1.1 What Are Cells?

Learning Outcomes

- Identify and state the functions of the following cell structures (including organelles) of typical plant and animal cells from diagrams, light micrographs and as seen under the light microscope using prepared slides and fresh material treated with an appropriate temporary staining technique: cell wall, cell membrane, cytoplasm, nucleus, cell vacuoles (large, sap-filled in plant cells, small, temporary in animal cells), chloroplasts.
- Identify and state the functions of the following membrane systems and organelles from diagrams and electron micrographs: endoplasmic reticulum, Golgi body, mitochondria, ribosomes.
- Compare the structure of typical animal and plant cells.

Imagining Cells as Chemical Factories

All living things are made up of billions of tiny cells, just as a building is made of bricks. *Cells are the building blocks of life. They are the simplest structural and functional units of life.*

What do you think cells do? To answer this question, you need to imagine your cells as chemical factories. Many chemical reactions occur continually inside these factories to keep you alive. For example:
- A cell takes in raw materials.
- Then, it processes these materials to make new molecules.
- These molecules can either be used by the cell itself or transported to other parts of the body.

In any factory, there are different departments that carry out different functions. A cell also has different structures that perform different roles within the cell. For example, mitochondria provide energy for cell activities, and chloroplasts carry out photosynthesis. Such division of labour increases efficiency within the system. It ensures that the cell can survive and perform its role within the body.

How Did Cells Get Their Name?

The term 'cells' was first introduced by an English scientist, Robert Hooke, in 1667. He used one of the earliest microscopes to examine thin slices of cork from the bark of a tree (Figure 1.1). Hooke saw closely packed little boxes with thick walls. He named the boxes 'cells', just like the cells in a honeycomb or a prison. In fact, Hooke only saw the walls of dead plant cells.

Figure 1.1 Robert Hooke observed that cork is made up of tiny cells.

How Can We Study the Parts of the Cell?

Most cells are too small to be seen with our eyes alone. We can use light and electron microscopes to help us to see cells and their parts. Over 300 years ago, biologists like Robert Hooke and Antonie van Leeuwenhoek created their own light microscopes to study microscopic objects!
- **Light microscopes** magnify objects up to 1000x (spoken: one thousand times) (Figure 1.2(a)).
- **Electron microscopes** magnify objects to more than 200 000x (spoken: two hundred thousand times) (Figure 1.2(b)).

A camera can be fitted to either type of microscope to take pictures. These pictures are called **micrographs**.
- **Light micrographs** can come out as colour images.
- **Electron micrographs** are black-and-white images, but they can be artificially colourised.

Figure 1.2 Microscopes

To get a clearer picture of how a cell is constructed, we may need to make a section of the cell at different planes (Figure 1.3).

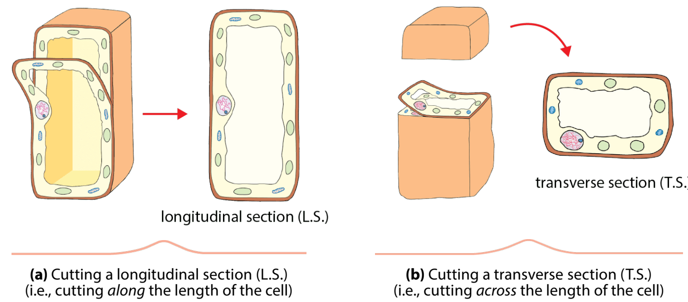


Figure 1.3 We may cut a cell in two different ways in order to view cell structures from different angles. This helps us to build up a three-dimensional picture of the cell.

Biology Connect

Scan the QR code to watch a clip and have a glimpse of the structures inside the cell.

What Does a Cell Consist Of?

A **cell** is a unit of life. It consists of a mass of living matter called protoplasm.

While all the cells of your body may not look the same, they all have similar parts. Each living cell consists of living material called **protoplasm** (Greek: *protos* = first; *plasm* = form).

Protoplasm is a complex jelly-like substance. Many chemical activities that allow the cell to survive and grow are carried out in the protoplasm.

The protoplasm of a cell is made up of three parts: the **cell membrane** (also known as **cell surface membrane**), **cytoplasm** and **nucleus** (Figure 1.4).

