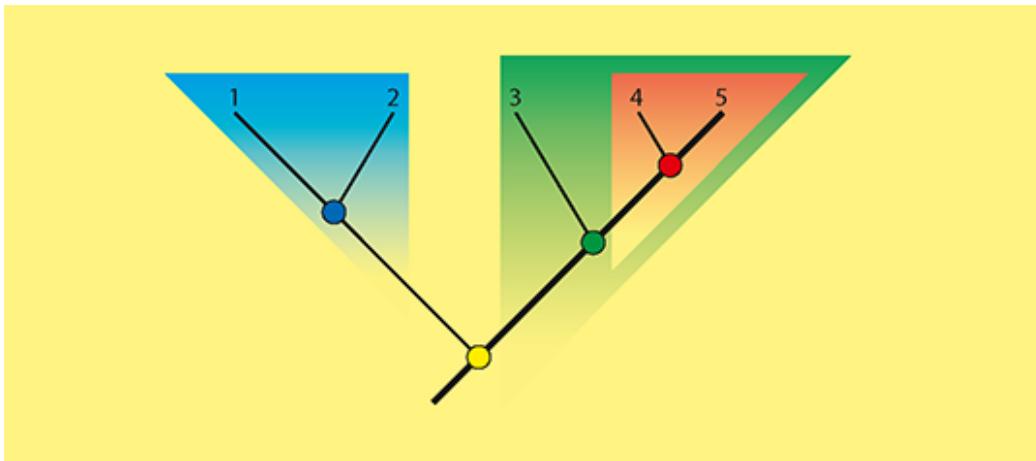


Figure 11.1.4: A cladogram with four clades.

- Organisms 1, 2, 3, 4 and 5 belong to the yellow clade.
- Organisms 1 and 2 belong to the blue clade.
- Organisms 3, 4 and 5 belong to the green clade.
- Organisms 4 and 5 belong to the red clade.
- The common ancestor for each clade is shown by the coloured spot at the branch point, or node.

Why do biologists need cladistics?

There are three important reasons for using cladistics to organise and discuss organisms.

- 1 Cladistics is useful for creating systems of classification so that biologists can communicate their ideas about species and the history of life.
- 2 Cladograms are used to predict the properties of organisms. A cladogram is a model that not only describes what has been observed but also predicts what might not yet have been observed.

- 3 Cladistics can help to explain and clarify mechanisms of evolution by looking at similarities between the DNA and proteins of different species.

11.1.4 Finding evidence for clades and constructing cladograms

Phylogenetics is the study of how closely related organisms are and it is used to establish clades and construct cladograms.

Historically, the evidence used to construct a phylogeny was based on visible characteristics but molecular phylogenetics is the modern approach. Molecular phylogenetics examines the sequences of DNA bases or of amino acids in the polypeptides of different species to establish the evolutionary history of a group of organisms. Species that are the most genetically similar are likely to be more closely related. Genetic changes are brought about by mutation and, provided a mutation is not harmful, it will be retained within the genome. Differences in DNA accumulate over time at an approximately even rate so that the number of differences between genomes (or the polypeptides that they specify) can be used as an approximate evolutionary clock. This information can tell us how far back in time species split from their common ancestor. A greater number of differences in a polypeptide indicates that there has been more time for DNA mutations to accumulate than if the number is smaller. There is a positive correlation between the number of differences between two species and the time they evolved from a common ancestor.

KEY POINT

phylogeny a diagram showing relationships between different organisms that represents their evolutionary history.

Evidence from amino acids

We can expect that related organisms will have the same molecules carrying out particular functions and that these molecules will have similar structures. So by comparing proteins in different groups of organisms, and checking them for similarities in amino acid sequences, it is possible to trace their ancestry. Chlorophyll, hemoglobin, insulin and cytochrome *c*, which are found in many different species, have all been studied in this way. Cytochrome *c* is found in the electron transport chain in mitochondria, where it plays a vital role in cell respiration. Its primary structure contains between 100 and 111 amino acids and the sequence has been determined for a great many plants and animals.

Table 11.1.2 shows the number of amino acid differences in cytochrome *c* between humans and four other species.

