

Figure 6.1.8: A rod-shaped bacterium.

Use these names to identify the structures A–F.

naked DNA; 70S ribosomes; cell wall; cell membrane;
flagellum; cytoplasm

TEST YOUR UNDERSTANDING

- 1 State the difference between hydrophilic and hydrophobic molecules.
- 2 Name three organelles found in a eukaryotic cell.
- 3 State two roles of integral proteins.

6.1.3 Organelles and interactions between them

The phospholipid molecules in a membrane bilayer are free to move between layers and within a layer. This fluid nature of the membrane allows membranes from different organelles, or the same organelle, to stick to or fuse with one another.

The endoplasmic reticulum (ER) is a membrane that makes up about half of the total amount of membrane in an animal cell. It is composed of folded, flat, sealed sacs that are joined to the nuclear membrane. It occurs throughout the cell but is more concentrated close to the nucleus and Golgi apparatus. The ER is called rough endoplasmic reticulum (RER) if ribosomes are attached to it. Attached ribosomes produce the characteristic grainy appearance seen in electron micrographs. Both ER and RER are present in cells at the same time and are parts of the same organelle. If a cell is actively synthesising protein it will contain more RER. (A liver cell contains more than 10 million ribosomes.) Many of the substances produced by the RER are exported to other organelles. Ribosomes synthesise proteins but there are two separate groups of ribosomes in the cytoplasm. Membrane-bound ribosomes, attached to the ER synthesise proteins that are produced for export from the cell whereas free ribosomes synthesise all the other proteins that are encoded by the nuclear genome and are to be used within the cell. Membrane-bound and free ribosomes are structurally and functionally identical. They differ only in the proteins they are making at any given time. Many ribosomes can bind to a single mRNA molecule forming a polyribosome and this becomes attached to the ER membrane.

The Golgi apparatus is also made of membranes and is closely linked to the ER. Some substances produced by the RER pass directly between the two organelles, whereas others are packaged as droplets in vesicles that carry them through the cytoplasm. The Golgi apparatus processes proteins which it receives from the ER and sorts them for transport to their final destinations which may be lysosomes, the plasma membrane or for secretion out of the cell.

Coated vesicles are vesicles that are coated with a protein complex called clathrin. These structures act as a link between different parts of the cell and they transport proteins between the plasma membrane, Golgi network and lysosomes. Coated vesicles also bud from the plasma membrane, where the addition of the clathrin coat gives them a polyhedral pattern (Figure 6.1.9). The combination of proteins in the coat of a coated vesicle determines the vesicle's destination in the cell.

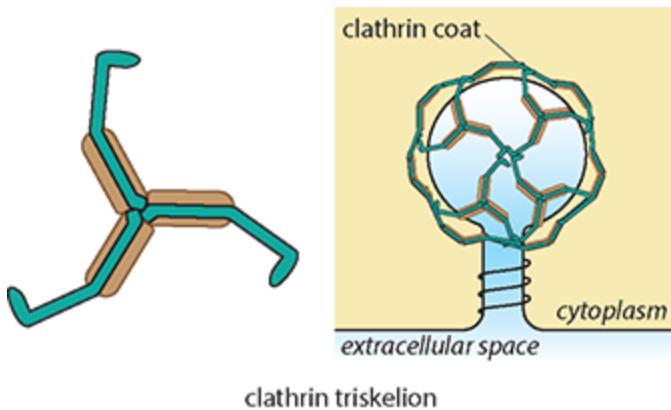


Figure 6.1.9: A clathrin-coated vesicle is formed when clathrin triskelion proteins assemble over the surface of a membrane to form a structural scaffold.

Lysosomes are small spherical organelles that contain hydrolytic enzymes, including proteases, amylases, nucleases and lipases. Lysosomes bud off from the Golgi apparatus and the enzymes

they contain are formed in the endoplasmic reticulum. The enzymes must be kept separated from the contents of the cytoplasm, where they would damage cell structures because the pH inside the lysosome is different from that of the cytoplasm. The function of lysosomes is to engulf and break down unwanted macromolecules and respond to and destroy invading particles, such as bacteria or viruses, that enter the cell. They are also capable of destroying a cell if they burst and release their enzymes; they are sometimes called the cell's 'suicide packets'.

Membranes in mitochondria

Mitochondria have two membranes and chloroplasts have three (Figure 6.1.5). The inner membrane of the mitochondrion and the thylakoid membrane of the chloroplast are both highly folded and both provide a large surface area for the reactions of respiration and photosynthesis ([Sections 2.2 and 2.3](#)).

The membranes of mitochondria divide the organelle and form compartments in which the reactions of aerobic respiration take place ([Section 2.2](#)). In the centre, the inner membrane contains the compartment known as the matrix which separates the enzymes needed in the reactions of the Krebs cycle from the contents of the inner membrane space. The inner membrane space, between the outer membrane and the folded cristae of the inner membrane, has a much smaller volume than the matrix. A high concentration of H⁺ ions from the Krebs cycle can build up between the two membranes and so the pH is much lower than in the matrix. Membranes of the cristae, which have a large surface area due to their folding, contain ATP synthase molecules through which H⁺ ions flow to produce ATP.

Membranes in chloroplasts

Chloroplasts and their membranes provide compartments in which the reactions of photosynthesis can take place (Figure 6.1.5). The interior of the chloroplast, inside the two outer membranes, is filled with liquid stroma that contains the enzymes for the Calvin cycle, the light-independent reactions of photosynthesis (Section 2.3). These reactions are separated from the light-dependent reactions which occur on the thylakoids. The thylakoid membranes are folded to produce grana and lamellae and have a large surface area with a small volume of intramembrane space. The thylakoid membrane supports the chlorophyll molecules of the two photosystems and contains protein pumps through which H⁺ ions pass into the thylakoid space. This inner thylakoid space is a compartment of the chloroplast that has a low pH. During photosynthesis, H⁺ ions are pumped through ATP synthase that is embedded in the thylakoid membrane and back into the stroma to produce ATP.

Table 6.1.1 summarises the similarities in the membranes of mitochondria and chloroplasts.

Mitochondria	Chloroplasts
two layers of membrane	three layers of membrane
enzymes of the Krebs cycle are contained in the matrix	enzymes of the Calvin cycle are contained in the stroma
cristae have a large surface area and a small intramembrane volume at a low pH	thylakoid membranes and intergranal lamellae have a large surface area and small intramembrane volume with a low pH
membranes of the	membranes of the thylakoid contain

cristae support channel proteins and ATP synthase molecules	channel proteins, ATP synthase and photosynthetic pigments of photosystems 1 and 2
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Table 6.1.1: The similarities in the membranes of mitochondria and chloroplasts.

Membranes of the nucleus

The nucleus has a double membrane known as the nuclear envelope surrounding it. It consists of an outer and an inner phospholipid bilayer. The thin space between the layers connects with the space (lumen) between the layers of the rough endoplasmic reticulum and the outer membrane links to the RER so that mRNA from the nucleus can be passed directly to the site of protein synthesis. The inner membrane has a protein lining which binds to chromatin and other contents of the nucleus and provides the structural framework of the nucleus. The nuclear envelope separates the contents of the nucleus from the cytoplasm and act as barriers that prevent the free movement of molecules between the nucleus and the cytoplasm. The nuclear envelope contains many nuclear pores which do allow the nucleotide DNA and RNA, as well as adenosine-triphosphate, which provides the energy for synthesizing genetic material, to enter. Histones and other large proteins can also pass through the pores. The pores also regulate the export of the mRNA and subunits of ribosome from the nucleus to the cytoplasm.

EXAM TIP

You must be able to label and annotate diagrams of mitochondria and chloroplasts to show the adaptations of these two organelles to their functions. You should be able to

identify the structures that are shown in Table 6.1.1 and summarise their importance in respiration and photosynthesis.

TEST YOUR UNDERSTANDING

- 4 Why are membranes important in separating compartments in chloroplasts?
- 5 What is the function of the rough endoplasmic reticulum?

Links

- How is evidence for endosymbiosis provided by chloroplasts and mitochondria? (Chapter 5)
- How does the solubility of a substance in water affect its movement across phospholipid membranes? (Section 6.2)
- How do the hormones that do not cross membranes influence cell activities? (Chapter 7)

6.2 Movement across membranes

LEARNING OBJECTIVES

In this section you will:

- learn that the plasma membrane is semi-permeable
 - discover that ions and molecules move across membranes by simple diffusion, facilitated diffusion, osmosis and active transport
 - recall that only water moves by osmosis
 - recognise that proteins in the membrane act as pores or pumps for transport
 - learn that channel proteins allow facilitated diffusion
 - discover that active transport via protein pumps allows substances to move by active transport against a concentration gradient
 - recognise that active transport requires energy in the form of ATP
 - learn that the fluid nature of membranes allows endocytosis and exocytosis to transport substances in and out of the cell by active transport
- recognise that neurons are very specialised cells that receive and transmit impulses

- learn that gated ion channels allow ions to move in and out of nerve fibre membranes by passive transport
- recognise that the sodium–potassium pump in the neuron membrane allows active transport of Na^+ and K^+ ions in both directions
- discover that saltatory conduction of nerve impulses is possible due to myelination of nerve fibres.

GUIDING QUESTIONS

How do cells control how substances enter and leave?

6.2.1 Diffusion, facilitated diffusion and osmosis

Many molecules pass across the plasma membrane. Particles may move by simple diffusion, facilitated diffusion or osmosis, which are passive processes, or by active transport, which involves the use of energy. Water, oxygen, carbon dioxide, excretory products, nutrients and ions are continuously exchanged. Many cells also secrete products such as hormones and enzymes through the plasma membrane. The different methods that enable each substance to move ensure that these substances travel across the plasma membrane quickly and efficiently. The membrane is permeable to some molecules but not others, for this reason it is said to be selectively permeable.

Simple diffusion

The simplest way for molecules to move into or out of a cell is by simple **diffusion** through the plasma membrane. Diffusion is a passive process, which takes place as molecules move randomly. No energy input is required, and movement occurs via the **concentration gradient**. Molecules move from an area of high concentration to an area of lower concentration. A concentration gradient is a difference in concentration of a substance between two regions. Diffusion will always occur where such a gradient exists until particles of the substances are evenly distributed and equilibrium is reached.

Gas molecules move in and out of cells by simple diffusion, which means that diffusion has an important role in cell respiration. Oxygen is needed continuously because, as a cell respires, the oxygen concentration inside it decreases. As the oxygen concentration inside the cell becomes less than the

concentration outside, oxygen molecules diffuse in. In a similar way, as carbon dioxide forms during respiration, its concentration builds up inside the cell and it diffuses out through the plasma membrane to an area where the concentration is lower. Simple diffusion occurs where the membrane is fully permeable to the substance or where channel proteins in the membrane are large enough for the substance to pass through.

Diffusion via channel proteins

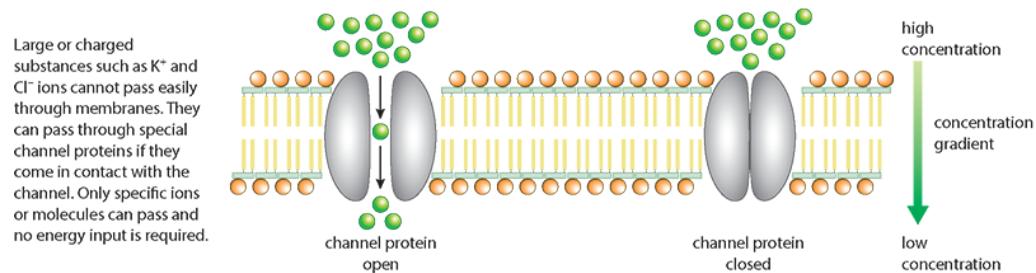
Large molecules, and charged particles such as chloride ions (Cl^-) and potassium ions (K^+), cannot pass through the membrane by simple diffusion. So, certain protein channels in the membrane form pores which provide a route for them to travel through. As with simple diffusion, no energy is used by the cell because the transport relies on the kinetic energy (the energy due to motion) of the particles moving down their concentration gradient. Channel proteins have an interior which is hydrophilic (Figure 6.2.1) so water-soluble materials can pass through them. In addition, they are specific: that is, they only allow one particular substance to move through.

Some channels are permanently open, whereas others are gated and only open to allow certain ions to pass when they are stimulated to do so. For example, gated channels in the axons of nerve cells open when there is a change in the voltage (potential difference) across the membrane. Gated potassium channels only allow K^+ ions to pass out through the membrane after a nerve impulse has passed along the axon. You can read more about nerve impulses in [Chapter 7](#).

Facilitated diffusion

Substances such as glucose and amino acids, which are polar, cannot diffuse through the lipid layer of the membrane. They are transported across membranes by **facilitated diffusion** through special channel proteins. A carrier protein combines with the diffusing molecules on one side of the membrane, carries them through the channel protein and then releases them on the other side (Figure 6.2.1). Facilitated diffusion allows a faster diffusion rate for molecules that an individual type of cell needs; for example, the diffusion of glucose into active muscle cells. No energy input is required because the molecules move down their concentration gradient.

Diffusion through a protein channel



Facilitated diffusion via a carrier protein

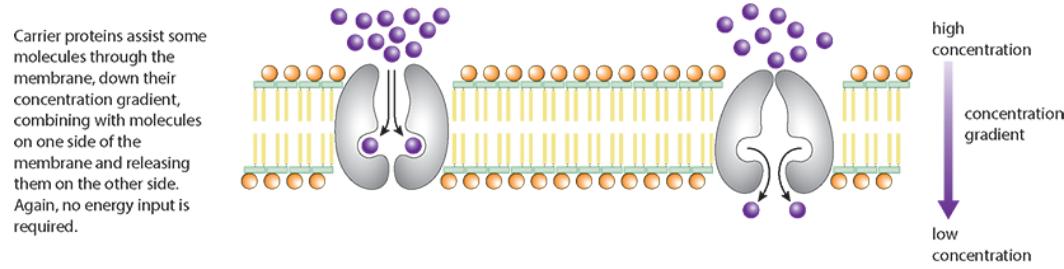


Figure 6.2.1: Some large or charged ions and molecules pass through the membrane via special channel proteins.

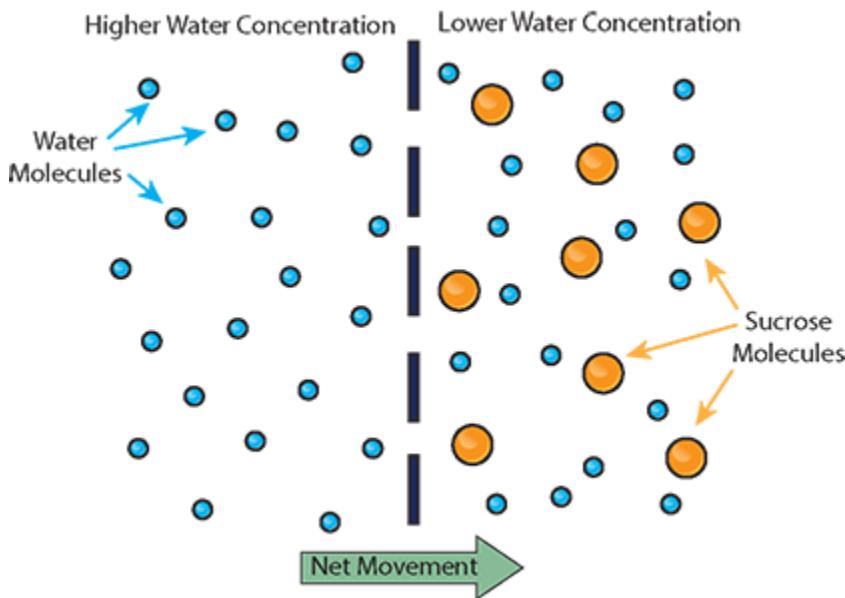


Figure 6.2.2: Solute molecules cannot move across the semi permeable membrane but water molecules can move in either direction. The net movement of water is shown by the arrow. Water moves from an area of lower solute concentration to an area of higher solute concentration.

Osmosis

Osmosis is a special case of diffusion that moves water in and out of cells (Figure 6.2.2). Osmosis is the **passive movement** of water across the **semi-permeable** plasma membrane from an area of lower solute concentration to an area of higher solute concentration. Water moves through special protein channels known as **aquaporins**.

KEY POINTS

osmosis is the passive movement of water molecules across a membrane from a region of lower solute concentration, where there is a high concentration of water molecules, to a region of

higher solute concentration, where the concentration of water molecules is lower.

passive movement is the movement of substances down a concentration gradient from an area of high concentration to an area of lower concentration without the need for energy to be used.

when the plasma membrane is semi-permeable; it is permeable to some molecules but not other usually larger particles. It allows certain molecules or ions to pass through it by diffusion, while others pass by facilitated diffusion, passive transport or active transport.