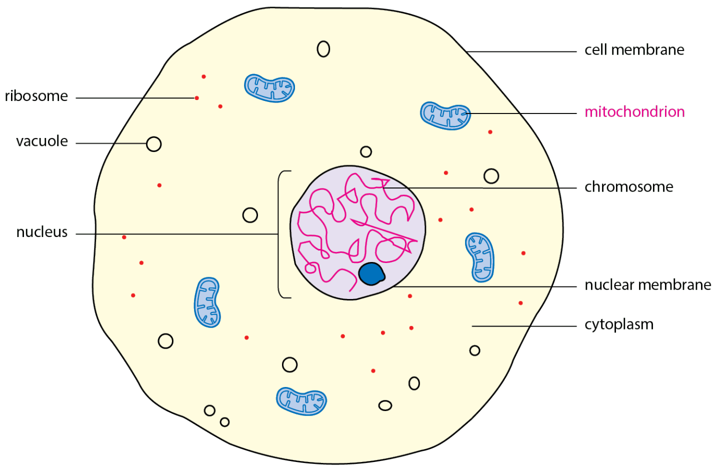


Figure 1.4 A generalised animal cell showing some major organelles

Cell Membrane

The cell membrane surrounds the cytoplasm of the cell. The cell membrane is made up of lipids and proteins. It is a **partially permeable membrane**. This means that it allows only some substances to pass through it. Hence, the cell membrane controls the movement of substances in and out of the cell.

Cell Wall

A plant cell also has a **cell wall** that encloses the entire plant cell, surrounding the cell membrane (Figure 1.5). This cell wall is made of **cellulose**. It protects the cell from injury and gives the plant cell a fixed shape. The cell wall is **fully permeable**, so it does not control the type of substances that enter or leave the cell. The cell wall is absent in animal cells.

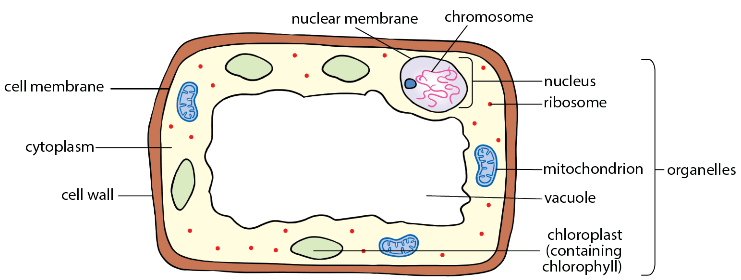


Figure 1.5 A generalised plant cell

Disciplinary Idea

Systems

Cells are highly organised biological systems with many organelles. While each organelle performs specific functions, the various organelles work as a co-ordinated system within the cell to carry out processes needed to sustain life.

Word Alert

Mitochondrion: singular for mitochondria

Lipids: biological molecules that are not soluble in water. Examples of lipids are fats, waxes and oils.

Helpful Note

The terms 'cell surface membrane' and 'cell membrane' are used in this book to refer to the membrane enclosing the entire cell. Organelles inside the cell are also enclosed by their own membranes.

Cytoplasm

The cytoplasm is a jelly-like substance that fills the inside of the cell and is enclosed by the cell membrane. It is the part of the protoplasm between the cell membrane and the nucleus. It is where most cell activities occur. The cytoplasm contains organelles. An **organelle** is a cellular structure that performs a specific job within a cell.

Organelles carry out many functions in the cell. You will learn more about them in later parts of this chapter. Many organelles, such as **mitochondria**, **endoplasmic reticulum**, **Golgi body** and **ribosomes** are not visible under the light microscope. They can only be studied under the electron microscope.

What Are the Parts of the Cytoplasm?

The cytoplasm contains tiny structures called organelles (Figure 1.6). Each **organelle** is specialised for a particular function. Examples of these organelles are nucleus, rough endoplasmic reticulum, ribosomes, Golgi body, mitochondria, chloroplasts and vacuoles.

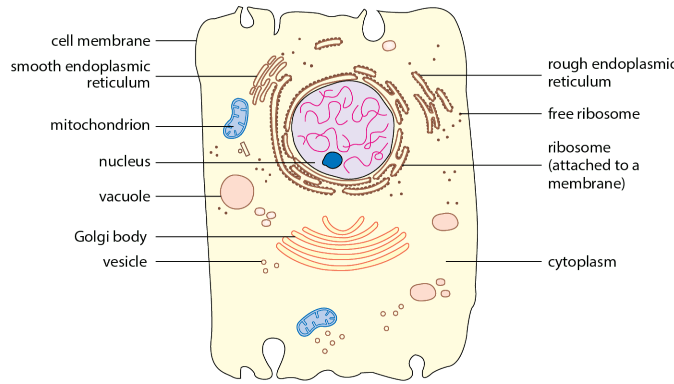


Figure 1.6 Organelles in an animal cell seen under an electron microscope

Nucleus

The nucleus is surrounded by a membrane called the **nuclear membrane**. The nucleus contains genetic information in the form of chromosomes. You will learn more about chromosomes later in this section.

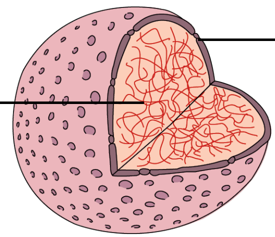
These are the functions of the nucleus:

- It controls cell activities such as cell growth and the repair of worn-out parts.
- It is essential for cell division. Cells without a nucleus, like the red blood cells of a mammal, are unable to divide.