From these data, it is possible to construct a cladogram showing the relationships between these five organisms, as shown in Figure 11.1.5. There are no differences between rabbit and mouse cytochrome *c*, so they have to be drawn together at the end of a branch, and the same applies to the chimpanzee and human. Rhesus monkey differs from chimpanzee and human by only one amino acid and so the branch point must be one unit from the end. Rabbit and mouse differ by nine amino acids and so the branch point must be nine units further down.

Biochemical analysis of other molecules or comparison of DNA sequences would be needed to complete the separation of rabbit from mouse and human from chimpanzee.

| Organism | Number of amino acid differences in cytochrome <i>c</i> compared with human |
|------------|---|
| human | — |
| chimpanzee | 0 |

| | |
|---------------|---|
| rhesus monkey | 1 |
| rabbit | 9 |
| mouse | 9 |

Table 11.1.2: Table comparing cytochrome *c* in five species.

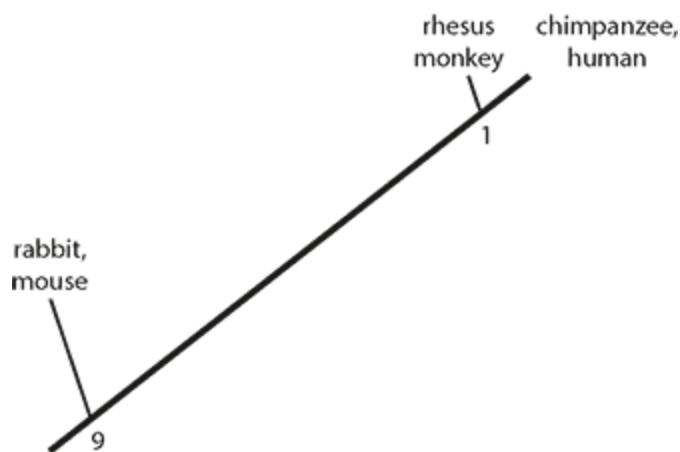


Figure 11.1.5: A cladogram for five mammal species based on the amino acid differences in cytochrome *c*.

There is only one difference between the human cytochrome *c* and that of a rhesus monkey but rabbits and mice have nine differences when compared with humans, which indicates they are less closely related. This biochemical evidence supports the classification of the animals that has been made from morphological observations.

Sequence differences accumulate gradually so there is a positive correlation between the number of differences between two species and the time since they diverged from a common ancestor.

11.1.5 The shapes of cladograms

Cladograms can be drawn in one of two ways, as shown in Figure 11.1.6, which shows two formats for a cladogram of living vertebrate animals. By looking at the left-hand diagram we can see that the organism with the greatest number of differences from mammals branches off first. These organisms are the least closely related to mammals.

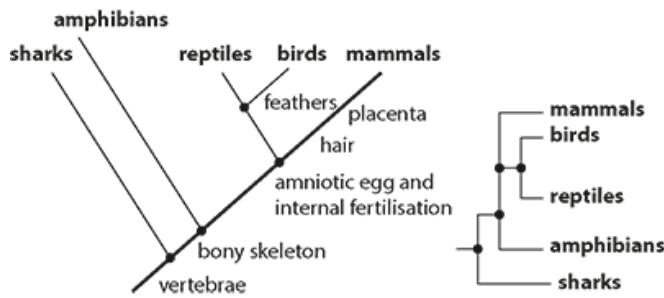


Figure 11.1.6: A cladogram shown in two different formats.

The relationship between reptiles and birds has been the subject of much debate amongst scientists. Some reptiles (e.g. crocodiles and dinosaurs) are more closely related to birds than other reptiles (e.g. lizards and turtles). Cladists tell us that ‘reptiles’ is not a clade and that a better grouping would be Archosauria (crocodiles, dinosaurs and birds), Lepidosauria (snakes and lizards) and Testudines (turtles and tortoises).

NATURE OF SCIENCE

How does our scientific understanding develop over time?