When the solute concentrations inside and outside a cell are the same, the same number of water molecules will pass across the membrane into the cell as those that leave. You can read more about water potential and its effect on cells in [Section 6.3](#).

Water enters the root tissue of a plant by osmosis, while ions enter by diffusion and active transport. Water enters through root hair cells, tiny extensions of the root cells, which increase the area for absorption (Figure 6.2.3). Water passes through the root to the xylem and from there is drawn up the plant in the **transpiration** stream as water evaporates from leaves.

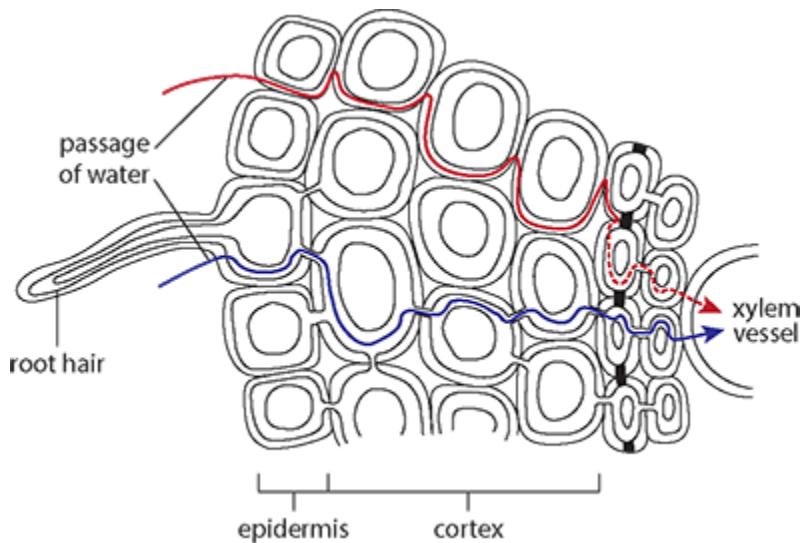


Figure 6.2.3: Cross-section of a root. Water enters the root hair cells by osmosis and passes to the xylem vessel. We need to extend the caption to explain the red and blue lines. "90% of the water moves through the cellulose cell walls (red line) and some passes through the cytoplasm through cell connections known as plasmodesmata (blue line)

SCIENCE IN CONTEXT

In medical procedures, tissues and organs are bathed in a solution of 'normal saline', which has exactly the same osmolarity (a measure of the solute concentration in a solution) as human cell cytoplasm. The saline is said to be **isotonic** with the cytoplasm. The saline solution ensures that osmosis does not occur, water does not enter or leave body cells and the cells are not damaged.

6.2.2 Active transport

Many of the substances a cell needs occur in low concentrations in the surroundings outside the plasma membrane. For example, plants must take in nitrate ions from very dilute solutions in the soil to build their proteins, and muscle cells actively take in calcium ions to enable them to contract. To move these substances into the cell against a concentration gradient, the cell must use metabolic energy released from the breakdown of ATP. This is called **active transport** (Figure 6.2.4). Specific proteins in the plasma membrane act as transporters or ‘carriers’ to move substances through. Many of the carrier proteins are specific to particular molecules or ions so that they can be selected for transport into the cell.

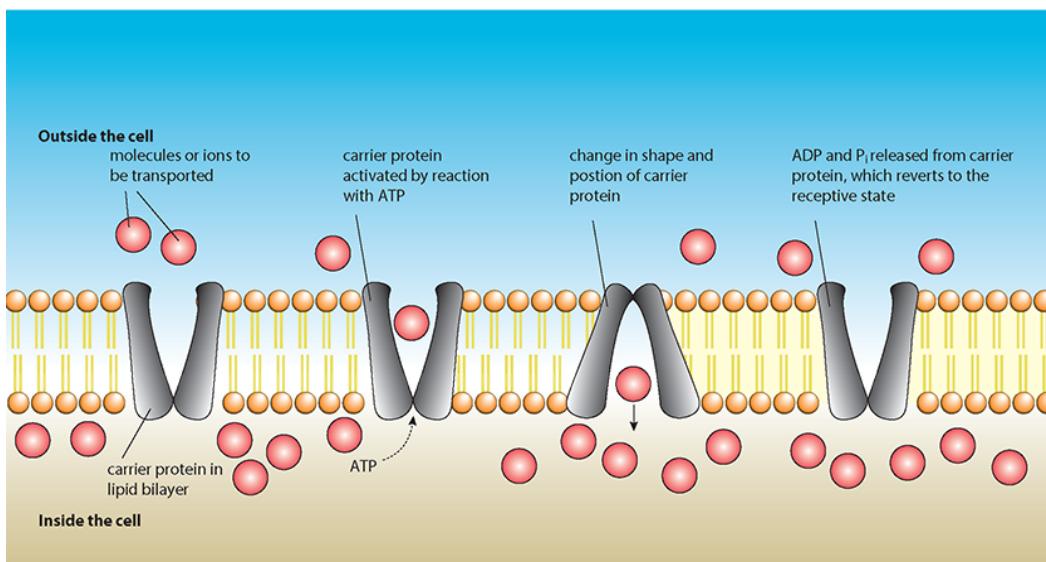


Figure 6.2.4: Active transport of a single substance.

The sodium–potassium pump found in nerve cell fibre membranes (Figure 6.2.5) is important in keeping the correct proportions of ions on the inside and outside of the nerve cell. Active transport is used to move these ions against their

concentration gradients. The sodium–potassium pump maintains the concentration of sodium and potassium ions in the cells and extracellular fluid. Cells are able to exchange sodium ions for potassium ions against concentration gradients using energy provided by ATP. Figure 6.2.5 shows this very important example of active transport. [Chapter 7](#) covers nerve impulses in more detail.

KEY POINTS

endocytosis is the movement of liquids or solids into a cell, by the indentation of the plasma membrane to form vesicles containing the substance; endocytosis is an active process requiring ATP.

exocytosis the movement of liquids or solids out of a cell by the fusion of vesicles containing the substance with the plasma membrane; exocytosis is an active process requiring ATP.

Exocytosis and endocytosis

Cells often have to transport large chemical molecules or large materials across the plasma membrane. Neither diffusion nor active transport are suitable for this. Instead, cells can release or take in such materials in vesicles, as shown in Figure 6.2.6. Uptake into a cell is called **endocytosis** and export from a cell is **exocytosis**. Both require energy from ATP and both rely on the fluid nature of the plasma membrane.

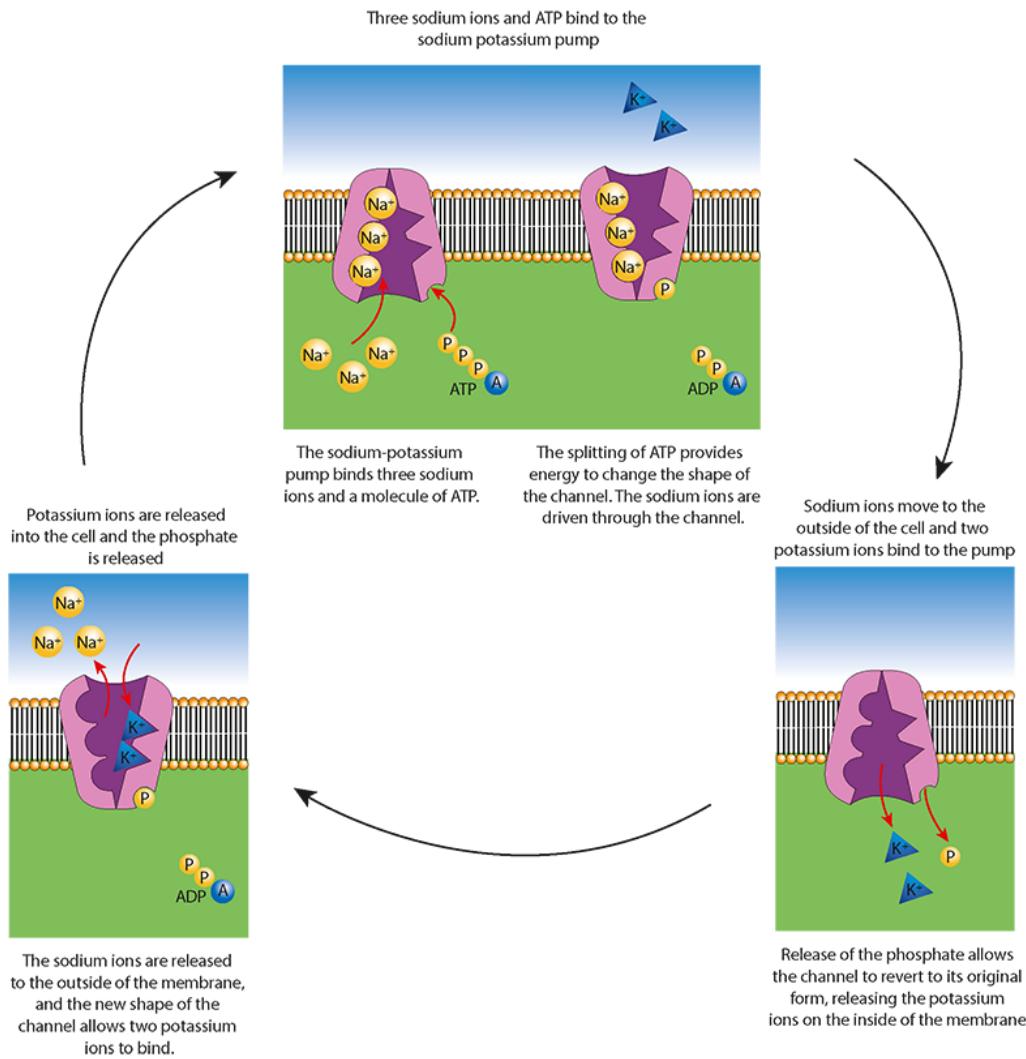
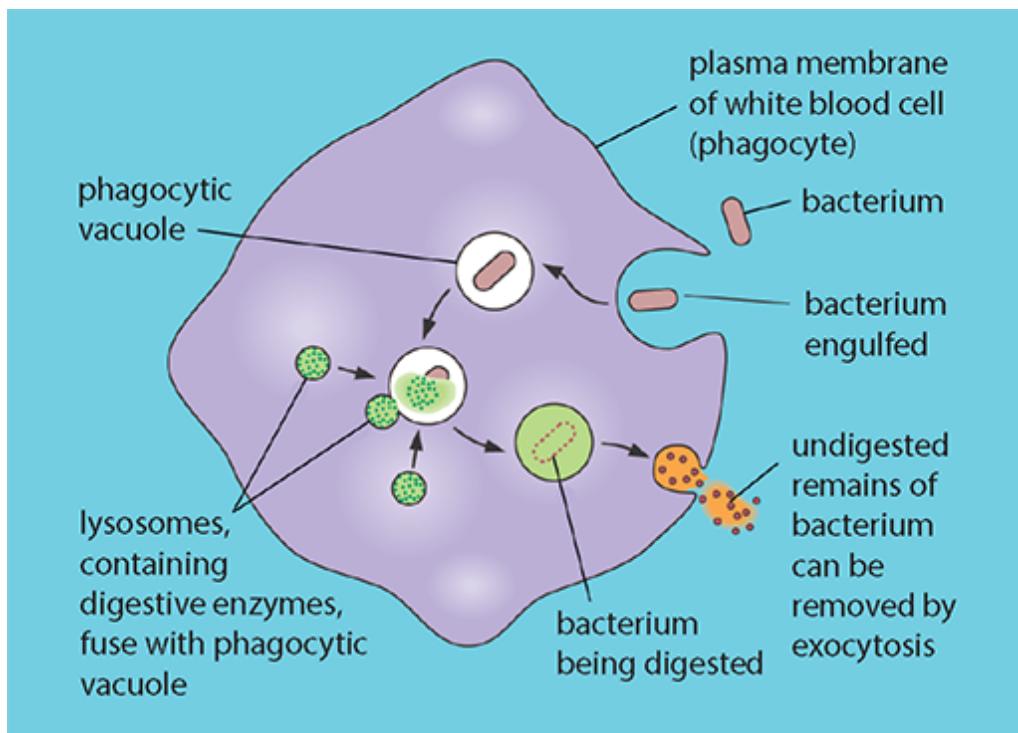


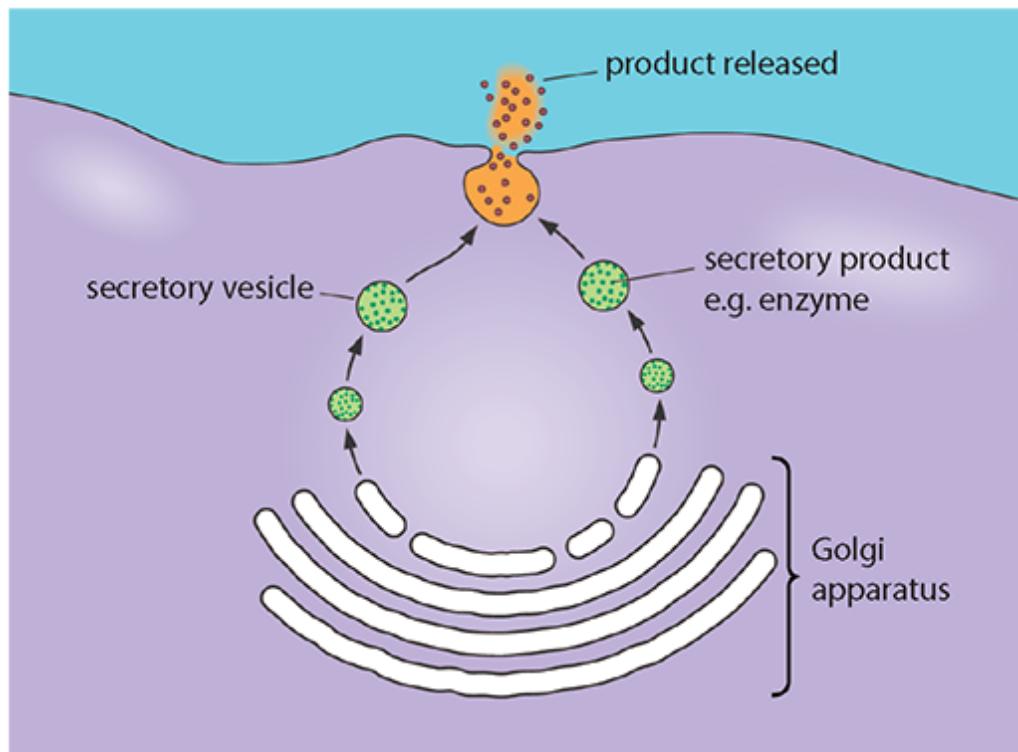
Figure 6.2.5: Sodium–potassium pump. At rest, sodium ions are pumped out of a nerve cell fibre and potassium ions are pumped in, to establish the resting potential.

During endocytosis, part of the plasma membrane is pulled inward and surrounds the liquid or solid that is to be moved from the extracellular space into the cell. The material becomes enclosed in a vesicle, which pinches off from the plasma membrane and is drawn into the cell. This is how white blood cells take in bacteria (Figure 6.2.6).

Materials for export, such as digestive enzymes, are made in the RER and then transported to the Golgi apparatus to be processed. From here they are enclosed within a membrane-bound vesicle, and moved to the plasma membrane along microtubules ([Chapter 5](#)). The arrangement of phospholipid molecules in the membrane of a vesicle is very similar to that in the plasma membrane. As a vesicle approaches the plasma membrane, it is able to fuse with it and in doing so release its contents to the outside. The flexibility and fluidity of the plasma membrane are essential to enable both endocytosis and exocytosis to happen. Vesicles also help to transfer and organise substances in the cell. They are involved in metabolism, transport and enzyme storage and some chemical reactions also occur inside them, separated from the cytoplasm in their own compartment.



Phagocytosis of a bacterium by a white blood cell – an example of endocytosis.



Exocytosis in a secretory cell. If the product is a protein, the Golgi apparatus is often involved in chemically modifying the protein before it is secreted, as in the secretion of digestive enzymes by the pancreas.

Figure 6.2.6: Examples of endocytosis and exocytosis.

There are two types of endocytosis. If the substances being taken in are particles, such as bacteria, the process is called phagocytosis. If the substances are in solution, such as the end products of digestion, then it is called pinocytosis.