To see the individual parts of the nucleus clearly, we will need to use an electron microscope (Figure 1.7).

Chromosomes

- Each chromosome is a long thread-like structure found within the nucleus. (A human cell contains 46 chromosomes.)
- It is made up of proteins and a compound called deoxyribonucleic acid or DNA. Hereditary information is stored in DNA. DNA carries instructions that a cell needs for carrying out its activities.
- When the cell is dividing, the chromosomes condense and shorten to become thick, rod-shaped structures.



Nuclear membrane separates the contents of the nucleus from the rest of the cytoplasm.

Figure 1.7 Diagram showing parts of the nucleus (three-dimensional reconstruction of images seen under an electron microscope)

Figure 1.8 shows the appearance of chromosomes during cell division.

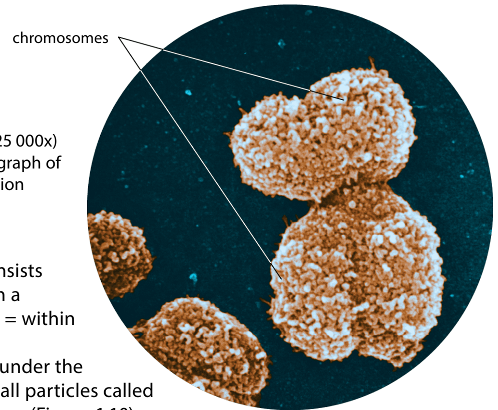


Figure 1.8 Highly magnified (25 000x) and colourised electron micrograph of chromosomes during cell division

Rough Endoplasmic Reticulum

Rough endoplasmic reticulum (RER) consists of a network of flattened spaces lined with a membrane (Figure 1.9). (Greek: *endoplasm* = within the cytoplasm; *reticulum* = network).

- Its surface appears rough when viewed under the electron microscope. This is because small particles called ribosomes are attached to its outer surface (Figure 1.10).
- The outer surface of the RER is continuous with the nuclear membrane.

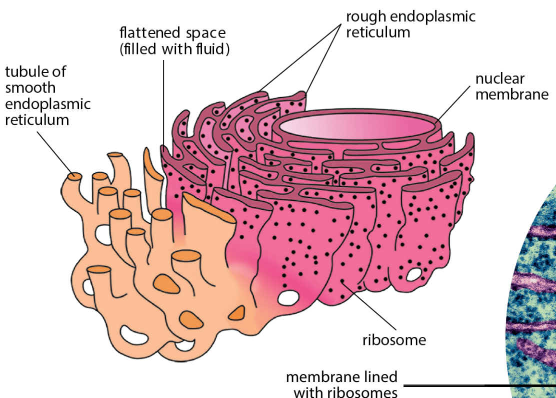


Figure 1.9 Three-dimensional diagram of endoplasmic reticulum

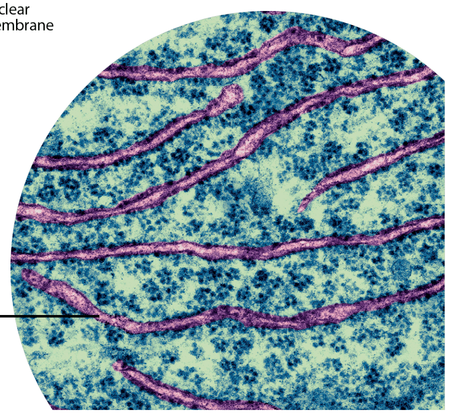


Figure 1.10 Colourised electron micrograph of membrane lined with ribosomes

Ribosomes

Ribosomes are small round structures. They are either attached to the membrane of the rough endoplasmic reticulum (RER) or lie freely in the cytoplasm (Figure 1.6 on page 5). They are needed to synthesise proteins in the cell.

- The ribosomes attached to the RER make proteins that are usually transported out of the cell.
- The ribosomes lying freely in the cytoplasm make proteins that are used within the cytoplasm of that cell.

The RER transports proteins made by ribosomes to the Golgi body for secretion out of the cell.

Link

What role do fats play in your body? Read more about them in Chapter 3. What role do sex hormones play in your body? Read more about them in Chapter 17.

Smooth Endoplasmic Reticulum

Smooth endoplasmic reticulum (SER) does not have ribosomes attached to its membrane. SER is more tubular than RER (see Figure 1.11). It is connected to the RER.

