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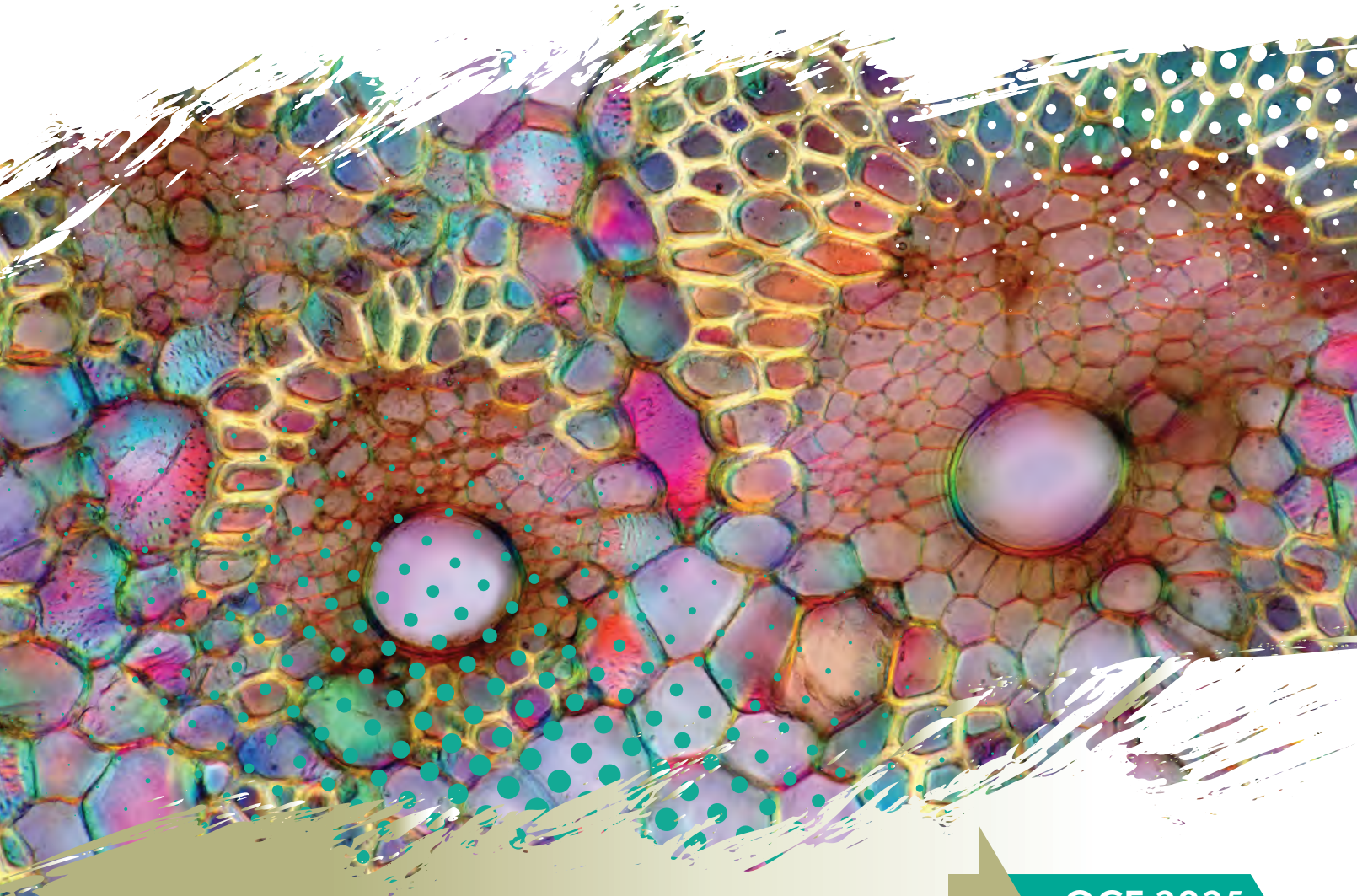
BIOLOGY

QUEENSLAND

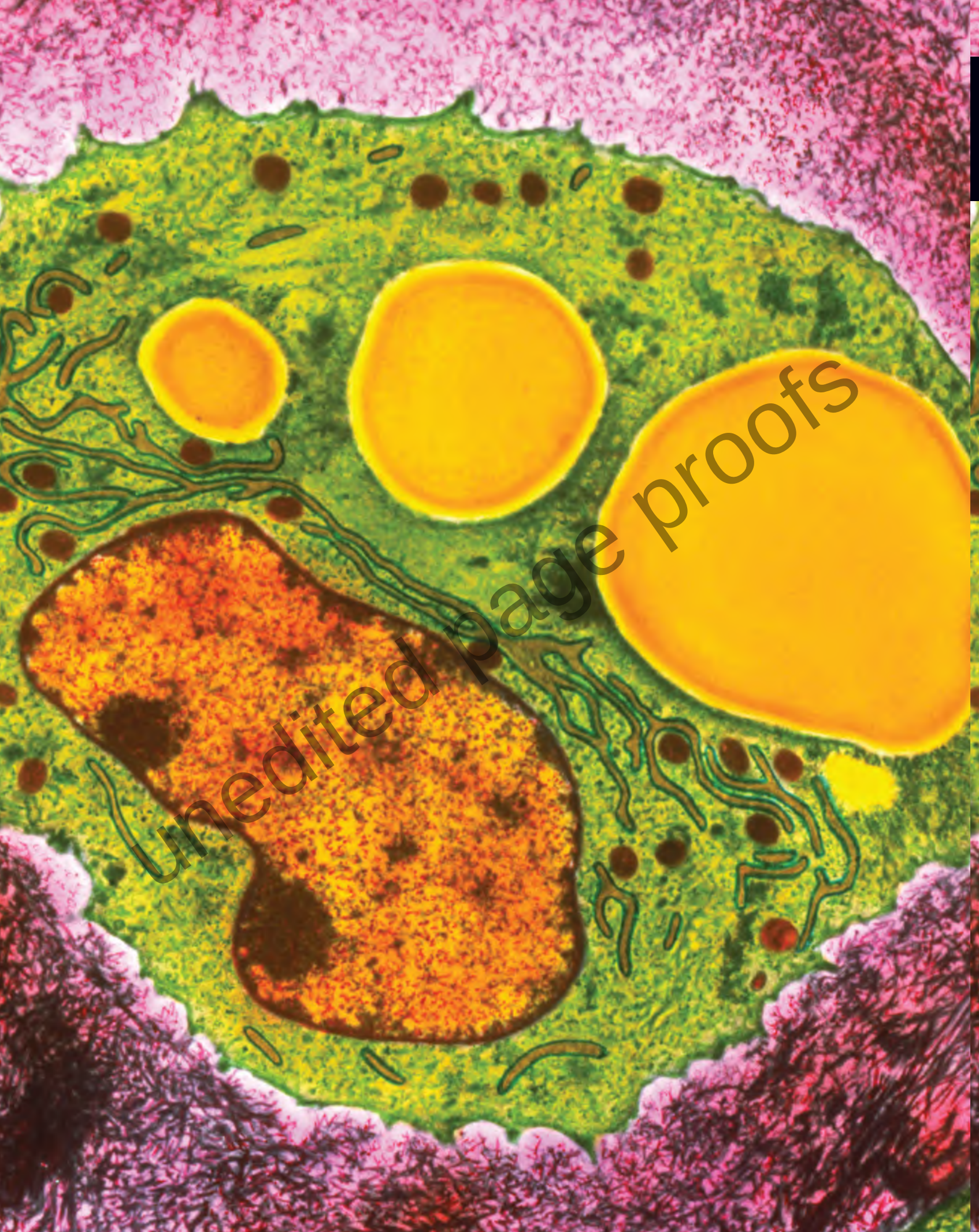
UNITS 1 & 2

2nd EDITION



Student Book

QCE 2025
Biology
SYLLABUS



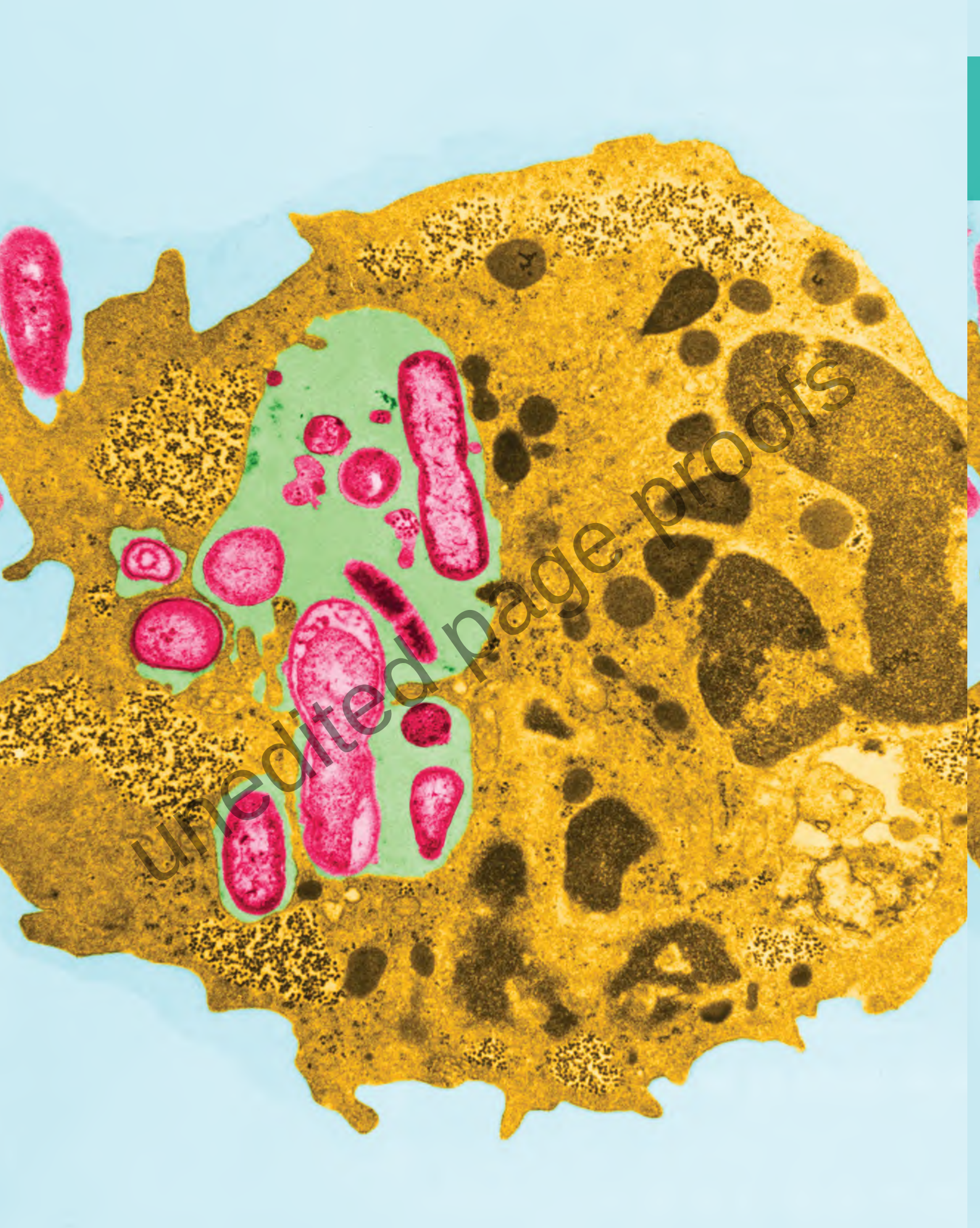
UNIT 1 Cells and multicellular organisms

TOPIC 1 Cells as the basis of life

TOPIC 2 Exchange of nutrients and wastes

Unit 1 objectives

- Describe ideas and findings about cells as the basis of life, exchange of nutrients and wastes, and cellular energy and gas exchange.
- Apply understanding of cells as the basis of life, exchange of nutrients and wastes and cellular energy and gas exchange.
- Analyse data about cells as the basis of life, exchange of nutrients and wastes, and cellular energy and gas exchange.
- Interpret evidence about cells as the basis of life, exchange of nutrients and wastes, and cellular energy and gas exchange.
- Evaluate processes, claims and conclusions about cells as the basis of life, exchange of nutrients and wastes and cellular energy and gas exchange.
- Investigate phenomena associated with cells as the basis of life, exchange of nutrients and wastes, and cellular energy and gas exchange.



CHAPTER

02 The fundamental cell

By the end of this chapter, you will understand the importance of cells as the basic structural and functional units of life on Earth and how the development of new technology continues to enhance our understanding of the structure of the cell and cellular processes. You will learn about the components of different types of cells, and how the structures and systems of cells function to sustain life. You will also have an understanding of the fluid mosaic model of the cell membrane and of the different processes by which a cell moves substances across this membrane.

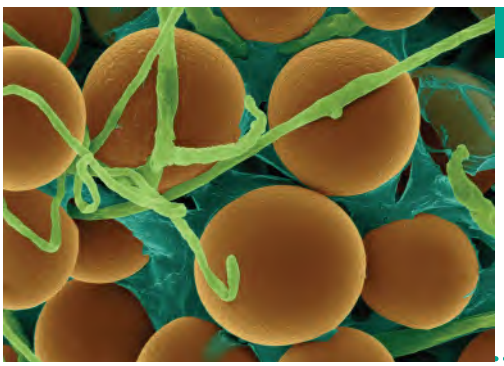
Syllabus subject matter

WS 1.1.1

Topic 1 • Cells as the basis of life

- Compare prokaryotic and eukaryotic cells. **2.1**
- Identify key organelles and their functions, including the nucleus, mitochondria, rough endoplasmic reticulum, ribosomes, smooth endoplasmic reticulum, Golgi apparatus, lysosomes, vacuoles and chloroplasts. **2.2**
- Describe the structure and function of the cell membrane based on the fluid mosaic model, including the role of protein channels, phospholipids, cholesterol and glycoproteins. **2.3**
- Explain how the cell membrane regulates movement of substances into and out of the cell via
  - osmosis
  - simple diffusion
  - facilitated diffusion
  - protein-mediated active transport
  - endocytosis and exocytosis. **2.4**
- Compare active and passive transport. **2.4**
- Explain how the size of a cell is limited by surface area-to-volume ratio and rate of diffusion. **2.4**

2.1 Cell types



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the importance of cells as the basic structural and functional units of life on Earth
- understand the differences and similarities between prokaryotes and eukaryotes
- identify key organelles and their functions
- explain the role of the cell membrane
- understand the difference between active and passive transport.

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

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

CELL THEORY

The cell theory was developed over hundreds of years by scientists of various nationalities and depended on the technology available at the time.

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

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

Biogenesis

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

Until the 1850s, the idea of spontaneous generation was accepted as the origin of small organisms, such as maggots. According to the theory of spontaneous generation, some organisms could suddenly form from certain types of matter, such as a grain of sand or dead flesh.

However, experiments by Francesco Redi on maggots in the 17th century and Lazzaro Spallanzani on microorganisms in the 18th century refuted spontaneous generation. These scientists showed that the presence of maggots and microorganisms was a result of contamination rather than spontaneous generation.

The first primitive microscopes allowed little detail of a cell's internal structure to be seen but new technologies have resulted in a greater knowledge of the structure and function of cells.

COMMON CELL FEATURES

Although there are different types of cells, the cells of plants, animals and bacteria have a number of common features. These common features include:

- a **cell membrane (also called a plasma membrane)**, which separates the interior of the cell from the outside environment
- **cytoplasm**, which consists of the **cytosol** and specialised structures called **organelles**. Cytosol is a gel-like substance that is made up of more than 80% water and contains ions, salts and organic molecules

- **deoxyribonucleic acid (DNA)**, which carries hereditary information, directs the cell's activities and is passed from generation to generation
- **ribosomes**, which are organelles responsible for the synthesis of **proteins**.

CELL SIZE

Cells vary greatly in size, as can be seen in Figure 2.1.1. Most cells are microscopic and, thus, you need a microscope to see them. Cell size is usually measured in micrometres. There are 1000 micrometres (μm) in 1 millimetre (mm). There are exceptions, such as the egg cell of some bird species, which can be many centimetres in diameter. Some typical cell sizes are as follows:

- bacterium: 0.1–5 μm long
- human: 10–200 μm long
- *Paramecium* (a single-celled eukaryote): about 150 μm long.

The thickness of cell membranes also differs and can be 0.004–0.1 μm.

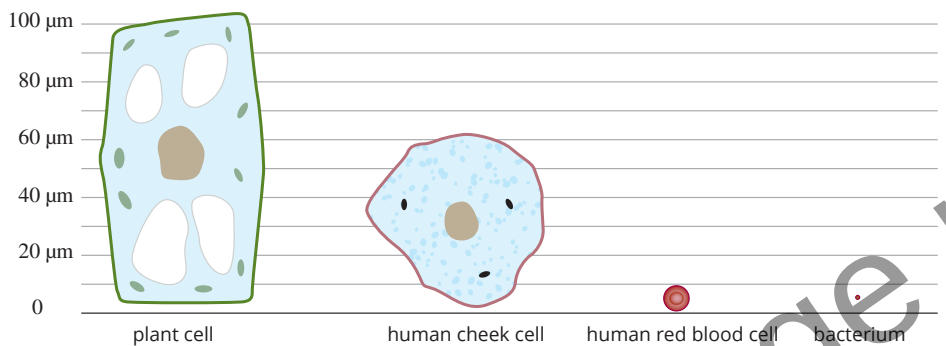


FIGURE 2.1.1 A typical plant cell, human cheek cell, human red blood cell and bacterium. Note the great difference in size between the plant and animal (human) cells and the bacterium.

The development of sophisticated microscopy technology to observe cells and intracellular particles has allowed scientists to measure increasingly smaller objects (Figure 2.1.2). This has led to the development of appropriate units of measurement to describe microscopic lengths.

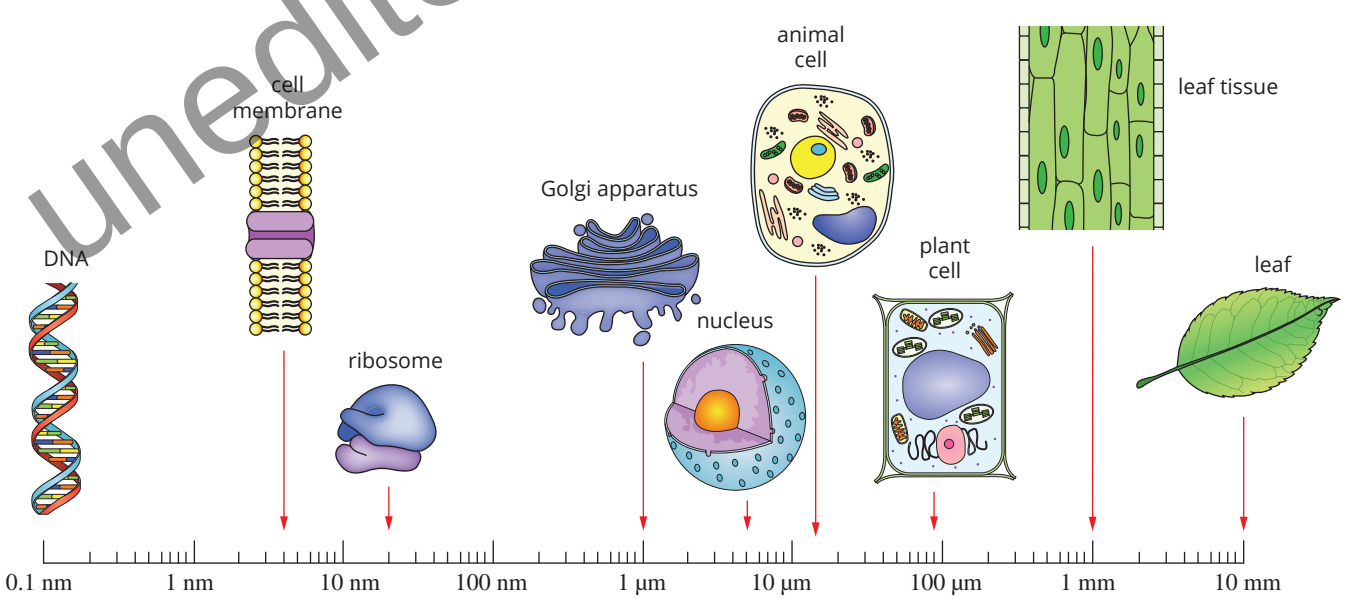
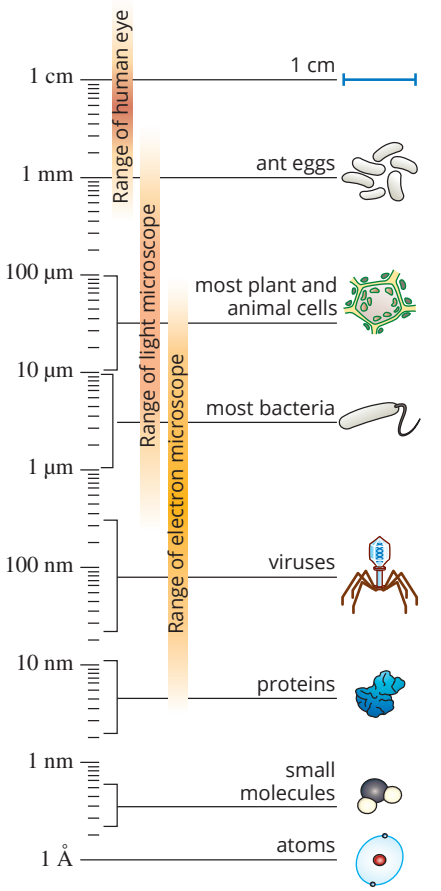


FIGURE 2.1.2 The scale shows the range of size of a variety of cells, organelles and molecules within a cell. The scale is logarithmic to accommodate the range of sizes shown.



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

FIGURE 2.1.3 A comparison of the ranges of the light and electron microscopes (the scale is logarithmic)

In the International System of Units (SI units), the unit for length is the metre (m). Table 2.1.1 illustrates the derivation of the smaller units of length in relation to the metre. Refer to Chapter 1 (Part AXX) for detailed assistance with units of measurements.

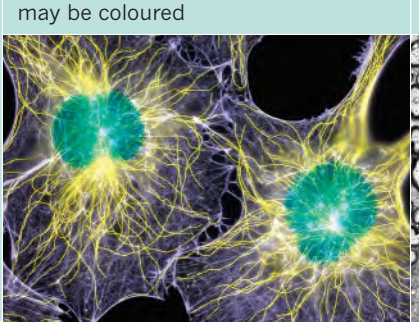
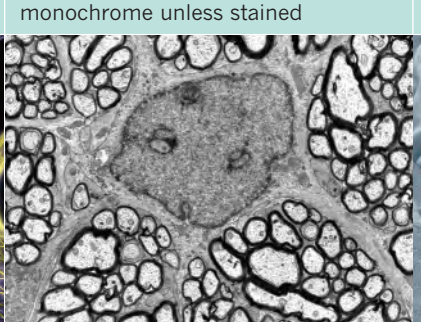
TABLE 2.1.1 SI units for smaller units of length relative to the metre

Fraction of a metre	Units	Symbol	
one hundredth $= \frac{1}{100} = 0.01 = 10^{-2}$ m	centimetre	cm	$1\text{ m} = 10^2$ cm
one thousandth $= \frac{1}{1\,000} = 0.001 = 10^{-3}$ m	millimetre	mm	$1\text{ m} = 10^3$ mm
one millionth $= \frac{1}{1\,000\,000} = 0.000\,001 = 10^{-6}$ m	micrometre	µm	$1\text{ m} = 10^6\ \mu$m
one thousand millionth $= \frac{1}{1\,000\,000\,000} = 0.000\,000\,001 = 10^{-9}$ m	nanometre	nm	$1\text{ m} = 10^9$ nm

INVESTIGATING CELLS

Cytology is the study of cells. Cytologists (scientists who study cell structure and function) and histologists (scientists who study tissue structure) use a variety of tools and techniques, including several microscopy techniques. Modern microscopy techniques, including light and electron microscopy (Table 2.1.2), have greatly advanced our understanding of the structure and function of cells. The type of microscope used depends on the characteristics and properties of the specimen to be observed, such as the size of cell or cell component and whether it is living or dead (Figure 2.1.3). Scientists also consider the access to and costs of using specialist facilities and preparing specimens when deciding which microscopy technique to use.

TABLE 2.1.2 A comparison of modern microscopy techniques

	Light microscope	Transmission electron microscope	Scanning electron microscope
Radiation source	light	electrons	electrons
Wavelength (nm)	400–700	0.005	0.005
Lenses	glass	electromagnetic	electromagnetic
Specimen	living or non-living supported on glass slide	non-living supported on a small copper grid in a vacuum	non-living supported on a metal disc within a vacuum
Maximum resolution (nm)	200	1	10
Maximum magnification	1500×	250 000×	100 000×
Stains	coloured dyes	impregnated with heavy metals	coated with carbon or gold
Type of image	may be coloured	monochrome unless stained	monochrome unless stained
			

Light microscopy

Most cells are so small that they can only be seen with a microscope like the one shown in Figure 2.1.4. The light microscope uses light and a system of lenses to magnify the image. One lens is called the objective lens, and the other is the eyepiece or ocular lens. Most school laboratories use the compound light microscope. Other types of light microscopes are the fluorescent light microscope which can be used to see materials which fluoresce naturally, or which have been stained with a fluorescent dye and the confocal microscope which can produce highly detailed three-dimensional pictures of microscopic structures.

One of the main advantages of light microscopy is that it allows you to view living cells in colour.

Sample preparation is usually quick and simple. Stains can be used to highlight different components of cells in colour. A thin specimen is mounted on a glass slide and placed on the stage under the lenses. Light travels through the specimen and into the lens system, and the image is viewed by eye or with a digital camera (Figure 2.1.5).

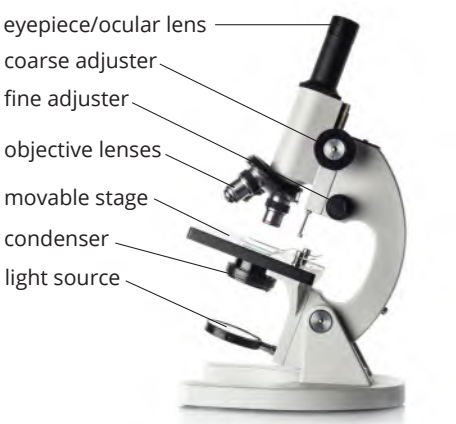


FIGURE 2.1.4 A light microscope and its parts

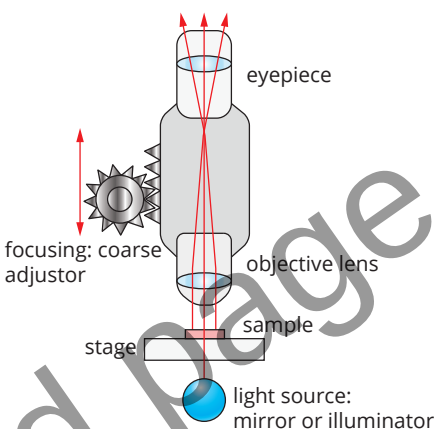


FIGURE 2.1.5 The lenses of a light microscope magnify the image.

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

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

Electron microscopy

In electron microscopy, an object is viewed by using an electron beam instead of light. This allows you to see structures in far more detail than is possible with light microscopy. An electron microscope produces a narrow beam of electrons that is maintained by electromagnetic lenses, which are coils that surround the tube and emit an electromagnetic field. Electrons striking the specimen are absorbed or scattered, or pass through it. The image is then recorded digitally and processed.

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

Transmission electron microscopy

Figure 2.1.6 shows a transmission electron microscope. In transmission electron microscopy (TEM), the electron beam travels through an ultrathin section (less than 100 nm thick) of a specimen. This allows very fine details of cellular structures to be seen, like those shown in Figure 2.1.7.

FIGURE 2.1.6 A transmission electron microscope. Specimens are specially prepared, and the image is taken within a vacuum to ensure the electron beam remains focused. Therefore, only non-living materials can be observed under the transmission electron microscope.

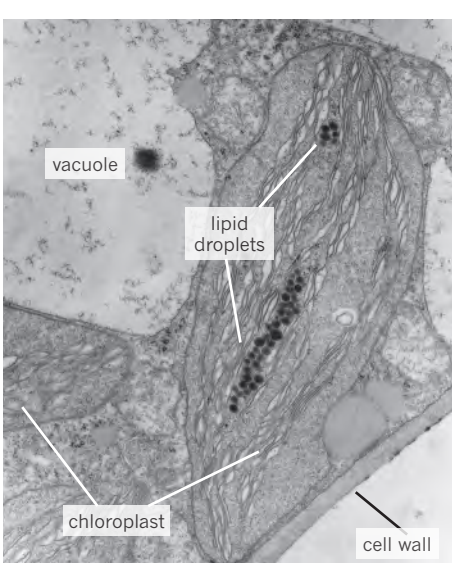


FIGURE 2.1.7 A transmission electron micrograph of a plant leaf, showing chloroplasts, with lipid droplets showing in one. The pale area to the upper left is a vacuole and the cell wall is also visible at the lower right.