EXTENSION

Nerve impulses are able to pass across synapses (the tiny gaps between one nerve cell and the next) due to exocytosis and endocytosis. Neurotransmitters are secreted at the end of a nerve cell fibre by exocytosis. They stimulate the adjacent nerve and are then reabsorbed by endocytosis to be recycled and reused. You can find out more about the transmission of nerve impulses in [Section 7.2](#).

SCIENCE IN CONTEXT

Artificial membranes

As well as natural semi-permeable membranes, artificial membranes can be made using cellulose and they are used in both laboratory experiments and medicine. You may have used Visking tubing (also known as dialysis tubing) in your laboratory experiments to demonstrate diffusion and osmosis. The tubing can be produced in a variety of different forms with pores that have sizes between 1 and 10 nm, so that different types of membrane can restrict the passage of molecules with different molecular sizes. In your experiments you may have discovered that large molecules such as starch cannot pass through the tubing but smaller molecules such as glucose or maltose can do so. Unlike the membranes of living

cells dialysis tubing is not semi-permeable based on the charge of molecules, which means that ions can move freely across it.

Artificial semi-permeable membranes are also used to separate molecules from blood or DNA samples and are very important in kidney dialysis machines. If a person's kidneys fail, a dialysis machine can be used to clean their blood and remove excess salts, urea and water, a process usually done by the kidneys. A kidney dialysis machine contains an artificial semi-permeable membrane that uses the same selective absorption process as plasma membrane. The patient's blood passes through the machine and the dialysis membrane uses differential diffusion to restrict the entry of certain materials, such as glucose, which the body needs, but allows other waste products, such as urea, to diffuse through it. A concentration gradient on the different sides of the membrane is maintained by refreshing the dialysis fluid so that only unwanted substances diffuse across the membrane and the correct levels of other substances remain in the blood.

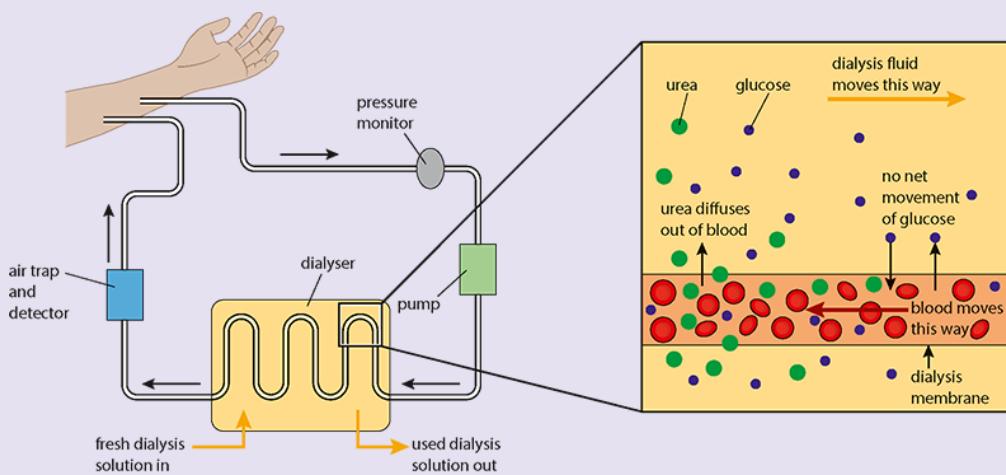


Figure 6.2.7: A dialysis machine.

TEST YOUR UNDERSTANDING

- 6 Outline the difference between simple diffusion and facilitated diffusion.
- 7 List three ways that substances move from one side of a membrane to the other.
- 8 State one transport mechanism across a membrane that requires energy from ATP and one that does not.
- 9 State one difference and one similarity between exocytosis and endocytosis.

6.2.3 Membranes and transmission of nerve impulses

Movement of ions across plasma membranes is essential for the conduction of nerve impulses. Neurons (nerve cells) are specialised cells which receive and transmit impulses throughout the body. A neuron consists of a cell body with two types of extensions that carry messages to and from the cell body. Long extensions called axons carry messages away from the cell body. Shorter, branched extensions called dendrites receive messages from other cells and carry them towards the cell body ([Section 7.2](#)). Active transport and the sodium–potassium pump not only maintain the sodium/potassium balance in these cells but also are key to the way nerve impulses are passed along the nerve cell fibres.

Gated ion channels are a special group of membrane protein channels that are activated by changes in **membrane potential** close to them (membrane potential is the difference in electrical potential between the inside and outside of the cell). Gated ion channels are important in nerve fibres because they allow ions to pass quickly in and out of a neuron when they are opened. When a neuron is not active, sodium ions are pumped out of the cell and potassium ions are pumped into the cell to establish a ‘resting potential’. At rest, the inside of the nerve fibre is negatively charged with respect to the outside (Figure 6.2.8). The resting potential is about -70 mV .

When a neuron is stimulated the distribution of charge across its membrane is reversed for a millisecond. This change in membrane potential changes the shape of the sodium channel proteins and triggers a rapid **depolarisation** (the distribution of

charge is reversed from negative to positive). Sodium ions diffuse into the neuron down the concentration gradient into the nerve fibre. Nerve impulses pass along the neuron because as charge is reversed in one area of a nerve fibre, the adjacent ion channel is affected so that the depolarisation spreads rapidly along the axon. As this happens, a nerve impulse is passed along the nerve fibre.

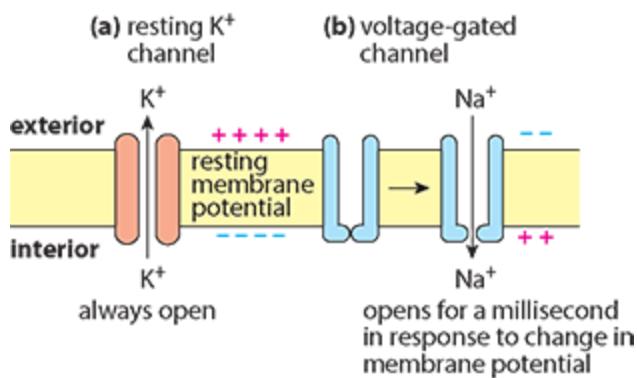


Figure 6.2.8: When a neuron is depolarised, voltage-gated protein channels open to allow sodium ions to rush in.

After a nerve impulse has passed, the gated sodium channels close and the resting potential is re-established. This happens as gated potassium channels open to allow potassium ions to flow out, in a process known as repolarisation.

Speed of transmission

A nerve fibre with a simple structure carries impulses at a speed of about 1 metre per second. Nerve fibres with a larger diameter conduct impulses faster than smaller ones and part of the reason for this is that most large fibres are enclosed in a fatty covering called a myelin sheath (Figure 7.2.3). The sheath is produced by special cells known as Schwann cells which wrap themselves many times around the nerve fibre, producing several membrane

layers around it. The myelin prevents the flow of ions across the membrane for most of its length but at intervals there are gaps in the sheath known as nodes of Ranvier. Impulses can ‘jump’ from node to node in a process called **saltatory conduction** which speeds up the transmission of the nerve impulse (action potential). Changes in the membrane potential (the action potential) only occur at the nodes of Ranvier which makes the process much faster than if the process occurred continuously along the whole nerve fibre. The speed can reach up to 100 metres per second in some neurons with a myelin sheath. Clusters of sodium-gated channels are found at the nodes of Ranvier. The transmission of nerve impulses is explained in more detail in [Section 7.2](#).

NATURE OF SCIENCE

What role do chance meetings and unexpected discoveries play in scientific progress?

Theodor Schwann discovered the existence of the myelin covering around nerve fibres that now bears his name. But, by chance, in the 1830s Schwann met another scientist Matthias Schleiden and the two men spoke about a very different subject, the nuclei of plant and animal cells. Schleiden said that he thought that new plant cells formed from the nuclei of existing cells and Schwann recalled seeing similar things occurring in animal cells. After the conversation, Schwann put forward his idea that ‘All living things are composed of cells and cell products’. By the 1860s his ideas were accepted and formed the basis of what we know today as Cell theory. Schwann’s theory and observations formed the foundation of modern cell biology.

TEST YOUR UNDERSTANDING

- 10** What stimulates a gated ion channel to open?
- 11** What effect does a myelin covering have on the transmission of a nerve impulse?

REFLECTION

Reflect upon the most interesting new aspects of biology that you have learned from this chapter.

Links

- Why is phagocytosis important for leucocytes? ([Chapter 10](#))
- Why is membrane transport important at synapses? ([Chapter 7.2](#))
- How is the uptake of glucose into cells regulated by insulin? ([Chapter 8.4](#))

6.3 Water potential

LEARNING OBJECTIVES

In this section you will:

- recall (from [Chapter 1](#)) that water is a good solvent because of the interaction between solute and water molecules
- learn that water potential defines whether water will enter or leave a solution. It is determined by solute potential and pressure potential of the solution
- learn that the more negative the solute potential, the more solutes are dissolved in the solution
- recognise that a higher pressure potential means more pressure is exerted on the solution
- discover that the movement of water into a plant cell produces turgor pressure but that water moving into an animal cell can cause it to burst
- learn that in a hypertonic solution water leaves cells, resulting in cell shrinkage, in a hypotonic solution water enters cells and that in an isotonic solution there is no net movement of water
- recognise that isotonic solutions have important medical uses
- define osmoregulation as the maintenance of a consistent osmotic pressure in an organism

- › appreciate that water moves from a higher to lower water potential
- › understand that solute potential and pressure potential contribute to the water potential of plant cells
- › explain in terms of solute and pressure potentials the changes that occur when plant cells are placed in hypotonic and hypertonic solutions

GUIDING QUESTIONS

- Why is the regulation of water content in living organisms important?
- How is internal water content regulated?

6.3.1 Water potential in plants and animals

An understanding of the processes of osmosis is important for learning how the human kidney works and how plants absorb water from the soil. Water potential is the term used to explain whether water will enter or leave a solution or a cell. It is affected by the concentration of solute molecules present and by the pressure of water molecules in the solution.

Water molecules, enclosed inside a semi-permeable membrane, hit the membrane as they move about and generate pressure. This pressure is called the water potential. The more molecules that hit the membrane in a certain time, the higher the pressure and higher the water potential.

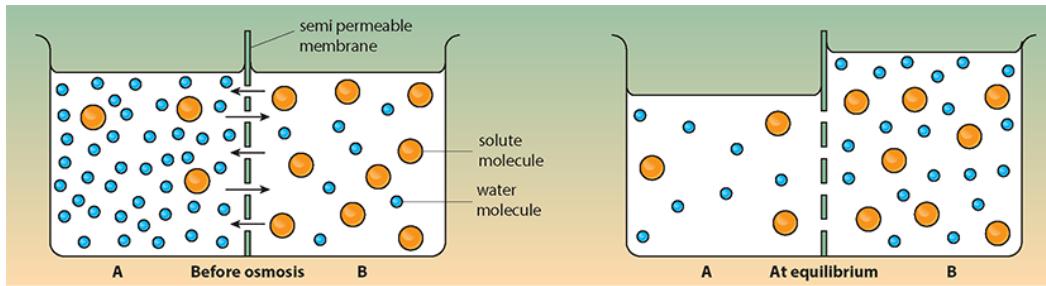
Water potential is represented by the Greek letter psi (ψ) and is measured in kilopascals (kPa). The water potential of pure water is 0 kPa. Water potential determines whether water will move into or out of a solution.

The presence of solutes (dissolved substances) increases the tendency of water to move from one solution into a more concentrated solution by osmosis.

$$\text{Water potential} = \text{pressure potential} + \text{solute potential}$$

$$\psi = \Psi_p + \Psi_s$$

Osmosis occurs when there is a net movement of water molecules from a region where their concentration is higher to one where their concentration is lower. This occurs through a semi-permeable membrane such as the plasma membrane (Figure 6.3.1).



Two solutions are separated by a semi-permeable membrane. B has a higher solute concentration than A. The solute molecules are too large to pass through the pores in the membrane but the water molecules are small enough.

As the arrows in the left diagram indicate, more water molecules moved from A to B than from B to A, so the net movement has been from A to B, raising the level to the solution in B and lowering it at A. The water potentials (the tendency of water molecules to move in each direction) in A and B are now the same.

Figure 6.3.1: Osmosis and water potential.

When the solute concentrations inside and outside a cell are the same, the same number of water molecules will pass across the membrane into the cell as those that leave.

An animal cell that is placed in pure water will take in water by osmosis until eventually it may burst (Figure 6.3.2). This is because the cell contains many dissolved substances in its cytoplasm and water enters freely through the plasma membrane. If the cell is placed in a solution with a very high concentration of solutes, the cell will shrink as water leaves the cell by osmosis. This shrinkage is known as **crenation**. In either situation, animal cells will not function properly and their metabolism will be affected.

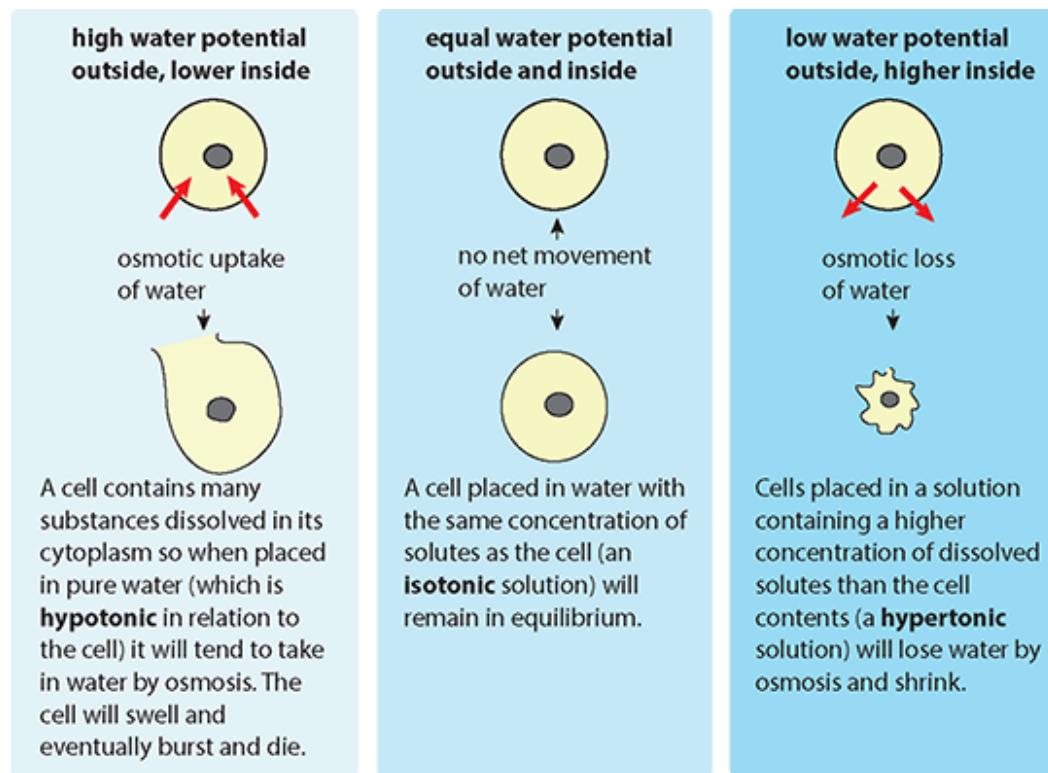


Figure 6.3.2: Responses of animal cells to solutions containing different concentrations of solutes.

KEY POINTS

water potential defines of the tendency of water to move from one area to another due to concentration of solute molecules present and the pressure of water molecules in the solution. Water potential is determined by these two factors, the solute potential and the pressure potential of a solution.

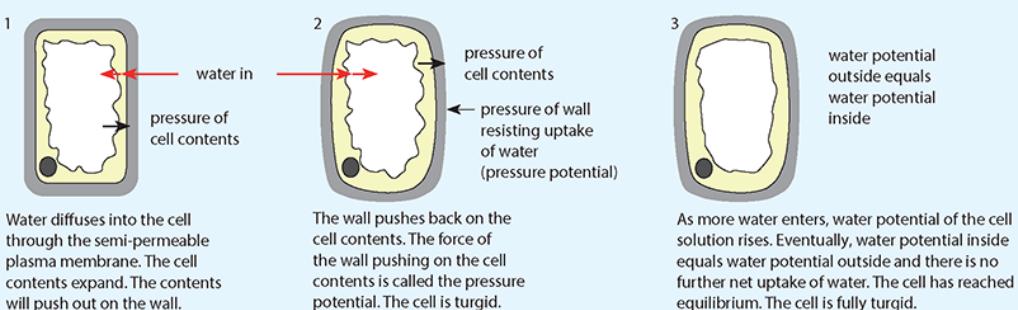
pressure potential the component of water potential due to the hydrostatic pressure that is exerted on water in a cell; in a turgid plant cell it has a positive value, water enters the vacuole and the cell membrane is pushed up against the cell wall.