The SER:

- synthesises substances such as fats and **steroids** (sex hormones in mammals are steroids)
- converts harmful substances into harmless substances through a process known as **detoxification**

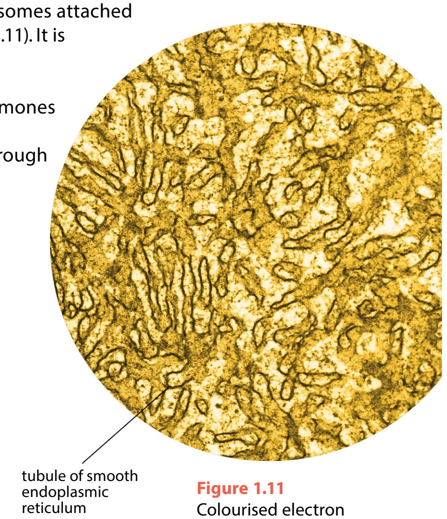


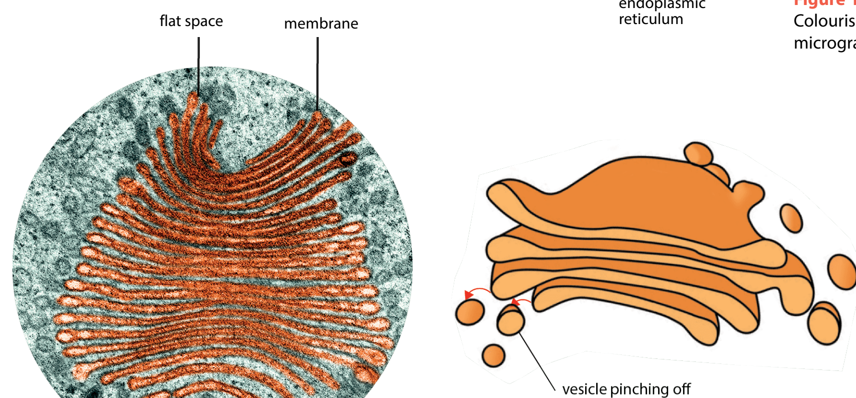
Figure 1.11 Colourised electron micrograph of SER

Golgi body

The **Golgi body** (also known as **Golgi apparatus**) is shaped like a disc. It consists of a stack of flattened spaces surrounded by membranes. **Vesicles** (tiny spherical spaces enclosed by a membrane) can be seen fusing with one side of the Golgi body and pinching off from the opposite side (Figure 1.12).

The Golgi body:

- chemically modifies substances made by the ER
- stores and packages these substances in vesicles for secretion out of the cell



(a) Colourised electron micrograph of Golgi body (6 250×)

(b) Three-dimensional view of Golgi body

Figure 1.12 Golgi body

Figure 1.13 shows how substances made by the ER are moved out of the cell.

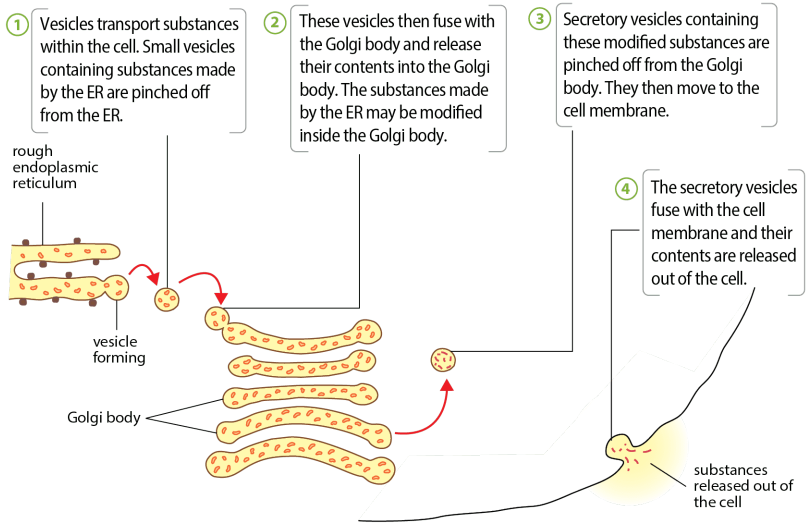


Figure 1.13 How substances made by the endoplasmic reticulum enter the Golgi body and are finally secreted out of the cell

Other organelles embedded in the cytoplasm are the mitochondria, chloroplasts (only in plant cells) and vacuoles.

Mitochondria

Mitochondria (singular: mitochondrion) are small oval or sausage-shaped organelles (Figure 1.14). Aerobic respiration occurs in the mitochondria. During aerobic respiration, food substances are broken down to release energy (see Chapter 7). This energy may be used by the cell to perform cell activities such as growth and reproduction.

Figure 1.14 Mitochondrion

Compare the general structure of the plant cell (Figure 1.15(a)) with that of the animal cell (Figure 1.15(b)). Do you notice any difference(s) between the two cells?