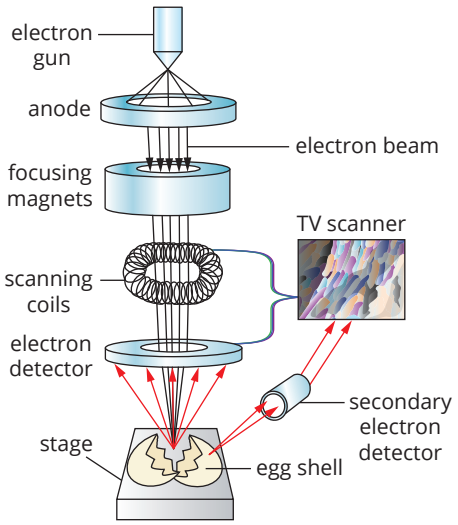


FIGURE 2.1.8 The scanning electron microscope detects secondary electrons emitted by atoms excited by the electron beam. The specimen is prepared by coating it with an electron-dense, electrically conductive material such as gold and therefore can only be used on non-living objects.

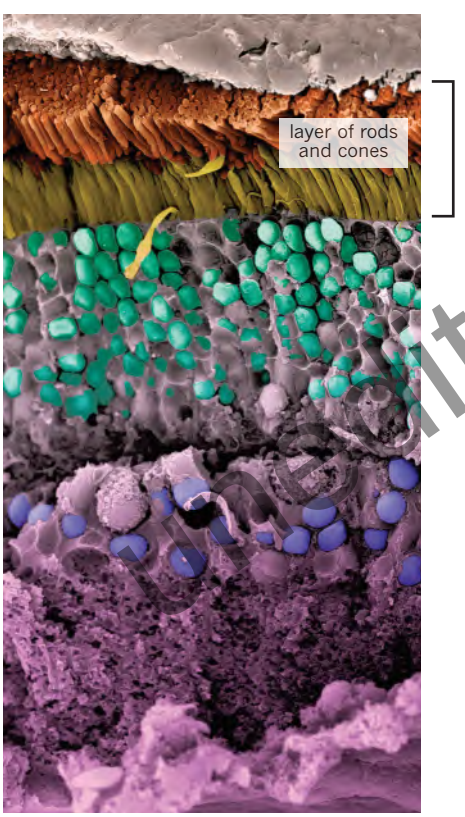


FIGURE 2.1.9 A coloured scanning electron micrograph of a section through the retina of an eye, showing cone and rod cells.

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

Scanning electron microscopy

Figure 2.1.8 shows a scanning electron microscope. In scanning electron microscopy (SEM), the electrons bounce off a specimen that has been coated with an extremely thin layer of an electrically conducting material such as gold. This gives a high-resolution image of the surface features but cannot show internal details (Figure 2.1.9).

Autoradiography

Autoradiography is a method that allows scientists to identify specific organelles or the location of molecules within a cell or tissue. The tissue is first treated with a radioactively labelled substance that is taken up into the part of the cell that is being investigated, such as the nerve tissue shown in Figure 2.1.10. The tissue is sliced into very thin sections that are placed against a very thin, high-resolution photographic film. The radioactive substance emits beta particles that produce an image on the film. The tissue sections are stained so that the photographic image can be located in relation to cellular structures. This technique can be used to indicate which organelles are active under particular circumstances.

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

CELL CLASSIFICATION

As the study of cells advanced it became clear that cells show one of two patterns; simple cells, called **prokaryotes**, and more complex cells, called **eukaryotes**. In earlier classification systems, all organisms were divided into five ranks, called kingdoms. Prokaryotic organisms were placed in the kingdom, Monera, and eukaryotic organisms were placed in the kingdoms: Protista, Plantae, Fungi and Animalia. These systems were based on the morphology (appearance and structure) of the organisms and their cells.

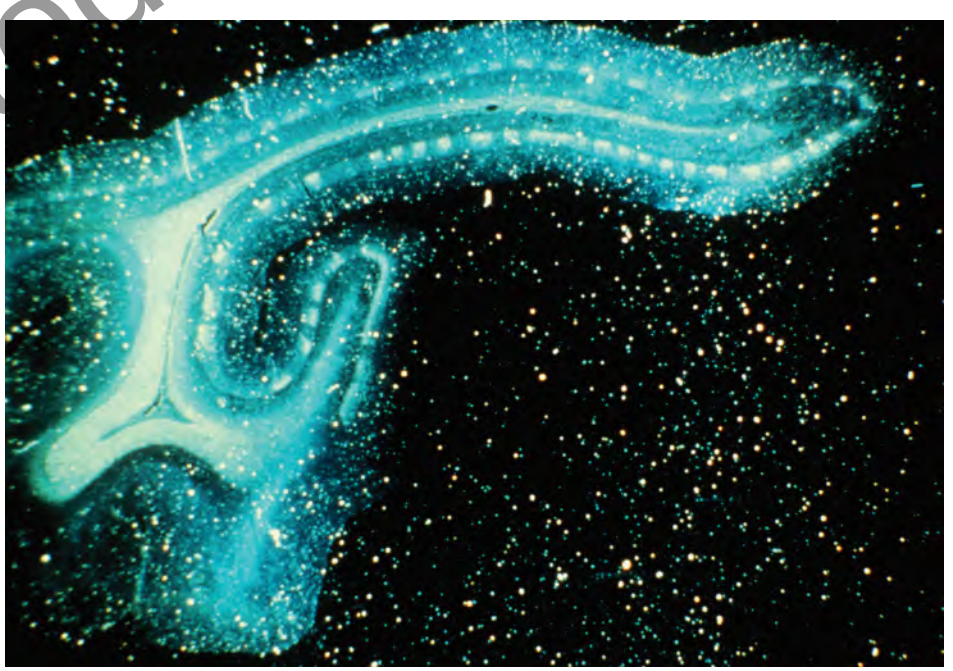


FIGURE 2.1.10 An autoradiograph of a slice through nerve tissue from the visual centre of the brain, showing how visual messages from one eye are received by the brain. Rows of neuron (nerve cell) cubes are laid out in columns on the outside of the brain tissue, and the active areas of the brain have absorbed a radioactive chemical. The glow is developed onto photographic paper and produces an autoradiograph.

In the late 1970s, the use of **DNA (deoxyribonucleic acid)** techniques in the emerging field of evolutionary genetics led to the discovery of two different types of prokaryotic cells. This resulted in the development of a system used today, with three domains and six kingdoms (Figure 2.1.11). Domains are now the highest rank in **taxonomy**, instead of kingdoms. Prokaryotes are divided into two domains: Bacteria and Archaea. All eukaryotic organisms are placed in a third domain called Eukarya. The four kingdoms within the Eukarya domain remain the same: Protista, Plantae, Fungi and Animalia.

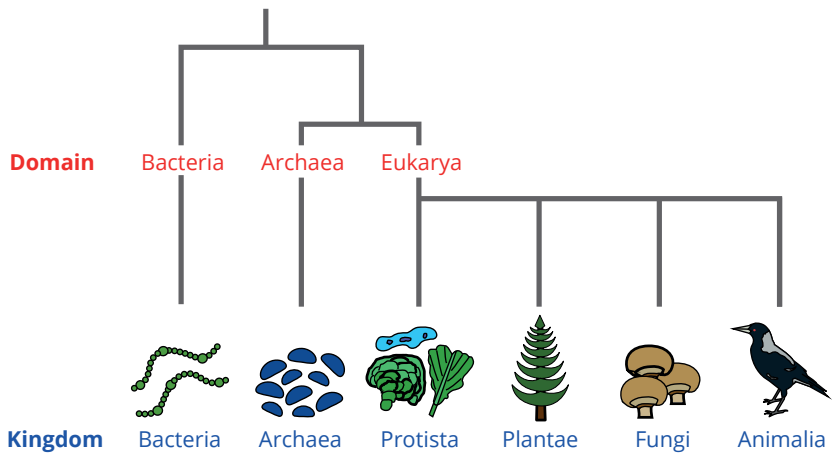


FIGURE 2.1.11 The classification of living things, showing the three domains based on cell types, and the six kingdoms. Bacteria and Archaea have prokaryotic cells. Protista, Plantae, Fungi and Animalia have eukaryotic cells.

PROKARYOTIC CELLS

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

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

The structure of a typical prokaryotic cell is shown in Figure 2.1.12. Prokaryote cells lack membrane-bound organelles, and their cytoplasm contains scattered ribosomes that are involved in the synthesis of proteins. The genetic material of prokaryotic cells is usually a single, circular DNA **chromosome** called a **genophore**. The genophore is contained in an irregularly shaped region called the **nucleoid**. Unlike the nucleus of eukaryotes, the nucleoid does not have a nuclear membrane.

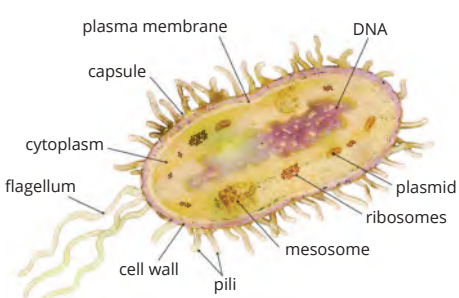


FIGURE 2.1.12 A typical prokaryotic bacterial cell

The chromosomal DNA of prokaryote cells is attached to the cell membranes by a region of the chromosome called the origin. In addition to this chromosomal DNA, many prokaryotic cells also contain small rings of double-stranded DNA called **plasmids**.

The cell membrane of prokaryotic cells is surrounded by an outer cell wall. Many bacteria also have a capsule outside the cell wall. The capsule protects the cell from damage and dehydration.

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

Bacteria

Most prokaryotes in the domain Bacteria are microscopic single-celled organisms. Fossil evidence dated at 3.5 billion years old confirms that bacteria were the first

type of living organisms on Earth. Today, bacteria are still the most numerous type of organism in the biosphere.

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

Other species of bacteria need little oxygen to survive because they have evolved specialised chemical pathways to extract energy from their environment and manufacture complex energy-rich molecules such as carbohydrates (see Chapter 3XX). Bacteria can obtain energy from sunlight (photosynthesis) or by reducing **inorganic compounds** such as sulfates or ferric ions (chemosynthesis).

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

Carbohydrates are organic compounds of carbon, hydrogen and oxygen, with the number of hydrogen and oxygen atoms in the ratio 2:1. This ratio of 2:1 is the same ratio of hydrogen to oxygen for water. Sugars and starches are examples of carbohydrates. Proteins and carbohydrates molecules sometimes combine as complex structures (peptidoglycans) to become part of the cell wall of bacteria.

Archaea

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

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

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

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

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

The lipids in eukaryotic cell membranes have fluidity and selective permeability, but only in a narrow range of temperatures and pressure. The lipids in archaean membranes are different because they form a unique cell membrane structure. The structure remains fluid and permeable over a wide range of temperatures, from freezing cold to boiling hot, and at extreme depths of the ocean floor.

There are many different types of extremophiles. Hyperthermophiles such as *Pyrococcus furiosus*, which is shown in Figure 2.1.13, can survive in very hot environments such as undersea vents, where temperatures are often above 100°C. *Pyrococcus* can also thrive under high pressure—they are barophilic. This means they can withstand the extremely high pressure at the ocean floor. *Sulfolobus* species, which live in volcanic springs, are thermophiles as well as acidophiles—they can survive both high temperatures and high acidity. You can see *Sulfolobus* in

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

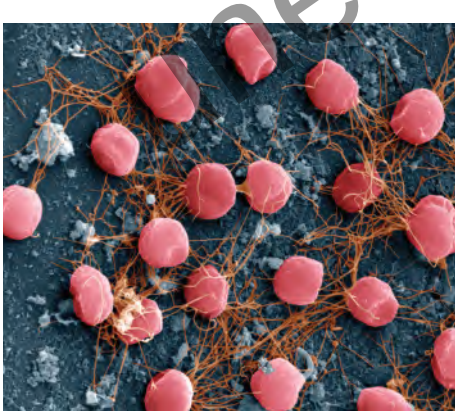


FIGURE 2.1.13 A scanning electron micrograph of hyperthermophile *Pyrococcus furiosus*. *Pyrococcus* can only exist in very hot environments such as hot undersea vents.

Figure 2.1.14. Extremophiles have evolved many unique adaptations to ensure their continued existence in environments where most organisms are not able to survive.

Differences between bacteria and archaea

Despite their name, archaea are not the most ancient group of organisms. DNA studies have shown that bacteria are the most ancient group. The evolutionary relationship between archaea, eukaryotes and bacteria remains unclear. While archaea and Gram-positive bacteria share many structural features and metabolic pathways, suggesting a common ancestor, many other archaea genes are more similar to the genes found in eukaryotic cells.

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

- Archaea have a different type of lipid structure in the cell membranes.
- Bacterial cell walls contain **murein**; archaean cell walls do not contain murein (although there is a similar compound in some archaea).
- Both have diverse metabolic systems, but methanogenesis (in which methane is produced) is unique to archaea.

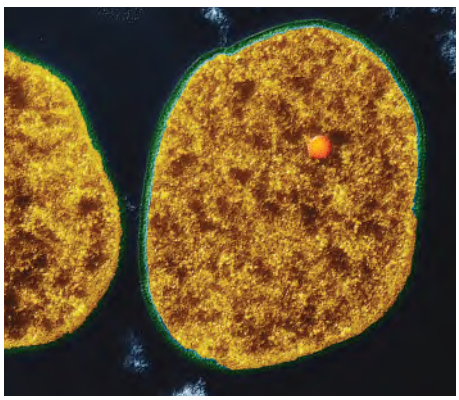


FIGURE 2.1.14 *Sulfolobus* are thermophiles as well as acidophiles. They thrive in hot, acidic environments.

EUKARYOTIC CELLS

Eukaryotic cells are relatively large and more complex than prokaryotic cells. They possess membrane-bound organelles such as a nucleus and mitochondria. Protists, fungi, plants and animals are called eukaryotes because they are composed of eukaryotic cells. A typical plant cell and a typical animal cell is shown in Figure 2.1.15.

As well as a cell membrane surrounding the cytoplasm, eukaryotes have internal membranes that form specialised compartments within the cell. This is known as **cell compartmentalisation**. The membrane-bound compartments are organelles, which are specialised structures that have specific functions. You will learn more about cell compartmentalisation in Module 2.2XX Cell organelles. As well as compartmentalisation, many eukaryotic cells are specialised, with particular cells undertaking particular functions (e.g. producing hormone or making particular enzymes).

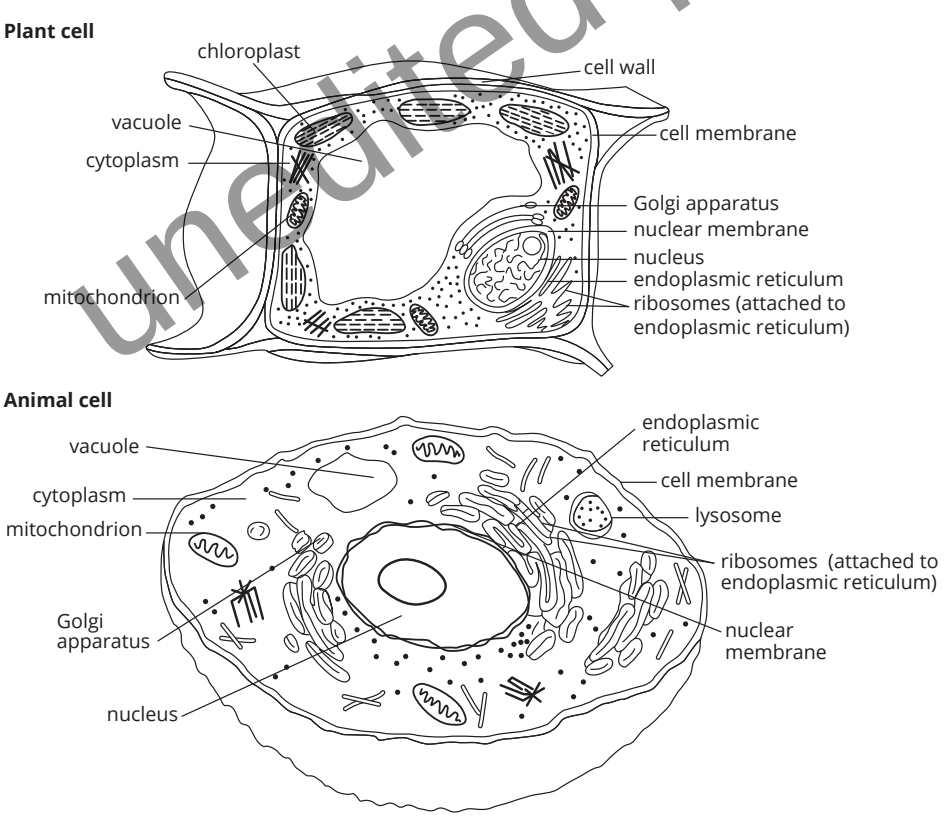


FIGURE 2.1.15 Diagram of a typical plant cell and an animal cell, showing major organelles.

Gram staining is used to classify bacteria into two groups—Gram-positive and Gram-negative. The stain reacts to chemicals in the cell walls of bacteria and makes the bacteria appear pink/red (Gram-positive) or blue/purple (Gram-negative).

Organelles in eukaryotic cells include a nucleus, mitochondria, rough endoplasmic reticulum, smooth endoplasmic reticulum, Golgi apparatus, lysosomes, vacuoles and chloroplasts. These are all membrane-bound organelles and are only found in eukaryotes. Also present in eukaryotic cells are ribosomes which have no membrane and are also found in prokaryotes. You will learn more about these organelles in Module 2.2XX Cell organelles. Centrioles, which are found in some eukaryotes, also have no membrane. They are involved in assisting cells to divide and will be discussed in Chapter XX. Movement of substances into, out of and around the cell allows the maintenance of basic metabolic processes such as cellular respiration, homeostasis and reproduction. Eukaryotic cells also have large numbers of protein channels and organelles specialised for internal transport.

Comparing prokaryotic and eukaryotic cells

There are a number of similarities and differences between prokaryotic and eukaryotic cells (Table 2.1.3). For example, both prokaryotes and eukaryotes contain DNA as their genetic material and use ribosomes to build their proteins. The shared features of prokaryotes and eukaryotes are evidence that supports the theory that they have a common ancestor. Figure 2.1.16 shows typical prokaryotic and eukaryotic cells and their features.

Prokaryotic cells are much smaller than eukaryotic cells, giving them a much larger surface area in comparison to their volume. This means that movement by diffusion into and out of prokaryotic cells is much faster than for eukaryotic cells. This results in prokaryotes having a higher metabolic rate, generally growing faster and having a shorter generational turnover. Bacteria can reproduce in between four and twenty minutes under ideal conditions.

TABLE 2.1.3 Comparison of prokaryotic and eukaryotic cells

Feature	Prokaryotic cells	Eukaryotic cells
Size	• Very small	• Larger, with large variation in size
Surface area to volume ratio (SA:V)	• Large • Allows materials to diffuse in and out of the cell rapidly	• Smaller • Results in slower diffusion
Membrane-bound organelles	• Absent	• Many organelles bound by membranes, forming an organised internal structure.
Chromosomal DNA	• Dna chromosome in the form of a single-stranded loop • Located in a region of cytoplasm called the nucleoid, lacking a membrane	• Dna in the form of linear, thread-like chromosomes wound around proteins called histones. • Located in the nucleus, which is separated from the cytoplasm by a double-layered membrane
Ribosomes	• Many tiny ribosomes scattered in the cytoplasm.	• Many ribosomes, either attached to the endoplasmic reticula, or free in the cytoplasm
Cell membrane	• Bilayer of phospholipid molecules enclosing the cytoplasm in bacteria. • Phospholipids are different and sometimes fuse into a monolayer in archaea. • Contains fewer protein channels	• Bilayer of phospholipid molecules enclosing the cytoplasm • Contains many protein channels
Cell wall	• In bacteria, consists of a protein–carbohydrate compound called murein.	• Present in fungi, plants and some protists • Consists mainly of carbohydrates: chitin in fungi and cellulose in plants
Flagella	• May have flagella to provide movement • Consist of three protein fibrils coiled in a helix and protruding through the cell membrane and wall	• May have flagella or cilia for motility (but not in fungi) • Consist of a highly organised array of microtubules (hollow protein tubes) enclosed by the extended cell membrane

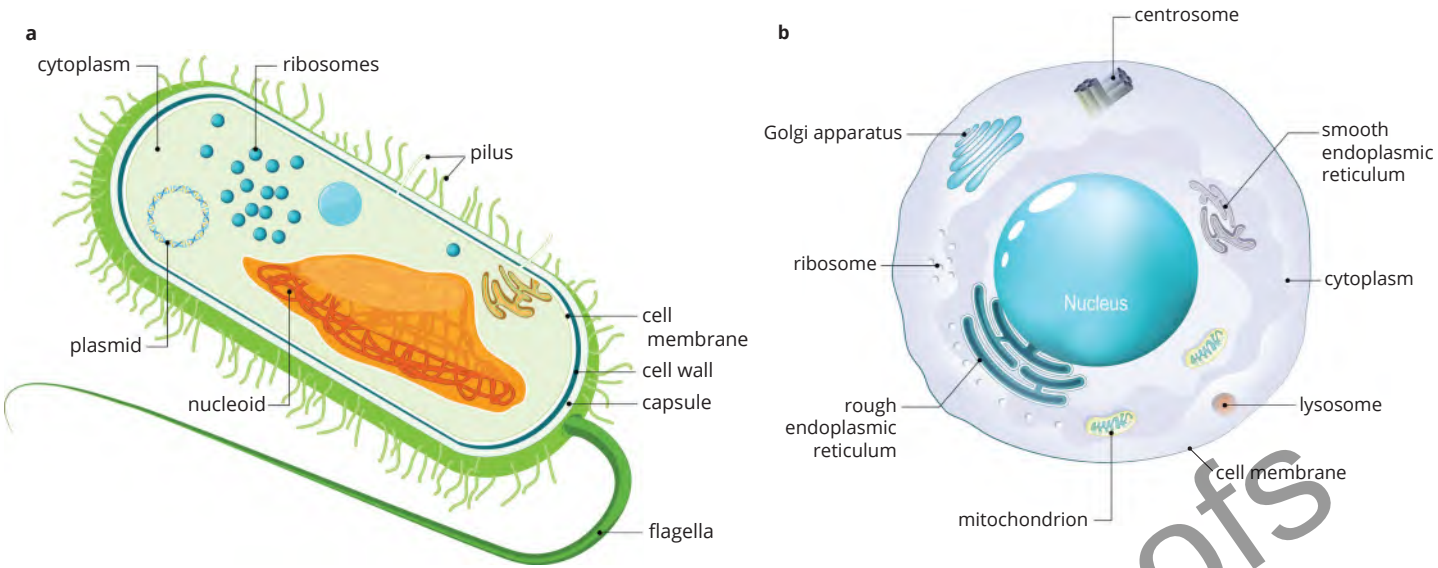


FIGURE 2.1.16 (a) A typical prokaryotic cell and (b) and a typical eukaryotic cell. Note the different membrane-bound organelles in the eukaryotic cell and the lack of such organelles in the prokaryotic cell. Prokaryotic and eukaryotic cells share some features, including a cell membrane, cytoplasm, DNA and ribosomes.

Both prokaryotes and eukaryotes have a cell membrane composed of a phospholipid bilayer with embedded proteins which is further evidence of their common evolutionary relationship. However, eukaryotic membranes possess more protein channels than prokaryotes which helps to increase the movement of materials across the membrane and helps offset the disadvantage that eukaryotes have when considering surface area to volume.

Differences in the structures of the chromosomes means that eukaryotic cells have a much tighter control over gene expression than that seen in prokaryotes. This means that different genes can have different levels of activity, or none at all, in different cells. This differentiation in gene action results in cell specialisation and permits the development of multicellular organisms which have specialised tissues and organs.

Membrane-bound organelles allow eukaryotes to have a more complex metabolism than prokaryotes. This is because different processes can occur at the same time in different organelles, even if they require very different conditions to occur or would normally inhibit each other. The processes that occur inside organelles are also insulated from the external environment of the cell so changes outside the cell are less likely to inhibit cellular processes.

Organelles that are involved in transport, such as Golgi apparatus and the endoplasmic reticula, allow eukaryotic cells to be much larger than prokaryotic cells as the use of transport channels makes movement of substances within the cell much faster. The presence of specialised channels means eukaryotes do not rely on diffusion alone for the movement of substances.

The attachment of ribosomes to a transport channel, the endoplasmic reticula, results in a more efficient movement of proteins around the cell. The endoplasmic reticula also provide an isolated compartment in which a particular environmental condition can be maintained in order to form the protein into the shape needed for it to function correctly.

CELL REQUIREMENTS FOR LIFE

Like organisms, all cells have certain requirements. All life requires a source of energy. The amount of energy required depends on the type of cell, its stage of growth, and its level of activity. Cells also require nutrients and water for growth, maintenance and repair, and constant environmental conditions to be maintained so that they survive and reproduce. Photosynthetic organisms can use inorganic materials from their environment to manufacture their own organic materials in the process of photosynthesis. All cells use these organic materials to produce energy in the process of cellular respiration. This relationship is shown in Figure 2.1.17.

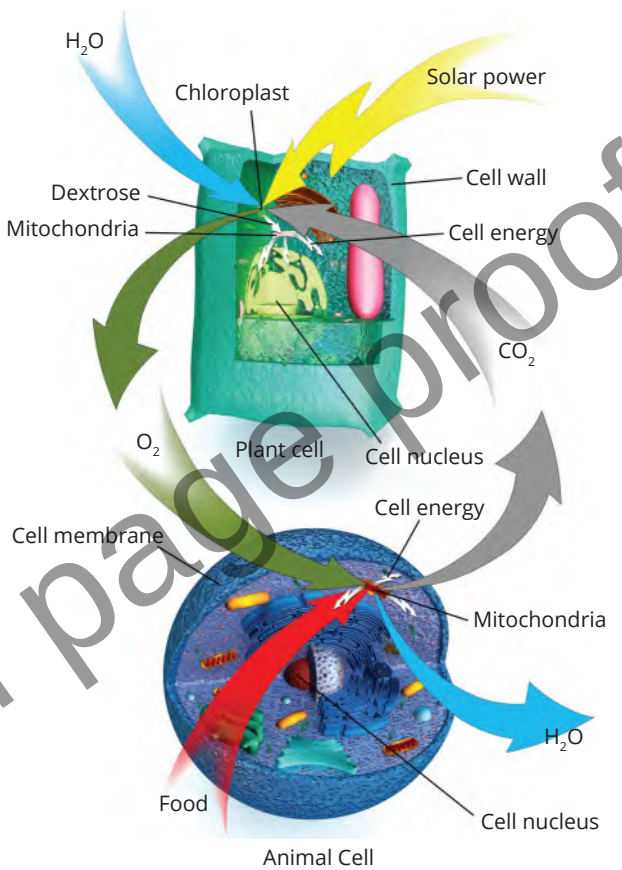


FIGURE 2.1.17 The relationship between photosynthesis and cellular respiration for the production of cellular energy in plant and animal cells.

The inputs and outputs of cells depend on the fundamental nature of the cell. Photosynthetic cells (some plant cells, protists and all cyanobacteria) and non-photosynthetic cells (all animal and fungal cells, some protists and bacteria) have different metabolisms. Photosynthetic cells make many of their requirements from simple inorganic substances, while non-photosynthetic cells must absorb complex chemicals for survival. Photosynthetic cells absorb carbon dioxide and water, along with minerals such as nitrates, and use these substances to make complex molecules such as carbohydrates, proteins, lipids and nucleic acids (DNA and **RNA (ribonucleic acid)**). Table 2.1.4 shows these compounds and their building blocks. Non-photosynthetic cells absorb the building blocks of these compounds, which they then use to make the compounds that they need.

TABLE 2.1.4 Essential compounds made by photosynthetic organisms and their building blocks

Compound	Building blocks	Made by photosynthetic organisms from
Carbohydrate (monosaccharides, disaccharides and polysaccharides – (figure 2.1.18)	Simple sugars such as glucose, fructose and galactose (figure 2.1.18b)	Carbon dioxide and water
Protein	Amino acids such as valine and leucine	Carbohydrates and nitrogen from nitrates and other nitrogen-containing minerals
Lipid	Fatty acids and glycerol	Carbohydrates
Nucleic acids	Nucleotides	Carbohydrates and nitrogen from nitrogen-containing minerals

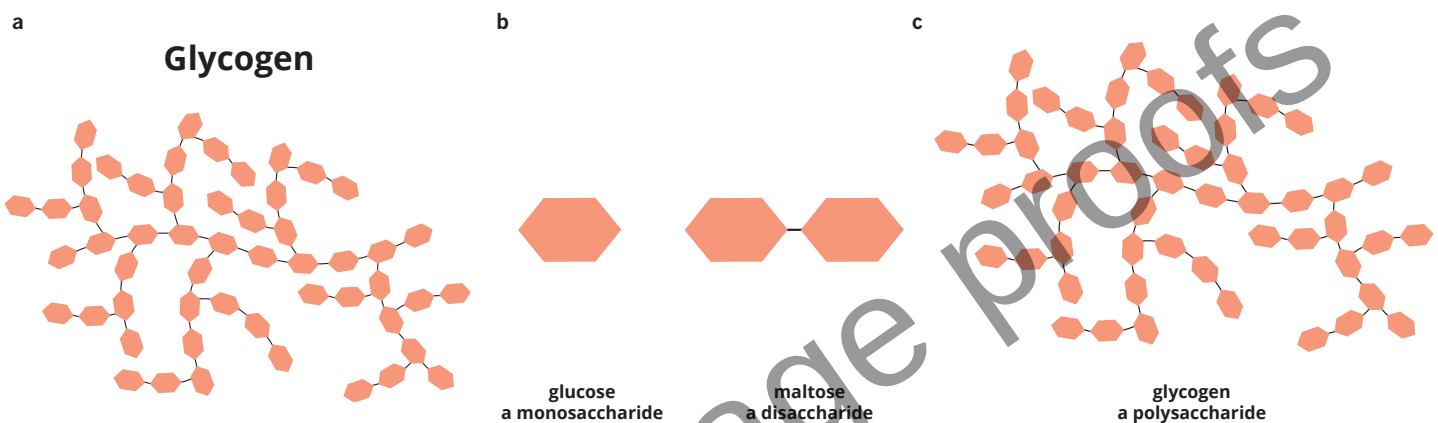


FIGURE 2.1.18 (a) Glucose (a monosaccharide) is the building block of many carbohydrates. (b) Monosaccharide molecules can be joined to make more complex molecules such as disaccharides and (c) polysaccharides.