KEY POINT

solute potential also known as osmotic potential; pressure needed to be applied to a solution to prevent the inward flow of water across a semi-permeable membrane.

Plant cells are also affected by the movement of water into and out of their cells but the presence of a cell wall prevents plant cells being damaged or bursting. If a plant cell is put into water that is hypotonic to the content of the plant cell, that is containing a lower concentration of solute than the inside of the cell, water will enter by osmosis. However, the plant cell wall resists the entry of further water once the cell is full. A plant cell that is full becomes firm and rigid, a condition known as turgor. The force within a cell that pushes the plasma membrane against the cell wall is known as turgor pressure.

A plant cell in a solution that is less concentrated than the cell solution absorbs water by osmosis



A plant cell in a solution that is more concentrated than the cell solution loses water by osmosis

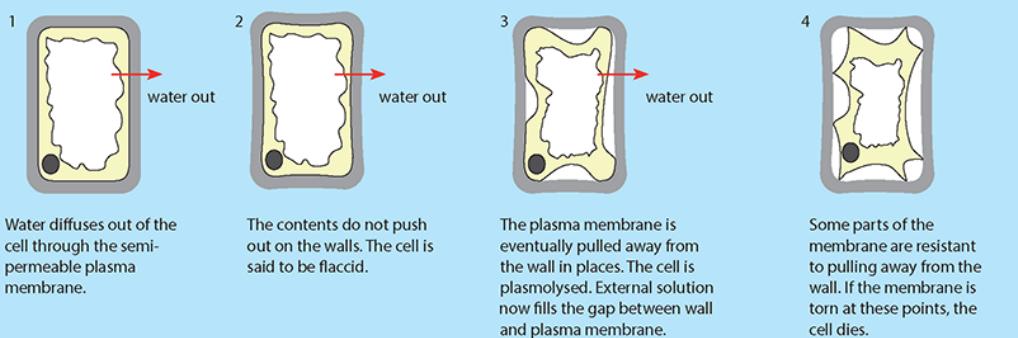


Figure 6.3.3: The effect of hypotonic and hypertonic solutions on a plant cell. Plant cells are not damaged when water enters by osmosis because their cell wall protects them.

If a plant cell is placed in an isotonic solution, water will enter and leave the cell in equal amounts. But, if the cell is placed in a hypertonic solution, containing a higher concentration of solute than the inside of the cell, water will move out of the cell (Figure 6.3.3). The cell inside the cell wall becomes flaccid and the plasma membrane is pulled away from the cell wall. This is called **plasmolysis**.

TEST YOUR UNDERSTANDING

- 12** Look at the graph in worked example 6.2. Describe and explain the change in mass in 0.0 M (distilled water) and 1.0 M sucrose solution.
- 13** What is the term used to describe the appearance of the cells in 0.0 M distilled water?
- 14** Why is it important to use three samples for each molarity of solute?
- 15** Why is the percentage change in mass used in the experiment?

KEY POINTS

hypotonic is when a solution is having a lower concentration of solutes (a more negative water potential) than the cell contents; this causes water to enter the cell making it swell.

isotonic is having the same osmotic concentration of the same water potential as another solution; there is no net movement

of water.

turgor pressure is the force within a cell that pushes the plasma membrane against the cell wall.

hypertonic having a higher solute concentration (less negative water potential) than inside the cell; this causes water to leave the cell, making it shrivel.

Isotonic solutions are used in hospitals to replace lost bodily fluids if a person is dehydrated due to burns or intestinal disorders (Figure 6.3.5). They are also used to surround organs that are being prepared for transplantation. The intracellular and extracellular environments have the same osmotic pressure. This means that there is no net movement of water into or out of the patient's cells or the organ for transplant, so the cells are kept alive and healthy.

WORKED EXAMPLE 6.2

Estimating the water potential of potato tissue

To estimate the water potential of potato cells we can bathe potato samples in hypotonic and hypertonic solutions to establish when there is no net movement of water between the intracellular environment and the extracellular (external) environment of the cells. You may have carried out these experiments yourself. When the pressure inside the cell becomes large enough, no additional water will enter the cell due to the presence of the cell wall. The movement of water cannot be predicted from the relative solute concentrations inside and outside the plant cell wall. Instead, we must consider the water

potential to predict the direction in which water will diffuse.

- 1 Equally sized samples of potato are cut, blotted to remove excess water and carefully weighed. Their mass is recorded.
- 2 The samples are placed in sucrose or salt solutions of different molarity. Three samples are used in each solution.
- 3 After a period of time the samples are removed, blotted and reweighed.
- 4 The percentage change in mass for each sample is plotted against the molarity of the solutions (Figure 6.3.4).
- 5 The graph shows that in this experiment the concentration of sucrose causing no change in mass has a molarity of 0.3 M. At this point we can say that there is no net movement of water molecules and the solutions inside and outside the cells are isotonic.

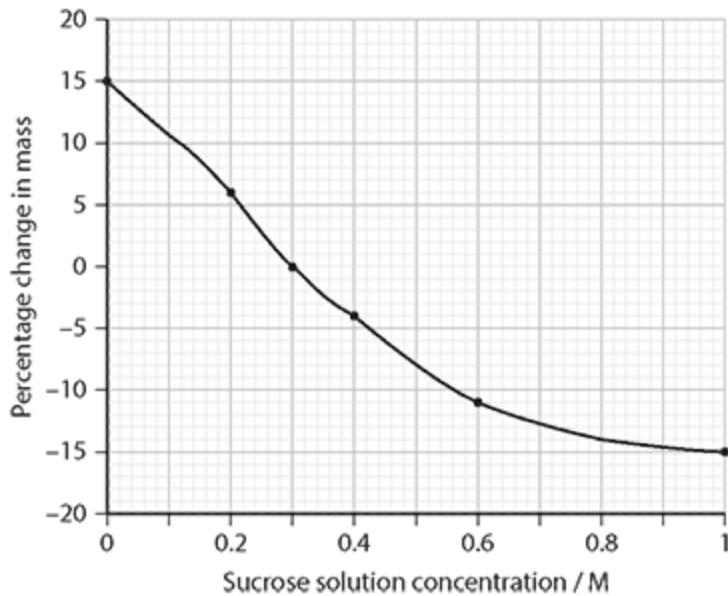


Figure 6.3.4: Graph to show the percentage change in mass of potato samples placed in different molarities of sucrose solution.

Answer

Pure water has a water potential of 0, which is higher than the water potential inside the cell. In these conditions there will be a net movement of water into the cell. The pressure potential inside the cell will increase as water enters until the cell reaches a state of equilibrium. In different molarities of sucrose solution, water will either enter or leave the potato cells. Where the line on the graph crosses the x-axis is the point at which the molar concentration of sucrose has a water potential that is equal to the water potential of potato tissue.



Figure 6.3.5: This person is being given intravenous fluid from an isotonic saline drip to replace lost body fluids quickly.

SCIENCE IN CONTEXT

Sports drinks and exercise

If you take exercise you may have bought a sports drink to refresh yourself afterwards. Manufacturers advertise these drinks to help athletes hydrate before, during and after exercise to improve their sports performance and minimise fatigue. Rehydration is important during exercise as performance deteriorates rapidly when a person is dehydrated. Sports drinks supply energy, replace salts such as sodium and potassium, which are lost through sweat, and replace water.

There are several types of sports drinks available and all of them contain various levels of fluid, electrolytes (salts) and carbohydrate. Hypotonic drinks have low carbohydrate

content and a lower concentration of salt and sugar than human cells. They are designed to replace fluids rapidly. Athletes, such as gymnasts, who require water but not carbohydrate during their performances, may use them. Isotonic drinks have a similar concentration of salts and sugar as human cells and also replace fluids quickly. These supply carbohydrates and most athletes who are involved in middle- or long-distance running would choose them. Popular sports drinks are a compromise designed to meet the needs of most people in many different situations. No one formula will suit everyone because individuals vary. Check the labels and ingredients of drinks you buy and ask yourself:

- Are you paying for a product you don't need?
- Could you drink water instead of a commercially made sports drink?

6.3.2 Advanced water potential

Water potential is a measure of the potential energy in water as well as the difference between the potential in a given sample and pure water. Potential energy is the energy that is stored in water but this is impossible to measure precisely. For this reason, values relative to pure water at atmospheric pressure and 20°C are used. Water potential is measured in kilopascals (kPa)

The plasma membrane of a plant cell is differentially permeable and a plant cell functions as an osmotic system. Water can pass through the plant membrane and so can some solutes, but not others. The cell wall is permeable to practically all solutes and not to water. This means that there is a relationship between the water potential of the cell contents and the turgor pressure of the cell and the water potential of the cell as a whole. Water molecules and mineral ions enter plants cells by physical processes. Water will always move from regions of higher water potential to regions of lower water potential, that is from a region of higher potential energy to a region where the potential energy is lower.

$$\Psi = \Psi_p + \Psi_s$$

- Where Ψ is the water potential
- Ψ_p is the pressure potential
- Ψ_s is the solute potential

Solute potential and pressure potential both contribute to the water potential within the walls of plants. Solute potential (Ψ_s) is negative in a plant cell and zero in distilled water while pressure potentials are usually positive inside cells. If a plant cell is

immersed in water it will become fully turgid as water enters it. If it is immersed in a solution with a water potential of –0.5 MPa it will soften and lose its turgor as water leaves the cell, if it is immersed in a solution of –1.0 MPa it will lose all turgor.

If some plant cells were examined they might have the following values:

$$\begin{aligned}\psi &= \psi_p + \psi_s \\ -0.5 \text{ MPa} &= +0.5 \text{ MPa} + (-1.0 \text{ MPa})\end{aligned}$$

If this cell were placed into a **hypotonic** solution of pure water with a water potential of 0.0 MPa water would flow into it with a force equal to the difference between the water potential of the cell (ψ) and the zero potential of the water, that is a force of 0.5 MPa. This would eventually raise the pressure potential (ψ_p) of the cell until it reached its maximum of 1.0 MPa and full turgor. At this point the cell would have a water potential of zero.

$$\begin{aligned}\psi &= \psi_p + \psi_s \\ 0.0 &= +1.0 + (-1.0)\end{aligned}$$

If a fully turgid cell is placed in a **hypertonic** solution of salt with a solute potential of –0.5 MPa. Then the cell with a ψ of 0 would be at a higher water potential than the surrounding solution. Water would flow out of the cell and reduce its turgor until a new equilibrium was reached and pressure potentials inside and outside the cell are equal. This can be shown in this equation

$$\begin{aligned}\psi_s &= \psi_p + \psi_s \\ \text{External pressure} &= \psi_p + \text{Internal pressure} \\ -0.5 &= +0.5 + (-1.0)\end{aligned}$$

REFLECTION

Reflect upon the most interesting discoveries you made when working on this chapter. How does your experience compare with that of your classmates?

TEST YOUR UNDERSTANDING

- 16** Describe the effect of a hypotonic solution on a plant cell and on an animal cell.
- 17** Outline the reasons for plasmolysis in a plant cell and crenation in an animal cell.
- 18** Why are isotonic solutions important in medical treatments?

Links

- How are concentration gradients important in moving materials in and out of cells? ([Chapter 6.2](#))
- Which are the most useful properties of water to living organisms? ([Chapter 1](#))

6.4 Limitations to cell size

LEARNING OBJECTIVES

In this section you will:

- understand that cells obtain substrates for metabolism from their environment and remove wastes through the plasma membrane
- learn that a large surface area to volume ratio ensures that this process is efficient
- recognise that as cells grow larger they require more resources, but the rate of exchange of materials depends on the surface area of the cell
- understand that as cells grow the surface area to volume ratio decreases
- discover that structures, such as folds, or flattening of a cell can increase the surface area to volume ratio
- learn that cells maintain their volume but increase their surface area by dividing in two

- understand that the size of cells in a tissue depends on rate of growth and rate of division
- learn that cells are influenced by extracellular signals including growth factors and mitogens.

GUIDING QUESTIONS

- Why are surface area and volume important for growing cells?
- How do cells maintain a high surface area to volume ratio?

6.4.1 Surface area to volume ratio

Cells are very small, no matter what the size of the organism that they are part of. Cells do not and cannot grow to be very large and this is important in the way living organisms are built and function. The volume of a cell determines the level of metabolic activity that takes place within it. The surface area of a cell determines the rate of exchange of materials with the outside environment. As the volume of a cell increases, so does its surface area, but not in the same proportion. Table 6.4.1 shows this for a theoretical cube-shaped cell. As a cell grows larger, it has proportionately less surface area to obtain the materials it needs and to dispose of waste.

As a cell grows in size, the rate of exchange of materials across the outer membrane may become limiting and will not keep up with the cell's requirements. The distance from the plasma membrane to the interior of the cell also increases. This makes diffusion to the centre of the cell slower, so that that cell cannot function efficiently.

Side of cube/mm	Surface area/mm ²	Volume/mm ³	Ratio of surface area : volume
1	6	1	6 : 1
2	24	8	3 : 1
3	54	27	2 : 1

Table 6.4.1: Surface area to volume ratios for a cube.

Increasing surface area

Some cells have specialised structures, such as folds and microvilli, to provide a larger surface area relative to their volume (Figure 6.4.1). Many multicellular structures, such as the digestive system and the lungs ([Section 8.3](#)), also have folded surfaces to increase their surface areas for the exchange of materials.

TEST YOUR UNDERSTANDING

- 19** Many cells are roughly spherical in shape. The volume of a sphere is πr^3 and its surface area is $4\pi r^2$, where r is the radius. Make a table similar to Table 6.4.1, this time for a sphere using different radii as a starting point. Describe the relationship between surface area and volume in this case.
- 20** Take a 2 cm cube of modelling clay. Change its shape so that it becomes a cuboid, a thin cylinder or a sphere. Calculate its surface area each time. Try creating folds in the surface. Which shape produces the greatest surface area?

A flattened or elongated shape also increases a cell's surface area to volume ratio (Figure 6.4.2).

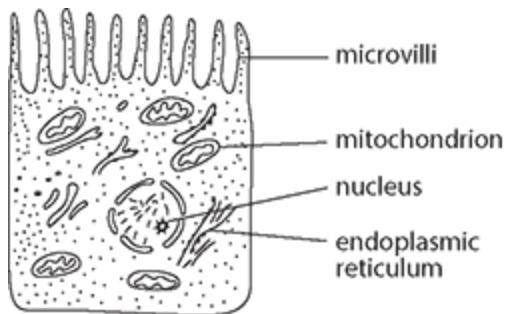


Figure 6.4.1: Microvilli are folds that increase the surface area of cells so that materials can be exchanged. Cells like these are

found in the intestine and in the lining of the trachea.

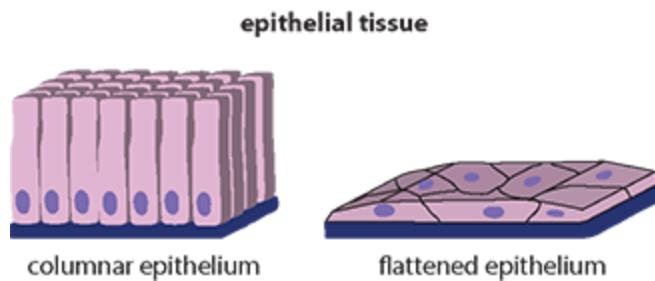


Figure 6.4.2: Flattening and elongation are methods of increasing the surface area to volume ratio of cells.

But, whatever the modifications a cell adopts, there will always be a limit to the size of a single cell. When a cell becomes too large and its surface area to volume ratio is insufficient to supply its needs, it must divide. Division maintains the same total volume in the two new cells that form, but each has its own surface to provide an optimum rate of movement across the plasma membrane ([Section 6.5](#) for more on cell division).

6.4.2 Cell growth and division

The size of cells in the body varies depending on the rate of growth of the cells and their rate of division. Table 6.4.2 shows the volumes of some human cells. Their sizes and shapes are related to the function of each type of cell. Red blood cells are very small, biconcave discs (round cells which are concave on both sides). This is a shape which maximises the surface area to volume ratio available for the exchange of oxygen and carbon dioxide. Epithelial cells are bound together and form layers called epithelium which line the inside of the intestine and other hollow structures in the body. These cells are small with a large surface area which is very important for absorption and secretion of materials.

Cell type	Average volume / μm^3
red blood cell	100
columnar epithelium in the intestine	1400
fibroblast (cells which secrete collagen and form a framework for tissues)	2000
heart cell	30 000
fat storage cell	600 000
oocyte	4 000 000

Table 6.4.2: The average volume of some cell types.