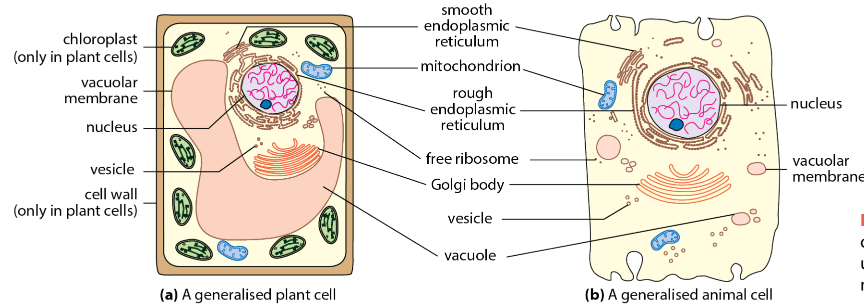


Figure 1.15 Diagrams of cells as seen under an electron microscope

Chloroplasts

- **Chloroplasts** are oval structures found in plant cells (Figure 1.16).
- Chloroplasts contain a green pigment called **chlorophyll**.
- Chlorophyll is essential for photosynthesis, the process by which plants make food (see Chapter 12).

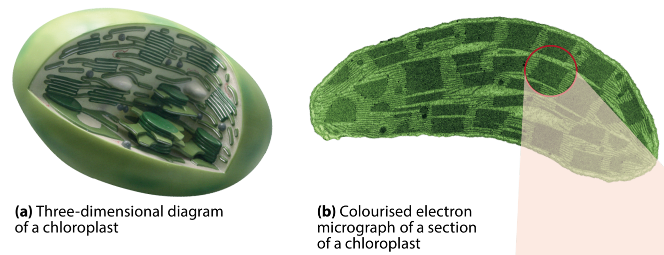


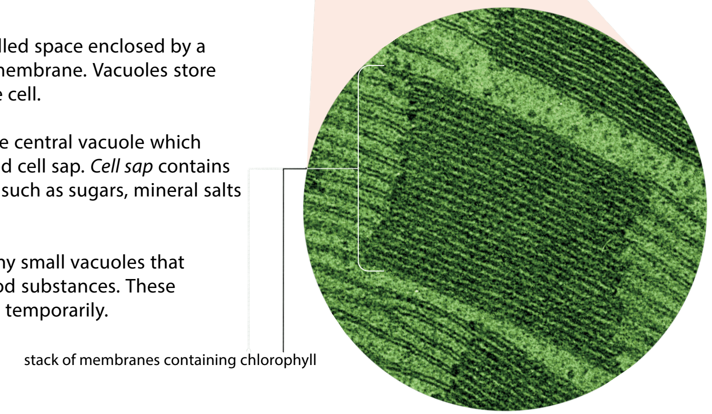
Figure 1.16 Chloroplast

Vacuoles

A **vacuole** is a fluid-filled space enclosed by a partially permeable membrane. Vacuoles store substances within the cell.

Plant cells have a large central vacuole which contains a liquid called cell sap. *Cell sap* contains dissolved substances such as sugars, mineral salts and amino acids.

Animal cells have many small vacuoles that contain water and food substances. These vacuoles usually exist temporarily.



Helpful Note

Methylene blue is a dye that stains structures in a sample, making parts of the cell more visible.

Let's Investigate 1.1

Aim

To examine animal cells using a light microscope

Procedure

1 Place a drop of methylene blue on a clean microscope slide.
2 Gently scrape the inside of your cheek with a blunt end of a clean toothpick. Swirl the toothpick end in the drop of methylene blue.
3 Carefully lower a cover slip at an angle over the slide.
4 Examine the cells on the slide under a light microscope.
5 Draw one cheek cell and label it as fully as you can.

Observation

Figure 1.17 shows human cheek cells viewed under the light microscope.

Discussion

1 Compare your drawing with the diagram of an animal cell in Figure 1.4 on page 4. Which structures shown in Figure 1.4 are not visible under the light microscope?
2 Why must the cover slip be lowered at an angle in step 3?

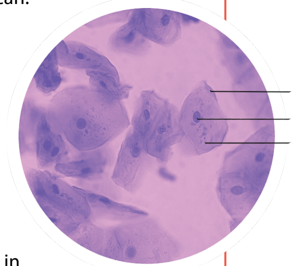


Figure 1.17

Let's Investigate 1.2

Aim

To examine plant cells using a light microscope

Procedure

1 Take a fleshy scale leaf from an onion bulb and bend the leaf until it breaks into two. Gently peel off the skin, called the epidermis, from the inner surface of the leaf using a pair of forceps.
2 Place the epidermis on a clean glass slide.
3 Add a drop of iodine solution (or methylene blue) in the middle of the slide. Carefully lower a coverslip at an angle over the slide.
4 Examine the epidermis under the microscope.
5 Draw one epidermal cell and label it as fully as you can.

Observation

Figure 1.18 shows onion epidermal cells viewed under the light microscope.

Discussion

1 How does this cell differ from the plant cell in Figure 1.5 on page 4?
2 State **two** differences between plant and animal cells that are visible under the light microscope.
Hint Look at shape and cell structures.