Non-photosynthetic cells rely on the provision of more complex substances from other cells and organisms for their survival. Many cells can take these building blocks and modify them. For example, humans can make some **amino acids** by modifying other amino acids but are unable to make any from inorganic substances the way plants can. The amino acids are then used to build proteins.

In using energy (e.g. from monosaccharides, disaccharides and polysaccharides, lipids and proteins, all explained in Module 3.1XX) and carrying out the processes of growth, maintenance and repair, cells produce substances that are of no use to them or may be harmful to them. These waste substances (e.g. carbon dioxide, oxygen, urea, ammonia, uric acid, water and ions), along with metabolic heat, are often removed by releasing them into the external cellular environment. The ways that cells exchange substances with their environment depend on the type of material being exchanged. Cells must also be able to sense and respond to changes in their internal and external environments.

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

2.1 Review

SUMMARY

- Living organisms have common characteristics and requirements—they are made of cells, are chemically complex and highly organised, exchange energy and materials with their environment, grow and reproduce, sense and respond to their environment, and show changes that are often adaptive.
- Cells use materials such as carbohydrates, proteins, lipids, vitamins and minerals to provide energy, and as raw materials for the formation of new structures, and produce wastes such as carbon dioxide, urea and excess heat.
- The cell theory is a fundamental principle of biology and is based on evidence collected over the last 300 years.
- The cell theory states that:
  - all organisms are composed of cells
  - all cells come from pre-existing cells
  - the cell is the smallest living organisational unit.
- All cells have a cell membrane, cytoplasm, genetic material in the form of DNA and ribosomes.
- There are two fundamentally different types of cells: prokaryotic and eukaryotic.
- Organisms with prokaryotic cells are called prokaryotes. They are classified into two domains: Bacteria and Archaea.
- Organisms with eukaryotic cells are called eukaryotes. They are classified into the domain Eukarya, which is divided into four kingdoms: Protista, Fungi, Plantae and Animalia.
- Prokaryotic cells have a simple structure, with a nucleoid lacking a membrane, scattered ribosomes, and DNA mainly in a single-stranded loop in the nucleoid.
- Eukaryotic cells have a complex structure, membrane-bound nucleus, many organelles in the cell cytoplasm, and DNA mainly in chromosomes in the nucleus.
- Archaea (the extremophiles) are often found in very harsh environments where their unique cell membrane structure protects them.
- Compartmentalisation (presence of membrane-bound organelles) in eukaryotic cells:
  - allows enzymes and reactants to be concentrated in particular organelles of the cell
  - maintains the right conditions for enzymes and reactants to function
  - allows incompatible chemical reactions to take place simultaneously within the cell
  - reduces the cell's vulnerability to environmental changes.
- Cells vary greatly in size, and a microscope is needed to see most cells.
- Laboratory research techniques include microscopy.
  - Light microscopes use visible light and a system of lenses to magnify images.
  - Electron microscopes use an electron beam focused by electromagnets to view objects. They have a much higher magnification and resolution than a light microscope.

KEY QUESTIONS

Describe

1 State the cell theory.

2 Name three components that all cells possess.

3 List three substances needed by cells to maintain life.

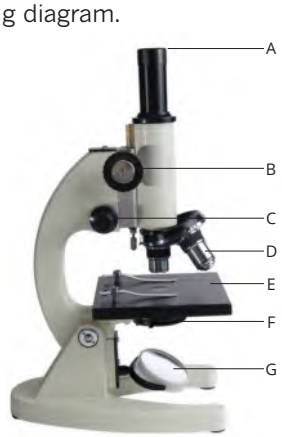
4 What are three wastes materials produced by cells?

5 Describe the differences between prokaryotes and eukaryotes.

6 Explain why eukaryotic cells can be significantly larger than prokaryotic cells.

7 Identify which kingdoms contain organisms that are composed of eukaryotic cells. Recall some examples from each kingdom.

8 Label the parts of the light microscope labelled A–G in the following diagram.



Apply

9 Draw and label a typical plant and animal cell.

10 Explain what is meant by 'cell specialisation'.

11 Explain what is meant by 'cell compartmentalisation'.

12 Outline the main differences between light microscopy and electron microscopy.

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

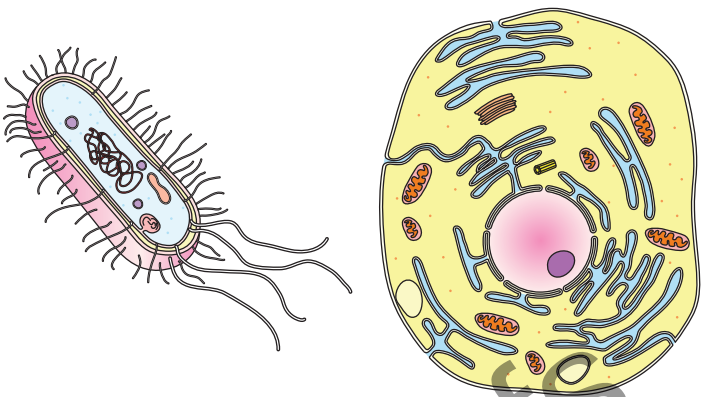
14 A structure is seen under a microscope. It is 0.5 µm long. Is this structure most likely to be a prokaryote cell, a eukaryote cell or an organelle from a eukaryote?

Analyse

15 The following diagrams are of two cells observed with an electron microscope.

a Describe evidence that cell A is prokaryotic.

b Describe evidence that cell B is eukaryotic.

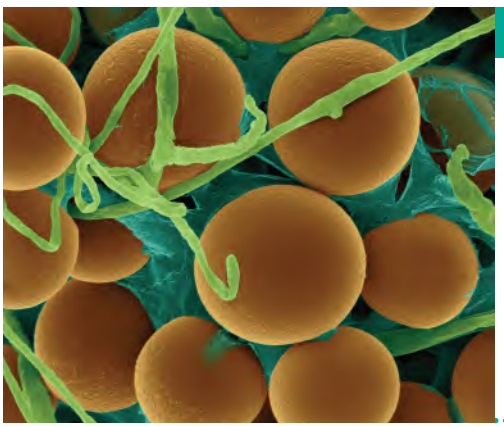


cell A (4500×) cell B (3000×)

16 Compare the structure of prokaryotes and eukaryotes.

17 Compare transmission electron microscopy and scanning electron microscopy.

2.2 Cell organelles



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- know and understand that eukaryotic cells have specialised organelles to facilitate cellular processes such as the synthesis of complex molecules, energy transformation, the storage of materials and the removal of cellular wastes and products
- identify key organelles and their functions, including the nucleus, mitochondria, rough endoplasmic reticulum, ribosomes, smooth endoplasmic reticulum, Golgi apparatus, lysosomes, vacuoles and chloroplasts
- identify organelles in electron micrographs.

You will recall from Module 2.1 that the two fundamentally different types of cells are prokaryotic and eukaryotic cells, and that organisms are classified into one of three domains (Bacteria, Archaea or Eukarya), according to their cell type.

Bacteria and archaea are prokaryotes. Their cells do not contain membrane-bound organelles. Prokaryotic cells have some non-membrane-bound organelles, such as ribosomes, a cell wall and sometimes flagella, although the structure and composition of these organelles are usually different from those of eukaryotic cells.

Animals, plants, fungi and protists are eukaryotes. Membrane-bound organelles are only present in eukaryotic cells. While eukaryotic cells may differ in appearance and function, they all contain membrane-bound organelles, such as those seen in Figure 2.2.1.

FUNCTION AND STRUCTURE OF ORGANELLES

Cells contain **organelles**, which have specialised functions. Organelles are subcellular structures involved in specific functions of the cell. Each organelle is functionally and structurally distinct. Most organelles are surrounded by membranes to separate their processes from other parts of the cell and to provide an optimal cellular environment for the biochemical reactions occurring in the cell.

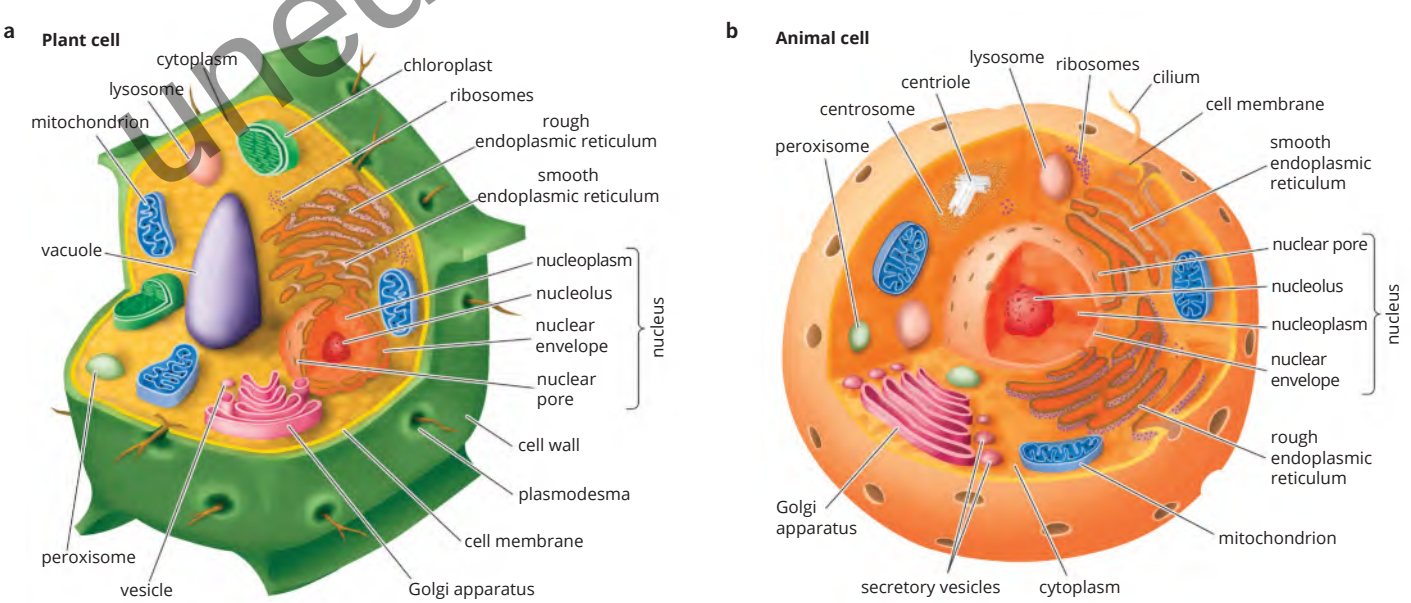


FIGURE 2.2.1 The many membrane-bound organelles of eukaryotic cells can be seen in these illustrations of (a) a plant cell and (b) an animal cell.

Prokaryotic cells do not contain any membrane-bound organelles. The number and types of organelles present in a cell depends on the function of the cell. Some organelles, such as chloroplasts, are only found in a limited number of types of cells, while others, such as ribosomes, are thought to be universal. Mitochondria, which liberate energy for cellular use, are found in very large numbers in active cells, such as muscle cells, and are relatively fewer in less active cells.

Typically, eukaryotes possess a nucleus, mitochondria, Golgi apparatus, rough and smooth endoplasmic reticulum, lysosomes and vacuoles. However, there are some exceptions, such as mature red blood cells, which lack both a nucleus and any lysosomes. Photosynthetic cells also contain chloroplasts (Figure 2.2.2). Eukaryotic cells also have many ribosomes. These may float freely in the **cytosol** or may be attached to the endoplasmic reticulum.

Each membrane-bound organelle has a different function, so each organelle requires a different internal composition, including a high concentration of enzymes and reactants.

Enzymes are protein molecules that act as biological catalysts. Enzymes speed up the rate of reactions that would otherwise have taken place more slowly. Their action is specific: they catalyse only one type of reaction. You will learn more about the role of enzymes in cellular processes in Chapter 3.

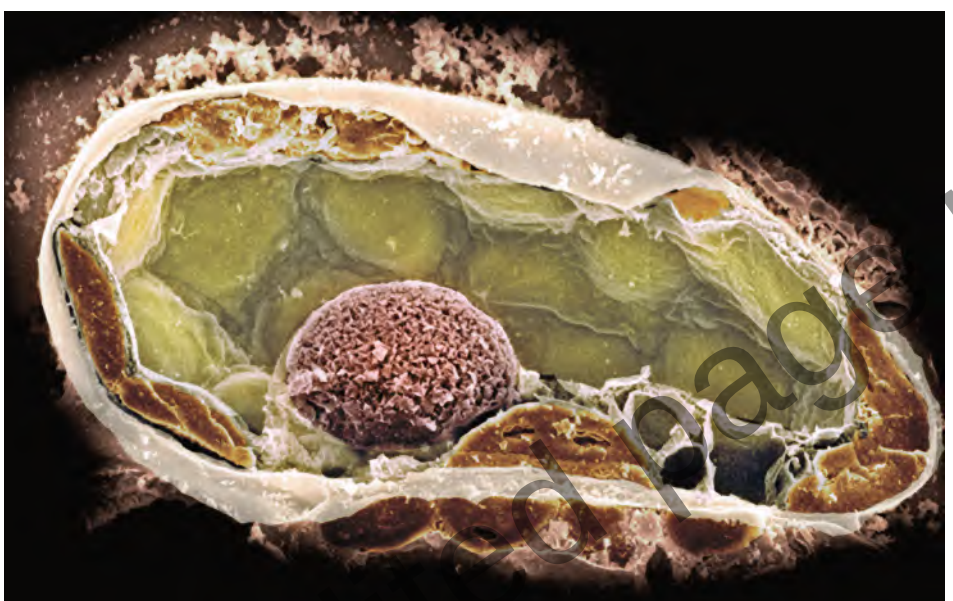


FIGURE 2.2.2 Plants are eukaryotes and so their cells have membrane-bound structures, some of which can be seen in this scanning electron micrograph (SEM). The cell wall is the external layer. Inside the cell wall are chloroplasts (brown), the nucleus (pink) and a large vacuole in the centre of the cell.

Organelle membranes

The membranes surrounding organelles control the movement of substances between the organelle and the cell's cytosol. Just as cell membranes enable the cytosol to have a different composition from the cell's surrounding environment, membrane-bound organelles can have a different composition from the surrounding cytosol and other organelles. Because the environment on either side of the membrane is regulated, different types of biochemical reactions can occur in each region. Therefore, the metabolic reactions performed within the cells can occur efficiently within regions of optimal environmental conditions. The role of membranes to regulate cell function will be explored in Module 2.4XX.

Cell compartmentalisation

Membrane-bound organelles in eukaryotic cells create compartments where specialised functions are carried out. This compartmentalisation of the cell ensures that chemical processes can occur efficiently. Compartmentalisation benefits the cell in several ways:

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

Organelles are involved in a number of different functions (Table 2.2.1). Their functions include the synthesis and processing of proteins and lipids, energy transformations, storage, and maintaining the structure of the cell.

TABLE 2.2.1 Organelles and their functions

Function	Organelle	Present in plants	Present in animals
Involved in synthesis and processing of proteins and lipids	Nucleus	✔	✔
	Ribosome	✔	✔
	Rough endoplasmic reticulum	✔	✔
	Golgi apparatus	✔	✔
	Lysosome	✘	✔
	Smooth endoplasmic reticulum	✔	✔
Involved in energy transformations	Mitochondrion	✔	✔
	Chloroplast	✔	✘
Involved in storage and cell structure	Centrioles	Sometimes	✔
	Flagellum or cilium	✔	✔
	Vacuole	✔	Small
	Cell wall	✔	✘

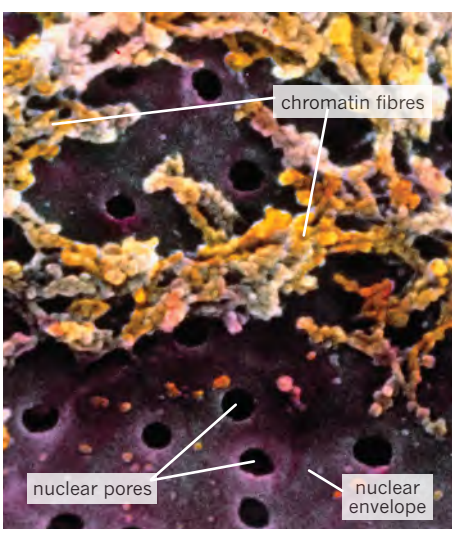


FIGURE 2.2.3 A scanning electron micrograph of the external surface of a nuclear envelope in an onion root tip cell. The envelope consists of a double membrane (purple), which encloses the nuclear DNA. The nuclear pores (black circles) are pathways for the transport of larger molecules between the nucleus and the cytoplasm. Contained within the nucleus are the chromatin fibres (yellow and orange), which contain the chromosomes.

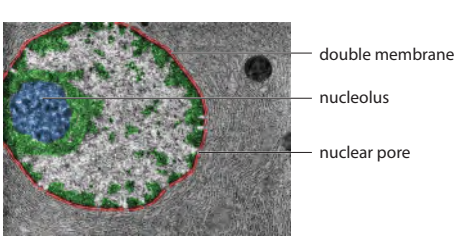


FIGURE 2.2.4 A coloured transmission electron micrograph of the nucleus of a plant. The double layered nuclear membrane (red), nuclear pores and nucleolus (blue) are clearly visible.

Synthesis and processing of proteins and lipids

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

Nucleus

The **nucleus** of a eukaryotic cell contains the DNA which carries the information needed for all cellular functioning. The genetic material in the nucleus takes the form of linear chromosomes composed of DNA and proteins. Chromosomes are usually not clearly visible, except during cell division. The nucleus is a large organelle and is easily viewed under a light microscope, however, an electron microscope is needed to see the nuclear membrane. The nucleus is surrounded by a double membrane which regulates the flow of materials between the nucleoplasm and the cytosol. The nuclear membrane has pores through which substances can pass in a regulated way. You can see these pores in Figures 2.2.3 and 2.2.4. The outer layer of nuclear membrane is continuous with the endoplasmic reticulum.

The most visible structure inside the nucleus of a non-dividing cell is the **nucleolus**. The nucleolus is composed of proteins, DNA and RNA, and is where ribosomes are assembled.

Ribosomes

Cells contain many thousands of ribosomes, which are only about 30 nm in diameter and, therefore, only visible using an electron microscope. Ribosomes are composed of proteins and **ribosomal RNA (rRNA)** and are sites of protein synthesis. They consist of two subunits joined together, as shown in Figure 2.2.5.

The subunits in eukaryote ribosomes are similar in structure but different in size from those in prokaryote ribosomes. Ribosomes are either free in the cytoplasm or bound to rough endoplasmic reticulum.

Ribosomes translate **messenger RNA (mRNA)** into proteins. Proteins produced in free ribosomes will function in the cell's cytoplasm, while proteins synthesised in ribosomes bound to the rough endoplasmic reticulum are secreted out of the cell, packaged into organelles or inserted in cell membranes.

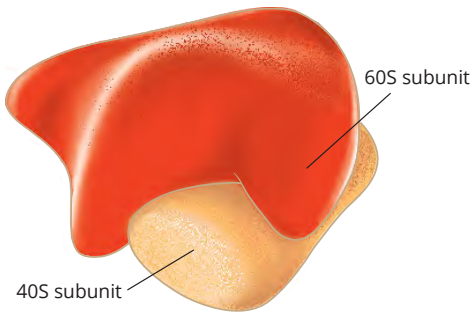


FIGURE 2.2.5 A single eukaryote ribosome consists of a larger 60S subunit and a smaller 40S subunit.

Endoplasmic reticulum

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

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

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

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

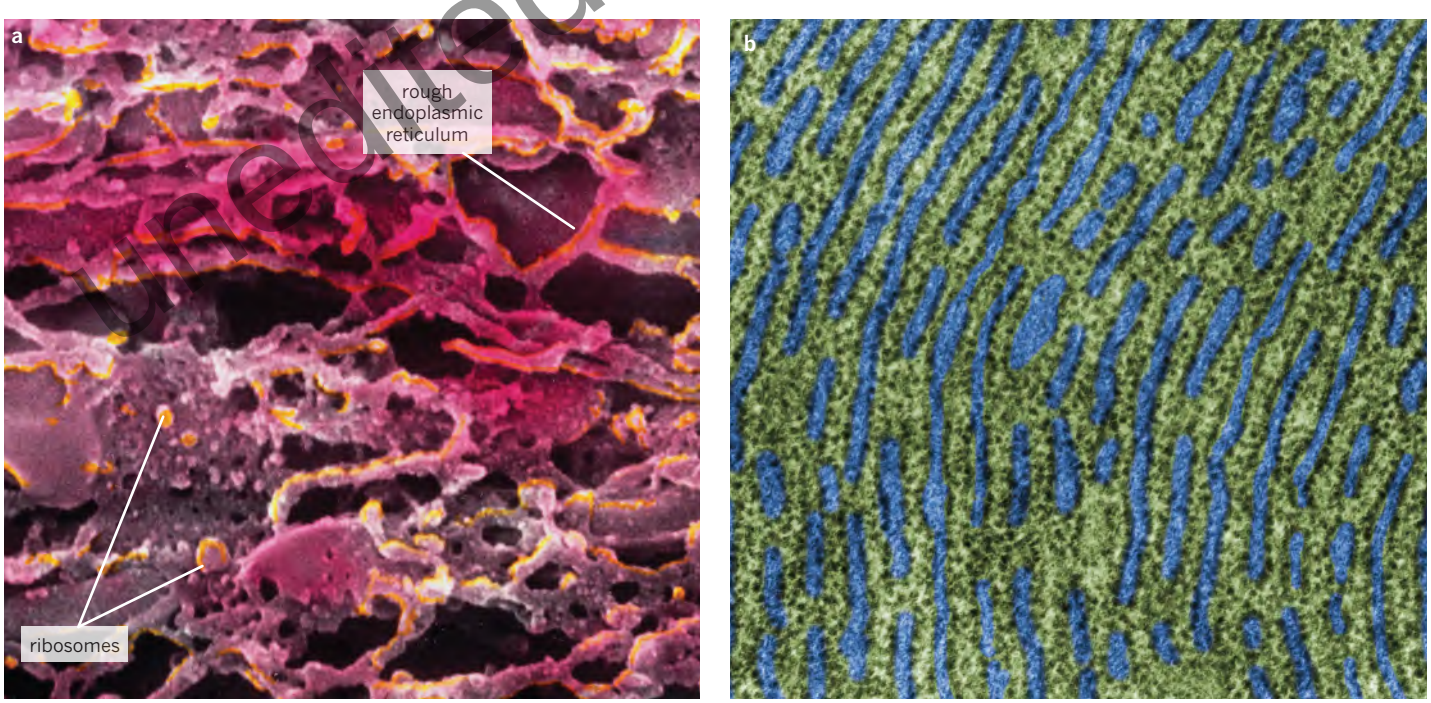


FIGURE 2.2.6 (a) A scanning electron micrograph of endoplasmic reticulum in a cell found in the olfactory epithelium (inside the nasal cavity). Endoplasmic reticulum is a network of folded membranes forming sheets, tubes or flattened sacs in the cell cytoplasm. On the surface of some of the endoplasmic reticulum membranes are ribosomes (yellow spheres). (b) Coloured transmission electron micrograph of rough endoplasmic reticulum (green) with ribosomes (faint black dots) and area inside the membrane, coloured blue.

Golgi apparatus

Figure 2.2.7 shows the **Golgi apparatus** (also called the Golgi body or Golgi complex), which is a stack of flattened smooth membrane sacs called cisternae. Unlike the rough endoplasmic reticulum, the cisternae in the Golgi apparatus are not connected. When proteins formed in the rough endoplasmic reticulum reach the Golgi apparatus, **vesicles** are formed from each cisternae to transport the proteins from one cisternae to the next. The proteins are modified for use by the cell, or for transport out of the cell. The cisternae then form transport vesicles to move these materials into the cytosol or out of the cell, such as secreted hormones. Vesicles budding from the Golgi apparatus also carry membrane-bound proteins to the cell membrane and digestive enzymes into lysosomes.

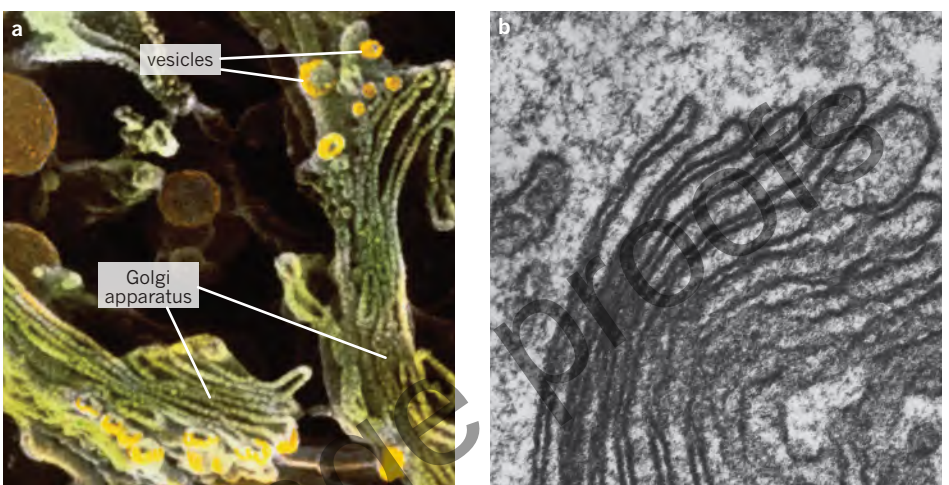


FIGURE 2.2.7 (a) A scanning electron micrograph of the Golgi apparatus of an olfactory bulb cell (part of the brain involved with smell). (b) A transmission electron micrograph of a Golgi apparatus. The Golgi apparatus consists of a stack of flattened interconnecting membranous sacs. It is the site in the cell of synthesis of biochemicals that are packaged into swellings at the margins of the sacs and become pinched off as vesicles (small yellow spheres in the TEM).

The Golgi apparatus has two faces: the *cis* face and the *trans* face, as shown in Figure 2.2.8. The cisternae of the *cis* face are connected to the endoplasmic reticulum, either directly or by small transport vesicles. This allows the proteins made in the rough endoplasmic reticulum to enter the Golgi apparatus. The cisternae of the *trans* face are connected to the cell membrane by large secretory vesicles, which

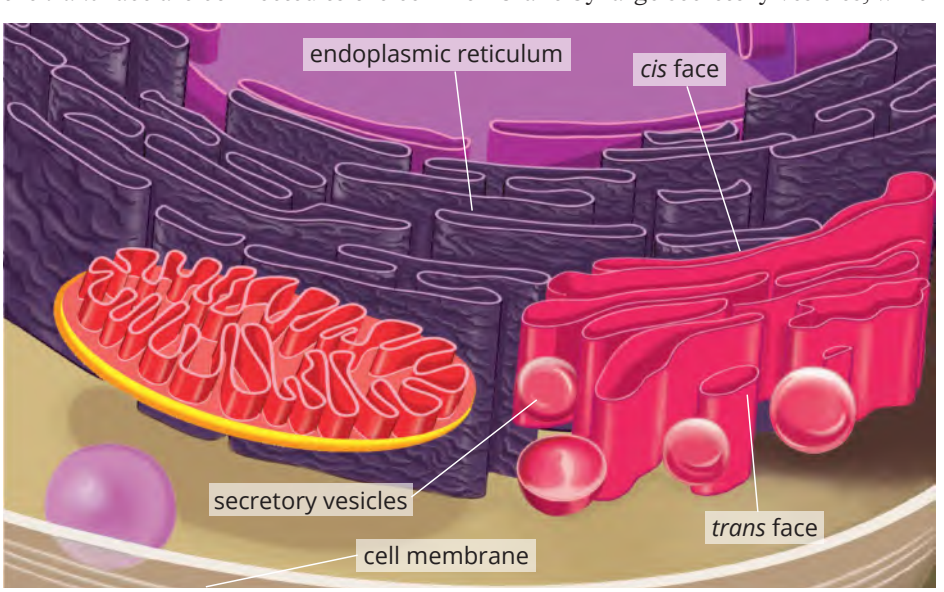


FIGURE 2.2.8 The Golgi apparatus has a *cis* face, which faces the endoplasmic reticulum, and a *trans* face, which faces the cell membrane.

contain proteins to be secreted outside the cell. The membranes of the *cis* face more closely resemble the membranes of the endoplasmic reticulum, and the membranes of the *trans* face more closely resemble the cell membrane in their composition.

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

Lysosomes

Figure 2.2.9 shows two **lysosomes**, which are specialised vesicles that digest (break down) unwanted matter. They are the recycling units of the cells. They are found only in animal cells. Lysosomes are formed when a transport vesicle containing enzymes is released from the Golgi apparatus and fuses with another vesicle called an endosome. The endosome contains molecules brought into the cell by endocytosis.