Our understanding of terms such as birds, reptiles and dinosaurs has changed as more information has become available. Today we can say that birds are not only the descendants of dinosaurs, biologically they are dinosaurs. Molecular evidence tells us that during the Triassic period (251–199 million years ago) the major groups of what we now call the reptiles evolved. These animals were the ancestors of both crocodiles and dinosaurs.

About 65 million years ago a massive extinction event wiped out all but one group of small, feathered dinosaurs. These feathered dinosaurs developed over time to become what today we call birds. Despite their shared evolutionary history and close relationship to other reptiles, birds are not normally grouped with reptiles. So why is this?

The Linnaean system of classification divides animal into groups based on their physical similarities. In this system, reptiles are organisms that are ectothermic (do not produce their own body heat) and have scales, so birds do not fit into this group. But using phylogeny and grouping the same organisms based on genetic similarities we discover that birds (and all dinosaurs), lizards, turtles, snakes and crocodilians were all descended from the original reptile ancestor. So why are birds still separated from the group we call reptiles?

The answer is probably for convenience. When a scientist studies features such as flight or behaviour which are unique to birds, it is easier to separate birds from the ‘non-avian reptiles’ and to consider them as a separate group.

We have two systems of classification for reasons of history but both are useful. The Linnean system is more useful for understanding how organisms live while the phylogenetic system and cladograms are more useful for understanding relationships between organisms.

To consider:

- 1 How has phylogeny helped in our understanding of evolution?
- 2 What new problems arise from new knowledge?

WORKED EXAMPLE 11.1

Which apes are the closest living relatives of *Homo sapiens*?

Answer

Gibbons, orangutans, gorillas and chimpanzees have many physical similarities to humans. For example, humans, chimpanzees and gorillas all have a cavity in the skull, just above the eyes, known as a frontal sinus. Gibbons, orangutans and other primates do not have this, so the physical evidence suggests that chimpanzees and gorillas are more closely related to humans than gibbons and orangutans. Evidence from the analysis of blood proteins also suggests that orangutans are more closely related to humans than gibbons. This evidence can be shown as in Figure 11.1.7.

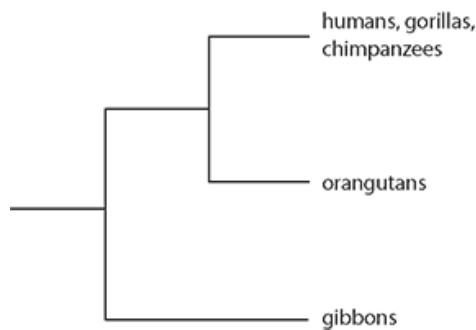


Figure 11.1.7: A cladogram showing the relationship between five apes.

Chimpanzees and gorillas are more closely related to humans than other living animals are but which are our closest living relatives?

To sort out the relationships between human beings, chimpanzees and gorillas, we must assess the evidence and check which features are shared. We can construct a table to summarise the evidence (Table 5.3).

Consider which of the three cladograms shown in Figure 11.1.8 is supported by most evidence.

| Characteristic | Other primates such as baboons | Gorillas | Humans | Chimpanzees | Cladogram supported by evidence (Figure 11.1.8) |
|-----------------------------------|--------------------------------|-------------------------------|---------------------|-------------------------------|---|
| DNA evidence: | | | | | |
| number of chromosomes | 42 or more | 48 | 46 | 48 | C |
| structure of chromosomes 5 and 12 | | different from other primates | like other primates | different from other primates | C |
| chromosome Y and 13 | | same as human beings | same as gorillas | like other primates | A |
| % genetic | orangutan | 1.6% | — | 1.2% | B |

| | | | | | |
|--|--------------------------|---------------------------|---------------------------------|----------------------------|---|
| difference from humans | 3.1% rhesus monkey 7% | | | | |
| Molecular evidence: | | | | | |
| α -hemoglobin compared with human | several differences | one amino acid difference | – | identical to humans | B |
| protein factor in blood | not variable | not variable | same variability as chimpanzees | same variability as humans | B |

Table 11.1.3: Summary of molecular and DNA evidence for the relatedness of primates.