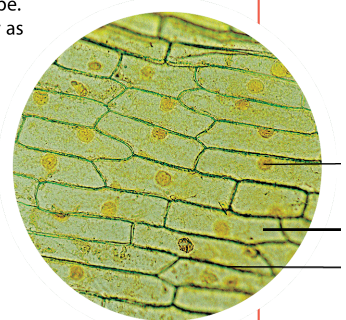


Figure 1.18

Link

Practical Workbook
Experiments 1A–1B

Differences Between Plant and Animal Cells

Table 1.1 shows the key differences between plant and animal cells.

Table 1.1 Differences between plant cells and animal cells

Plant Cell	Animal Cell
Cell wall present	Cell wall absent
Presence of a large, central vacuole	Presence of many small vacuoles
Chloroplasts present	Chloroplasts absent

Disciplinary Idea

The Cell

Cells are the basic units of life. The different organelles of a typical plant and animal cell carry out specific cellular process. The differences in organelles found in plant and animal cells can explain the differences in functions between plants and animals.

Helpful Note

A tissue is a group of cells with similar structures which work together to perform a specific function. There are two types of tissues: simple tissue and complex tissue. An example of simple tissue is the muscular tissue. Complex tissues contain more than one type of cells, e.g. blood (Figure 1.19) and xylem (Figure 1.20).

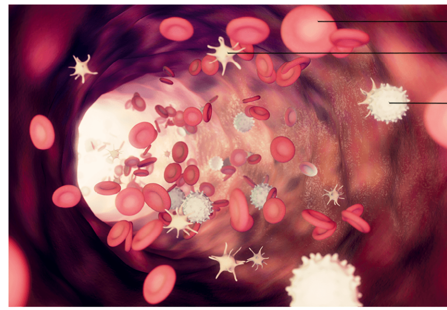


Figure 1.19 Blood contains red blood cells, white blood cells, platelets and plasma.

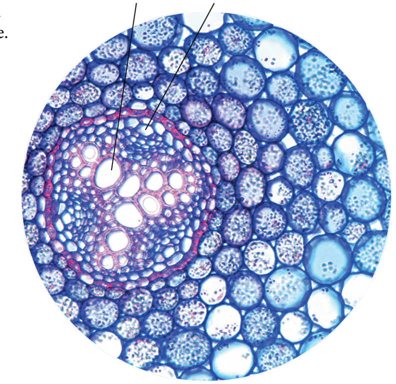


Figure 1.20 Plants contain xylem and phloem tissues that work together for a specific function.

An organ consists of more than one kind of tissue, all working together to perform a specific function. Examples of organs are the stomach and leaf.

An organ system consists of several organs working together for a common purpose. Examples of organ systems in humans include the digestive system, circulatory system, respiratory system and transport system. In plants, examples of organ systems include the root system and the shoot system. Various systems together make up the entire body of an organism.

Link

Theory Workbook
Worksheet 1A

Let's Practise 1.1

1 State the functions of the following membrane systems and organelles in the cell:
(a) chloroplasts
(b) Golgi body
(c) mitochondria
(d) ribosomes
(e) rough endoplasmic reticulum
(f) smooth endoplasmic reticulum
(g) vacuoles

2 State **three** differences between a plant cell and an animal cell.

3 Figure 1.21 shows a picture of a typical cell.
(a) Identify the parts A, B and C.
(b) Is this an animal cell or a plant cell? Give **three** reasons for your answer.

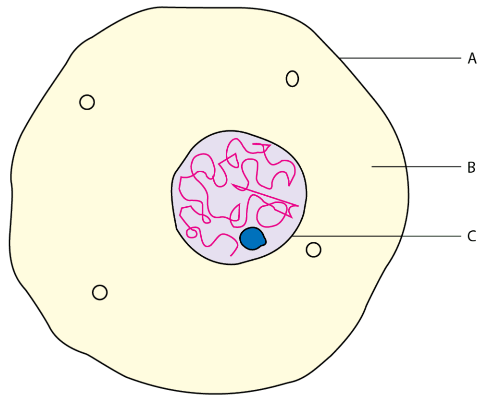


Figure 1.21

1.2 How Are Cells Adapted to Their Functions?

Learning Outcome

- Explain how the structures of specialised cells are adapted to their functions (e.g. muscle cell – many mitochondria to supply more energy, root hair cell – large surface area of cell membrane for greater absorption, red blood cell – lack of nucleus allowing it to transport more oxygen).

There are many different types of cells in living organisms. These cells differ in size and shape and they perform specific functions. For example:

- the human body has liver cells, nerve cells and skin cells, and
- the bougainvillea plant has guard cells and root hair cells.

Link

A nerve cell looks very different from the generalised cell you have learnt. Read more about it in Chapter 10.