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

FIGURE 2.2.9 A scanning electron micrograph of two lysosomes in a pancreatic cell. Lysosomes (green) are small spherical vesicles bound by a single membrane (clearer on lower lysosome). Material that probably represents partially digested cell organelles can be seen in each lysosome.

Summary: synthesis and processing proteins and lipids

Protein and lipid synthesis and processing is shown in Figure 2.2.10. DNA is transcribed inside the nucleus into RNA. RNA moves out of the nucleus and binds to ribosomes. Ribosomes synthesise proteins using the information on the RNA. Proteins that are secreted out of the cell are made in the ribosomes bound to the rough endoplasmic reticulum. These proteins are modified and packaged in the Golgi apparatus. Vesicles arising from the Golgi apparatus fuse with the cell membrane, releasing their contents from the cell. They also insert membrane-bound proteins into the cell membrane. Lipids, such as glycolipids and steroids, are synthesised and processed in the smooth endoplasmic reticulum.

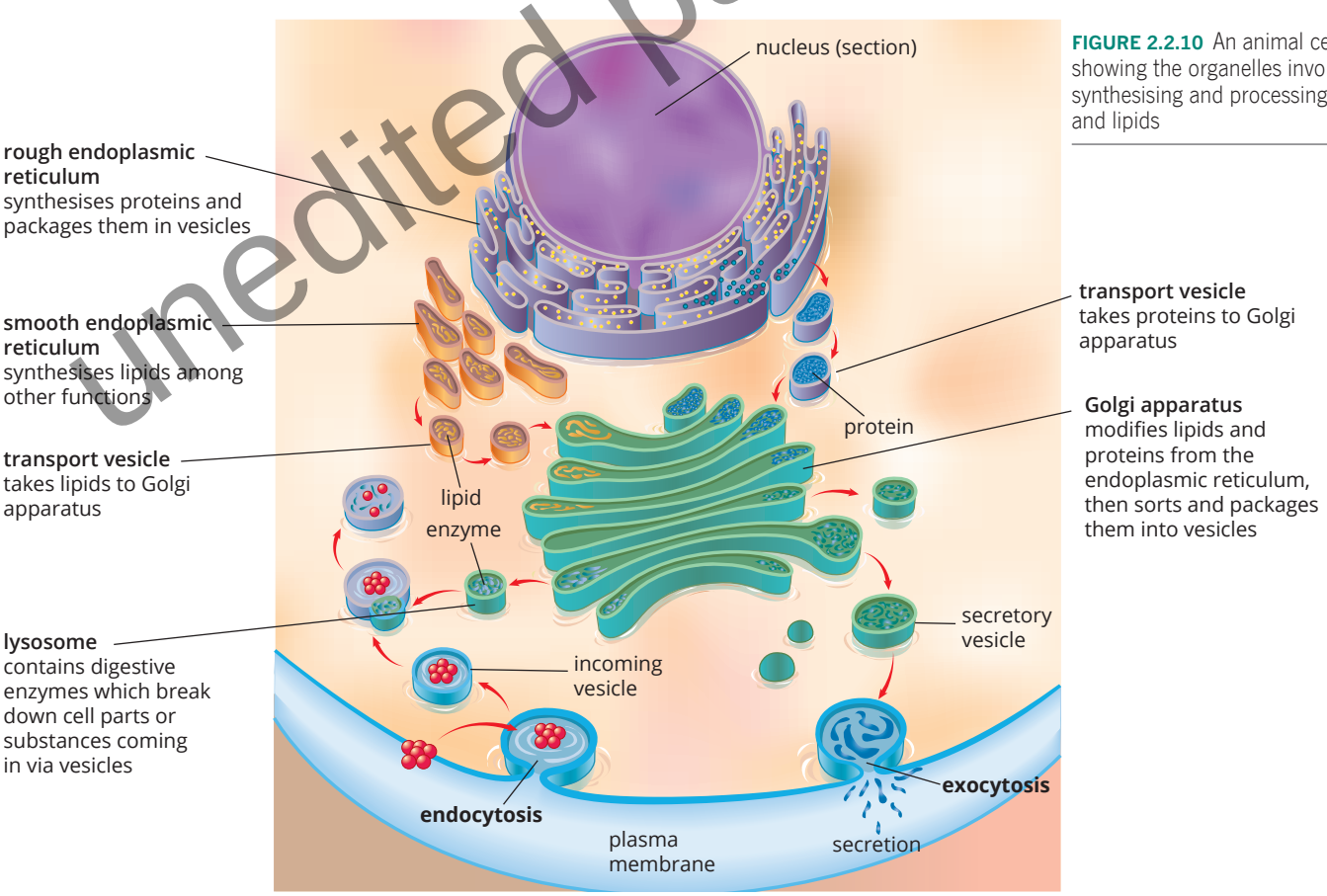


FIGURE 2.2.10 An animal cell, showing the organelles involved in synthesising and processing proteins and lipids

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

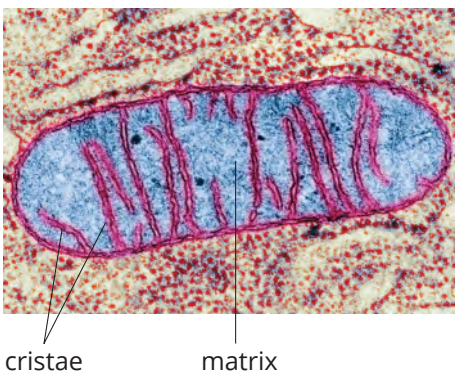


FIGURE 2.2.11 A transmission electron micrograph of a mitochondrion showing the matrix and cristae, which provide a large surface area for the reactions of aerobic respiration to occur.

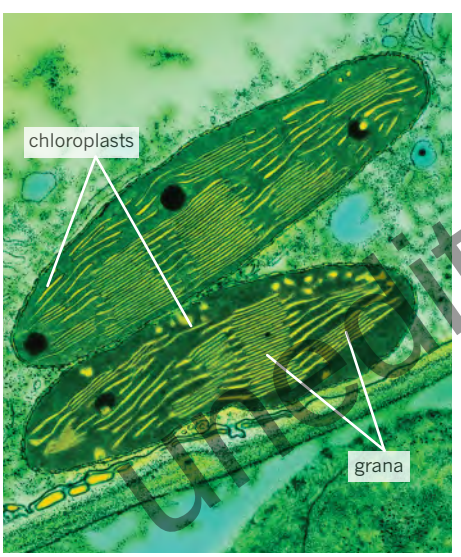


FIGURE 2.2.12 A transmission electron micrograph of two chloroplasts seen in the leaf of a pea plant, *Pisum sativum*. Each chloroplast is seen cut lengthways and contains stacks of flattened membranes (yellow) known as grana. The chloroplasts contain chlorophyll and are surrounded by an external double membrane.

The presence of all of these transport structures makes movement of substances into, out of and around the cell efficient and relatively fast. It is this increase in efficiency that is one of the reasons that eukaryotic cells can be larger than prokaryotic cells.

Energy transformations

Mitochondria and chloroplasts are the organelles involved in energy transformations within eukaryotic cells. Both mitochondria and chloroplasts contain their own DNA. They have a circular chromosome similar to that of prokaryotes. They also have their own ribosomes and make some of their own proteins.

Mitochondria

Mitochondria are the main site of cellular respiration (Figure 2.2.11). In this organelle, complex organic molecules are broken down into simple molecules such as carbon dioxide and water. During this process energy is released. This energy is used for cellular processes such as cell division, making new organelles and building molecules such as proteins. The mitochondrion (singular) consists of two membranes. Both membranes regulate what goes into and out of the mitochondrion. The outer membrane completely surrounds the inner membrane and between the two membranes is the inter-membrane space. The inner membrane is relatively large and is very folded. The area inside the inner membrane is called the matrix. The matrix contains enzymes and other substances which allows the second stage of cellular respiration to occur (the first stage occurs in the cytosol). It is also where the mitochondrion's chromosome is found. The folds are called cristae. Embedded in the cristae are proteins which enable the final reactions of respiration to occur.

The mitochondrion is a fairly large organelle and can just be seen using a powerful light microscope, but an electron microscope is needed to see any of its internal detail.

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

Chloroplasts

Figure 2.2.12 shows **chloroplasts**, which are organelles involved with photosynthesis. They have a circular double-stranded DNA molecule and are green because of the large amounts of chlorophyll (a green pigment) they contain. They are present in plants and many protists, but never in animals or fungi.

Chloroplasts are composed of a system of three membranes: the outer membrane, the inner membrane and the thylakoid system. Thylakoids are disc-shaped sacs. This system of membranes forms compartments within the chloroplast that contain different enzymes. The stacks of thylakoids are the grana (singular granum), single thylakoids joining the grana are lamellae (singular lamella) and the fluid-filled spaces inside are the stroma. The thylakoids contain the light-trapping pigment, chlorophyll, and are where water is split into hydrogen and oxygen. In the stroma the hydrogen from the water and carbon dioxide from the air are used to build glucose. The oxygen is released into the atmosphere as a waste product.

Storage and cell structure

Vacuoles, plastids, cell walls, the cytoskeleton, centrioles, cilia and flagella are involved in storage and also support the cell structure in eukaryotic cells.

Vacuoles

Vacuoles are membrane-bound, liquid-filled spaces that store enzymes, and other organic and inorganic molecules. They occur in most cells, in different numbers. Figure 2.2.13 illustrates a plant cell vacuole. Vacuoles in animal cells and plant cells are different. Animal cells contain many small temporary vacuoles, but most plant cells contain a single large permanent vacuole surrounded by a membrane called the **tonoplast**. In plants, the vacuole provides structural support by helping maintain turgor and it seems that lysosome function also occurs here in the plant vacuole.

Plastids

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

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

Amyloplasts, as shown in Figure 2.2.14, are a type of leucoplast in plants. They are commonly responsible for synthesising and storing starch, but can also convert the starch back to sugar when the plant requires energy.

Tannosomes are a newly discovered organelle formed in chloroplasts which are the source of tannins. Tannins are polyphenols, and are part of the defence mechanism against bacteria and viruses in plants. Their bitter taste also discourages animals from eating the plants.

Cell wall

The **cell wall** is a rigid structure outside the cell membrane of plant cells, fungal cells and some prokaryotic cells. You can see the cell wall in a *Hookeria* moss cell in Figure 2.2.15. In plants, the cell wall is composed mainly of cellulose. The fungal cell wall is made of chitin.

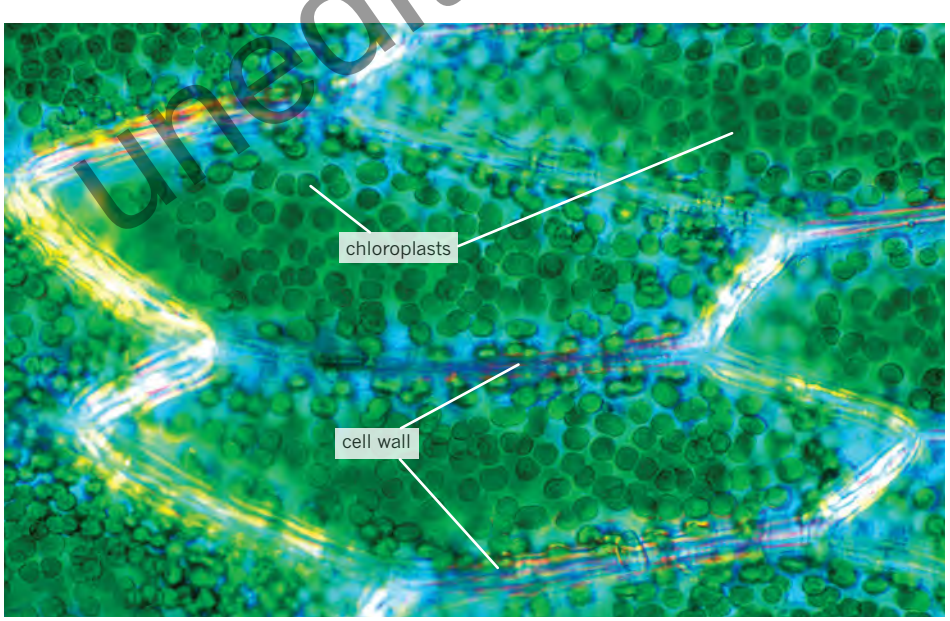


FIGURE 2.2.15 A light micrograph of cells in a leaf of shining *Hookeria* moss (*Hookeria lucens*). The leaf is made up of a single layer of cells. A cell wall (blue) encloses each cell, and numerous chloroplasts containing the pigment chlorophyll (green, round) are seen in each cell.

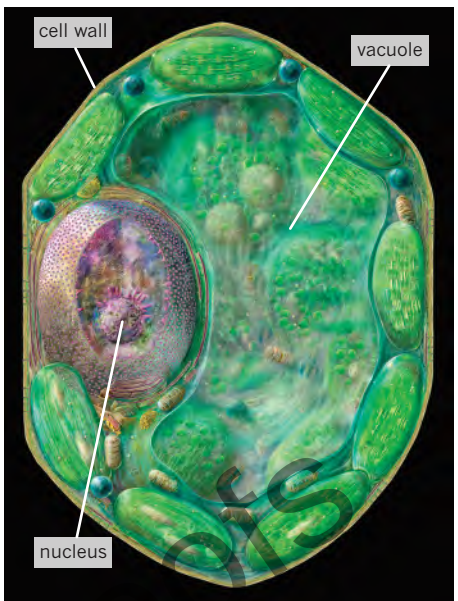


FIGURE 2.2.13 An illustration of a section through a plant cell, revealing its internal structure. At the centre of the cell is a large vacuole, which maintains the cell's shape, stores useful materials and digests the cell's waste products.

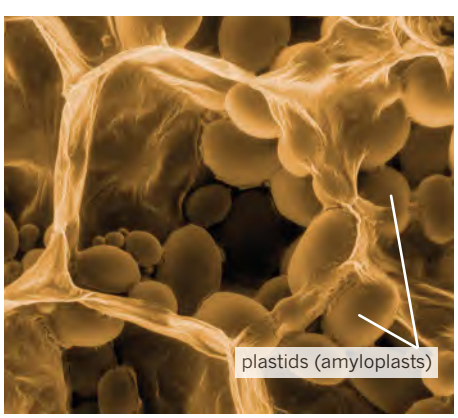


FIGURE 2.2.14 A scanning electron micrograph of amyloplasts (oval) in the sectioned cells of a potato (*Solanum tuberosum*). Amyloplasts are starch-storing plastids, or plant organelles.

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

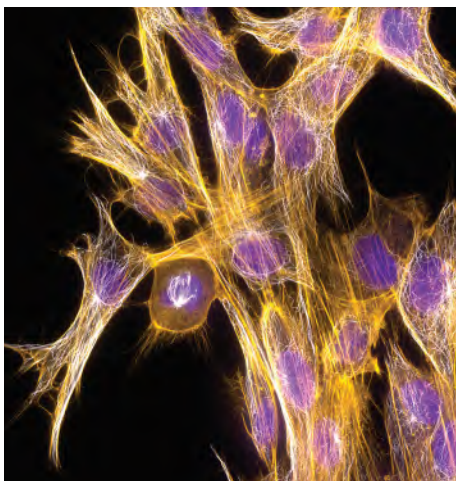


FIGURE 2.2.16 A fluorescent LM of fibroblast cells. Fibroblasts are cells that give rise to connective tissue such as collagen, the main structural protein in the body. The proteins that make up the cytoskeleton are shown in yellow (actin) and white (tubulin). The cell nuclei are shown in purple.

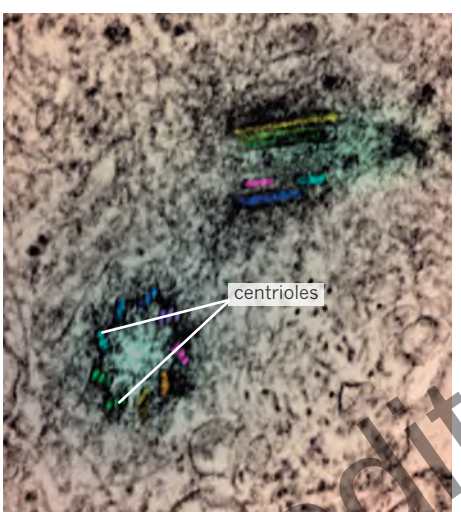


FIGURE 2.2.17 TEM of centrioles (rainbow coloured structures), the organelles that are involved in cell division and the formation of some cell structures.

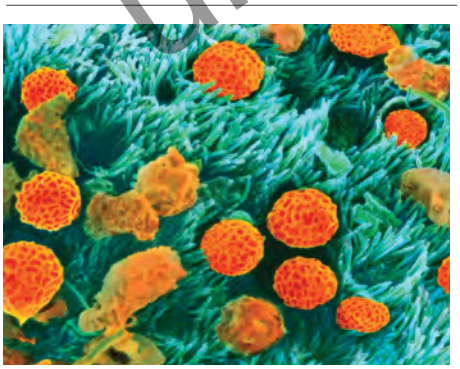


FIGURE 2.2.19 SEM of the internal surface of the trachea (windpipe) with inhaled pollen (orange) and dust (brown). The surface cells have hair-like cilia (green) which, together with mucus, trap airborne particles for removal of foreign matter from the airways and lungs.

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

Cytoskeleton

The **cytoskeleton** consists of microtubules of the protein tubulin and filaments of the protein actin. The cytoskeleton supports the cell's structure, allows the cell to move and assists in the transport of organelles and vesicles within the cell. Figure 2.2.16 shows fibroblast cells and their components.

Centrioles

Centrioles are a pair of small cylindrical structures composed of microtubules, as shown in Figure 2.2.17. They are present in most eukaryotic cells, but many plant cells do not have centrioles. Centrioles are involved in cell division and in the formation of cell structures such as cilia and flagella.

Cilia and flagella

Cilia and flagella (singular cilium and flagellum, respectively) are hair-like structures on the surface of cells and are shown in Figures 2.2.18 and 2.2.19. They consist of an arrangement of microtubules enclosed by an extension of the cell membrane. Cilia move with an oar-like motion and are usually shorter and more numerous than flagella. Both structures are involved in the movement of the cell.

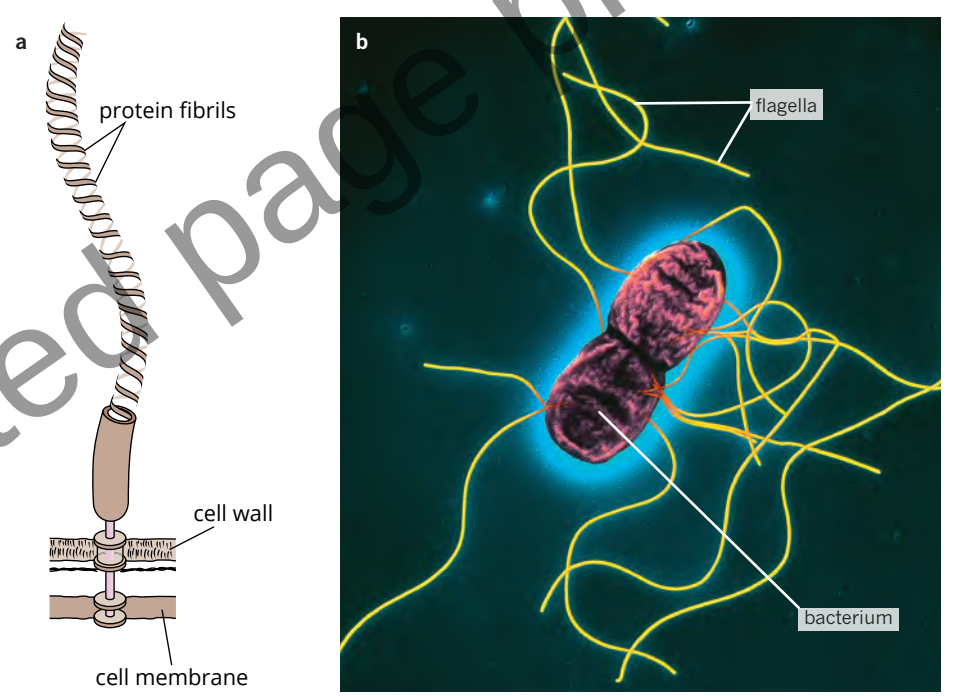


FIGURE 2.2.18 (a) Bacterial flagella consist of three protein fibrils coiled in a helical pattern. (b) A scanning electron micrograph of a *Salmonella typhimurium* bacterium. This rod-shaped, Gram-negative bacterium moves by using its long, hair-like flagella (yellow).

A summary of the structure and function of the major cell organelles is given in Table 2.2.2.

TABLE 2.2.2 Summary of organelle structure and function

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

2.2 Review

SUMMARY

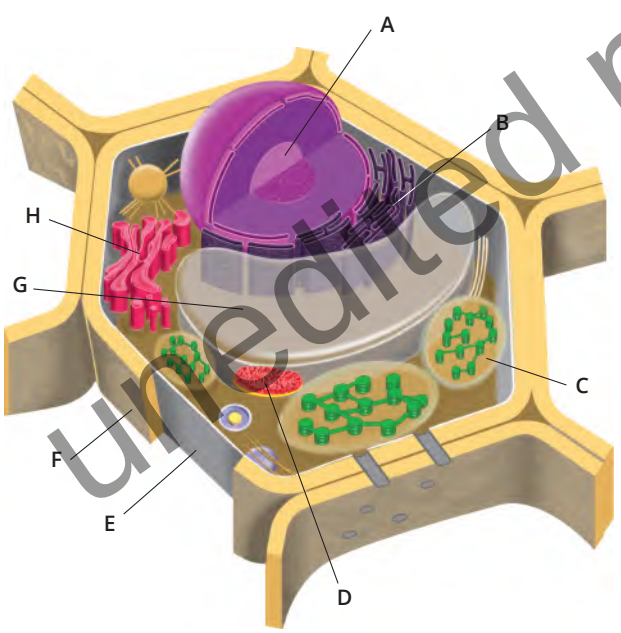
- Organelles are the functioning units of the eukaryotic cell.
- The main structures in a plant cell include the nucleus, tonoplast, vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum, ribosomes, plastids, mitochondria and cell wall.
- The main structures in an animal cell include the nucleus, ribosomes, Golgi apparatus, rough and smooth endoplasmic reticulum, vacuoles, mitochondria, lysosomes, vesicles and centrioles.
  - The nucleus contains DNA and controls all cellular functions.
  - Golgi apparatus, rough and smooth endoplasmic reticulum, and vesicles are involved in transport of substances within the cell.
  - Ribosomes (proteins) and smooth endoplasmic reticulum (lipids) are responsible for synthesis of organic compounds for the cell.
  - Mitochondria and chloroplasts are responsible for energy transformations.
  - Lysosomes assist in the destruction of waste materials.

KEY QUESTIONS

Describe

1 What is the common role of mitochondria and chloroplasts in a cell?

2 Label the parts of the following plant cell.



3 Which organelles are responsible for each of the following functions?

a protein synthesis
b transport from Golgi apparatus to the cell membrane
c lipid synthesis
d storage
e destruction of waste

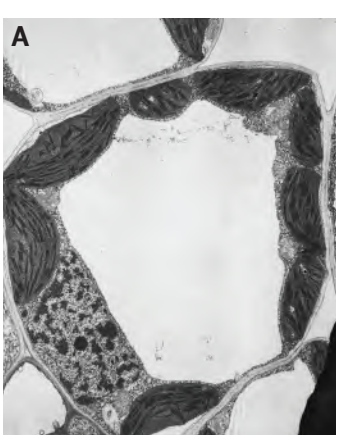
4 What function or functions do rough and smooth endoplasmic reticula have in common?

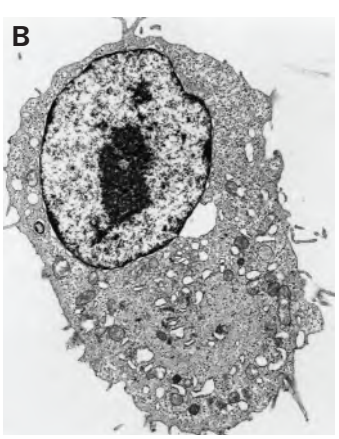
Apply

5 Which organelles would be most abundant in each of the following cell types? Explain your reasoning in each case.

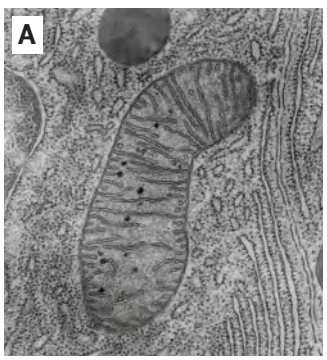
a enzyme-secreting cells
b muscle cells
c storage cells in a potato
d cells that carry out photosynthesis in a leaf
e cyanobacteria

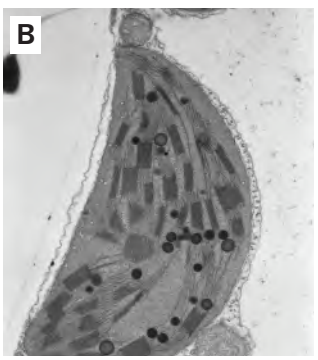
6 Consider the following images. Identify which is a plant cell and which is an animal cell. Explain your reasoning.

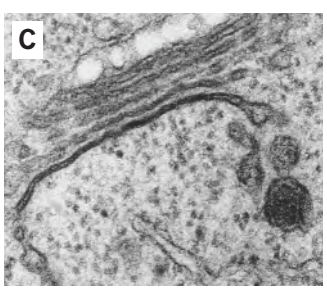


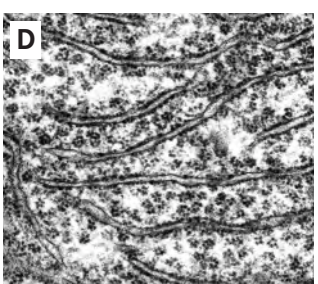


7 For each of the images (A–D):
- **a** identify the name of the organelle
- **b** describe the organelle's function.



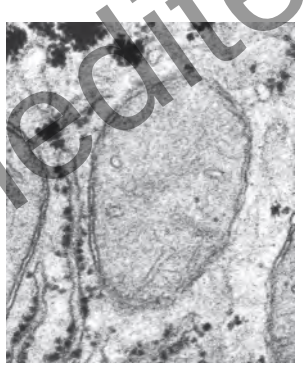






8 The cristae of the mitochondria and thylakoids of the chloroplasts provide large surface areas. Explain why this is advantageous for the cell.

9 The image below is of a mitochondrion as seen using a transmission electron microscope, but it is not how mitochondria typically appear. Explain why.



Analyse

10 You have been assigned the task of determining whether a sample contains plant or animal cells. Identify what features of the sample would help you in this task.

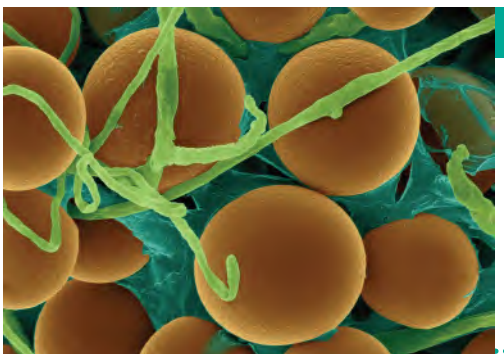
11 An experiment was conducted to investigate the synthesis of a type of organic substance from β-cells in the pancreas.

A radioactive material was injected into the secretory tissue. The level of radioactivity in various organelles of this type of cell was then measured every 60 minutes. The results are summarised in the table below.

	Percentage of total radioactivity			
Time (min)	**Rough endoplasmic reticulum**	**Golgi apparatus**	**Immature secretory vesicles**	**Mature secretory vesicles**
0	77	10	0	13
60	17	57	15	11
120	20	15	45	10
180	21	13	16	50
240	21	11	13	55
300	20	11	12	57

- **a** What type of substance is being synthesised?
- **b** What is the trend or pattern in radioactivity in the:
  - **i** endoplasmic reticulum
  - **ii** Golgi apparatus?

2.3 The cell membrane



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the role of the cell membrane in the regulation of movement of materials into and out of the cell
- describe the structure of the cell membrane (including protein channels, phospholipids, cholesterol and glycoproteins) based on the fluid mosaic phospholipid bilayer model
- sketch a diagram of the phospholipid bilayer and explain the functions of each of the molecules that make up the membrane.

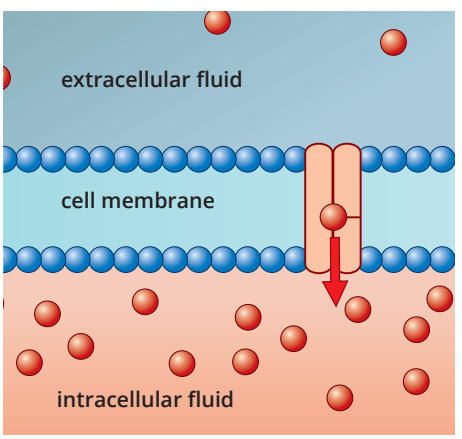


FIGURE 2.3.1 The cell membrane regulates the movement of substances between the extracellular fluid and intracellular fluid.

Extracellular fluid is body fluid outside the cell membranes; it includes blood plasma and interstitial fluid.

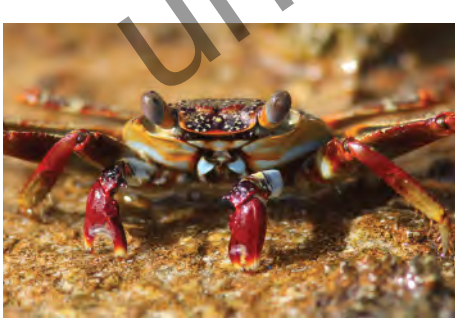


FIGURE 2.3.2 Crabs have an external skeleton that protects them from water loss when on land.