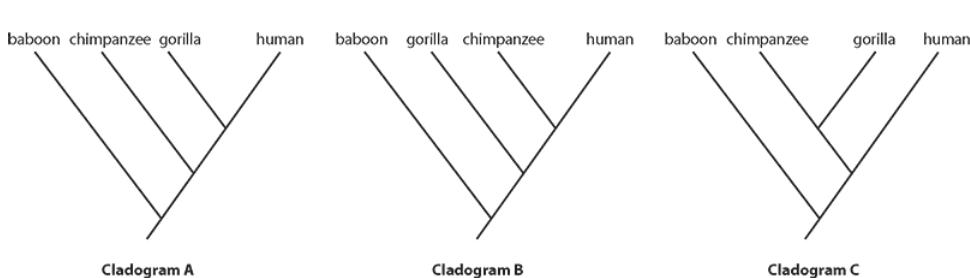


Figure 11.1.8: Three possible cladograms to show the relationship between humans, chimpanzees and gorillas.

None of the cladograms can be proved to be correct from this evidence but cladogram B is the best supported based on the data. It is therefore hypothesised to best reflect our current understanding of the evolutionary relationships of human beings. If further evidence is collected in future, the hypothesis may be changed.

NATURE OF SCIENCE

Re-classifying the figwort family

Using DNA sequences has shown that classifications of some groups which were based on visible characteristics do not correspond with the evolutionary origins of the group or species. One example of this is the figwort. Figwort is a family of flowering plants that includes black root, Culver's root and the mulleins (*Verbascum* spp.). In the past the family was

named Scrophulariaceae and contained about 275 genera and 5000 different species. Since the early 1990s, research into the DNA sequences of three chloroplast genes has revealed at least five separate clades. The traditional group Scrophulariaceae was found to be an unnatural group, which was not made up of clades. There were few, clear distinguishing physical characteristics to separate members of the old group which meant that taxonomists were unable to identify clades until molecular evidence became available. The new classification now places some genera into completely different families as the molecular studies have shown that they are not closely related to the figwort family after all.

To consider:

- How important is molecular evidence in modern classification?
- Will molecular evidence supersede observations of physical characteristics in the future?

TEST YOUR UNDERSTANDING

- 4 Define the term ‘clade’.
- 5 Suggest why DNA is so useful in establishing evolutionary relationships.
- 6 Explain how evidence from cladistics can lead to new classifications.

REFLECTION

Can I use my new knowledge to explain to others in my class why classification is important in understanding of the living world?

Links

- Why is it better to use genetic sequences and not anatomical features when classifying organisms? ([Chapter 4](#))
- How does classification help our understanding of evolution? ([Chapter 11.3](#))

11.2 Selection

LEARNING OBJECTIVES

In this section you will:

- learn that natural selection is the mechanism driving evolution
- learn that variation between individuals is required for natural selection to occur
- discover that variation can be caused by mutation, meiosis and sexual reproduction
- understand that adaptations are features that make an individual better suited to its environment and way of life
- recognise that more offspring tend to be produced than the environment can support, which means there is a struggle for survival between individuals
- discover that better-adapted individuals tend to survive and produce more offspring while less well adapted individuals tend to die or produce fewer offspring
- recall that when individuals reproduce, they pass on their heritable characteristics to their offspring
- understand that natural selection increases the frequency of well adapted individuals in a population and thus leads to changes in the species

- recognise that human activity can provide evidence for natural selection if populations are exposed to pesticides, pollution or antibiotics
- recognise that selective breeding of domesticated species shows that artificial selection can cause evolution
- recognise that sexual selection is natural selection for mating success

- discover that there are three modes of selection: directional, disruptive and stabilising
- learn that gene and allele frequencies change over time leading to evolutionary change

GUIDING QUESTIONS

- How can a species adapt to changing environmental conditions?
- What is the mechanism for natural selection?
- What is the importance of variation in selection and evolution?

11.2.1 A mechanism for evolution

The theory of evolution by means of natural selection was proposed by Charles Darwin (1809–1882) and Alfred Wallace (1823–1913). Darwin explained his ideas in a book called *On the Origin of Species by Means of Natural Selection*, published in 1859. The explanation remains a theory because it can never be completely proved but there is an abundance of evidence to support the key ideas, which are based on the following observations and deductions. Some terms we use now were not used by Darwin, who had no knowledge of genes or alleles. However, the fundamental basis of his argument was the same as outlined here.