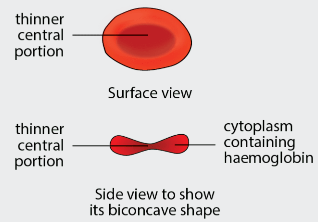
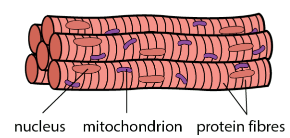
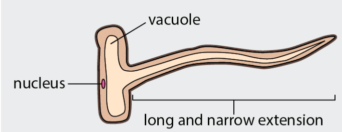
Some cells develop special structures or lose certain structures to enable them to carry out specific functions. This process of development is called **differentiation**.

Differentiation is the process by which a cell becomes specialised for a specific function.

How Is the Structure of a Cell Related to Its Function?

Table 1.2 shows some specialised cells and how they have been modified for specific functions.

Table 1.2 Examples of specialised cells and their adaptations

Cell Structure	Adaptation to Function
Red blood cell 	• Contains **haemoglobin** (a red pigment) which binds to oxygen and transports it around the body • Has a circular, biconcave shape which increases the surface area-to-volume ratio so that oxygen can diffuse in and out at a higher rate • Lacks a nucleus, enabling the cell to store more haemoglobin for transport of oxygen • Is flexible and can squeeze through capillaries easily
Muscle cell 	• Is elongated and cylindrical in shape, contains many nuclei and mitochondria • Has mitochondria to provide the energy for the contraction of the muscle cell
Root hair cell 	• Has a long and narrow root hair to increase the surface area-to-volume ratio to absorb water and mineral salts at a higher rate

Disciplinary Idea

Structure and Function
Specialised cells have structures which help them carry out their functions more efficiently.

Link

How does surface area-to-volume ratio affect the movement of substances into and out of cells? Read more about it in Chapter 2.

Word Alert

biconcave: curving in on both sides, hence being thinner in the middle than the edges

Cool Career

Plant Tissue Culture Scientist

Plant cells have an amazing ability to develop into an entire plant. This ability is called cellular totipotency. Plant tissue culture scientists make use of this ability to develop plants in the laboratories from plant tissue culture (Figure 1.22). This method reduces the time to produce new varieties, as compared to traditional breeding methods.

Plant tissue culture has far-reaching applications, especially in agriculture. Specific breeds of plants that are resistant to diseases can now be produced in large numbers. In forestry, this technique is useful for large scale propagation of forest trees.

How do you think this technique can help our environment and improve the lives of people in less developed countries?

Word Alert

Propagation: growing and planting new trees

Figure 1.22 Scientist cutting plant tissue culture in a Petri dish

Let's explore some ideas about cells (Figure 1.23). Are all cells in an organism the same? Which student is correct?

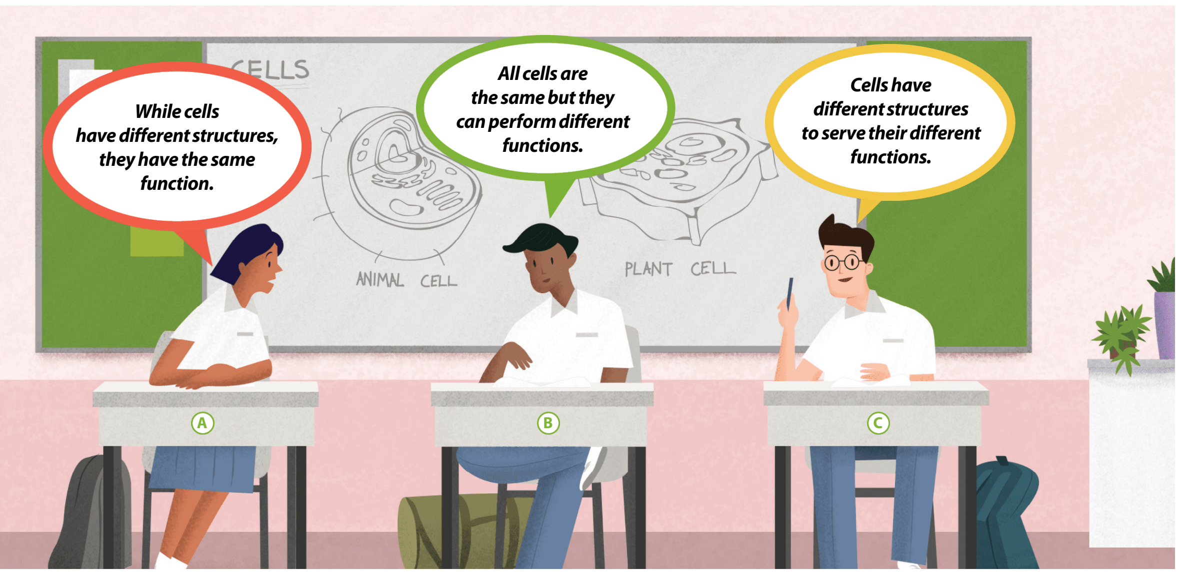


Figure 1.23 Three students are giving their views on cells. Which student is correct?