In this module, you will learn about the composition and characteristics of the cell membrane. You will also study the ways cells can increase the surface area of the cell membrane available for the exchange of substances.

THE CELL ENVIRONMENT

Cells exist in a watery environment of **extracellular fluid**, which can be a large amount of fluid or a thin surface layer of fluid. In plants, the cell wall is porous and has little effect on the movement of molecules. All living cells exist in an environment that is a layer of fluid in contact with the outer cell membrane. The composition of this fluid is critical to the stability of cells because it is from this environment that cells obtain the nutrients they need. The cell membrane controls the movement of substances between the extracellular fluid outside and the **intracellular fluid** (or cytosol) inside the cell. A diagram of the cell membrane is shown in Figure 2.3.1.

Extracellular fluid in unicellular organisms

For unicellular organisms, the extracellular fluid is simply the watery external environment in which they live. Unicellular organisms can do little to control their environment and may die if it changes significantly.

However, some unicellular organisms such as yeasts can become dormant until their environment returns to optimal conditions. Other organisms can move slowly to a place where conditions are more suitable for their needs. For example, unicellular algae can move towards light, and some bacteria can detect and move towards nutrients or away from toxic substances.

Extracellular fluid in multicellular organisms

Conditions for cells in multicellular organisms are more stable than those of unicellular organisms. The more complex the organism, the more control it has over the environment in which its cells exist, and the more independent the organism is from its external environment. Whether they live in water or on land, multicellular organisms have an outer layer that acts as a protective barrier, such as a crab's exoskeleton as shown in Figure 2.3.2. This outer layer creates an internal environment for the organism that is different from their external environment, and organisms can better regulate their internal environment for optimal cell function. Therefore, in multicellular organisms, the environment of the cells is the extracellular fluid that surrounds them.

Most multicellular organisms can regulate their internal environment, often very precisely. This allows them to provide the specific conditions needed by specialised cells and tissues, and for their cells to function more efficiently. Commonly regulated aspects of the internal environment are:

- temperature
- oxygen concentration
- carbon dioxide concentration

- pH (acidity or alkalinity)
- osmotic pressure (concentrations of salts or ions)
- nitrogen waste concentration
- glucose concentration.

Importantly, the way cells interact with the extracellular fluid of the internal environment is regulated by the cell membrane.

CELL MEMBRANE COMPOSITION

Cell membranes have the same basic structure in all organisms, which serves to separate the interior of the cell (the cytoplasm) from its external environment. Most membranes are also asymmetrical, meaning one layer has different properties from the other. For example, the pattern of proteins and carbohydrate molecules in the external surface is different from the pattern in its internal surface.

The composition and characteristics of the cell membrane are related to the needs and function of the cell. The cell membrane performs important functions such as transporting molecules into and out of the cell, and recognising and communicating with other cells.

Phospholipids and the phospholipid bilayer

The cell membrane is a lipid–protein barrier that surrounds the cell and regulates the movement of materials between the inside and outside environment of a cell. It is typically about 7 nm wide. The **phospholipids** found in the cell membrane are composed of a phosphate group, a glycerol molecule and two **hydrophobic** fatty acid tails, as shown in Figure 2.3.3. The phosphate end of the molecule, which is polar and therefore hydrophilic ('water loving'), faces the aqueous regions of the cellular environment. The non-polar, fatty acid, part of the phospholipid is hydrophobic ('water hating') and faces inwards to the bilayer to form an oily region that becomes the barrier for most water-soluble materials.

A phospholipid is a molecule consisting of long-chain fatty acids (which are hydrophobic), a phosphate group and glycerol (which is hydrophilic). It is the major component of cell membranes.

Cell membranes are phospholipid bilayers that enclose the cytoplasm and subdivide the cell into compartments (organelles).

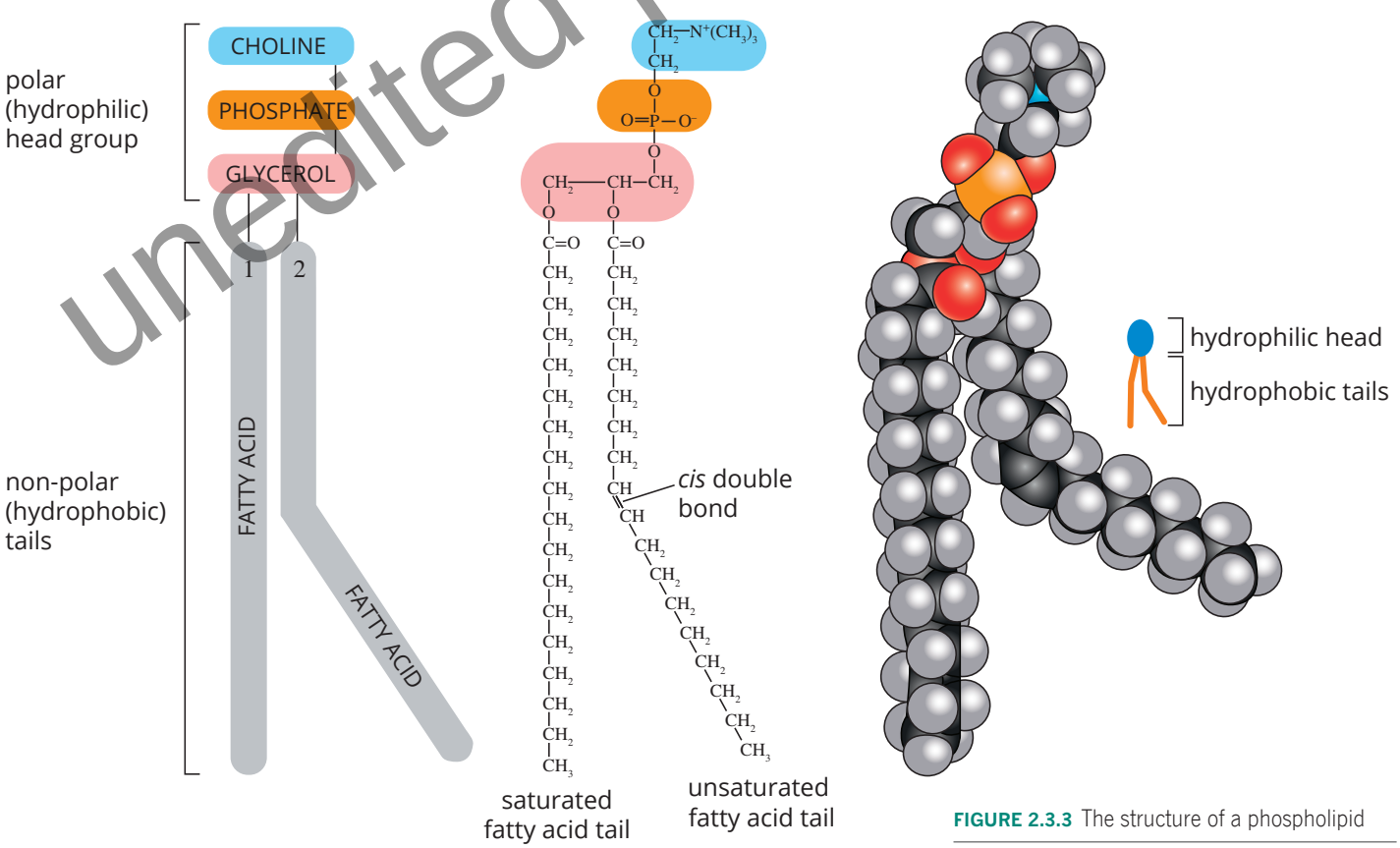


FIGURE 2.3.3 The structure of a phospholipid

The phospholipid bilayer of the cell membrane is called a bilayer because it has two layers of phospholipids. The hydrophilic heads form the outside and inside lining of the cell membrane, and the hydrophobic tails of the two layers of phospholipids meet in the middle. This is illustrated in Figure 2.3.4.

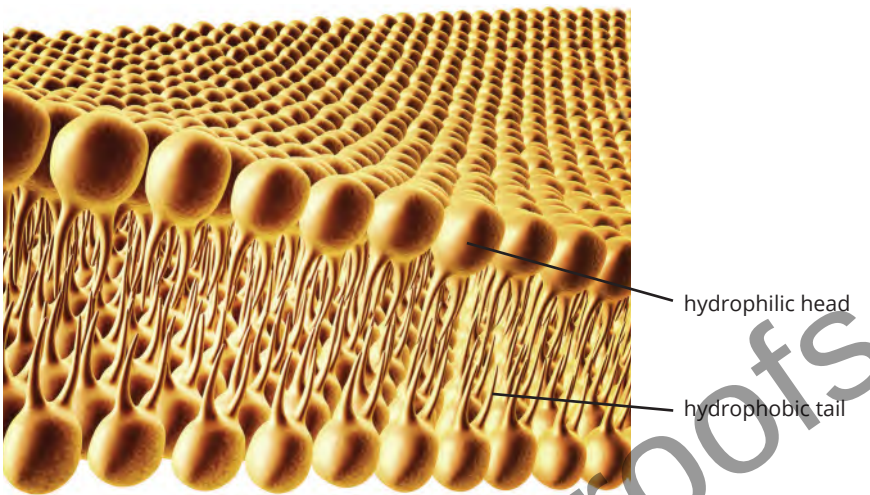


FIGURE 2.3.4 A phospholipid has a hydrophobic 'tail' and a hydrophilic 'head'.

Figure 2.3.5 shows how phospholipids arrange themselves in water and in oil. The phospholipids make cell membranes impermeable to water-soluble particles, ions and polar molecules. The movement of these molecules across the membrane is controlled by protein channels, which allow the cell to regulate the exchange of molecules with the environment. Controlling the movement of substances into and out of the cell is central to important processes that keep the cell alive, such as cell respiration, digestion and elimination of wastes. You will learn more about transport across cell membranes later in this module and in Module 2.4XX.

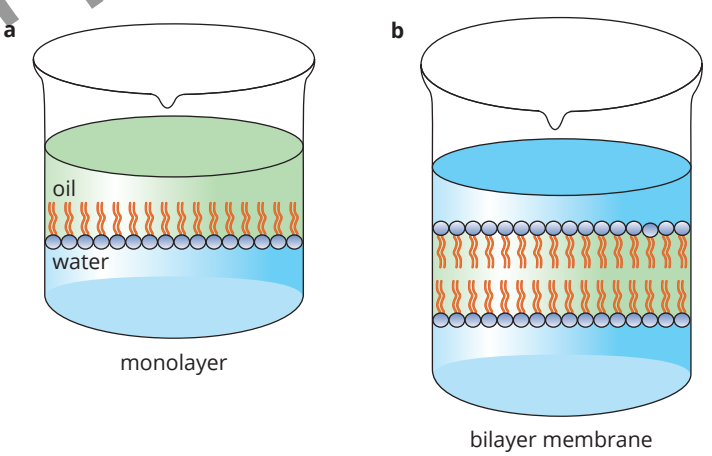


FIGURE 2.3.5 (a) The arrangement of phospholipids when water is on one side and oil is on the other side. (b) The arrangement of phospholipids when water is on both sides—a bilayer is formed.

Fluid mosaic model

Singer and Nicolson initially described the dynamic nature of the cell membrane as a 'fluid mosaic' in 1972. In their model, the phospholipids can move within the membrane by diffusion and a mosaic of discontinuous protein particles may be found floating in the phospholipid bilayer like icebergs. Figure 2.3.6 illustrates the fluid mosaic model.

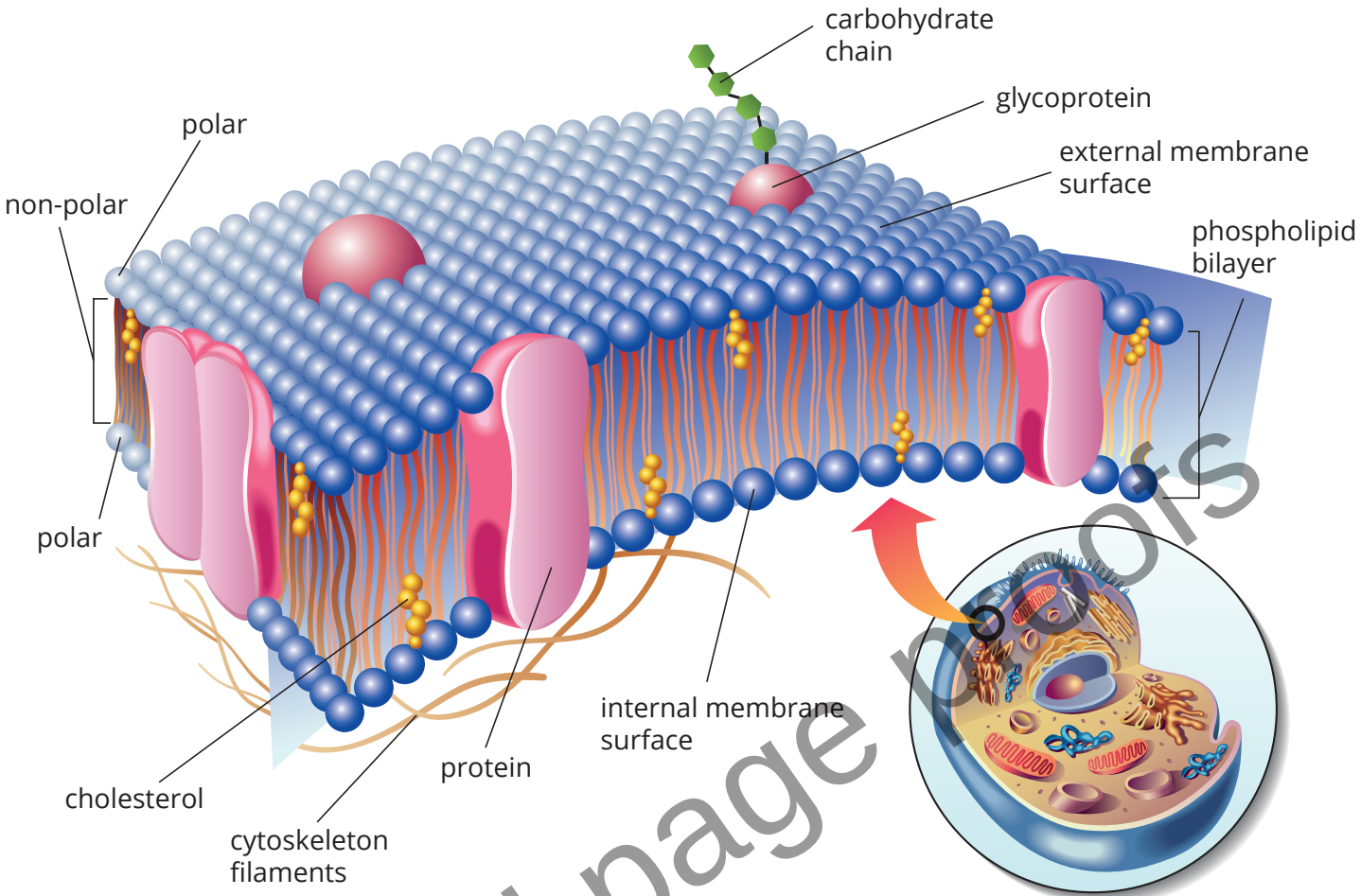


FIGURE 2.3.6 The fluid mosaic model of a cell membrane, showing the phospholipid bilayer in which large protein molecules are embedded.

This fluid mosaic model is now widely accepted as the basic model of all biological membranes. According to this model, cell membranes consist of two layers of phospholipid molecules, with other molecules such as proteins, carbohydrates and cholesterol scattered throughout the membrane.

Molecules of the cell membrane are not fixed in place. Cell membranes are fluid structures, which means that individual phospholipid molecules (and some proteins) are free to move about within the layers. However, they rarely cross from one side of the membrane to the other. Most of the phospholipids and some of the proteins can move laterally, and sometimes some molecules are able to flip-flop transversely across the membrane. This movement is shown in Figure 2.3.7. The rate at which the molecules move within a layer of the cell membrane varies. Proteins in the membrane can move sideways throughout the membrane, but they move much slower than the phospholipids.

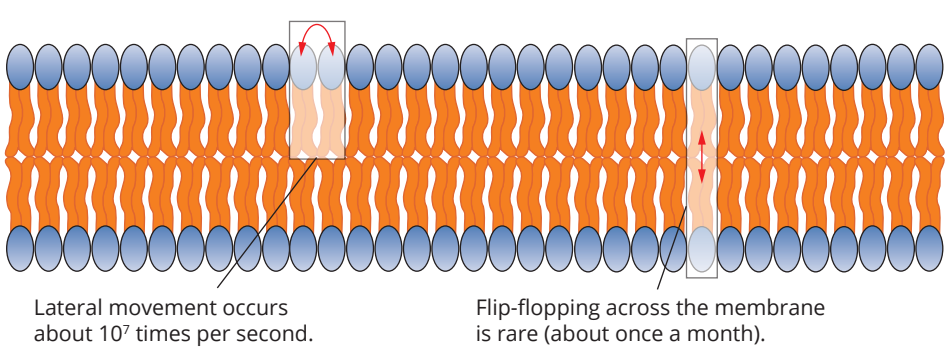


FIGURE 2.3.7 The movement of phospholipids in cell membranes

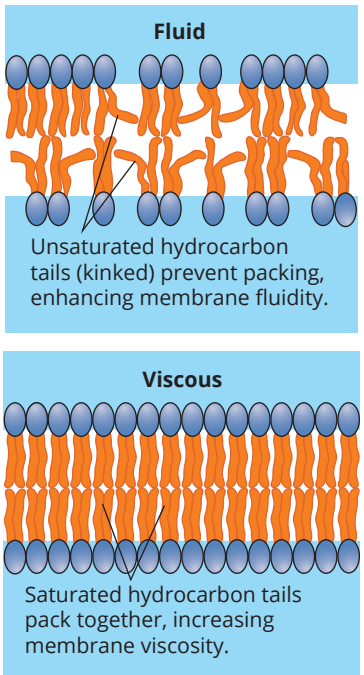


FIGURE 2.3.8 These two diagrams show the effects of unsaturated and saturated fatty acid tails on the fluidity of the cell membrane.

The ability of the phospholipids and proteins to move gives the cell membrane its fluid nature. Membrane fluidity is also influenced by how much unsaturated fatty acids are in the phospholipid molecules—more unsaturated fatty acids make the membrane more fluid, as shown in Figure 2.3.8. The fluidity of the cell membrane is very important because it affects how permeable the membrane is. It also makes it possible for proteins to move within the membrane to particular areas where they are required to carry out their function.

Figure 2.3.9 shows the components of the cell membrane. As well as the phospholipid bilayer, the cell membrane comprises cholesterol, proteins and carbohydrates.

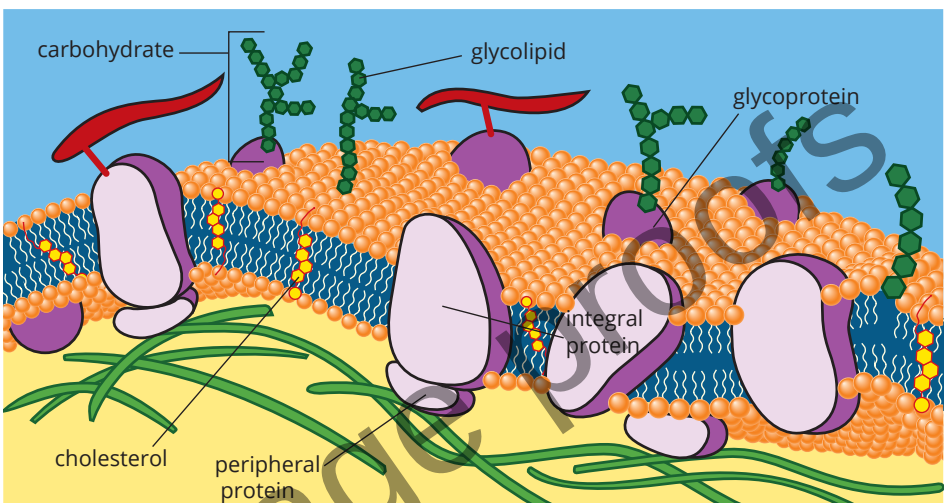


FIGURE 2.3.9 Components of the cell membrane

Cholesterol

Figure 2.3.10 shows how the cell membranes of eukaryotes contain **cholesterol**, a type of fatty molecule, between the phospholipid molecules. Cholesterol stabilises the membrane but does not affect its fluidity and reduces the permeability of the membrane to small water-soluble molecules.

Cholesterol acts as a buffer against changing temperatures. At high temperatures, cholesterol stops the cell membrane from becoming too fluid by restricting the movement of phospholipids. At low temperatures, cholesterol prevents the cell membrane from solidifying by restricting the tight packing of phospholipids.

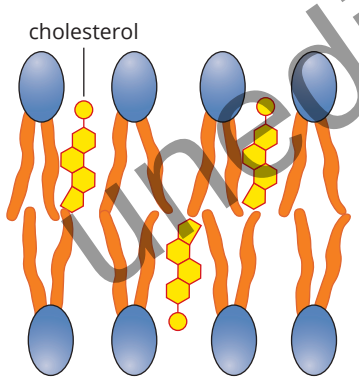


FIGURE 2.3.10 The cholesterol molecules are embedded within the hydrophobic fatty acid region of the cell membrane.

Proteins

Like phospholipid molecules, proteins in the cell membrane can move about to some extent, but this movement may be limited to particular regions of the cell membrane.

Proteins that are a permanent part of the cell membrane are called **integral proteins**. Proteins that are a temporary part of the cell membrane are called **peripheral proteins**. Peripheral proteins bind to integral proteins or penetrate into one surface of the cell membrane (Figure 2.3.9). When integral proteins span both phospholipid layers, they are also called **transmembrane proteins**. Transmembrane proteins are involved in a number of important cellular and intercellular activities. These activities are illustrated in Figure 2.3.11.

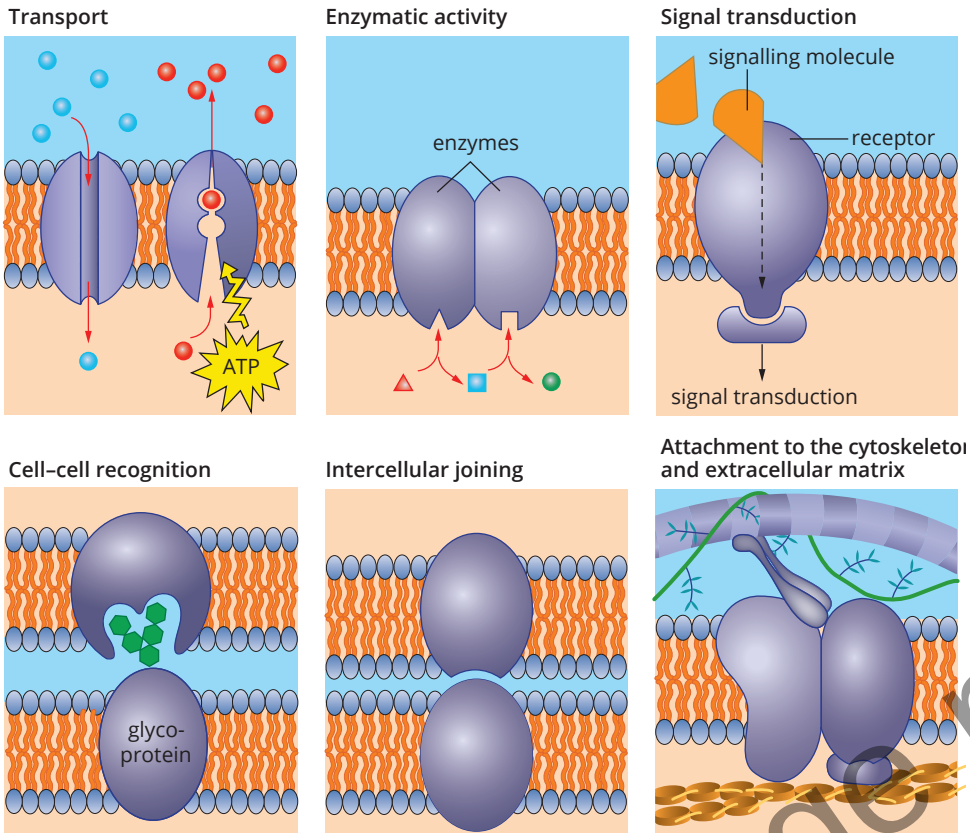


FIGURE 2.3.11 Different functions of cell membrane proteins

Integral proteins have many functions in the cell membrane (Figure 2.3.11). For example, these proteins:

- act as transport channels to transport molecules and ions through the membrane
- function as enzymes
- are involved in signal transduction (responding to hormones, neurotransmitters of other communication molecules from outside the cell)
- function in cell–cell recognition
- connect cells to each other
- act as attachments to the cytoskeleton and the extracellular matrix.

Protein channels

Protein channels are integral transmembrane proteins which enable the movement of polar and charged molecules to cross the cell membrane. Like all proteins, they are made of amino acids. Some amino acids are polar and are thus hydrophilic and lipophobic ('lipid hating'), and others are non-polar and are thus hydrophobic and lipophilic ('lipid loving'). The amino acids in a protein channel are arranged such that the outside of the channel has non-polar amino acids and the inside has polar amino acids. This creates an area inside the channel which is 'friendly' to molecules and ions which are repelled by the lipid bilayer of the cell membrane. The cell can regulate whether these channels are open or closed and can determine which substances can enter or leave the cell.

Carbohydrates

Carbohydrates associated with cell membranes are usually linked to protruding proteins (forming **glycoproteins**) or to lipids (forming **glycolipids**) on the outer surface of the membrane (Figure 2.3.9). They play a role in recognition and adhesion between cells, and in the recognition of antibodies, hormones and viruses by cells. Glycoproteins may act as receptors, receiving signalling molecules which trigger changes in cell functioning. They also often mark cells as self for recognition by white cells of the immune system.

WS 1.1.3

2.3 Review

SUMMARY

- The external environment of living cells is the layer of extracellular fluid that is in direct contact with the cell membrane.
- For unicellular organisms, the extracellular fluid is the watery environment in which they live and that they can do little to control.
- Multicellular organisms have an internal environment that is more or less independent from the external environment. The external environment of the cells is therefore the extracellular fluid that surrounds them.
- Cell membranes separate the interior of the cell, the cytoplasm, from the external environment and control the movement of substances between the two.
- Cell membranes consist of a double layer of phospholipid molecules. They contain protein molecules of various sizes as well as fatty molecules such as cholesterol. They are also associated with other molecules, including carbohydrates.
- The phospholipid nature of the cell membrane makes it impermeable to water-soluble particles, ions and polar molecules.
- Cell membrane proteins:
  - provide selective channels that enable water-soluble particles and ions to travel through the cell membrane
  - catalyse reactions associated with the cell membrane
  - communicate with the external environment and other cells
  - bind with other cells.

KEY QUESTIONS

Describe

1 List three functions of the cell membrane.

2 What is the component of the phospholipid molecule that does not allow most water-soluble substances to pass through the phospholipid bilayer barrier of the cell membrane.

3 How does cholesterol help maintain the cell membrane's structure?

4 What is an integral protein?

Apply

5 **a** The illustration below shows the structure of a typical cell membrane. Identify the compounds labelled A and B.

b With specific reference to the structure of compound A, describe how it is organised to form a bilayer.

6 Explain the importance of the fluidity of the cell membrane for the function of eukaryotic cells.

7 Explain the role the cell membrane plays in regulating the internal environment of a cell.

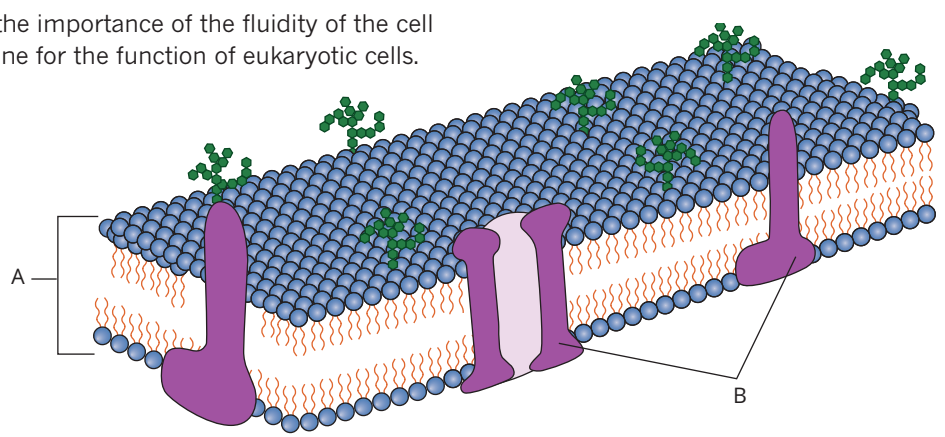
8 Why would a cell membrane containing only saturated fatty acids be very rigid?

9 Explain why protein channels are needed for cell functioning.

Analyse

10 You are asked to give a one-minute summary to the class on the fluid mosaic model of the cell membrane. Consider the key points necessary for your response and organise them appropriately to clearly explain the fluid mosaic model to your class.