Cells such as fat cells and oocytes have very large volumes because they store materials and oocytes do not divide. In contrast, cells of the intestine are many times smaller and divide

frequently as they are damaged by digesting food materials flowing past them. Neurons can be over 1 metre long to extend from the spinal cord to the legs but are only about 10 µm wide.

Both bacterial and eukaryotic cells have characteristic sizes but cell size is not rigidly fixed and varies slightly in response to external factors, such as nutrient levels. The average size of a cell can change when the conditions for its growth change. The size a cell eventually becomes when it is ready to divide is determined by a balance between cell growth (the increase in mass or volume) and the timing of division.

Cell division is influenced by signals from outside the cell. Cells increase in size under the stimulation of **growth factors**. Growth factors are protein molecules made by the body. They regulate cell growth and cell survival. Cell growth is a separate process to cell division: some cells can grow without dividing (fat cells, muscle fibres and neurons do this), or divide without growing (fertilised egg cells divide without growing as their cytoplasm is shared between many small cells in the early stages of development).

Most cells must reach a specific minimum size to progress in the cell cycle ([Section 6.5](#)) and this progress is controlled by another groups of proteins called mitogens. A **mitogen** is a peptide or small protein that causes a cell to enter mitosis. The proteins bind to receptors on the plasma membrane and activate cell division. Some stimulate division in many cell types while other are specific to just one type of cell.

NATURE OF SCIENCE

Models can help our understanding

Models are simplified versions of things that can be very complex. Think about the figures and calculations about surface area and volume shown in Table 6.4.1. We can make model cubes with different side lengths as an easy way to investigate surface area to volume ratios. We can use them to study what happens to the surface area of a cell as it becomes larger. The cubes do not have the same shape as real cells but the scale factor (as you enlarge the shape and each side is multiplied by the same number) will work in exactly the same way as that for cells.

TEST YOUR UNDERSTANDING

- 21** Explain the importance of surface area to volume ratio to a cell.
- 22** Outline two ways in which a cell can increase its surface area.
- 23** Name two substances that enter and one that leaves a cell through its plasma membrane.
- 24** Describe the difference between a growth factor and a mitogen.

Links

- How did the evolution of eukaryotes allow cells to become larger? ([Chapter 6.5](#))
- How does a cell wall influence the size of a plant cell? ([Chapter 6.3](#))

- Is there a relationship between cytoplasmic volume and nuclear volume? (Chapter 6.5)

6.5 Cell division

LEARNING OBJECTIVES

In this section you will:

- recall that new cells are produced by cell division
- learn that single-celled organisms reproduce asexually by binary fission
- discover that the cell cycle consists of interphase, mitosis and cytokinesis
- discover that cytokinesis can be asymmetric in some cases
- understand that metabolic reactions and DNA replication occur during interphase.
- define mitosis as the division of the nucleus
- learn that DNA assisted by histones, supercoils and condenses for mitosis
- define cytokinesis as the division of the cell which occurs after mitosis
- learn that cell division is controlled for appropriate growth, development and repair
- define meiosis as cell division that produces gametes
- understand that non-disjunction occurs if homologous pairs of chromosomes fail to separate during anaphase 1

- recognise that chromosome behaviour in metaphase I demonstrates the patterns of inheritance expressed in Mendel's second law
- learn that crossing over and random orientation of chromosomes at meiosis increases genetic variation

- recall that cell proliferation is needed for growth and repair
- understand the phases of the cell cycle and that cyclins are responsible for controlling stages of the cycle
- learn that mutations in genes that control the cell cycle can lead to the development of tumours
- recognise that malignant tumour cells have faster rate of cell division than normal cells and the capacity for metastasis
- define the terms benign, malignant, primary tumour in relation to tumour growth and cancers
- understand the use of mitotic index to monitor cell division

GUIDING QUESTIONS

- How does cell division make a species more resilient if environmental conditions change?
- Why must the cell cycle be efficiently controlled?

6.5.1 Binary fission in single-celled organisms

Simple single-celled organisms are usually much smaller in volume than more complex cells. Their means of reproduction is also simple. As they grow, their DNA replicates and separates into two different areas of the cytoplasm. The cytoplasm then divides in two and forms two identical new daughter cells. This is called **binary fission** (Figure 6.5.1). Many organisms reproduce themselves using binary fission; examples include the unicellular organisms such as amoebae, *Paramecium* spp. and yeast. Reproducing in this way is known as **asexual reproduction** as no gametes are involved and the offspring are genetically identical to the parent.

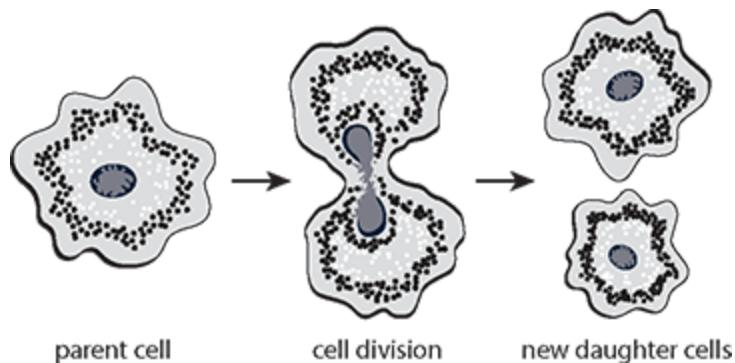


Figure 6.5.1: Binary fission in amoebae.

6.5.2 The cell cycle

In larger organisms, new cells are needed to replace cells that have died and to allow an organism to grow in size. The nucleus and cytoplasm of a cell divide in processes known as **mitosis** and **cytokinesis**, which are phases in a series of events known as the **cell cycle**. Mitosis occurs in tissues such as plant meristems and animal embryos where rapid growth is taking place. It also occurs in tissues that have been damaged and need repair, such as when the skin is cut or scratched and a wound needs healing.

The cycle of a cell's life can be divided into three stages, as shown in Figure 6.5.2:

- 1 interphase
- 2 mitosis (division of the nucleus)
- 3 cytokinesis (division of the cytoplasm).

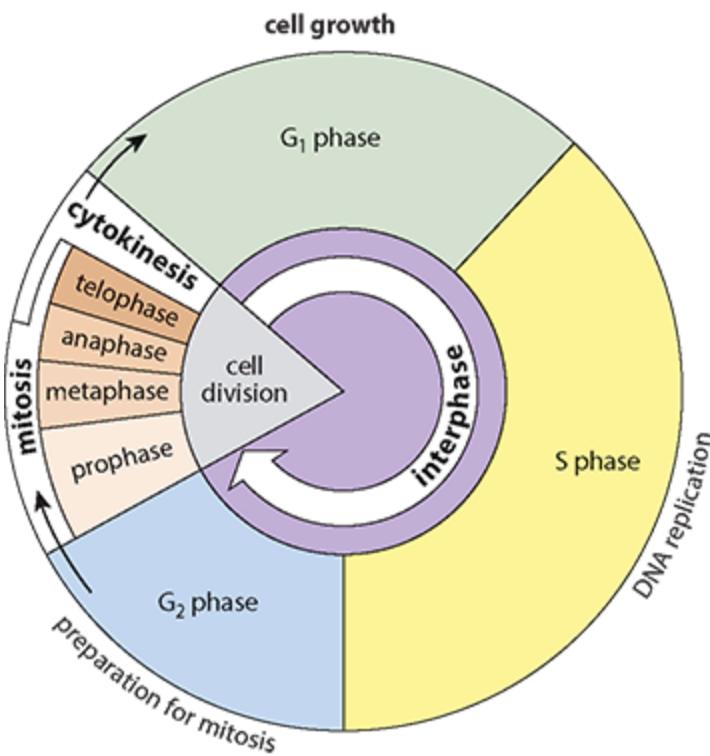


Figure 6.5.2: Summary of the cell cycle.

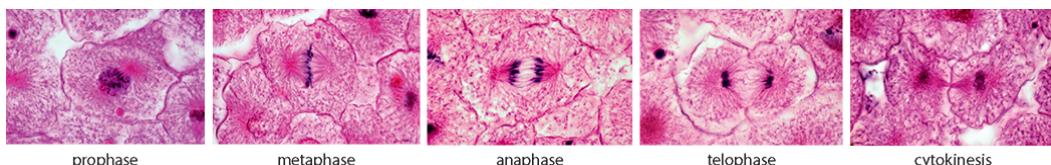


Figure 6.5.3: Stages of mitosis and cytokinesis in stained onion cells, as seen in a root squash preparation ($\times 900$ magnification).

G₁, S and G₂ are the three stages of the part of the cell cycle known as interphase, which is described in the next section. Mitosis and cytokinesis are the phases when the cell nucleus and cytoplasm divide. The phases of the cell cycle are summarised in Table 6.5.1.

Phase of the cell cycle	Activities in the cell	
interphase	G ₁	cell growth

	DNA transcription protein synthesis
S phase	DNA replication
G ₂ phase	cell prepares for division
mitosis	cell nucleus divides
cytokinesis	cytoplasm divides

Table 6.5.1: Summary of the phases and events of the cell cycle.

Interphase

During most of the life of a cell, it performs the task for which it has been pre-programmed during differentiation. This period is called **interphase**. Part of interphase is spent in preparation for cell division (the **G₂ phase**) and part of it is the period immediately after division (the **G₁ phase**). The two stages of cell division are the separation and division of the chromosomes (mitosis), and the division of the cell into two daughter cells (cytokinesis).

If you look at a cell during interphase using a light microscope, not much appears to be happening, but this is a very active phase of the cell cycle when the cell carries out its normal activities and also prepares itself for mitosis. In the nucleus, the DNA in the chromosomes is replicated, double-stranded DNA molecules are copied (**S phase**), so that after cell division there will be exactly the same number of chromosomes in the two daughter cells.

During interphase many proteins necessary for the division need to be synthesised at the ribosomes in the cytoplasm. The number of mitochondria increases so that the respiratory rate can be rapid enough to provide energy for cell division. In the case of plant

cells with chloroplasts, the number of chloroplasts increases so there will be enough for each daughter cell.

KEY POINTS

anaphase is the stage in cell division in which homologous chromosomes (in meiosis I) or chromatids (meiosis II and mitosis) separate and move to opposite poles.

centriole refers to a cylindrical structure in an animal cell that forms and organises the spindle microtubules in cell division.

centromere is the region where sister chromatids are joined and where the spindle microtubule attaches during cell division.

interphase refers to the period between successive nuclear divisions when the chromosomes are uncoiled and the cell is actively transcribing and translating genetic material.

metaphase is stage in nuclear division at which chromosomes become arranged on the equator of the spindle.

prophase is the first stage in cell division by meiosis or mitosis.

sister chromatids are two joined copies of a chromosome after it has replicated and before the centromeres separate at anaphase.

spindle is structure formed of microtubules to which centromeres attach during meiosis and mitosis.

supercoiling refers to winding of two complementary strands of DNA around one another and around a common axis.

telophase is the final phase of mitosis when duplicated genetic material is separated into the nuclei of two identical daughter cells

Mitosis

The two new cells that form after mitosis and cytokinesis are genetically identical. These processes allow an organism to grow more cells, or to repair injured tissue by replacing damaged cells, or to make new cells to replace old ones. Mitosis is also the way in which an embryo grows from a fertilised egg during development.

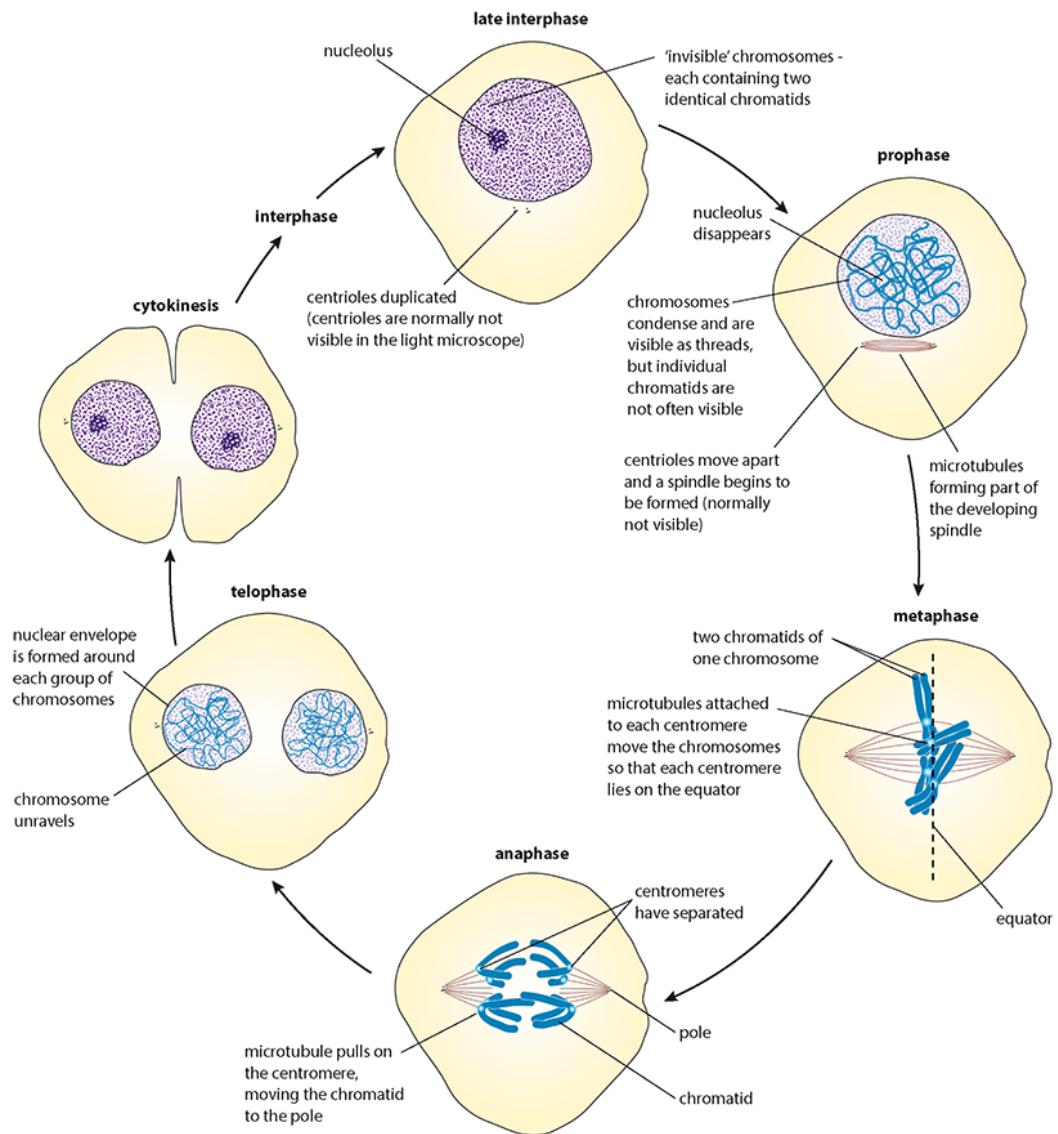


Figure 6.5.4: The stages of the cell cycle, including mitosis.
Note that the cells are shown with just four chromosomes here, to make it easier to understand the process.

There are four distinct stages in mitosis, although the process is continuous, with each stage running into the next. There are no intervals in between the stages. Figures 6.5.3 and 6.5.4 show the stages of mitosis in detail.

Prophase

During prophase, chromosomes become visible using a microscope. During interphase they have been drawn out into long threads, giving the cellular machinery access to the genes. But now, the chromosomes coil round histone proteins and around themselves several times to produce a supercoil (Figure 6.5.5). Supercoiling prevents transcription and makes the chromosomes shorter and thicker.

It also reduces the space that they take up and enables them to take part in the processes that follow.

We can follow the stages of mitosis because supercoiled chromosomes can be seen using a microscope. DNA was replicated during interphase so at this stage each chromosome consists of two identical copies. These two copies are called the sister chromatids and are attached to each other at a place called the centromere. Also visible at this time are structures known as centrioles, which move to opposite sides of the cell as microtubules form between them. This microtubule structure is called the spindle. As prophase draws to a close, the nuclear envelope breaks down.