1 Populations are generally stable despite large numbers of offspring

Organisms are potentially capable of producing large numbers of offspring, far more than the environment can support. Trees can produce thousands of seeds and fish produce hundreds of eggs. Yet few of these survive to maturity and we rarely see population explosions in an ecosystem.

2 Better-adapted individuals have a competitive advantage

Both plants and animals in a growing population will compete for resources. A resource may be food, territory or even the opportunity to find a mate. In addition, predators and disease will remove members of a population. This competition will bring about a struggle for survival between the members of a population. Organisms that have adaptations that make them well suited to the conditions will be good at competing. They will tend to survive long enough to reproduce, passing on heritable traits to their offspring. Others will die.

3 There is heritable variation within species

Different members of the same species are all slightly different and this variation is due to the mechanism of sexual reproduction. The process of meiosis ([Section 6.5](#)) produces haploid gametes. Furthermore, the genes in the gametes that an individual produces may be present in different forms or alleles. When an egg is fertilised, the zygote contains a unique combination of genetic material from its two parents. Sexual reproduction gives an enormous source of genetic diversity, which gives rise to a wide variation among the individuals of a species.

4 Advantageous heritable traits become more frequent over generations

As a result of variation, some members of a population may be better suited (better adapted) to their surroundings than others. They may have keener eyesight, or have better camouflage to avoid predators. These individuals will out-compete others; they will survive better, live longer and pass on the genes for their advantageous characteristics to more offspring. Gradually, as the process is repeated generation after generation, the proportion of the advantageous genes in the population as a whole increases. This is called natural selection, and it occurs as the ‘fittest’ (best adapted) survive to reproduce.

KEY POINTS

adaptations characteristics that make an organism suited to its environment.

evolution is the cumulative change in the heritable characteristics of a population.

heritable trait is a characteristic in an offspring that resembles its parents' corresponding characteristic more than that in any other individual in the population.

natural selection is a mechanism for evolution in which various genetic types in a population make different contributions to the next generation.

Sexual reproduction promotes variation

Mutations in genes create new variations, but sexual reproduction also increases variation in a population by forming new combinations of alleles.

- During meiosis, crossing over at prophase I and random assortment in metaphase I produce genetically different gametes ([Section 6.5](#)).
- Different alleles are also brought together at fertilisation, promoting more variation.

In species that reproduce asexually, variation can arise only by mutation.

11.2.2 Natural selection and the evidence for evolution

Once species have evolved to become well adapted to conditions in a stable environment, natural selection tends to keep things much the same. However, if the environment changes, a population will only survive if some individuals have heritable traits that suit them to the new conditions, and these then become more frequent in the population, because of natural selection. Three examples of how this can happen in a relatively short period of time are the beak adaptations of Galápagos finches after a change in food availability, the response of a moth population to pollution, and the emergence of new strains of bacteria following the introduction of antibiotics.

How human actions affect selection

Human actions cause changes to the variation in some populations. These influences can provide evidence for the action of selection and for evolution. Several species of bacteria have become resistant to antibiotics, and pesticides and pollution have also led to evolutionary changes in populations of plants and animals that humans have attempted to control.



Figure 11.2.1: Light and melanic forms of peppered moths on light and dark tree bark.

Industrial melanism – the influence of pollution

The peppered moth (*Biston betularia*) is a night-flying moth that rests during the day on the bark of trees, particularly on branches that are covered with grey-green lichen. It is a light speckled grey, and relies on camouflage against the tree branches to protect it from predatory birds.

In Britain in the mid-19th century, a black form of the moth was noticed (Figure 11.2.1). The appearance of this new colour coincided with the period of the Industrial Revolution when many factories were built and contributed to growing pollution in the atmosphere. This pollution killed the lichens that grow on the bark of trees, and the tree bark became blackened with particles of soot.

The colour of the moth is due to a single gene, which can be present in two forms. The common, recessive form gives rise to a