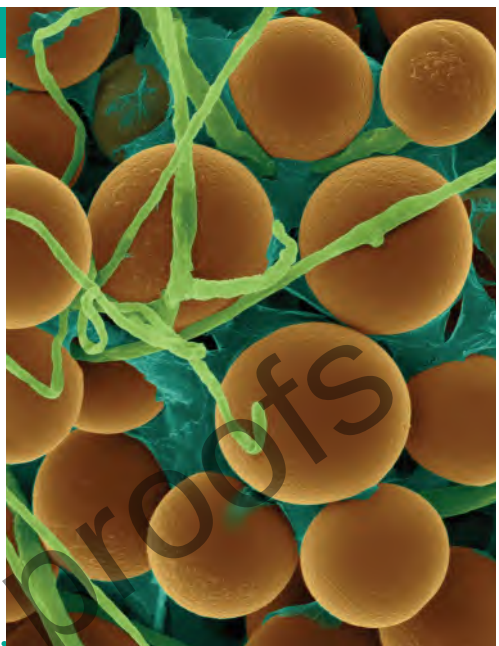
11 Marine mammals living in the Antarctic have a higher level of unsaturated fatty acids in their cell membranes than mammals living in more temperate regions. Suggest why this assists the survival of these animals.



2.4 Crossing the membrane

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the differences between diffusion, osmosis, facilitated diffusion and active transport and name some examples of the types of substances transferred by each method
- understand the importance of surface area to volume ratio for cell function
- understand that endocytosis is a form of active transport that usually moves large polar molecules that cannot pass through the hydrophobic cell membrane into the cell
- predict the direction of movement of materials across the cell membrane on the basis of factors such as concentration, physical and chemical nature of the materials
- explain how the size of a cell is limited by the relationship between surface area to volume ratio and the rate of diffusion
- calculate surface area to volume ratios
- conduct an investigation to compare the efficiency of movement of materials that have different surface area to volume ratios.



In the previous module, you learnt about the composition of the cell membrane, and that one of its main characteristics is exchanges of molecules between the cytoplasm and the external environment of the cell. Small molecules and water are constantly transported across the cell membrane in both directions. Depending on their size and polarity, molecules diffuse between the phospholipid molecules or pass through channels formed by proteins embedded within the membrane. For larger molecules such as proteins and polysaccharides, bulk transport across the cell membrane is used. In this section, you will learn about the selective permeability of the cell membrane. You will also explore the various methods employed to control the exchange of molecules, including diffusion, facilitated diffusion, osmosis, active transport and bulk transport by endocytosis or exocytosis.

CELL MEMBRANE PERMEABILITY

To maintain the composition of the intracellular fluid, cells can control which molecules move into and out of the cell across the cell membrane. The regulation of movement is because of two features of biological membranes. Cell membranes are **semipermeable** and have transmembrane proteins. The phospholipid bilayer acts like a molecular sieve, controlling what moves between the intracellular and extracellular environments. As Figure 2.4.1 shows, many different types of molecules can move across cell membranes, and they do so in different ways, depending on their properties, such as size, charge, polarity and solubility (Table 2.4.1).

Semipermeable membranes allow solvent molecules to pass through but prevent some of the solute molecules from doing so.

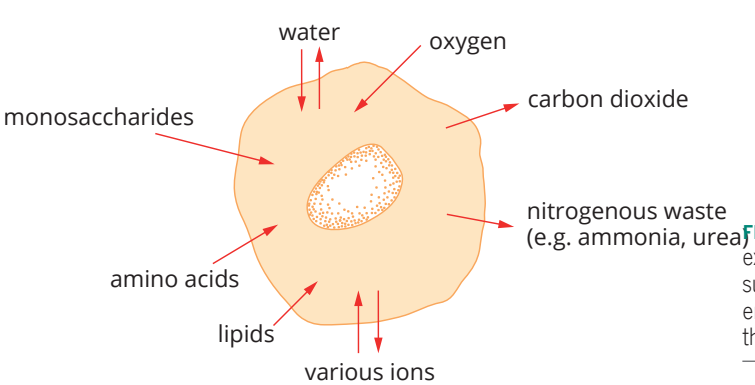


FIGURE 2.4.1 Cells exchange many substances with their environment across the cell membrane.

TABLE 2.4.1 The cell membrane's permeability to different molecules

Molecule or ion	Examples	Permeability of membrane to the molecule or ion
Small uncharged molecule	Oxygen, carbon dioxide	Permeable
Lipid-soluble, non-polar molecule	Alcohol, chloroform, steroids	Permeable
Small polar molecule	Water, urea	Permeable or semipermeable
Small ion	Potassium ion (k^+) sodium ion (na^+), chloride ion (cl^-)	Non-permeable (molecule passes through protein channels)
Large, polar, water-soluble molecule	Amino acid, glucose	Non-permeable (molecule passes through protein channels)

A solute is a substance dissolved in another substance, known as the solvent.

Permeable membranes are not selective in what molecules pass through them. All solutes and the solvent can pass easily across permeable membranes. Membranes are said to be 'semipermeable' or 'selectively permeable' when they allow some particles or solutes and the solvent to pass through the phospholipid part of the cell membrane, but not other solutes. Figure 2.4.2 illustrates the movement of particles across permeable and semipermeable membranes.

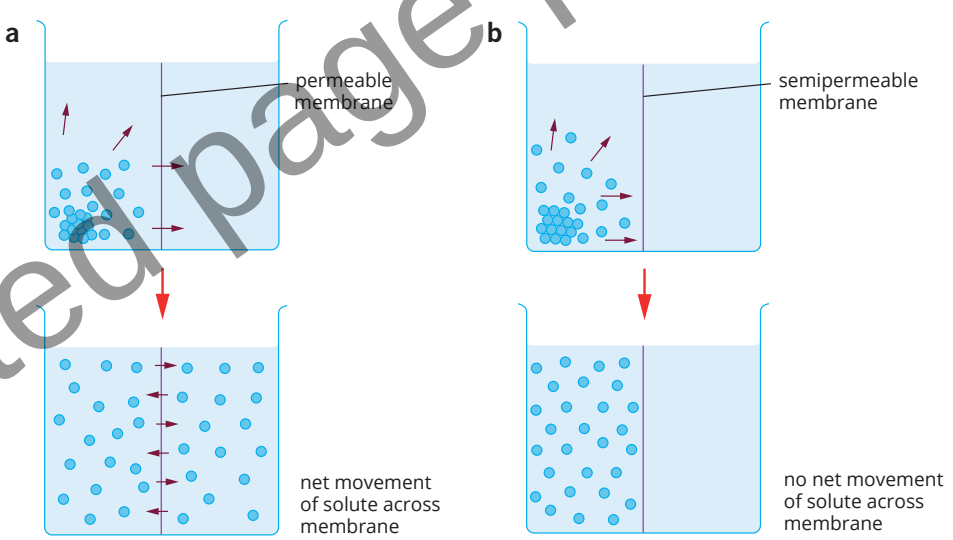


FIGURE 2.4.2 (a) When a membrane is permeable, to the solute and the solvent, the solute particles cross the membrane down the concentration gradient. (b) If the membrane is impermeable to the solute, then only the solvent can cross the membrane and the solute is prevented from diffusing through the membrane.

Because of their hydrophobic lipid nature, cell membranes are permeable to small, uncharged molecules and lipid-soluble molecules. In other words, small, uncharged molecules and lipid-soluble molecules can move freely through the phospholipid bilayer. However, the lipid nature of cell membranes makes them impermeable to:

- most water-soluble molecules
- ions (atoms or groups of atoms with an overall positive or negative charge)
- polar molecules (molecules with charged regions but no overall charge).

Membranes that do not allow substances to diffuse across them are referred to as **non-permeable**. Molecules that cannot diffuse across the phospholipid bilayer may enter and exit the cell through specific protein channels in the cell membrane, which are shown in Figure 2.4.3.

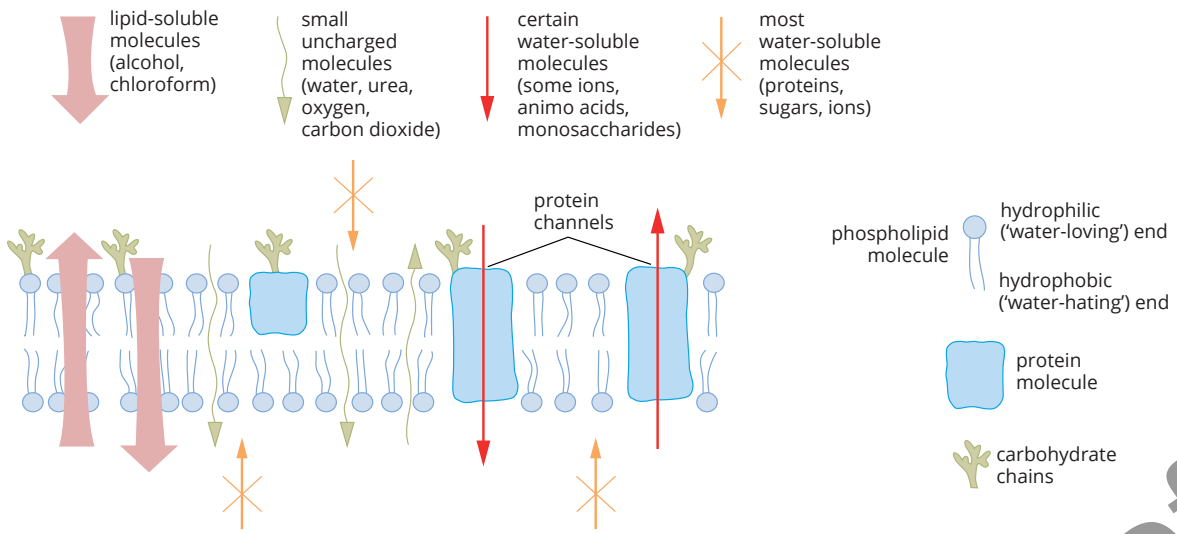


FIGURE 2.4.3 If the cell membrane is not permeable to molecules, protein channels must assist the molecules to cross the membrane.

PASSIVE TRANSPORT

Passive transport is the movement of molecules without the expenditure of energy. The three types of passive transport across membranes are: diffusion, facilitated diffusion and osmosis.

Diffusion

Particles in a solution move from an area of high concentration to an area of low concentration. This process is called diffusion and is shown in Figure 2.4.4.

Particles are always in constant random motion. The random motion is a result of the kinetic energy (energy of movement) of the molecules or ions and results in many collisions of the particles. Because there are many particles colliding with each other during this process, the overall movement of particles is very slow.

Solute molecules can diffuse across a membrane only if the membrane is permeable to them. There is a constant movement of solute molecules backwards and forwards across the membrane. If the solute concentration is higher on one side of the membrane than the other, more solute molecules cross from the area of higher concentration to the area of lower concentration (i.e. down its **concentration gradient**), as you can see on the left side of Figure 2.4.5. However, if the concentration of solute molecules is the same on both sides of the membrane, there is always about the same number moving across in either direction. That is, there is no net movement from one side to the other.

If the membrane is semipermeable (i.e. it is impermeable to some molecules) there is no movement of those molecules from the area of higher concentration to the area of lower concentration, as you can see on the right side of Figure 2.4.5.

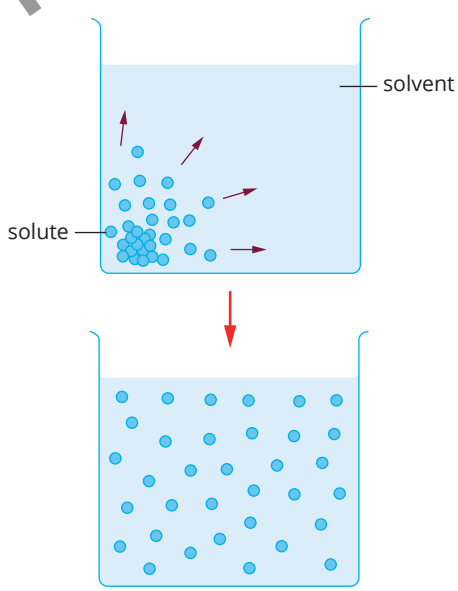


FIGURE 2.4.4 Diffusion results in the random dispersal of solute molecules throughout a solvent.

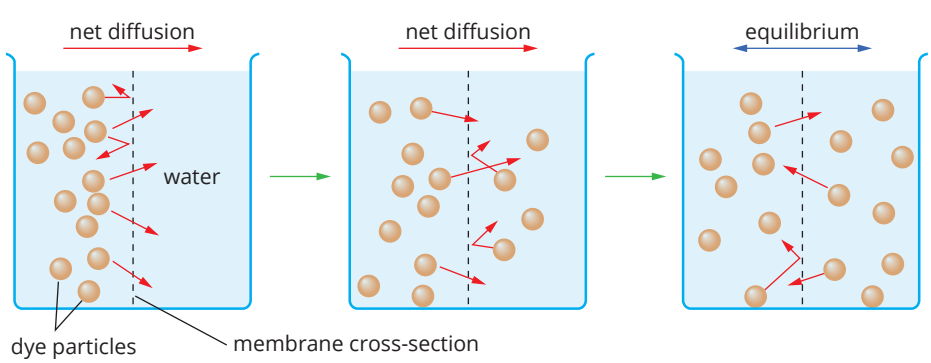


FIGURE 2.4.5 The solute particles are able to diffuse across the semipermeable membrane from high concentration (on the left) to low concentration. When equilibrium is reached, solute particles continue to randomly diffuse from both sides of the membrane but there is no change to the overall concentration. Dynamic equilibrium has been established.

Diffusion is the passive net movement of molecules from a region where they are in high concentration to a region where they are in low concentration.

Diffusion can be seen when a drop of ink (the **solute**) is placed in a jar of still water (the **solvent**). The dye particles in the ink move randomly through the water until the colour is homogenous (evenly spread). In other words, the solute particles move from an area of high solute concentration (the drop of ink) to the areas of low solute concentration (the rest of the jar). The solute particles are said to have moved down the concentration gradient.

Diffusion is called a passive process because it does not require additional energy from outside the system (in the form of ATP [adenosine triphosphate]). It occurs only because there is a concentration gradient.

Factors affecting the rate of diffusion

The three main factors that affect the rate of diffusion across a membrane are:

- concentration—the greater the difference in concentration, the higher the rate of diffusion. When the concentration is equal on both sides of the membrane, the net diffusion is zero, even at high temperatures
- temperature—the higher the temperature, the higher the rate of diffusion. Increasing the temperature increases the speed at which molecules move
- particle size—the smaller the particles, the higher the rate of diffusion through a membrane.

Facilitated diffusion

The phospholipid bilayer of the membrane is impermeable to certain particles, including ions and large polar molecules. However, certain proteins in the membrane allow for the diffusion of these particles into and out of the cell. Because the diffusion of these molecules is assisted by proteins and does not require any additional energy to be added to the system, the process is called **facilitated diffusion**.

In facilitated diffusion:

- the membrane transport proteins are specific for particular particles, so transport is selective; some particles are transported and others are not
- transport is more rapid than by simple diffusion
- the transport proteins can become saturated (fully occupied) as the concentration of the transported substances increases
- the transport of one particle may be inhibited by the presence of another particle that uses the same transport protein
- no additional energy is required; the particles move down their own concentration gradient.

The two main types of membrane transport proteins in facilitated diffusion are **channel proteins** and **carrier proteins**. Membrane proteins provide channels for the passage of water-soluble (polar) molecules and ions across the phospholipid bilayer. Channel proteins are specific for a substance. They do not usually bind with the molecules being transported. Channel proteins function like pores that open and close to allow the passage of specific molecules. They are mainly involved in the passage of water-soluble polar particles, such as ions. Special channel proteins, called **aquaporins**, facilitate the movement of water across the membrane.

Carrier proteins bind the molecules being transported, causing the protein to change shape (conformation), which allows specific molecules to be transported across the membrane. You can see this in Figure 2.4.6. After the molecule has crossed the membrane, the carrier protein is restored to its original shape.

Both carrier proteins and channel proteins are specific to the molecules they carry and without these proteins, active transport and facilitated diffusion of particular molecules cannot occur. A cell can regulate which substances can enter or leave the cell by controlling which carrier proteins or channel proteins are present in the membrane. The specific proteins will only be present if the genes that code for them in the nucleus are active. Different cells may have different carrier proteins and channel proteins present and thus be able to import or export different substances.

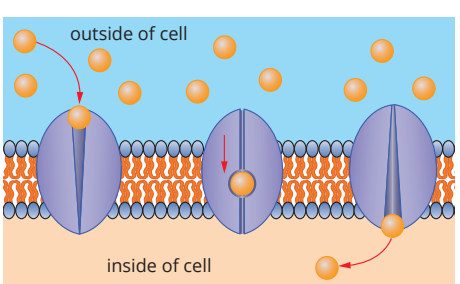


FIGURE 2.4.6 In facilitated diffusion, particles move from one side of the membrane down the concentration gradient mediated by specific carrier proteins or channel proteins.

Osmosis

Osmosis refers to the net diffusion of water molecules across a semipermeable membrane.

If a dilute and a concentrated solution are separated by a semipermeable membrane that allows the movement of free water molecules but not solute molecules, the free water molecules move across the membrane from the dilute to the concentrated solution.

In osmosis, net diffusion of water occurs through a semipermeable membrane from a dilute to a concentrated solution in an effort to achieve equilibrium. Diffusion occurs down water's concentration gradient, which is also known as the **osmotic gradient** and is shown in Figure 2.4.7. The pressure causing the water to move along this gradient is called **osmotic pressure**.

Osmosis is the movement of water from a solution of lower concentration to a solution of higher concentration.

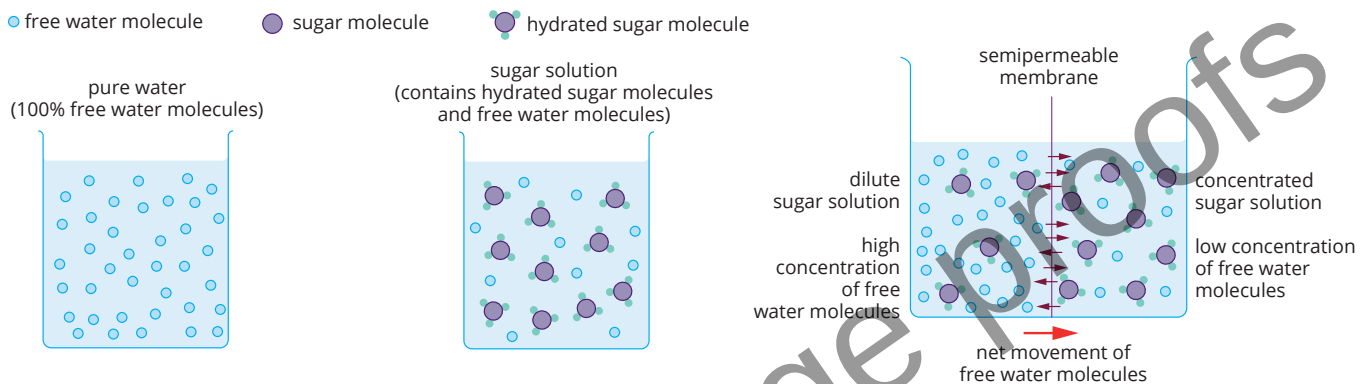


FIGURE 2.4.7 In osmosis there is a net movement of water molecules from a dilute solution through a semipermeable membrane into a concentrated solution.

Osmosis can be demonstrated by using Visking tubing (containing a strong sugar solution coloured with food dye) attached to a clear capillary tube and submerged in a beaker of water, as shown in Figure 2.4.8. Visking tubing is a synthetic semipermeable membrane made from cellulose. In the Visking tubing, water molecules bind to the sugar molecules. As a result, there are fewer free water molecules in the Visking tubing and a net movement of free water molecules into the tubing by osmosis occurs. This causes an increase in the volume of liquid in the tubing, increasing the pressure and forcing the coloured solution to rise up the capillary tube.

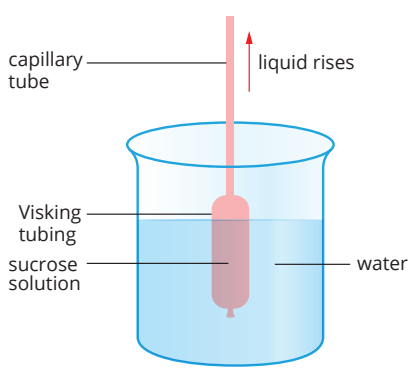


FIGURE 2.4.8 A Visking tubing apparatus for the demonstration of osmosis

In osmosis, we are always comparing solute concentration between two solutions. The terms 'isotonic', 'hypertonic' and 'hypotonic' solutions are often used to describe the difference.

- Isotonic solutions: the solutions being compared have equal concentrations of solutes.
- Hypertonic solutions: the solutions with higher concentration of solute (and hence lower concentration of free water molecules).
- Hypotonic solutions: the solutions with lower concentration of solute (hence higher concentration of free water molecules).

Effect of osmosis on cells

The cell membrane is permeable to water, so when cells are placed in fresh water, an osmotic gradient draws water into the cells. This is because the cytosol is a concentrated solution containing many dissolved substances. In other words, the cytosol has a low concentration of water. For example, if red blood cells are placed in fresh water, the cells absorb so much water by osmosis that they swell and may eventually burst (lysis), releasing red pigment into the water, as shown in Figure 2.4.9c. Conversely, if red blood cells are placed in a solution that is more concentrated than their cytosol, water leaves the red blood cells by osmosis and causes them to shrink (crenation). This is shown in Figure 2.4.9a.

For cells with cell walls, such as plant cells and prokaryotes, the cell wall helps to maintain the cell's water balance. For example, if a plant cell loses water by osmosis, it starts to shrivel, and the cell membrane starts to pull away from the cell wall—the cell is said to have become plasmolysed (Figure 2.4.9d). However, if the plant cell absorbs water by osmosis, it swells to some extent, but the relatively inelastic cell wall prevents the cell from bursting. The cell wall expands until it exerts a pressure back on the cell, known as turgor pressure. Turgor pressure prevents further water uptake. At this point, the plant cell is turgid (Figure 2.4.9f).

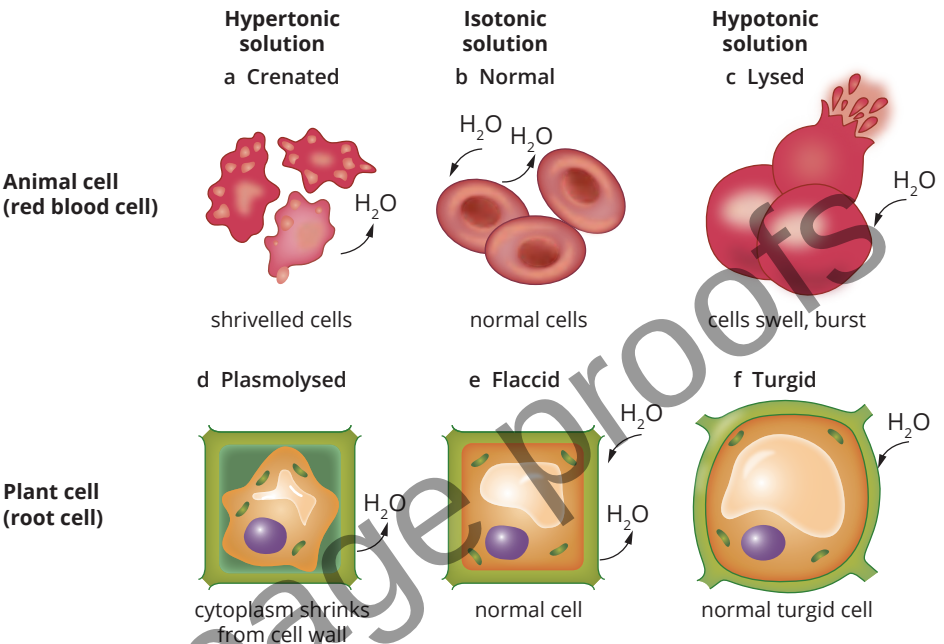


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FIGURE 2.4.9 The effect of three different solution concentrations on an animal cell and a plant cell

ACTIVE TRANSPORT

Active transport requires the use of energy to move substances against a concentration gradient.

Figure 2.4.10 illustrates **active transport**. Active transport involves the use of energy by the cell to transport particles across membranes. Because active transport uses energy, it can move substances against a concentration gradient from low concentration to high concentrations. Active transport enables a cell to maintain internal concentrations of small solutes that differ from concentrations in its environment. The membrane transport proteins in active transport are all carrier proteins.

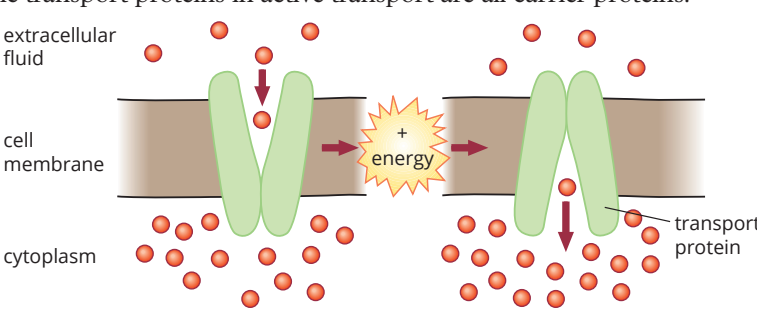


FIGURE 2.4.10 Active transport requires an energy source so that the molecules can be transported across the membrane.

In active transport, carrier proteins use energy in the form of ATP to move substances across the cell membrane. This process uses carrier proteins, of which there are three different types: **uniporter**—which carries only one type of molecule or ion, **symporter**—which carries two different molecules or ions in the same direction, and **antiporter**—which carries two different molecules or ions in two different directions (Figure 2.4.11). The processes involved in allowing the molecules to cross the membrane involve a change in shape of the carrier protein.

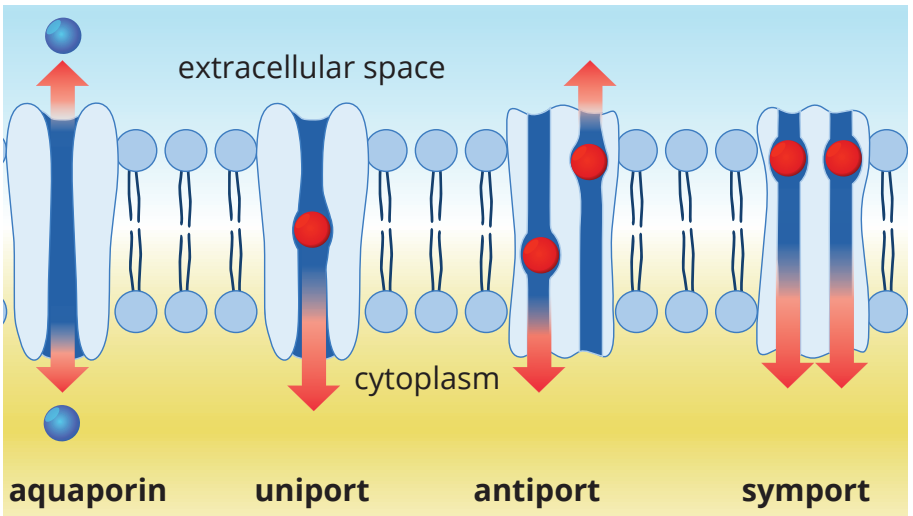


FIGURE 2.4.11 Four types of protein transport channels exist. Aquaporins mainly carry water. Uniport channels carry only one type of molecule or ion and antiport and symport channels carry more than one type of molecule or ion and can be involved in secondary active transport.

These transport proteins act as pumps moving ions across the membrane, resulting in an electrochemical imbalance with one side of the membrane being positively charged while the other side is slightly negative. This electrical difference supplies energy which can then be used to move other substances across the membrane.

One of the most important pumps is the sodium/potassium (Na^+/K^+) pump. The protein carrier has binding sites for three sodium ions and two potassium ions.

The process is as follows:

- Three sodium ions inside the cell bind to the protein then an ATP molecule donates its phosphate, which binds to the protein.
- The protein changes shape, and the three sodium ions are released outside the cell.
- Two potassium ions now bind to the carrier protein, causing the shape of the protein to change back and the phosphate to be released.
- The two potassium ions are released inside the cell.
- Three sodium ions leave the cell for every two potassium ions that enter the cell, causing the electrical imbalance between inside and outside the cell.

Once the electrical imbalance is formed the electrical energy stored can be used to power the movement of other molecules across the membrane in a process called secondary active transport.

There is now a high concentration of sodium ions outside the cell and a low concentration inside the cell. If another protein transporter which allows sodium into the cell is present, sodium ions will start to move back into the cell via this route. If the carrier is a symporter, it can carry another molecule, such as glucose, as a 'passenger' into the cell while carrying in the sodium. This may move the glucose up its concentration gradient. If the carrier is an antiporter, then the 'passenger' molecule is moved out of the cell. Although no ATP is used at this stage, it is still considered active transport because it relies on the high concentration of sodium ions outside the cell, which is created using ATP.

Active transport and facilitated diffusion compared

Passive transport does not require an additional energy source. There are three types of passive transport: diffusion, facilitated diffusion and osmosis. Diffusion (Figure 2.4.12a) occurs when substances move from high to low concentrations. In facilitated diffusion (Figure 2.4.12b), substances move from high to low concentrations with help from a transport protein. Osmosis is the movement of water from high to low water concentrations. Active transport (Figure 2.4.12c) requires an energy source. As a result, it usually moves substances from low to high concentrations.