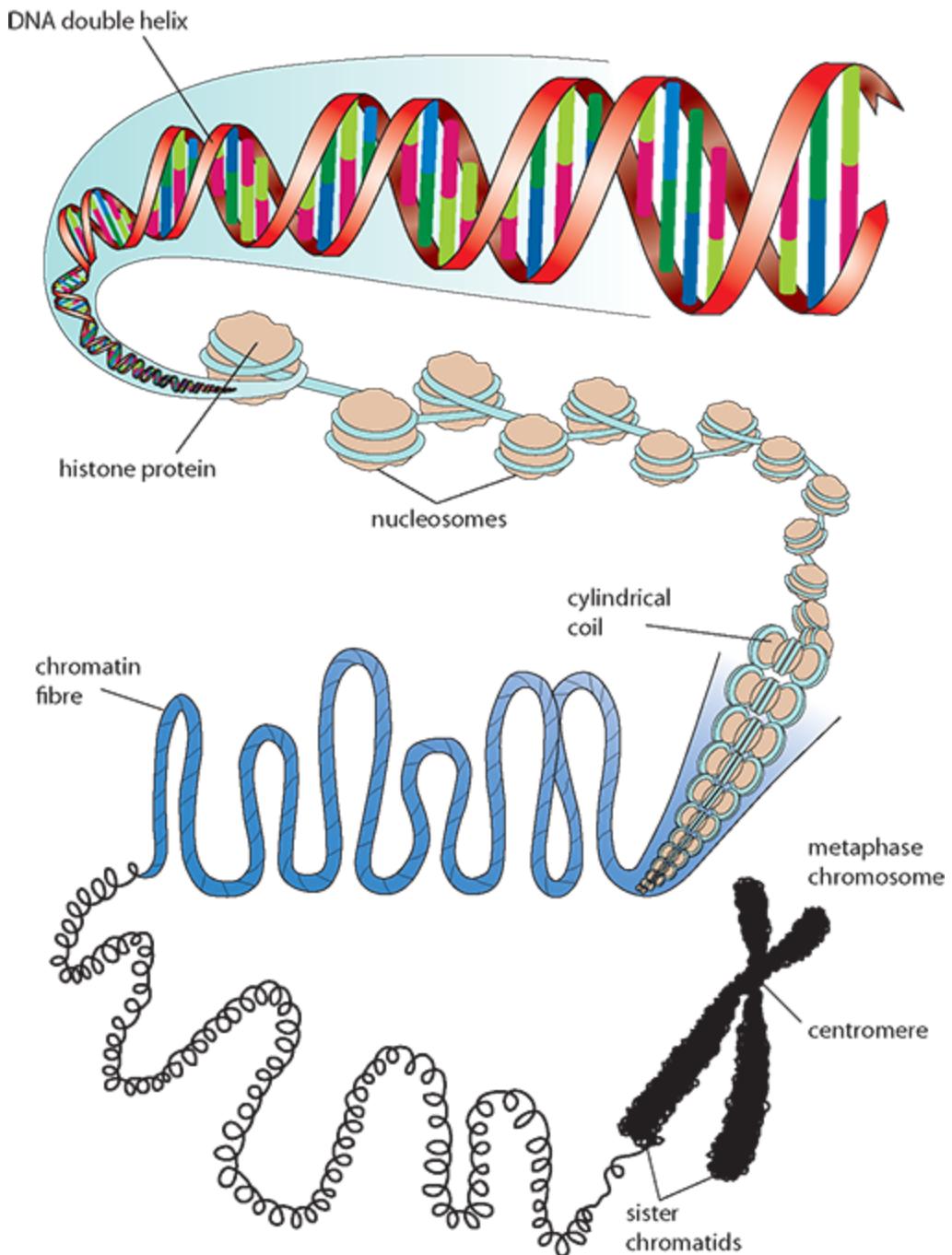


Figure 6.5.5: Supercoiling produces condensed, compact chromosomes in preparation for the next stages of mitosis.

Metaphase

Metaphase begins when the nuclear envelope has broken down. As it disappears, more space is created so that the chromosomes can move into position during their division. The sister chromatids align themselves on the microtubules in the middle, or equator, of the spindle and are attached by their centromeres.

Anaphase

During anaphase, the centromeres split and the sister chromatids are pulled apart. The chromatids move towards the centrioles at opposite sides (poles) of the cell as the spindle fibres shorten. Each sister chromatid is now called a chromosome again.

Telophase

Once the two sets of chromosomes reach opposite poles, the spindle fibres break down and a nuclear envelope forms around each set of chromosomes. At the same time, the chromosomes uncoil and become invisible through a light microscope.

Following telophase, in animal cells, the plasma membrane pinches in and the two new nuclei become separated as the cell enters cytokinesis.

Cytokinesis

During cytokinesis, the two sides of the plasma membrane meet and two completely new cells are formed. Each has a complete set of chromosomes, cytoplasm, organelles and a centriole. In animal cells a ring of contractile actin and myosin proteins pinch the cell membrane together to split the cytoplasm.

In plant cells, the cytoplasm divides in a slightly different way. Firstly, a cell plate forms along the centre of the cell, separating the cytoplasm into two regions. Vesicles accumulate at the edges of the cell plate and release cellulose and pectins, which are

needed to form a new cell wall. Gradually, a cell wall builds up along the cell plate separating the two nuclei and dividing the cytoplasm to form two new cells.

In most cases the division of cytoplasm between two new daughter cells is equal; both cells must receive at least one mitochondrion and other organelles that are made by dividing pre-existing structures. But in a few cases division of the cytoplasm is unequal. Oogenesis (formation of human ova) in humans is asymmetric and produces one large cell which receives all the cytoplasm while smaller polar bodies receive none. This unequal cytokinesis provides the ovum with a much greater amount of stored food than if an equal division were to occur. Another example of unequal cytokinesis occurs in yeast which reproduce by budding new cells from the original parent cell. The daughter cell is smaller and has a longer subsequent cell cycle than the parent cell which produced it.

EXAM TIP

Try to think of an acronym to help you remember the four stages of mitosis: PMAT.

Checkpoints in the cell cycle: cyclins and kinases

The rate and timing of cell division must match an organism's need for growth, development and repair. Cells in the intestine divide twice a day and those in the liver do so once a year. Nerve and brain cells divide very rarely. Understanding the factors that control the cell cycle is important in the study of cancer, which occurs when cell division is disrupted.

Checkpoints regulate the cell cycle so that division only takes place in favourable conditions when the cell is the correct size

and its DNA has been copied properly. There are three checkpoints during the cell cycle. At each one a set of conditions must be met before the cell can proceed to the next stage (Table 6.5.2).

Checkpoint	Conditions to be met
G ₁	cell has received signals from other cells cell is large enough cell has sufficient nutrients
G ₂	cell is large enough chromosomes have been duplicated
Metaphase	chromosomes are attached to the spindle

Table 6.5.2: Checkpoints in the cell cycle and cytokinesis.

At each stage of the cell cycle proteins called **cyclin-dependent kinases (CDKs)** are involved in control and regulation. CDKs are enzymes which modify various proteins needed for the cell cycle. To become active, CDKs require the presence of another group of proteins called **cyclins**. Cyclins have no enzymatic activity of their own but activate CDKs when they bind to them.

The interaction of CDKs and cyclins forms enzymes that direct cells through the cell cycle and control specific events such as microtubule formation and chromatid alignment. The levels of cyclins and kinases fluctuate at different stages of the cell cycle and allow the cell to move to the next stage of mitosis.

Cyclins are divided into four types based on observations from vertebrate and yeast cells (Figure 6.5.6) but some cyclins have different functions in different types of cell.

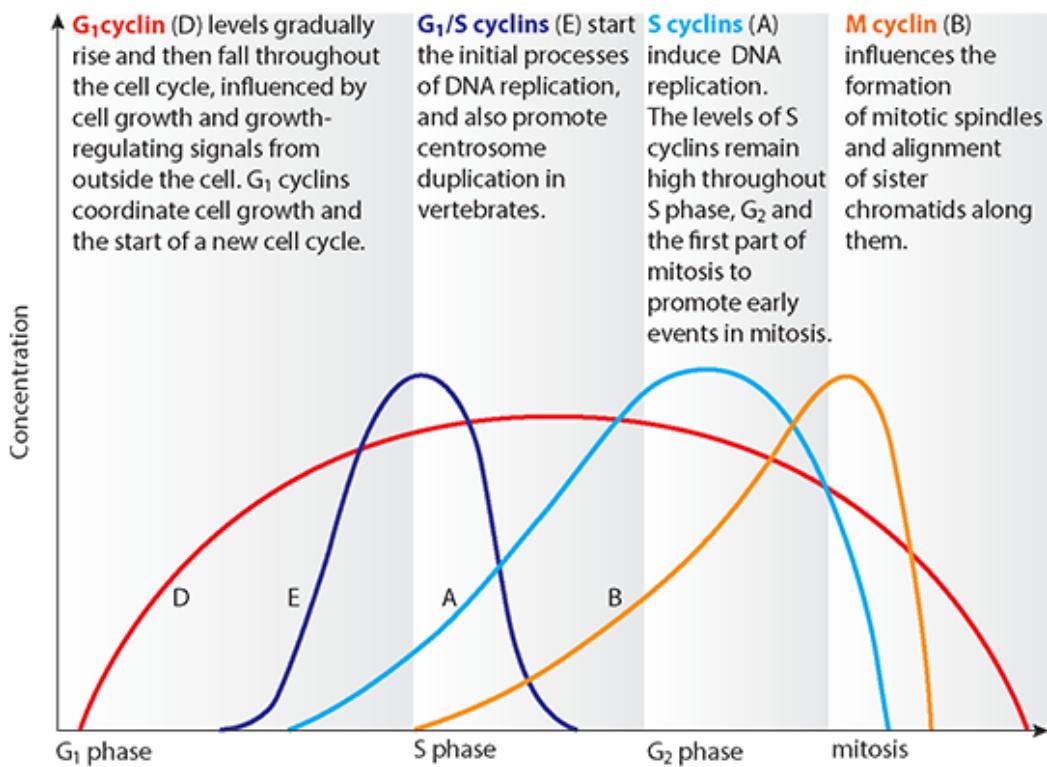


Figure 6.5.6: Cyclins can be divided into four types, which are important at different stages of the cell cycle: G₁ cyclins (D), G₁/S cyclins (E), S cyclins (A), M cyclins (B)

NATURE OF SCIENCE

Serendipity in science: the discovery of cyclins

Serendipity is a term derived from an old name for Sri Lanka. It is said to come from a Persian fairy tale ‘The Three Princes of Serendip’, about princes who made discoveries by accident. It has come to describe the role of chance in science and indicate how unexpected discoveries are sometimes made. Working scientifically, researchers often benefit from serendipity or ‘happy accidents’ as new discoveries are made by chance or from apparently unrelated findings.

The discovery of cyclins is one example of a serendipitous discovery. Timothy Hunt and two other scientists, Lee Hartwell and Paul Nurse, were all working on separate areas of the cell cycle and with different organisms. By chance the three strands of their work coincided. Hartwell worked with baker's yeast in the 1970s and discovered 'checkpoint' genes, which seemed to start the cell cycle. In the 1980s Nurse, worked with a different species of yeast. He found a gene that, if it became mutated, stopped the cell cycle or initiated early cell division, and he identified CDK. In 1982 Hunt, who worked with sea urchin eggs, discovered the other key factor that drives the cell cycle, the protein cyclin. Cyclin regulates the function of the CDK molecule and increases and decreases as cell division occurs.

In 2001, Hunt, Hartwell and Nurse were awarded the Nobel Prize in Physiology or Medicine for their work.

- You can read more about their discoveries on the Nobel Prize website by visiting the website (nobelprize.org) and searching for 'cyclins'.

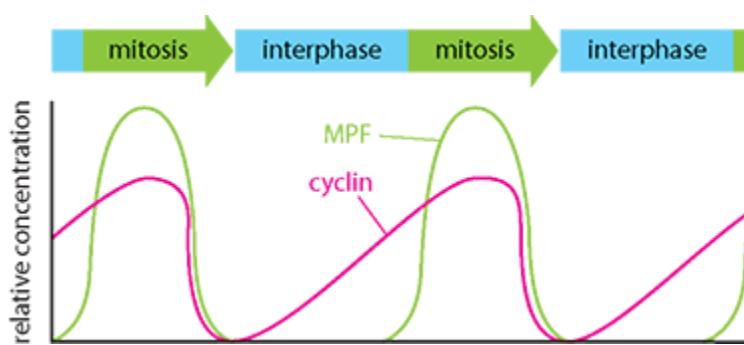


Figure 6.5.7: Levels of MPF rise as a cell enters mitosis, reach a peak and fall during anaphase.

Oncogenes and tumour suppressor genes

Tumour suppressor genes and oncogenes are two important types of gene that have important roles in controlling the cell cycle. Errors in the way they work can lead to the development of tumours and cancer.

Proto-oncogenes are functioning genes that help to regulate normal cell growth by providing signals that initiate cell division or regulate apoptosis. More than 40 different human proto-oncogenes have been identified. Many of them are important in development of the embryo and are switched off once the processes they control are complete. However, if a mutation occurs in these genes they can become permanently overactive, reactivated later in life or switched off. Activation can occur by a mutation or gene amplification. Most cancers are caused when proto-oncogenes are activated and become oncogenes.

Activation can happen when chromosomes rearrangements alter the positions of genes in relation to one another, or when gene duplication produces extra copies of a gene and an excess of certain protein is produced.

Many tumours are caused by activated oncogenes. Activated oncogenes can cause cells that should die during apoptosis to survive and divide instead. Most oncogenes become active as a result of some additional process such as mutation in another gene (often those which regulate cell growth or differentiation), direct exposure to a mutagen or another environmental factor such as a viral infection. Because of their importance in human cancers, oncogenes are specifically targeted in many new cancer treatments that are being developed in laboratories all over the world.

KEY POINTS

oncogene a gene that has the potential to cause cancer. In tumour cells, oncogenes can have mutations or be expressed at high levels.

tumour suppressor gene a gene that regulates cell division and replication.

Tumour suppressor genes are functioning genes that slow down cell division, repair DNA or control apoptosis. Without them cells can grow out of control and tumours can develop. The important difference between oncogenes and tumour suppressor genes is that oncogenes cause problems when they are activated but tumour suppressor genes cause cancer when they are inactivated. Some inherited abnormalities in tumour suppressor genes cause certain types of cancer to occur in several family members, but most tumour suppressor gene mutations are acquired during a person's lifetime, not inherited.

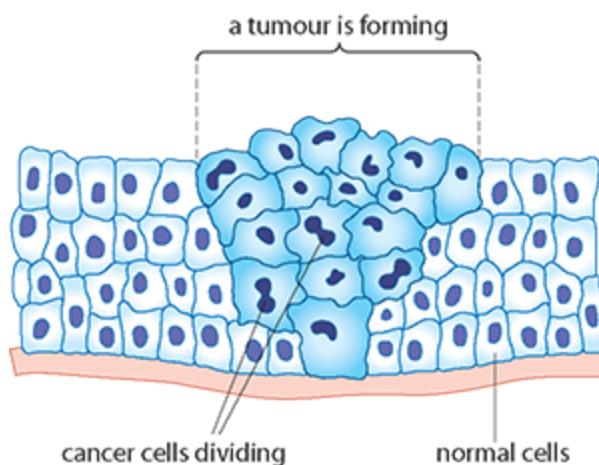


Figure 6.5.8: Formation of a primary tumour. If cells from a primary tumour become detached and form a new tumour in another part of the body, then the cells are said to be cancerous.

Cancer occurs when cells from a **primary tumour** (Figure 6.5.8) migrate to other tissues and form new **secondary tumours** in a process known as **metastasis**. Cancer is caused by damage to genetic material, producing cells that undergo uncontrolled, abnormal mitosis, but it cannot be thought of as a single disease. Cancer can take different forms in different tissues and the DNA damage that leads to cancer can be caused by a range of factors.

Apoptosis

Apoptosis is an orderly, controlled process. It is quite different from cell death caused by damage or injury. Apoptosis has two key functions: it enables cells to be removed during development (Figure 6.5.9) as structures form and grow, and it also removes cancerous cells or cells which are infected with viruses. Both cancerous cells and cells that are infected with viruses can be harmful to the rest of the organism so it is important that they are eliminated.



Figure 6.5.9: Cells between forming fingers are removed by apoptosis as the human hand develops.

If a cell is programmed to die, the contents of the plasma membrane will be packaged into their own membranes and removed by phagocytic cells of the immune system. During apoptosis a cell will shrink and develop ‘blebs’, which are bubble-like extensions on its surface. DNA is broken up and organelles are fragmented and packaged within a membrane. Signals on the outer plasma membrane attract phagocytic macrophages ([Chapter 10](#)) which engulf the cell fragments.

If a cell’s DNA is damaged, the cell will try to repair the damage using DNA polymerases. If this is not possible, the cell will cause their own death so that damaged DNA is not passed on. Damaged cells which fail to die may become cancerous. Pre-cancerous cells that do not cause their own death are often noticed by the cells of the immune system, which recognise external markers on their plasma membranes. If the cells are not removed they will be able to divide uncontrollably and form tumours.