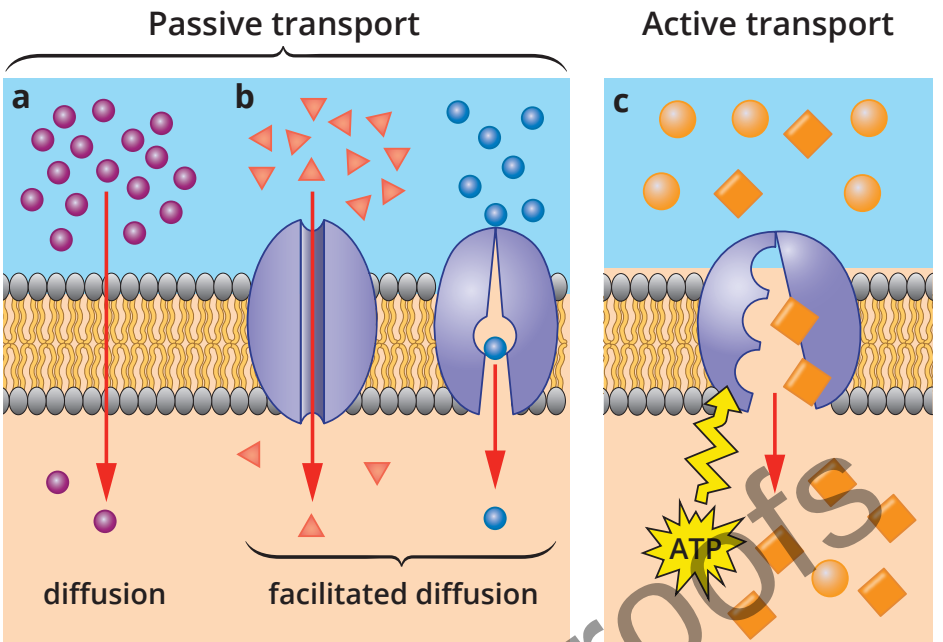


FIGURE 2.4.12 Passive transport of molecules across the membrane does not require energy. Active transport does require an energy source.

The comparison between passive transport and active transport can be seen in Table 2.4.2.

TABLE 2.4.2 A comparison of passive and active transport

	Passive transport			Active transport
	Simple diffusion	Osmosis	Facilitated diffusion	
Type of substance	Hydrophobic molecules, small polar molecules; for example, water, oxygen, carbon dioxide	Water	Hydrophilic molecules; for example, calcium ions, glucose, amino acids, sodium ions	Hydrophilic molecules; for example, glucose, amino acids, sodium ions, potassium ions
Type of membrane protein required	None	None	Channel protein Carrier protein	Carrier protein
Direction of movement of molecules	Down concentration gradient	Down concentration gradient	Down concentration gradient	Against concentration gradient
Energy requirement	None	None	None	Requires energy in the form of atp

Active transport has the same properties of selectivity, saturation and competitive inhibition as facilitated diffusion because it also occurs through transport proteins (Figure 2.4.13). Selectivity means that some substances are transported but others are not. Saturation means that there is no increase in the rate of transfer when all transport proteins are open. Competitive inhibition means that one substance can inhibit the transport of another substance by using the same transport protein.

But unlike facilitated diffusion, which can occur through either channel or carrier proteins, active transport only occurs through carrier proteins. Because active transport uses energy, it can move substances against a concentration gradient (from low concentrations to high concentrations). In comparison, facilitated diffusion uses no energy, so it can only move substances down a concentration gradient.

In different situations, either facilitated diffusion or active transport may be used to transport a particular molecule. Whether a cell uses facilitated diffusion or active transport depends on the specific needs of the cell.

For example, glucose is actively transported from the gut into epithelial cells lining the gut so it can enter the bloodstream. This process is regulated by hormones,

principally insulin and glucagon. If gut glucose levels are high, blood glucose levels increase. If gut glucose levels are low, active transport makes sure that the little glucose that is in the gut gets pumped into the epithelium from where it can move to blood through facilitated diffusion.

In contrast, red blood cells move glucose by facilitated diffusion. This makes sense because glucose concentration in the blood is usually maintained within a narrow range. In addition, cells convert glucose into other chemicals as soon as it enters the cell, keeping the intracellular concentration of glucose lower than the blood concentration of glucose.

BULK TRANSPORT

Large polar molecules and other substances that cannot pass through the hydrophobic cell membrane can enter or exit the cell via bulk transport. Bulk transport includes exocytosis and endocytosis (Figure 2.4.14). Both exocytosis and endocytosis are forms of active transport because they require energy.

Exocytosis and endocytosis

Figure 2.4.14 illustrates how cells transport large molecules into and out of the cell. **Exocytosis** is the movement of substances out of the cell, from the cytoplasm to the extracellular fluid. A transport **vesicle**, which may contain wastes or substances needed for secretion (e.g. digestive enzymes, hormones or neurotransmitters), fuses with the cell membrane and the junction then breaks down, releasing the enclosed materials. Transport vesicles are made of the same lipid bilayer as the cell membrane and are thus easily able to fuse with it. It should be noted as seen in the diagram that the contents of the vesicle exit the cell, but the vesicle becomes part of the cell membrane. Unicellular heterotrophs such as amoebas remove digestive wastes in this way.

Endocytosis is the movement of substances into the cell, from the extracellular fluid into the cytoplasm. Particles near the cell membrane are enclosed by the membrane, which then pinches off to form a vesicle enclosing the particles, as seen in Figure 2.4.15. In eukaryotes, this vesicle may become fused with a lysosome so that its contents can be digested for use by the cell.

The process varies slightly depending on the substance to be absorbed. The two forms of endocytosis are pinocytosis and phagocytosis (Figure 2.4.16).

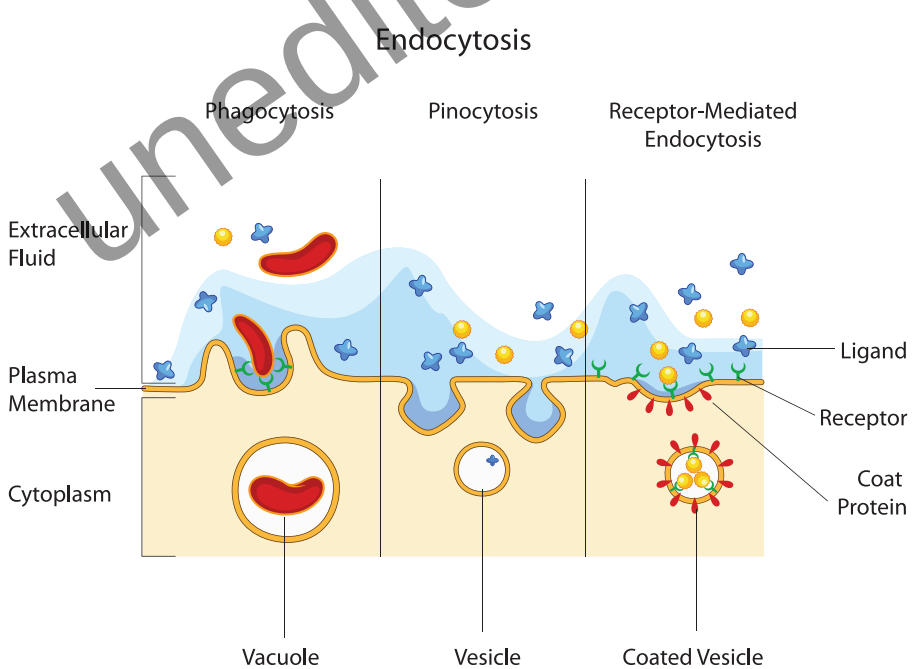


FIGURE 2.4.16 Substances move into the cell via phagocytosis or pinocytosis (the two forms of endocytosis).

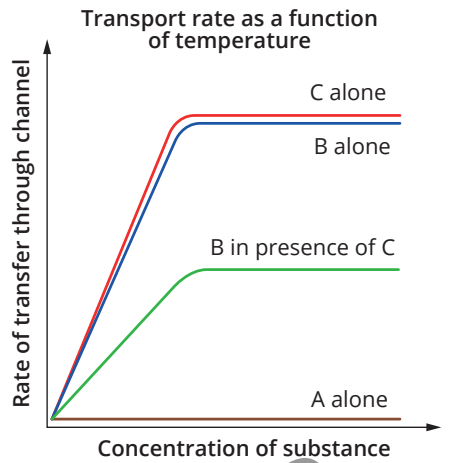


FIGURE 2.4.13 Theoretical transport rate versus concentration for the movement of three substances through a channel protein. Substances B and C are transported, but not substance A—this demonstrates selectivity. The rate of transfer of substances B and C flattens out when their concentrations reach a certain level, demonstrating saturation. The rate of transport of B is less when C is present, demonstrating competitive inhibition.

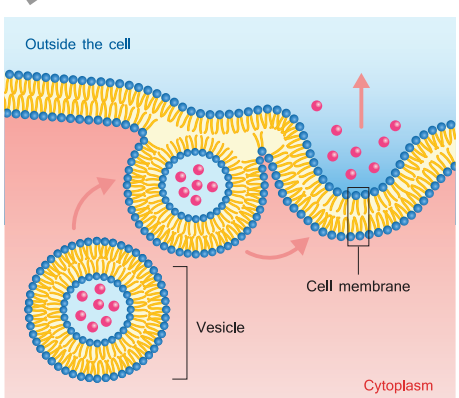


FIGURE 2.4.14 The secretory vesicle is made of a phospholipid bilayer and easily fuses with the cell membrane, releasing its contents out of the cell.

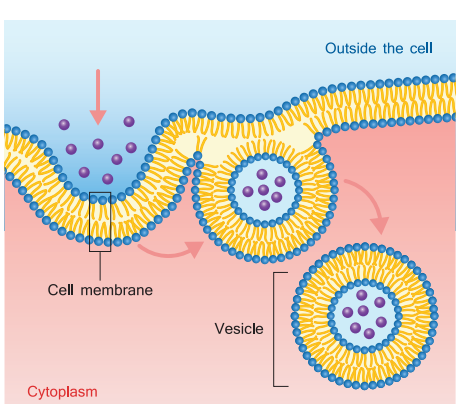


FIGURE 2.4.15 A vesicle forming from the cell membrane around a particle being absorbed by a cell.

Pinocytosis is the entry of extracellular fluid and substances such as proteins and sugars that are carried in it. **Phagocytosis** is the entry of large particles such as bacteria and cell debris to be broken down as an immune response. In phagocytosis, pseudopodia surround the particle whereas in pinocytosis a pocket forms around the liquid. Pseudopodia are formed around solid materials but not around liquids. Stimulation of receptors on the cell surface causes the formation of the endocytic vesicle.

Most endocytosis is receptor mediated. Receptors are proteins on the external surface of the cell membrane whose shape allows them to attach to a specific molecule (Figure 2.4.16). The attachment of the molecule to the receptor triggers the changes in the cell membrane to form the vesicle around the particle.

SURFACE AREA TO VOLUME RATIO AND CELL SIZE

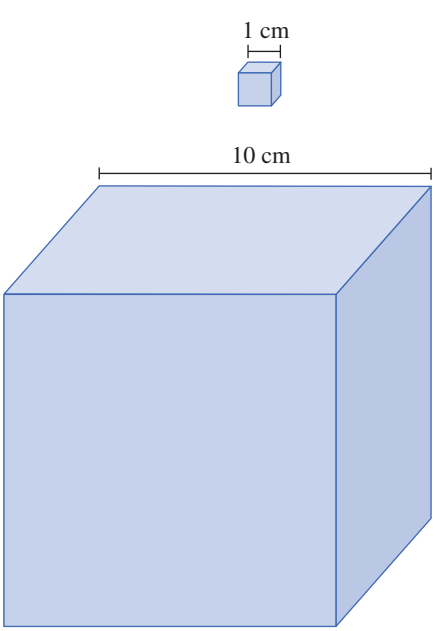
All cells must exchange nutrients and wastes with their environment via the cell membrane. In addition, enzymes that are bound to the cell membrane catalyse many important cellular processes.

The surface area of the cell membrane around a cell affects the rate of exchange that is possible between the cell and its environment and can affect certain processes catalysed by membrane-bound enzymes.

Larger cells have greater metabolic needs, so they need to exchange more nutrients and waste with their environment. However, because of the surface area to volume relationship, they do not have a proportionally larger surface area of cell membrane for this exchange to take place. Thus the small size of the cells help maximise their efficiency in exchanging matter with their environment.

Surface area versus volume

The relationship between surface area and volume can be explained using cubes, as shown in Figure 2.4.17. A cube with a side length of 1 cm has a surface area of 6 cm^2 and a volume of 1 cm^3. The surface area to volume ratio of a 1 cm cube is thus 6 : 1 (or 6). A cube with a side length of 10 cm has a surface area of 600 cm^2 and a volume of 1000 cm^3. A 10 cm cube thus has a surface area to volume ratio of 600 : 1000, or 0.6. Comparing these two cubes, it can be observed that, while the volume of the bigger cube is 1000 times larger than the volume of the smaller cube, its surface area is only 100 times larger.



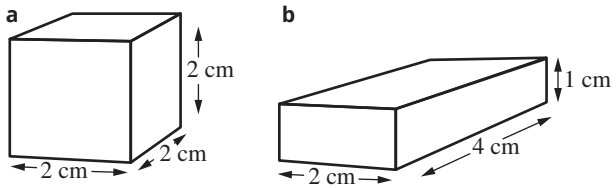
Side length	1 cm	10 cm
Surface area	6 cm^2	600 cm^2
Volume	1 cm^3	1000 cm^3
Surface area to volume ratio	6	0.6

FIGURE 2.4.17 Two cubes, showing the relationship between surface area and volume

Worked example 2.4.1

SURFACE AREA AND VOLUME

consider the two objects shown below. Both objects have a volume of 8 cm^3. Which shape has the greater surface area to volume ratio?

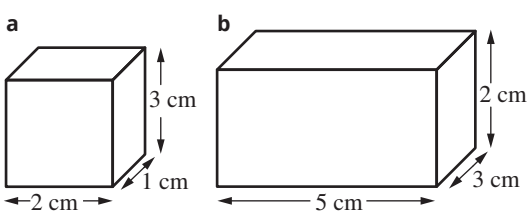


Thinking	Working
Look at shape A. Identify the dimensions of the cube.	Shape A: 6 sides, each with width of 2 cm and height of 2 cm
Calculate the surface area of shape A, given that there are six sides, each with the same area.	Surface area = $6 \times 2 \times 2$ = 24 cm^2
Calculate the surface area (SA) to volume (V) ratio of shape A.	$\frac{SA}{V} = \frac{24}{8}$ = 3
Look at shape B. Identify the dimensions of the cube.	Shape B: 2 sides, each with width of 2 cm and height of 1 cm 2 sides, each with width of 4 cm and height of 1 cm 2 sides, each with width of 2 cm and height of 4 cm
Calculate the surface area of shape B, given that there are six sides with three different areas.	Surface area = $(2 \times 2 \times 1) + (2 \times 4 \times 1) + (2 \times 2 \times 4)$ = 4 + 8 + 16 = 28 cm^2
Calculate the surface area to volume ratio of shape B.	$\frac{SA}{V} = \frac{28}{8}$ = 3.5
Compare the surface area to volume ratios.	Therefore, shape B has the greater surface area to volume ratio.

➤ Try yourself 2.4.1

SURFACE AREA AND VOLUME

Consider the two objects shown below. Which shape has the greater surface area to volume ratio?



2.4 Review

SUMMARY

- The lipid bilayer of membranes is impermeable to most water-soluble molecules, ions and polar molecules. These substances can only pass through protein channels.
- Lipid-soluble substances can diffuse through the phospholipid bilayer.
- Diffusion is the passive movement of solute molecules along a concentration gradient, from a region of high solute concentration to a region of low solute concentration.
- There are three types of diffusion across cell membranes: simple, facilitated and osmosis.
- Simple diffusion involves solutes to which the membrane is permeable, including lipid-soluble substances, small molecules and water molecules. The rate of diffusion is affected by concentration, temperature and particle size.
- Facilitated diffusion is through selective channels in membranes that permit or enhance the passive movement of particular ions and molecules down their own concentration gradient. Facilitated diffusion generally occurs at a more rapid rate than simple diffusion.
- Osmosis is the net diffusion of water across a semipermeable membrane down its own concentration gradient called the osmotic gradient (i.e. from a low solute concentration to a high solute concentration).
- In active transport, energy is expended to move substances across cell membranes through protein channels against their concentration gradient.
  - Protein channel mediated active transport and facilitated diffusion require the presence of suitable protein channels.
- Exocytosis (moving substances out of the cell) and endocytosis (moving substances into the cell) are forms of active transport involving vesicles that fuse with the cell membrane. These forms of active transport are generally used to transport larger molecules in bulk.
- A large object has a smaller surface area to volume ratio than a small object with the same shape.

KEY QUESTIONS

Describe

1 Complete the following table by recalling whether the phospholipid bilayer is permeable, semipermeable or not permeable to each substance described.

Substance	Examples	Permeability
small uncharged molecule	oxygen, carbon dioxide	
lipid-soluble, non-polar molecule	alcohol, chloroform, steroids	
small, polar molecule	water, urea	
small ion	potassium ion (K^+), sodium ion (Na^+), chloride ion (Cl^-)	
large, polar, water-soluble molecule	amino acid, glucose	

2 Define 'selective permeability'.

3 List the factors that increase the rate of diffusion.

4 When concentrations of solutions on both sides of a permeable membrane are in equilibrium, there is no net movement of particles. Explain this statement.

5 What are the three kinds of carrier proteins and what do they do?

6 How do active and passive transport differ?

Apply

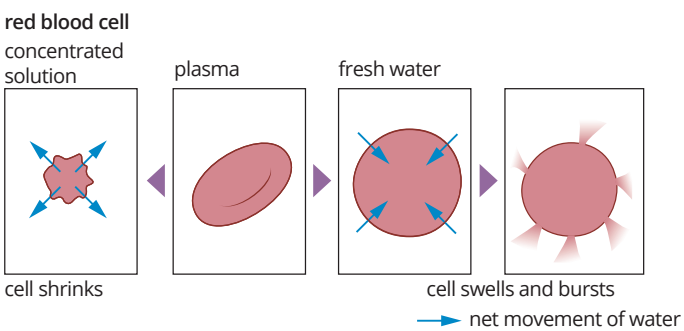
7 Osmosis is a special kind of diffusion. Define osmosis. Draw a diagram to illustrate your answer.

8 Explain how active transport is different from diffusion.

9 Consider the red blood cells in the illustrations below. The arrows indicate the net direction of water movement. Applying your understanding of osmosis, describe how red blood cells would:

a shrink

b swell and burst.



10 Explain why the cell membrane is permeable to chloroform (and equivalent chemicals).

11 Explain how the cell regulates the entry and exit of molecules and ions moving through protein channels across the cell membrane.

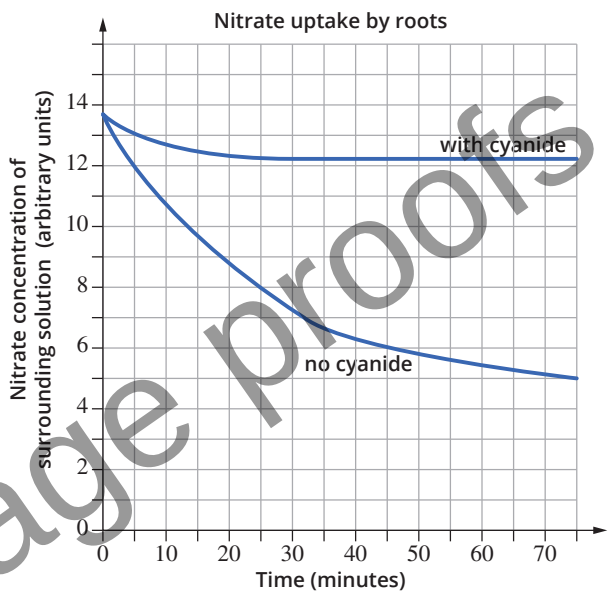
12 Determine why a large surface area to volume ratio is important in exchanging materials between cells/organisms and the external environment.

Analyse

13 Compare endocytosis, exocytosis, phagocytosis and pinocytosis. Describe where in your body you would expect each process to occur.

14 Compare simple and facilitated diffusion. Include an example of each.

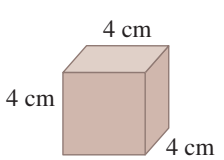
15 Plants use inorganic nitrate (NO_3^-) absorbed from the soil to make proteins. An experiment was undertaken to investigate how the nitrate enters the plant. Two groups of root cells were bathed in solutions containing nitrate ions. One of the solutions also contained cyanide, a chemical that inhibits cellular respiration. The results of the experiment are shown in the graph below.



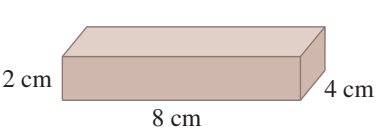
Explain the difference in the uptake of nitrate in the two situations.

16 Consider the two objects shown below which have the same volume of 64 cm^3. Determine which shape has the greater surface area to volume ratio.

a



b



17 Determine whether a round cell of 6 mm diameter will absorb substances via diffusion at a greater rate than a round cell of 3 mm diameter.

Chapter review

02

KEY TERMS

active transport
amino acid
antiporter
aquaporin
biogenesis
carrier protein
cell
cell compartmentalisation
cell membrane
cell wall
channel protein
chloroplast
cholesterol
chromosome
concentration gradient
cytology
cytoplasm
cytosol
diffusion
DNA (deoxyribonucleic acid)
endocytosis
endoplasmic reticulum
eukaryote
exocytosis
extracellular fluid
extremophile
facilitated diffusion
genophore
glycolipid
glycoprotein
Golgi apparatus
hydrophobic
hydrophilic
inorganic compound
integral protein
intracellular fluid
lysosome
mitochondria
mRNA (messenger RNA)
murein
non-permeable
nucleoid
nucleolus
organelle
organic compound
osmosis
osmotic gradient
osmotic pressure
passive transport
peripheral protein
phagocytosis
phospholipid
pinocytosis
plasmid
prokaryote
protein
ribosome
RNA (ribonucleic acid)
rough endoplasmic reticulum
rRNA (ribosomal RNA)
semipermeable
solute
solvent
smooth endoplasmic reticulum
symporter
taxonomy
tonoplast
transmembrane protein
uniporter
vacuole
vesicle

KEY QUESTIONS

Describe

1 The cell theory states that:
- **A** all organisms are made up of cells.
- **B** all cells arise from pre-existing cells.
- **C** the cell is the smallest functional unit of living things.
- **D** all of the above.

2 Why were prokaryotes divided into two domains?

3 Select the statement that accurately describes eukaryotic cells.
- **A** Eukaryotic cells have circular chromosomes and membrane-bound organelles, and some also have cell walls.
- **B** Eukaryotic cells have linear chromosomes but not membrane-bound organelles, and some have cell walls.
- **C** Eukaryotic cells have linear chromosomes and membrane-bound organelles, and some also have cell walls.
- **D** Eukaryotic cells have linear chromosomes and membrane-bound organelles, but not cell walls.

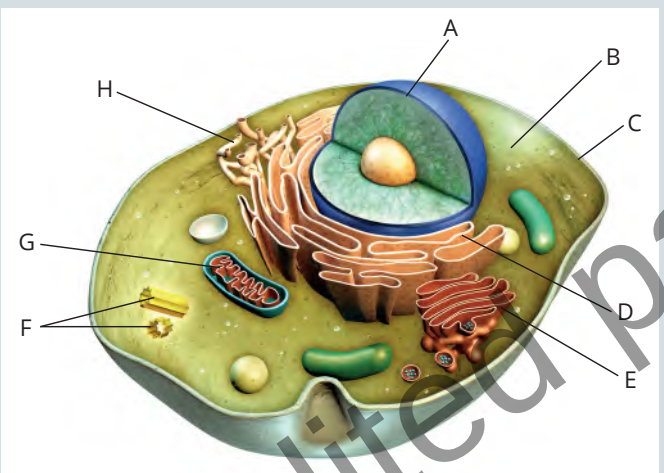
4 Identify which of the following is/are never found in prokaryotic cells.
- **A** DNA
- **B** mitochondria
- **C** cytosol
- **D** cell wall

5 List three features that distinguish prokaryotic from eukaryotic cells.

6 Copy **and complete** the table below by indicating if the organelles are present or absent in each type of cell.

Type of cell	Organelle					
	mitochondria	chloroplasts	endoplasmic reticulum	ribosomes	nucleus	Golgi apparatus
Animal kidney cell						
Plant leaf palisade cell						
Plant root cell						
Cyanobacterium						
Achaean						
Fungal cell						

7 Label the parts of the animal cell in this diagram.



8 Draw and prepare a table to summarise the major functions of phospholipids, cholesterol, glycolipids, glycoproteins and proteins in cell surface membranes.

9 Many single-celled organisms such as *Amoeba* feed by a process in which the cell membrane engulfs solid food particles to form a food vacuole. This process is called:
- **A** phagocytosis.
- **B** active transport.
- **C** pinocytosis.
- **D** osmosis.

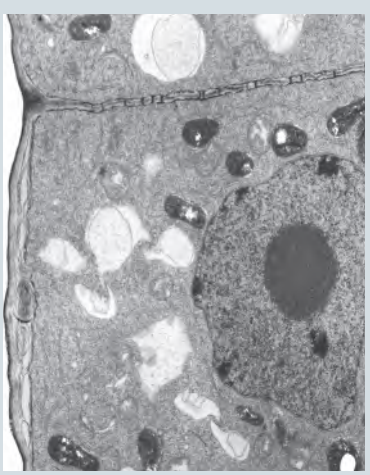
10 The organelle on which proteins are assembled is called the:
- **A** nucleus.
- **B** endoplasmic reticulum.
- **C** Golgi apparatus.
- **D** ribosome.

11 The sodium/potassium ion pump moves ions across the cell membrane. What type of protein channel does it use?

Apply

12 Explain which type of microscope would be best for the study of:
- **a** changes in a white blood cell
- **b** details of surface texture of a hair.

13 Identify whether this cell is from and animal or a plant. Give reasons for your choice.



14 Summarise the properties of archaean cell walls that allow them to be extremophiles.

15 Explain how the compartmental organisation of a eukaryotic cell contributes to its biochemical functioning.

16 According to the fluid mosaic model of membrane structure, proteins of the membrane are mostly:
- **A** spread in a continuous layer over the inner and outer surfaces of the membrane.
- **B** confined to the hydrophobic interior of the membrane.
- **C** embedded in a lipid bilayer.
- **D** randomly orientated in the membrane, with no fixed inside–outside polarity.
- **E** free to depart from the fluid membrane and dissolve in the surrounding solution.

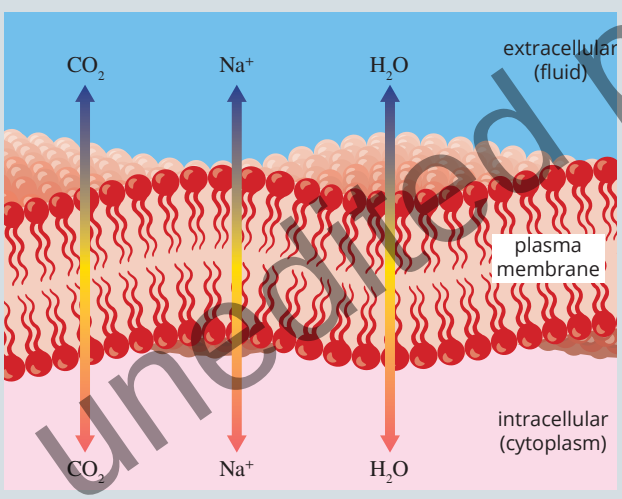
17 Identify which of the following factors would tend to increase membrane fluidity:
- **A** a greater proportion of unsaturated phospholipids
- **B** a greater proportion of saturated phospholipids
- **C** a lower temperature
- **D** a relatively high protein content in the membrane
- **E** a greater proportion of relatively large glycolipids compared with lipids having smaller molecular masses

18 Explain why the phospholipid heads of the cell membrane are always pointed towards the cytosol and extracellular fluid, whereas the 'tails' are always orientated toward the middle of the membrane.

19 Describe the two types of proteins used in facilitated diffusion.

20 A thyroid gland cell was examined using a light microscope.
- **a** What organelles are likely to be visible?
- **b** The same tissue was examined using a transmission electron microscope. What differences would become visible?

21 The diagram below contains a significant error. Explain what is wrong with it.



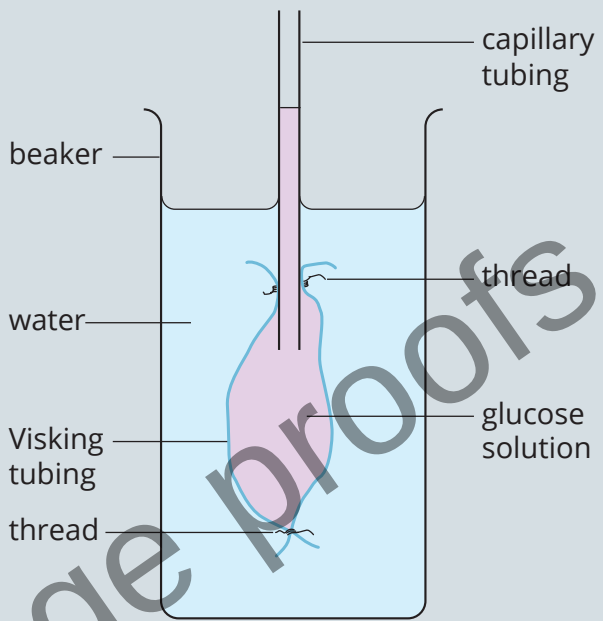
Analyse

22 Red blood cells have a nucleus when first formed, however, this is lost during the process of differentiation and maturation. The loss of the nucleus results in the shape of the cell changing from a sphere to a bi-concave disc. Explain how this change assists red blood cells to perform their function.