Mitotic Index

In a population of cells, the ratio of the number of cells undergoing mitosis to the number of cells not undergoing mitosis is known as the **mitotic index**. A higher than normal mitotic index is an indication that cells are dividing more rapidly than usual and can be an indicator of cancerous cells. You should be able to work out mitotic indices from photographs of dividing cells.

TEST YOUR UNDERSTANDING

- 25** State two reasons why a cell may need to divide.
- 26** During which stage of the cell cycle does chromosome replication take place?

27 Outline the events of cytokinesis in an animal and a plant cell.

6.5.3 Meiosis

Meiosis is a type of cell division that produces **gametes** (sex cells). Meiosis is called a reduction division because in any organism, each cell that is produced as a result of meiosis has half the number of chromosomes of other cells in the body.

Eukaryotic body cells have a **diploid** nucleus ($2n$), which contains two copies of each chromosome, in **homologous** pairs (Section 4.1). Humans have a diploid number of 46 chromosomes in 23 pairs, whereas mangos and soybean both have 40 chromosomes in 20 pairs, and camels have 70 chromosomes in 35 pairs.

During sexual reproduction, two gametes fuse together so, in order to keep the chromosome number correct in the offspring that are produced, each gamete must contain only one of each chromosome pair. A gamete must contain half the diploid number of chromosomes, which is a number called the **haploid** (n) number. During gamete formation, meiosis reduces the diploid number to the haploid number and for this reason, meiosis is called a reduction division. At the moment of fertilisation, the normal diploid number is restored as two gametes fuse. For example, in the camel, the haploid sperm (35 chromosomes) and haploid egg (35 chromosomes) fuse at fertilisation to form the diploid zygote, with 70 chromosomes.

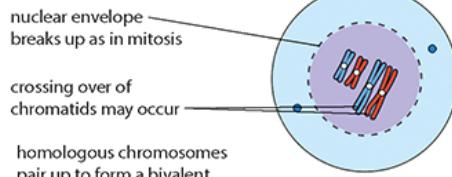
The process of meiosis

Meiosis occurs in a series of stages, as illustrated in Figure 6.5.10, which result in the production of four cells. Mitosis is achieved with one cell division but meiosis involves two divisions: the first reduces the number of chromosomes by half

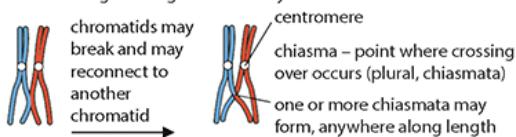
and the second produces four gametes each containing the haploid number of chromosomes. Exactly the same terms are used for the names of the stages, but since meiosis involves two divisions, the phases are numbered I and II.

Meiosis I

1 Prophase I

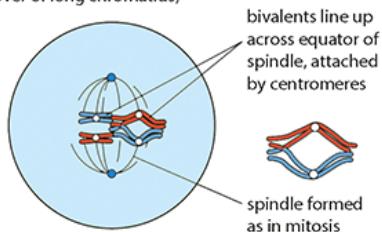


Bivalent showing crossing over that may occur:



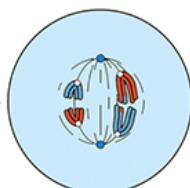
At the end of prophase I, a spindle is formed.

2 Metaphase I (showing crossing over of long chromatids)

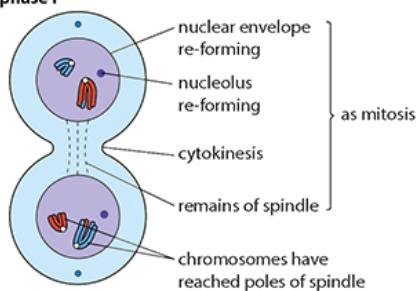


3 Anaphase I

Centromeres do not divide, unlike mitosis.
Whole chromosomes move towards opposite ends of spindle, centromeres first, pulled by microtubules.

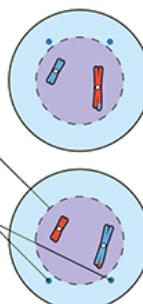


4 Telophase I

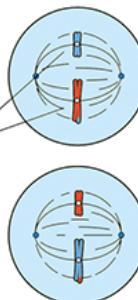


Meiosis II

5 Prophase II

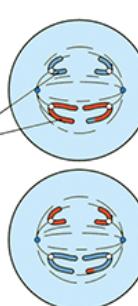


6 Metaphase II



7 Anaphase II

centromeres divide and spindle microtubules pull the chromatids to opposite poles



8 Telophase II

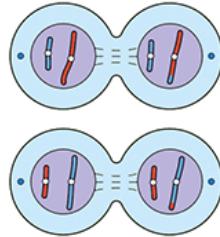


Figure 6.5.10: The stages of meiosis in an animal cell. Note that the cells are shown with just two homologous pairs of chromosomes to make it easier to understand the process.

The first division is very similar to mitosis and the second division is exactly the same as mitosis.

Prophase I

During interphase, before the start of prophase, chromosomes are replicated and consist of two identical sister chromatids joined at the centromere. In prophase I these chromosomes supercoil and the homologous pairs of chromosomes line up side by side.

These are called **bivalents**. A bivalent has two chromosomes and four **chromatids**, with one chromosome coming from each parent.

Although the genes carried by each chromosome pair are identical, the alleles may not be. Exchange of genetic material between the pair can occur at this point. Chromatids may become entangled, break and re-join so that alleles are exchanged between homologous chromosomes during a process called **crossing over**. New combinations of alleles are formed and genetic variety among the resulting gametes increases.

The final step in prophase I is the formation of spindle microtubules and the breakdown of the nuclear envelope.

Metaphase I

Chromosomes line up on the equator at the centre of the cell. Each one attaches by a centromere to the spindle microtubules. The alignment of the chromosomes is random so that maternal and paternal chromosomes can appear on either side of one another on the equator. This means that either chromosome from

a pair may move into each daughter cell during the first division at anaphase I, which results in increased genetic variety among the gametes.

Anaphase I

During anaphase I the microtubules contract towards opposite poles. The pairs of sister chromatids remain together but the homologous pairs are separated. This is the **reduction division** where the chromosome number is halved from diploid to haploid.

Telophase I

During telophase I spindles break down and a new nuclear envelope forms around each new nucleus. Cytokinesis follows and the cell splits into two cells, each containing only one chromosome of each homologous pair. Each chromosome, however, still consists of two sister chromatids at this point.

The second division of meiosis now follows to separate the two sister chromatids.

Prophase II

In each of the two cells resulting from meiosis I, new spindle microtubules start to form, the chromosomes re-coil and the nuclear envelope begins to break down.

Metaphase II

The nuclear envelope is broken down and individual chromosomes line up on the equator of each cell. Spindle fibres from opposite ends of the cell attach to each chromatid at the centromere.

Anaphase II

Sister chromatids are separated as the centromere splits and spindle fibres pull the chromatids to opposite ends of the cell.

Telophase II

Nuclear envelopes form around the four new haploid nuclei and the chromosomes now uncoil. A second cytokinesis occurs, resulting in four cells.

Meiosis and variation: crossing over and random orientation of chromosomes

Meiosis not only halves the chromosome number, it also promotes genetic variation in the gametes and individuals that are produced from them. There are several reasons for this:

- 1 Each chromosome of the homologous pair carries different genetic information so that the gametes formed are genetically different.
- 2 Random orientation: different homologous pairs arrange themselves independently on the spindle and also separate independently so that gametes contain different combinations of each chromosome pair (Figure 6.5.11).
- 3 Crossing over during prophase I (Figure 6.5.12) means that genetic material is exchanged between homologous chromosomes. This produces entirely new combinations. In each homologous pair, one chromosome is a maternal chromosome and the other a paternal chromosome. Homologous chromosomes contain the same genes, but since they came from different parents, they can have different alleles. As they line up together, the non-sister chromatids may touch and break. The two segments may

then re-join at the corresponding position on the other chromatid. In this way, chromatids are formed that are a mixture of paternal and maternal alleles. After crossing over, the chromatids recombine to produce new and unique combinations of alleles, different from both the maternal and the paternal arrangements. This is called recombination. The region where this happens is called a chiasma (plural: chiasmata) (Figure 6.5.12).

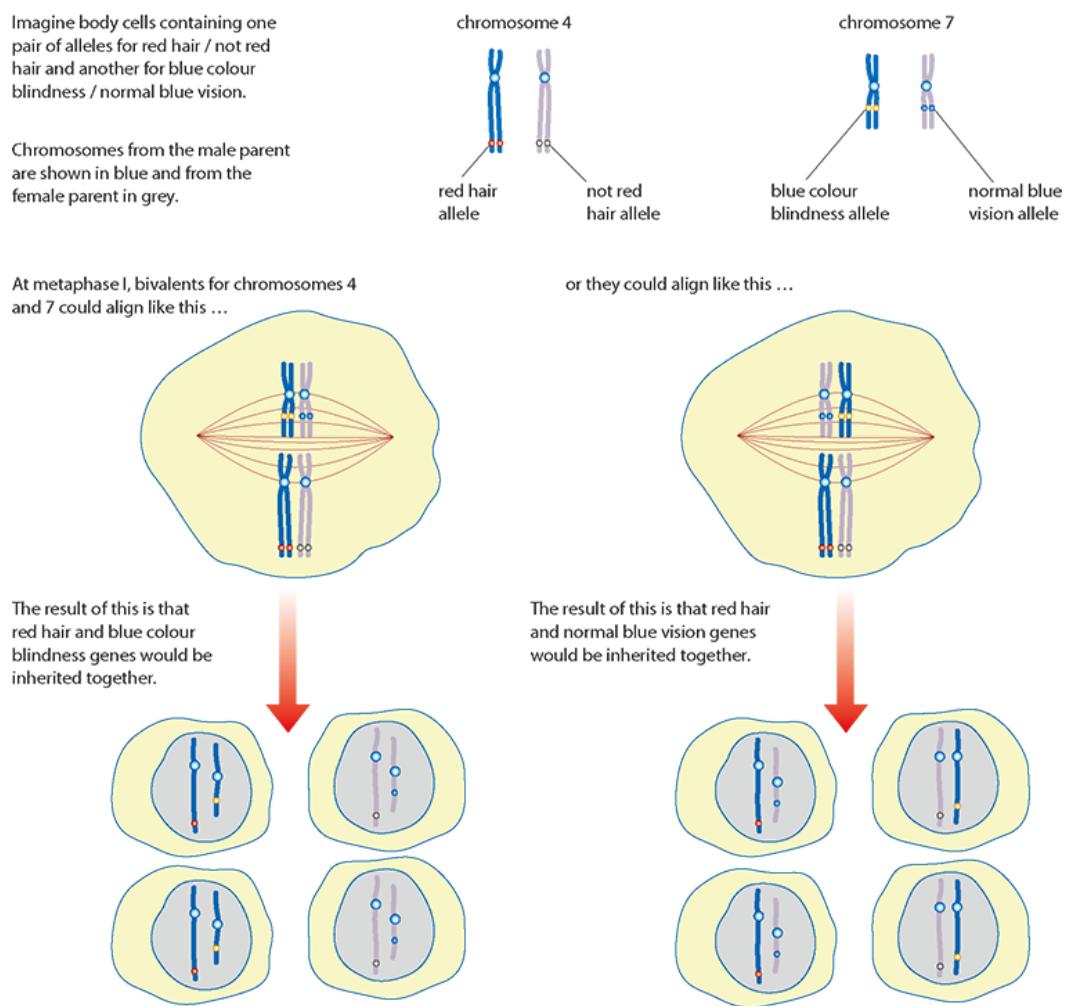


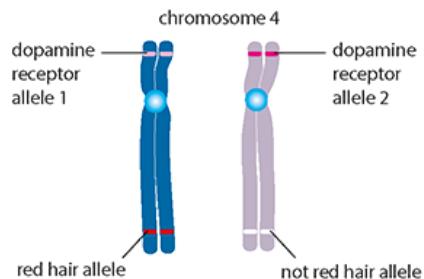
Figure 6.5.11: How random orientation produces variation.

Crossing over does not occur between the X and Y chromosomes. This is because the two chromosomes are

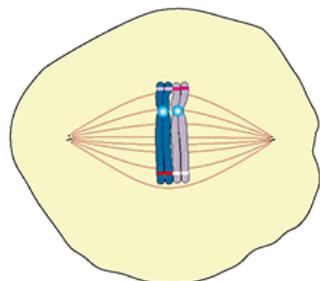
very different sizes and therefore do not sit alongside each other for their full length in the same way as other homologous pairs. The fact that there is no crossing over between the sex chromosomes is advantageous because it means that genes that determine sex remain on the appropriate chromosome.

- At fertilisation, gametes from different parents fuse together. This promotes yet more genetic variation among the offspring produced.

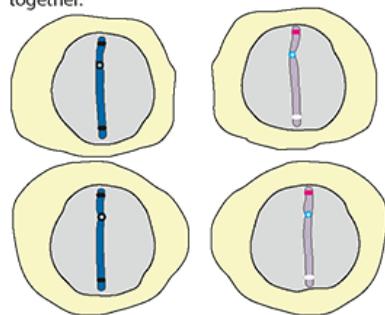
As well as the red hair locus, chromosome 4 also has a locus for a gene coding for dopamine receptors. Imagine that there are two different alleles of this gene.



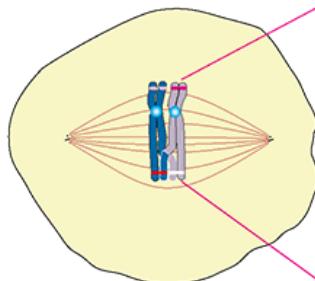
The chromosomes could do this ...



The result of this is that red hair and dopamine receptor allele 1 would be inherited together.



or their chromatids could cross over like this ...



The breakage and rejoining of chromatids in this crossing over allows new combinations of the alleles to be produced.

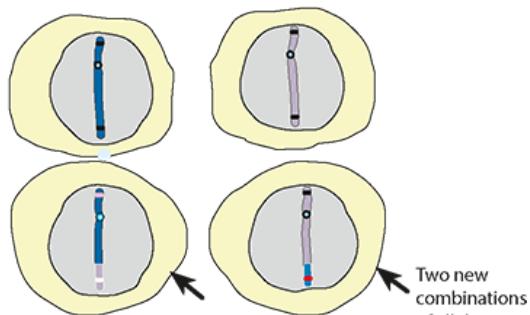


Figure 6.5.12: How crossing over produces variation. If a single cross-over occurs in a pair of chromosomes, four different daughter chromatids are produced instead of two.

TEST YOUR UNDERSTANDING

- 28** Why is meiosis often called a reduction division?
- 29** State the number of cells formed when meiosis in one parent cell is complete.
- 30** Describe what is meant by ‘random orientation’ of chromosomes during meiosis.

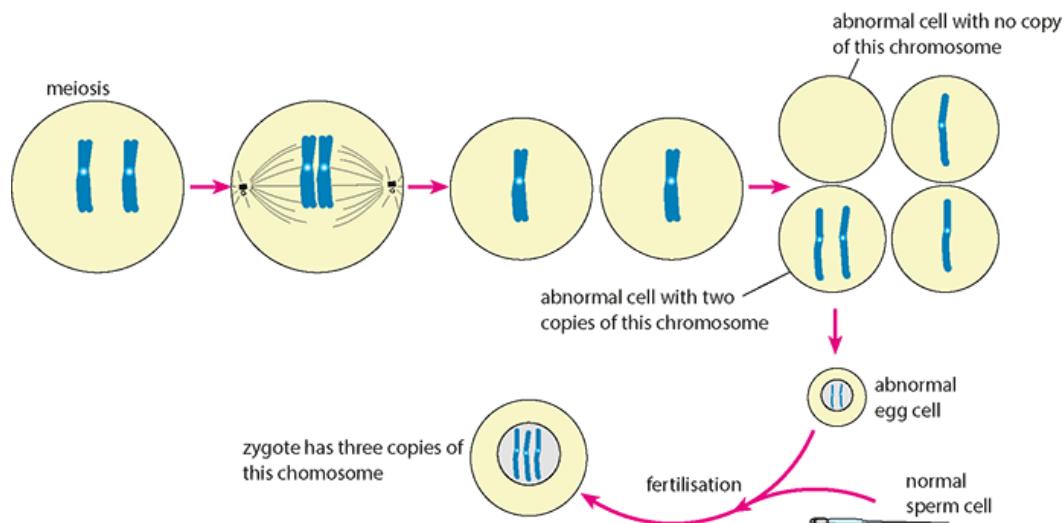


Figure 6.5.13: Non-disjunction at anaphase II of meiosis. Non-disjunction can also occur at anaphase I.