23 Compare active and passive transport.

24 Visking tubing is made of cellulose. It acts as a semipermeable membrane and can be used to model the cell membrane. Visking tubing has pores that range between 1 and 10 nm in diameter. Glucose molecules have a diameter of 0.7 nm and water is 0.00031 nm.

An experiment was undertaken by a group of students to investigate the effect of solute concentration on the diffusion of glucose molecules across the Visking tubing. The set up used is shown below:

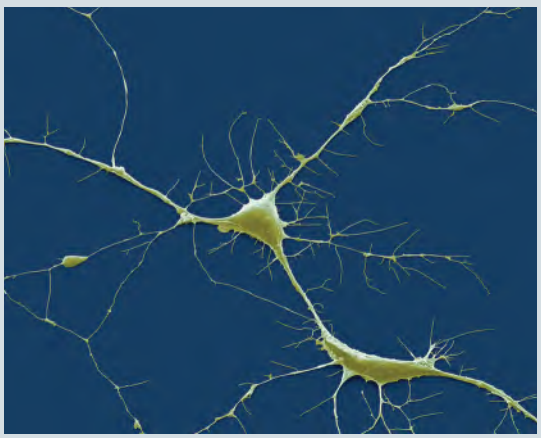


Students calculated the change in volume over a lesson at three different glucose concentrations (0.5 M, 1.0 M and 2.0 M). The class average results are shown in the table below.

Time (m)	% change in volume 0.5 M	% change in volume 1.0 M	% change in volume 2.0 M
0–3	1.5	2.8	4.4
3–6	1.1	2.2	3.3
6–9	0.9	2.1	3.0
9–12	0.9	2.0	2.9
12–15	0.8	1.9	2.9
15–18	0.8	1.7	2.6
18–21	0.8	1.7	2.5
21–24	0.8	1.7	2.4
24–27	0.7	1.6	2.3
27–30	0.6	1.6	2.3

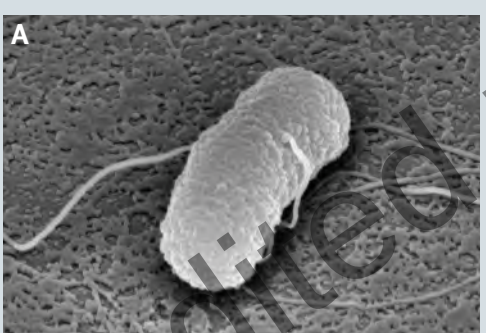
- **a** During which period of the experiment was the rate of osmosis the fastest? Justify your answer.
- **b** This experiment ran over 30 minutes, predict what would be seen if the experiment was left for 24 hours. Explain what would occur.

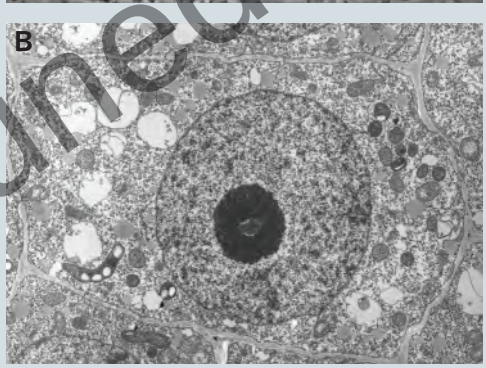
25 The following image is a nerve cell. With specific reference to the visible structures of the cell, deduce whether this image was taken using an electron microscope or a light microscope.



26 Visking tubing is often used as a model for the cell membrane. Discuss how accurately it truly represents the cell membrane.

27 Below are two cells observed under a scanning or a transmission electron microscope.





a One of the two cells is from a prokaryote. Explain which one.

b Determine if the eukaryotic cell is from an animal or a plant.

28 You are given a microscope slide with a sample of cells smeared on it and asked to identify the cell type. The cells are circular with a dark round mass at their centre. You estimate that the cells are approximately 20 µm in diameter.

a Classify the cells as prokaryotic or eukaryotic cells.

b Infer what organelle the dark round mass at the centre of the cells could be.

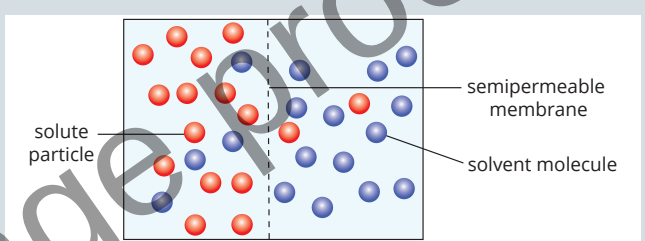
29 For each of the following responses to environmental factors, infer the most effective body shape and surface area to volume ratio of an organism for survival:

a gaining heat from its environment

b preventing heat loss

c maximising heat loss.

30 Two solutions are separated by a semipermeable membrane as illustrated below.



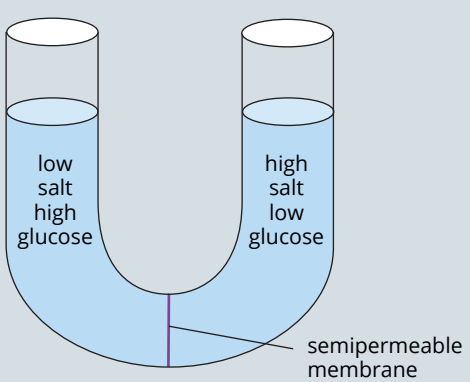
In which direction (if any) there would be a net movement of particles.

31 Two different solutions with the same volume are placed on either side of a semipermeable membrane in a U-shaped glass tube, as shown in the following diagram. The membrane is permeable to salt but not glucose. The tube is then left to stand for several days. Predict what would happen to the:

a salt concentration on each side of the membrane

b glucose concentration on each side of the membrane

c fluid levels on each side of the membrane.



32 In mammals, cells lining the:

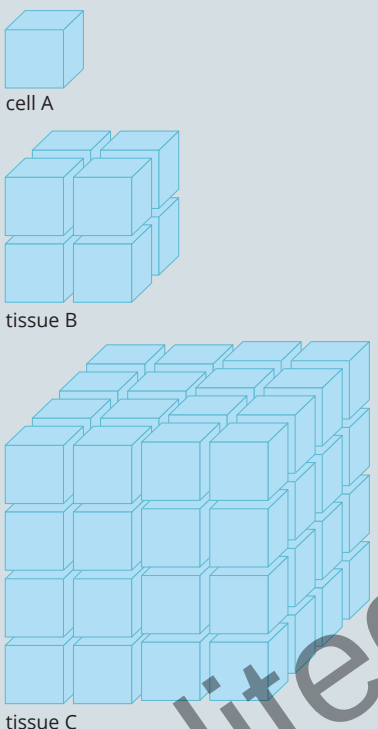
a alveoli of the lung take up oxygen by diffusion

b tubules of the kidney take up glucose by active transport

c small intestine take up fat droplets by pinocytosis.

Explain why the different methods of uptake are appropriate for the substances taken up in each case.

33 The following diagram represents living cells. Cell A, tissue B and tissue C all have the same volume.



Determine which one of the follow statements is correct.

A In distilled water, tissue B would gain water at a greater rate than cell A.

B In distilled water, the cells in tissue C would shrink at a greater rate than cell A.

C In a concentrated salt solution, tissue C would gain water at a greater rate than cell A.

D In a concentrated salt solution, tissue C would lose water more slowly than tissue B.

Interpret

34 It has been hypothesised that animals living in extreme temperatures will contain higher levels of cholesterol in their cell membranes in order to stabilise the membrane's structure. An investigation was undertaken into this idea. The membranes of liver cells from four species of fish were analysed to determine the amount of cholesterol present. Three species of Antarctic fish and one from temperate waters were used. The data collected is shown below.

Species	Habitat	Cholesterol (µmol/g of tissue)
Trematomus bernacchii	Antarctic	0.155
Pagothenia borchgrevinki		0.125
Chionodraco hamatus		0.11
Notolabrus celidotus	Temperate	0.17

Does the presented data support or disprove the hypothesis? Justify your answer.

35 A new unicellular organism has been discovered by light microscopy. Its characteristics include:

- internal membrane-bound circular structures composed of DNA
- two whip-like structures located close to each other at one end of the cell
- a semirigid structure outside the cell membrane
- a length greater than its width
- a chloroplast.

In your studies on cell biology, you have identified six main groups of organisms based on their cell structures: plant cells, animal cells, fungal cells, protists, bacteria and archaea.

Hypothesise which group this new organism would most likely belong to and give two reasons to support your answer.

36 At the cellular level, materials move through the cell membrane by several processes. At the organ level, the exchange of materials is facilitated by the arrangement of cells, which provides a large surface area. Discuss this statement with specific reference to the processes by which materials move through the cell membrane.

Outline three of the processes. For each process:

a give an example of a material taken up

b state where this uptake occurs

c explain why the process is appropriate.

Data analysis

DATA SET 1

The information below applies to Questions 1–5.

An experiment was conducted to investigate the effects of increased CO_2 levels on the mitochondria of a number of plant species. Plants were either grown in normal room air or in an environment with increased CO_2 levels. The number of mitochondria per 100 μm^2 of cell area was determined. The size of the mitochondria in all plants were equivalent in both normal and increased CO_2 conditions.

The data gathered from the experiment is shown in the table below.

TABLE 1: The number of mitochondria in normal CO_2 and increased CO_2 conditions in different plant species.

Species	Mitochondria per 100 μm^{-2} cell area		Ratio increased/normal
	Normal CO_2	Increased CO_2	
Glycine max	1.0 ± 0.1	1.6 ± 0.1	
Abutilon theophrasti	0.3 ± 0.03	0.4 ± 0.03	
Pinus radiata	14.0 ± 1.4	30.0 ± 1.8	
Piper auritum	0.4 ± 0.05	0.9 ± 0.08	
Pinus taeda	0.5 ± 0.07	0.9 ± 0.10	
Acer rubrum	0.3 ± 0.03	0.6 ± 0.06	
Liquidambar styraciflua	0.7 ± 0.06	1.5 ± 0.22	
Cercis canadensis	1.3 ± 0.15	2.4 ± 0.22	

1 Calculate the mean number of mitochondria per 100 μm^{-2} cell area for both normal and raised CO_2 levels. *(4 marks)*

2 Identify any outliers. *(2 marks)*

3 Complete the table by calculating the ratio of increased/normal mitochondria 100μm^{-2} cell area. *(2 marks)*

4 Discuss any trends in the data. *(2 marks)*

5 What conclusions, if any, can be drawn about the effects of increased CO_2 levels on mitochondrial numbers in plants? *(1 marks)*

Extra Styles

SKILLBUILDER

Significant figures

The accuracy of an answer in chemistry calculations is limited by the accuracy of the information given. An answer has the same number of significant figures as there are in the least accurate piece of information. In Worked Example 9.1.1, relative isotopic masses have 5 significant figures, but the relative abundances have only 4 significant figures. Therefore, the answer to this question has 4 significant figures. (See the Appendix at the end of the book for a more detailed treatment of significant figures.)

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SKILLBUILDER

Writing balanced equations

To write a balanced equation, follow these steps.

1. Find the correct formulas for all the reactants and products.
2. Write a 'skeleton' of the equation – place the formulas for reactants on the left and the formulas for products on the right separated by a yield (→) sign. If there is more than one reactant or product, separate them with a plus sign.
3. Determine the number of atoms of each element in the reactants and products. Remember that polyatomic ions work as a single unit and appear on both sides of the equation unchanged.
4. Balance the elements one at a time using coefficients. When no coefficient is written it is 1. Start by balancing elements that appear only once on each side of the equation. Remember, you cannot change the subscripts to balance an equation. Doing so would change the formula to a new substance.
5. Check the numbers of each type of atom on each side to make sure they are equal.
6. Make sure all coefficients are the lowest ratio and add other symbols (such as the state) if known

SPARK INQUIRY

Moles of household items

How are moles measured in chemistry?

Collect this

- digital kitchen scales
- measuring cup
- mobile phone or digital camera
- the following pure substances from your kitchen, $\frac{1}{2}$ a cup of each:
  - table sugar (sucrose, $C_{12}H_{22}O_{11}$)
  - water
  - aluminium foil
  - table salt (NaCl)
  - bicarbonate of soda ($NaHCO_3$)

Try to use at least one liquid, one element, one molecular substance and one ionic compound. Don't use cleaning products, vinegar, wood, steel, porcelain or glass, as these are mixtures.

Do this

1. Zero the scales with the measuring cup on the balance pan.
2. Measure out $\frac{1}{2}$ a cup of each substance and weigh. Record the masses in your table.
3. If the substance came in a packet, write down the mass of the packet when it was unopened.

Record this

1. Use number of moles = $\frac{\text{mass (g)}}{\text{molar mass}}$ to calculate the number of moles in $\frac{1}{2}$ a cup of each substance.
2. Calculate the number of molecules or particles in your sample using number of moles × 6.02 × 10^{23}.
3. Draw up this table in your workbook to record your results.

Reflect on this

1. How can you measure the number of moles of substances?
2. Rank the substances from largest to smallest number of moles in $\frac{1}{2}$ a cup and for each substance, state what type of substance it is, for example, liquid, ionic compound etc.
3. Identify any sources of error and explain how you could improve the experiment if you repeated it.

Substance	Mass (g)	Molar mass (kg mol^{-1})	Number of moles in cup	Mass of the full packet	Number of moles in the full packet
table sugar ($C_{12}H_{22}O_{11}$)		342.30			
water		18.02		–	–
aluminium		26.98			
table salt (NaCl)		58.44			
bicarbonate of soda ($NaHCO_3$)		84.01			

Cellular respiration

Living organisms are comprised of tiny membrane-bound compartments called cells. It is inside the cell where most of the chemical reactions occur that allow the cell to grow and function. Cells contain, and are made up of, a diverse assortment of chemicals. These range from simple ions to highly complicated molecules, all in an aqueous solution known as the cytoplasm.

All the chemical processes that occur within the cells of an organism constitute the metabolism of the cell. Metabolism involves many types of chemical reactions that are essential to maintain life, but they can be classified into a few broad types: condensation, hydrolysis, and oxidation–reduction reactions.

Condensation reactions occur when water molecules are removed from molecules to allow the assembly of complex molecules from simpler ones. For example, starch is formed when simple sugars are joined, with water molecules being liberated. This is how cells assemble large and complicated molecules.

Hydrolysis reactions

Hydrolysis reactions occur when water is added to allow the breakdown of complex molecules into simpler ones. This is how cells break down complex carbohydrates into sugars, or fats into fatty acids.

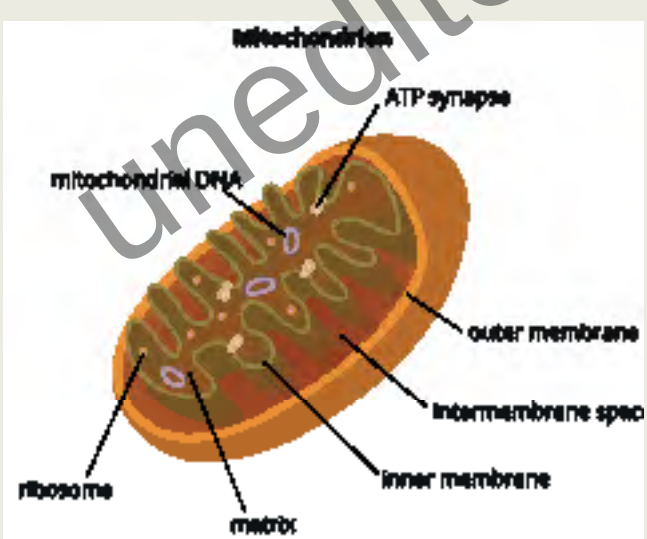

FIGURE 9.4.10 Cellular respiration occurs on the inner membranes of cell organelles called mitochondria.

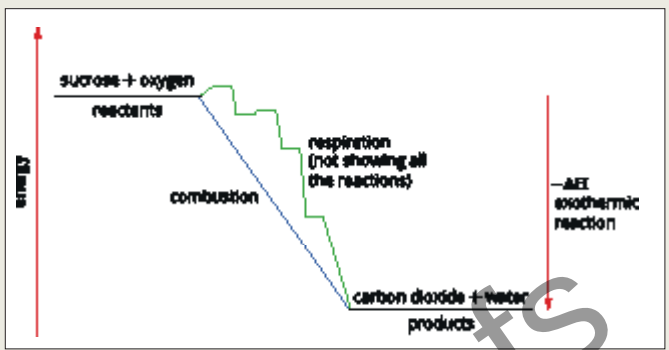

FIGURE 9.4.11 Enthalpy level diagram for the cellular respiration of sucrose

When foods such as carbohydrates are broken down, O_2 reacts with the atoms of the fuel to form oxides of carbon and hydrogen. The energy stored in the C–H and C–C bonds is released for the cell to use. This process is known as cellular respiration.

Nucleate cells

In nucleate cells, respiration occurs on the inner membranes of cell organelles called mitochondria (Figure 9.4.10). The process is complex and involves dozens of intermediate reactions. This is because some of the bonds, in particular the C–C bond, does not oxidise easily. Also, energy must be released in a controlled way that does not damage the cell. Food molecules are very energetic and if they released their energy rapidly, as in combustion, the cell would likely be destroyed. Figure 9.4.11 is an enthalpy level diagram for the cellular respiration of sucrose, a type of simple carbohydrate molecule.

There are two main types of cellular respiration.

- Aerobic respiration requires oxygen and is the main source of energy for the human body.
- Anaerobic respiration does not require oxygen and yields less energy.

In aerobic respiration, glucose is oxidised to carbon dioxide and water through a sequence of reactions. The overall equation for aerobic respiration is:

$$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$$
$$\Delta H = -2860 \text{ kJ mol}^{-1}$$

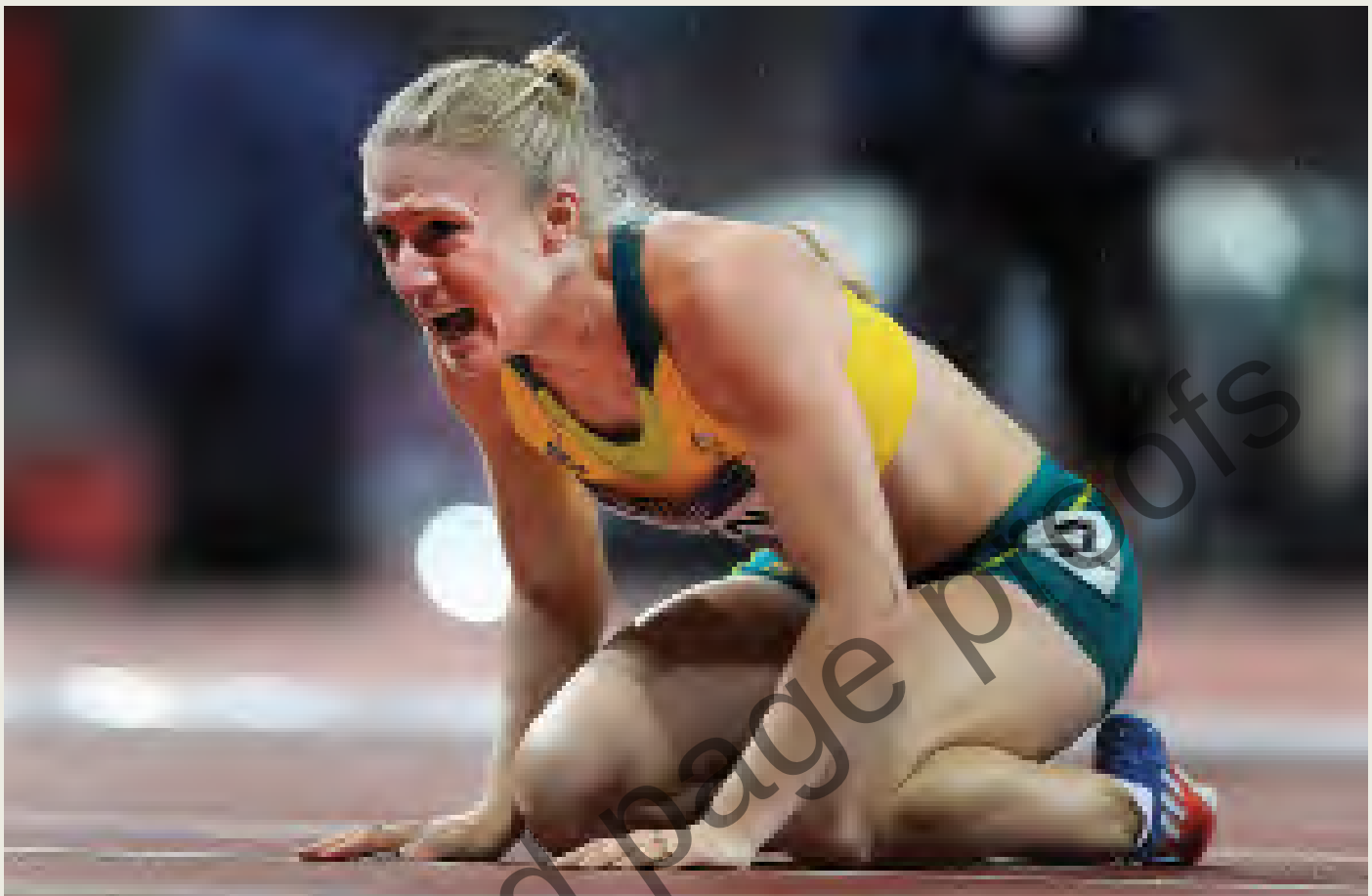

FIGURE 9.4.12 The fatigue experienced by an athlete is partly due to the formation of lactate ions produced by the anaerobic breakdown of glucose molecules in muscle cells.

In humans, an alternative form of respiration, called anaerobic respiration, can occur in muscles during prolonged and vigorous exercise, when the supply of oxygen is limited. It can result in the build-up of lactate ions, $CH_3CH(OH)COO^-$, which can cause painful muscular cramping (Figure 9.4.12). The overall equation for anaerobic respiration in humans is:

$$C_6H_{12}O_6(aq) \rightarrow 2CH_3CH(OH)COO^-(aq) + 2H^+(aq)$$
$$\Delta H = -120 \text{ kJ mol}^{-1}$$

In yeast, anaerobic respiration produces ethanol and carbon dioxide—this process is widely used to produce alcoholic beverages. The equation for this process is:

$$C_6H_{12}O_6(aq) \rightarrow 2C_2H_5OH(aq) + 2CO_2(g)$$
$$\Delta H = -69 \text{ kJ mol}^{-1}$$

Exothermic reactions

These reactions for anaerobic and aerobic respiration are all exothermic. Although anaerobic respiration yields less energy per mole of glucose, it is often a faster process than aerobic respiration. Short bursts of exercise, such as sprinting, rely on anaerobic processes for energy because the individual steps in the reactions involved in anaerobic respiration occur more rapidly.

1. Is cellular respiration an endothermic or exothermic process?
2. Explain why cellular respiration involves dozens of intermediate steps.
3. Research the respiration of glucose in yeast. Design an experiment that could be used to study the effect of temperature on respiration rate.

PRACTICAL INVESTIGATION 4

MP 1

Derive the empirical formula of a compound from reactions involving mass changes

Forming and finding

Aim

- To derive the empirical formula of magnesium oxide through experimentation
- To calculate the percentage by mass of magnesium in magnesium oxide

Rationale (scientific background to the experiment)

By definition a compound consists of elements chemically combined in fixed proportions by mass. When magnesium is heated in oxygen, the compound magnesium oxide forms. By finding the mass of the original magnesium and that of the magnesium oxide, using the law of conservation of mass, the mole ratio of magnesium to oxygen can be determined so that the empirical formula can be derived. The percentage composition of magnesium in magnesium oxide can also be calculated.

Timing

50 minutes

Materials

- magnesium ribbon 20–40 cm long
- steel wool
- crucible and lid
- pipeclay triangle
- Bunsen burner
- bench mat
- tripod
- tongs
- electronic balance
- safety glasses

Safety

- Wear safety glasses and a laboratory coat.
- Do not look directly at the magnesium during heating. The bright flame may damage your sight.
- Take care if handling a hot crucible.

Method

Risk assessment
• Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Activity Book or download from your eBook.

1 Your teacher will give you a 20–40 cm length of magnesium ribbon. Clean the magnesium ribbon thoroughly using steel wool.

2 Weigh the mass of a clean, dry crucible and lid. Place the magnesium loosely in the crucible. Weigh the total mass of crucible, lid and magnesium. Record your data in Table 9.5.1.

3 Set up your experiment as shown in Figure 9.5.1.

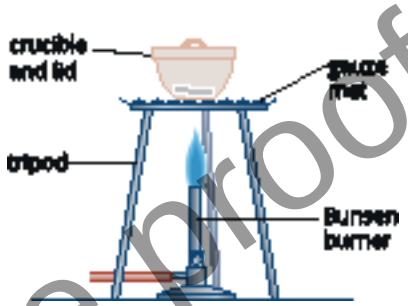

FIGURE 9.5.1 Experimental set-up

4 Heat the crucible strongly. Using tongs, occasionally lift the lid to allow air to enter the crucible but replace the lid quickly to avoid loss of magnesium oxide ash.

5 When the reaction appears complete, allow the equipment to cool to room temperature. Weigh the total mass of crucible, lid and magnesium oxide.

6 Calculate the original mass of magnesium used and the mass of magnesium oxide formed. Record the results in Table 9.5.1.

7 Assuming all the original magnesium is now in the form of magnesium oxide, calculate the percentage of magnesium in magnesium oxide. Record the result in Table 9.5.2. (Round off your result to the nearest per cent.)

8 Calculate:
- **a** the mass of oxygen that reacted with the magnesium
- **b** the number of moles of magnesium reacted
- **c** the number of moles of oxygen reacted
- **d** the simplest whole-number mole ratio of magnesium to oxygen in magnesium oxide
- **e** the empirical formula of magnesium oxide.

Variables

i Independent: the mass of magnesium

ii Dependent: the mass of magnesium oxide formed

iii Controlled: the crucible mass, the equipment and balance used

Analysing

Raw data

1 Record your data in Table 9.5.1.

TABLE 9.5.1 Mass results

Material	Mass (g)
Empty crucible and lid (1)	
Crucible, lid and magnesium (2)	
Crucible, lid and magnesium oxide (3)	

Processed data

2 Calculate the mass of magnesium that reacted.

3 Calculate the mass of magnesium oxide that formed.

At the end of this section, have you demonstrated the following characteristics?

- Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data
- Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data

Analysis

4 Calculate the percentage by mass of magnesium in magnesium oxide. Record your results in Table 9.5.2.

5 **a** Find out the result for percentage by mass obtained by three other groups that had different starting masses of magnesium. Record the results in Table 9.5.2.

TABLE 9.5.2 Group results

Group	Starting mass of magnesium (g)	Percentage by mass of magnesium (%)
Your group		
Other group 1		
Other group 2		
Other group 3		

b Explain why these results should be similar for each group, despite each group using a different mass of magnesium at the beginning of the experiment.

c If a group did not obtain a result similar to that of the other groups, suggest a reason for this occurring.

6 Calculate:

a the number of moles of magnesium that reacted

b the mass of oxygen, in grams, in your sample of magnesium oxide

c the number of moles of oxygen that reacted

d the ratio of moles of magnesium and oxygen.

7 Using the result you obtained in Question **6d**, derive the empirical formula of magnesium oxide.

8 How many atoms of magnesium were actually involved in your reaction? Use Avogadro's number to determine this.

9 **a** List each piece of equipment used in this experiment that had error associated with it. State the error value associated with each.

b Explain how this value may have had an effect on the determination of the empirical formula of magnesium oxide.

10 **a** Collect and process the data from your experiment and the results of three other groups. What is the most scientifically appropriate way to display the comparison between the initial mass of the magnesium used and the four mole ratios of magnesium : oxygen that were obtained, so that a clear and valid trend can be seen?

b Create this display and explain what you observe.

c Are there any points that do not fit the trend? Explain why this might be so.

At the end of this section, have you demonstrated the following characteristics?

- Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis
- Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships
- Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis

Interpreting and evaluating

Conclusion

1 **a** State your conclusion.

b What is the evidence that you have collected that leads you to this conclusion?

Evaluation

2 **a** Considering your analysis and conclusion, did the experiment provide an effective and efficient method of determining the empirical formula of magnesium oxide?

b Was the level of uncertainty that you calculated in Analysis Question **9** reasonable? (Provide values that were close to whole number ratios.)

Improvements

3 **If** you were to repeat the experiment, identify the steps that you would do differently. You should include in your answer:

- **a** how you would change the methodology and how this might improve the results
- **b** how you performed the tasks and the skills that you need to improve on in your technique
- **c** how the collection of data could be improved or uncertainty reduced.

Extension

4 **a** Do you think this methodology could be applied to determine the empirical formula of any metal oxide?

- **b** Identify any limitations and possible problems that might restrict the use of this methodology to determine the empirical formula of other metal oxides.

At the end of this section, have you demonstrated the following characteristics?

- Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respects to the error analysis and limitations or sufficiency of the data.
- Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment which are logically derived from the analysis of the evidence.

Enhancement questions

5 The percentage by mass of aluminium in alumina (aluminium oxide) is 52.9%. What mass of aluminium could theoretically be extracted from 800 tonnes of alumina?

6 A 10 g sample of a certain oxide of tellurium (Te) contains 8.0 g of tellurium. Find its empirical formula.