6.5.4 Non-disjunction

Non-disjunction is a failure of homologous pairs of chromosomes to separate properly during meiosis. It results in gametes that contain either one too few or one too many chromosomes. Those with too few rarely survive, but in some cases a gamete with an extra chromosome does survive and after fertilisation produces a zygote with three chromosomes of one type, as shown in Figure 6.5.13. This is called a trisomy.

Trisomy in chromosome 21 results in the human condition known as Down syndrome (Figure 4.1.3). A gamete, usually the female one, receives 24 chromosomes instead of 23 and a baby with 47 instead of the usual 46 chromosomes in each cell is born.

Karyotyping is used when there is concern about potential chromosome abnormalities. Cells from an unborn child are collected in one of two ways: chorionic villus sampling (CVS) or amniocentesis. The cells are grown in the laboratory and a karyogram is prepared. This is checked for extra or missing chromosomes ([Section 4.1](#)).

6.5.5 Chromosome behaviour and Mendel's laws

Mendel investigated inheritance in pea plants (Section 4.2) and when crossing purple and white plants he discovered that offspring were purple, indicating that one colour was dominant over the other. Mendel had no knowledge of chromosomes and genes, but nevertheless stated that each individual has two factors (alleles) for each characteristic, one from each parent.

His first law the law of segregation, states that individuals possess two alleles and that a parent passes only one allele to their offspring. One allele is given by each parent (Figure 6.5.14).

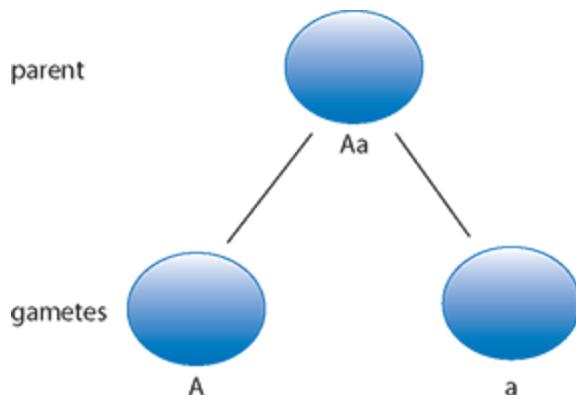


Figure 6.5.14: During meiosis one allele from each pair is passed from parent to gamete.

Mendel's second law – the law of independent assortment – states that during gamete formation the segregation of the alleles of one gene is independent of the segregation of the alleles of other pairs. When we examine the stages of meiosis and look closely at the alignment of chromosomes at metaphase I we can understand how this segregation and independent assortment of

alleles takes place. Chromosomes can line up in different combinations and produce different combinations in the resulting gametes.

KEY POINTS

independent assortment alleles of different genes are sorted into gametes independently of one another.

segregation separation of pairs of alleles at meiosis and their independent transmission in separate gametes to offspring.

Two possibilities are shown for two pairs of chromosomes in Figure 6.5.11.

During metaphase I, the bivalents line up on the equator and spindle microtubules become attached to their centromeres. However, the way in which they line up is random. This is shown in Figure 6.5.11, which illustrates the possibilities for just two chromosomes, 4 and 7.

- The paternal chromosomes could both line up together on one side of the equator with the maternal ones on the other side, as shown on the left. Two of the gametes that are produced, after the sister chromatids separate in meiosis II, contain just paternal chromosomes while the other two contain just maternal chromosomes.
- Another possibility is that the chromosomes line up as shown on the right, with maternal and paternal chromosomes on both sides of the equator. The end result here is that all four gametes contain a mixture of paternal and maternal chromosomes.

Independent assortment of alleles at metaphase I of meiosis results in the production of different combinations in gametes.

One gene does not influence any other gene, because alleles are sorted out into gametes: every possible combination of alleles for every gene is equally likely to occur. Independent assortment of genes is important to produce new genetic combinations that increase genetic variation in a population.

TEST YOUR UNDERSTANDING

31 Outline the result of non-disjunction of chromosomes.

REFLECTION

Reflect upon the level of difficulty of the ideas in this section. Is it one of the topics you find easier to tackle?

Links

- How does variation produced from sexual reproduction contribute to evolution? ([Chapter 11](#))
- Why is cell division important for multicellular organisms? ([Chapter 8](#))

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
draw and describe the structure of a membrane including phospholipid bilayer, membrane proteins and cholesterol and sterol	6.1.1			
outline why phospholipids form a bilayer and the importance of the fluid mosaic arrangement to cells	6.1.1			
define the term organelles	6.1.2			
explain why compartments that store, isolate and concentrate materials are important to cells	6.1.2			

state that prokaryotes do not contain organelles	6.1.2			
outline the functions of RER, Golgi apparatus, coated vesicles and lysosomes	6.1.3			
describe the importance of compartmentalisation in chloroplasts and mitochondria and how membranes form their compartments	6.1.3			
annotate diagrams of mitochondria and chloroplasts to link their structures and functions	6.1.3			
define: semi-permeable, diffusion, facilitated diffusion osmosis and active transport	6.2.1			
outline how gases move in and out of cells	6.2.1			
outline how glucose	6.2.1			

is moved into cells by facilitated diffusion				
state that membrane-bound proteins act as pores or pumps for transport of molecules	6.2.1 and 6.2.2			
understand that active transport requires energy in the form of ATP	6.2.2			
explain how exocytosis and endocytosis result from the fluid nature of the plasma membrane	6.2.2			
describe the structure of a neuron and its adaptations to carry impulses	6.2.3			
outline the importance of gated ion channels in the transmission of a nerve impulse	6.2.3			
outline how the sodium–potassium pump permits active	6.2.3			

transport in both directions				
summarise how myelinated nerve fibres allow for salutatory conduction at the nodes of Ranvier	6.2.3			
state the factors that determine whether water will move into or out of a cell	6.3.1			
define hypotonic, isotonic and hypertonic	6.3.1			
explain crenation and plasmolysis	6.3.1			
define turgor in plants	6.3.1			
outline an experiment to estimate the water potential of a plant cell	6.3.1			
outline how water moves from a higher to lower water potential	6.3.2			
recognise the contributions of	6.3.2			

solute and pressure potential to the water potential of plant cells				
explain the changes that occur when plant cells are placed in hypotonic and hypertonic solutions in terms of solute and pressure potentials	6.3.2			
state that cells interact with their environments to obtain substrates for their metabolism	6.4.1			
recall that cells require a maximum surface area to volume ratio to ensure substances can move across the membrane at optimum rate	6.4.1			
understand that larger cells have a smaller surface area to volume ratio	6.4.1			
outline how cells increase their surface area by becoming	6.4.1			

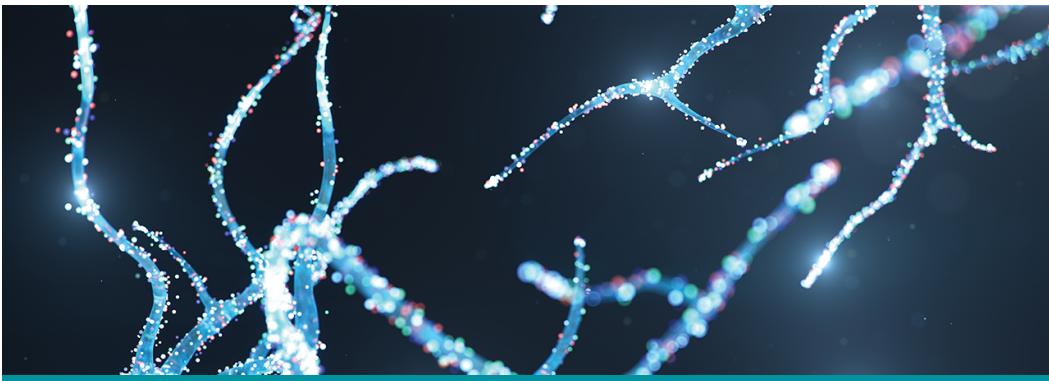
flattened or elongated, while some have villi and microvilli				
state that a cell conserves its volume but increases its surface area by dividing in two	6.4.1			
recall that the size of cells in a tissue depends on their rate of growth and rate of division	6.4.2			
define binary fission	6.5.1			
describe the stages of the cell cycle	6.5.2			
name the phases of mitosis and describe the events that occur during each	6.5.2			
understand the phases of the cell cycle and that cylins are responsible for controlling stages of the cycle	6.5.2			
recall that mutations in oncogenes and tumour suppressor	6.5.2			

genes can lead to uncontrolled division				
explain the difference between benign, malignant, primary and secondary tumours	6.5.2			
determine the mitotic index of dividing cells	6.5.2			
describe the events of meiosis and outline the importance of meiosis to sexual reproduction	6.5.3			
summarise crossing over and random orientation and how each increases genetic variation	6.5.3			
define non-disjunction and describe the consequence of a trisomy in chromosome 21 in humans	6.5.4			
outline how cell proliferation is needed for growth,	6.5.5			

replacement and repair in plant meristems, embryos and in wound healing.

EXAM-STYLE QUESTIONS

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



› Chapter 7

Cell control and communication

C2.1, C2.2

INTRODUCTION

Communication between cells is essential in both single-celled and multicellular organisms. It allows organisms to carry out more complex activities and coordinate the functions of cells, tissues and organs. Cells use different methods of communication to send, receive and process electrical and chemical messages.

7.1 Principles of cell signalling

LEARNING OBJECTIVES

In this section you will:

- learn that cell signalling is essential in single-celled and multicellular organisms
- learn that cells have protein receptors with binding sites for specific signalling chemicals (ligands)
- discover that cell signalling allows complex emergent properties to occur because cells, tissues and organs can work together
- recognise quorum sensing as an example of signalling in bacteria
- understand that a range of substances including ions, neurotransmitters, hormones and cytokines move inside and between cells to send and receive electrical and chemical messages

- discover that some molecules operate in a localised way and others have distant effects
- recognise that there are differences between transmembrane receptors and intra cellular receptors
- understand that as signalling chemicals bind to receptors a sequence of responses within cells takes place

- › understand the modes of action of acetylcholine, G proteins, epinephrine receptors and receptors with kinase activity
- › understand how steroid hormones affect gene expression
- › learn how cell signalling pathways are regulated by positive and negative feedback

GUIDING QUESTIONS

- How does cell signalling allow cells to interact effectively?
- How does the nervous system of animals rely on electrical and chemical signals?

KEY POINTS

receptors proteins with binding sites for specific proteins

hormone a chemical substance produced by an endocrine gland, which is transported in the blood and which affects the physiology or biochemistry of specific target cells.

ligand a signalling chemical which interacts with receptors in or on target cells

neurotransmitter a substance produced and released by a neuron, which passes across a synapse and affects a post-synaptic membrane.

cell surface receptors are found in the cell membrane

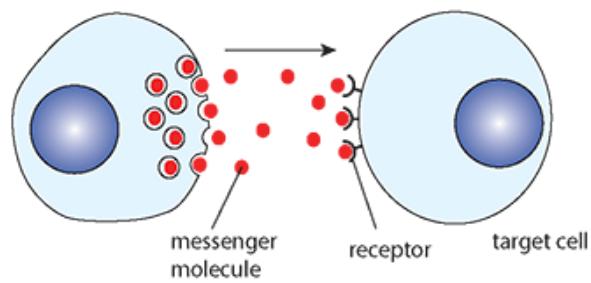
intracellular receptors are protein receptors found inside cells

7.1.1 Principles of cell signalling and cell interaction

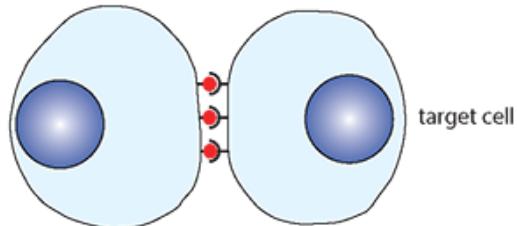
Cells signalling allows cells to communicate and is important in both single-celled and multicellular organisms.

Most cells communicate with each other using chemicals; proteins or other molecules, such as ions, that leave one cell, enter the extracellular space and pass to other cells that can receive the signals they carry. From the extracellular space signals interact with other different cells. Not all cells will be able to receive the signal that has been sent. Only cells with the correct receptors on their surfaces will be able to accept the molecules and respond to them. Once the signal message has bound to a receptor on the surface of another cell, it will trigger a change in the cell. For example, it may change the activity of a particular gene, or stimulate the cell to divide.

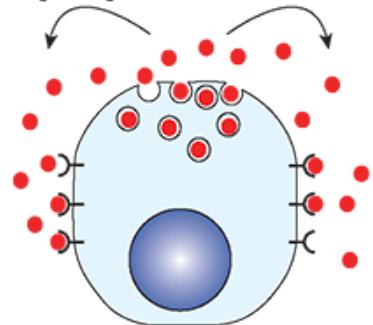
1. Paracrine signalling



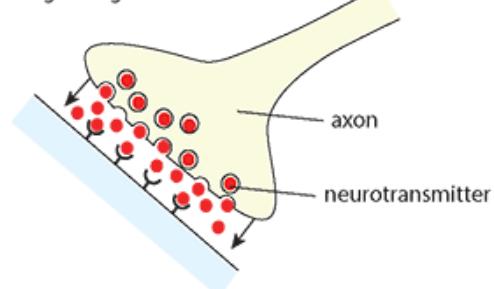
2. Contact-dependent signalling



3. Autocrine signalling



4. Synaptic signalling



5. Endocrine signalling

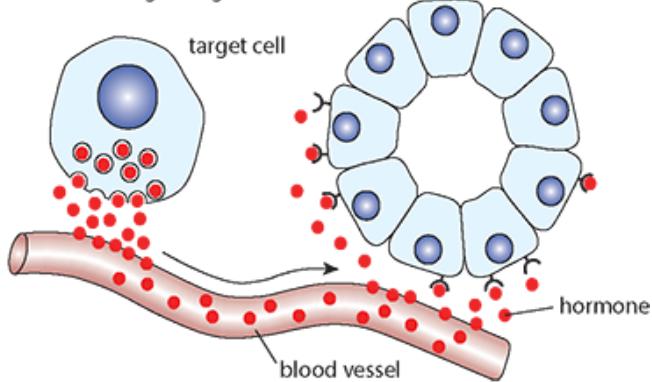


Figure 7.1.1: Cells can pass signals to other cells in a number of different ways.

There are several different forms of cell signalling (Figure 7.1.1):

- 1 Paracrine signalling allows cells that are close to one another to communicate over short distances to coordinate activities. This type of signalling is important during development and differentiation. Cells can tell nearby cells what type of cell to become.
- 2 Contact-dependent cell to cell signalling allows small molecules and ions to pass directly to adjacent cells that touch each other. Plant cells have microscopic channels, called plasmodesmata, through their cell walls and these allow communication and transport between every cell and its neighbours.
- 3 Autocrine signalling is a signal sent by a cell to itself. This is important in development when cells are differentiating into a specific cell type. It has also been implicated in the spread of cancer cells from one part of the body to another.
- 4 Synaptic signalling is used by neurons when an impulse triggers the release of a neurotransmitter at the end of a nerve fibre.
- 5 Endocrine signalling sends signals as hormones to target cells that may be a long way from the cell that produces them.

7.1.2 Cell signalling in unicellular organisms

Many types of bacteria use a type of signalling called quorum sensing. Bacteria regulate their activities and physiological processes by releasing, sensing and responding to small diffusible signal molecules. The signals allow them to assess the density of the local population and if the signals reach a certain level all the bacteria in the population will change their behaviour or gene expression at the same time. This increases their chances of survival.

Bioluminescence in the marine bacterium *Vibrio fischeri* is a good example of quorum sensing which the bacteria use to communicate with each other. *Vibrio fischeri* is a symbiotic bacterium found in the light organ of the bobtail squid (*Euprymna scolopes*). The bacteria only produce light (or bioluminescence) when they have multiplied to a high cell density. *V. fischeri* use proteins coded for by a set of genes known as the lux operon to produce light. The mechanism is controlled by the excretion of an inducer which interacts with a regulator and activates transcription of the lux operon. When cell density is high, all the bacteria bioluminesce together.

SCIENCE IN CONTEXT

Quorum sensing, biofilms and human health

Pseudomonas aeruginosa is a human pathogen; it is a bacterium that causes infections including pneumonia and urinary tract infections. Individual bacteria use quorum sensing to communicate with each other. Together they are able to form closely bonded groups called biofilms. As part of