Tech Connect

We can now create chicken meat from chicken muscle cells cultured in the laboratory (Figure 1.24). Would this mean that we can produce a functioning organ in the laboratory by using cells that form the particular organ?

Scientists may be able to make a three-dimensional model of an organ in the laboratory. However, many natural biological reactions taking place in an organ system cannot be reproduced in a model. Tissue engineers can now study a variety of natural biological reactions in an organ by placing the respective cells on a microchip. A simplified model for study is created in this way.

These do not look anywhere near how our natural organs may look, but they are functional and they enable scientists to study the processes that take place in each organ, with almost complete control within the laboratory.

Find out more about the benefits of using models to study processes in the human body.

Figure 1.24 Meat cultured in the laboratory from stem cells

Past to Present

For many years, scientists and doctors have been injecting healthy blood stem cells into patients who suffer from leukaemia, a type of cancer of the blood. This method, known as bone marrow transplant, has been a highly effective treatment, increasing the survival rates of patients substantially.

In recent years, scientists have developed several other methods of using cells to treat different diseases. These methods use a special type of cell called stem cells. Stem cells, unlike other cells in the body, are not specialised cells and thus have the ability to develop into other specialised cell types (Figure 1.25). This opens up a whole range of possibilities. Cells of different organs can be potentially grown in the laboratory and transplanted into the organs of humans. A patient's immune cells could be modified to recognise cancerous cells in the lymph nodes and destroy them.

There are still a lot of challenges that scientists need to overcome. In the near future, we may be able to make use of cells to treat diseases that were once considered untreatable.

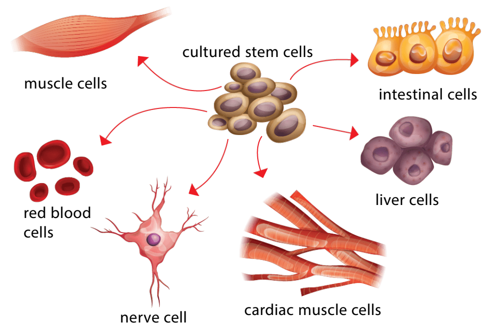
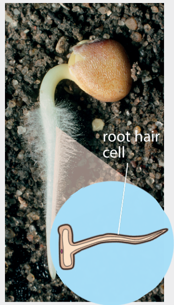
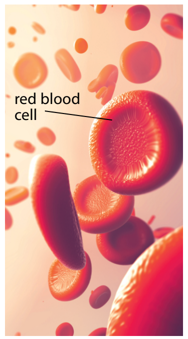


Figure 1.25 Human stem cells can be used to develop a variety of cells.

Let's Practise 1.2

Look at the structure and cells in Table 1.3. Complete the table to describe how these cells have been adapted to carry out its functions.

Table 1.3

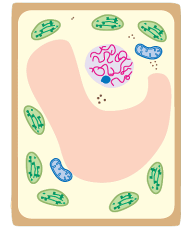
Cell	Function	Important Characteristic(s) to Serve Its Function Well	How These Characteristics Help It to Perform Its Functions
 root hair cell	To absorb water and mineral salts from the soil		
 red blood cell	To deliver oxygen to all parts of the body		

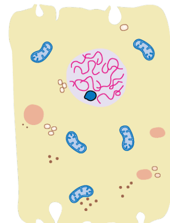
Link

Theory Workbook
Worksheet 1B
Let's Assess
Let's Reflect

Let's Map It

Cells include **Animal cells** and **Plant cells**





Plant cells also have:

- **Cell wall** which
  - is made of cellulose and is fully permeable
  - protects the cell from injury
  - gives the plant cell a fixed shape
- **Chloroplasts** which contain chlorophyll which is essential for photosynthesis

Animal cells and plant cells have:

- **Cell membrane** which controls the movement of substances in and out of the cell
- **Cytoplasm** which is the place where most cell activities occur
- **Nucleus** which controls cell activities and is essential for cell division
- **Ribosomes** which are needed for synthesis of proteins
- **Mitochondria** which is involved in energy release for cell activities
- **Vacuoles** which store substances within the cell, which are different
  - In animal cells: many small vacuoles which contain water and food substances
  - In plant cells: a large central vacuole which contains cell sap
- **Rough endoplasmic reticulum (RER)** which is involved in protein synthesis and transport of proteins
- **Smooth endoplasmic reticulum (SER)** which is involved in producing fats and steroids
- **Golgi body** which
  - chemically modifies substances made by the ER
  - stores and packages these substances for secretion out of the cell

Let's Review

Section A: Multiple-choice Questions

1 Which of the cell organelles is **not** visible under the ordinary light microscope?

A cellulose cell wall
B cellulose cell wall and nucleus
C chloroplasts
D Golgi body and rough endoplasmic reticulum

2 Figure 1.26 shows a typical plant cell. Which of the numbered structures are partially permeable?

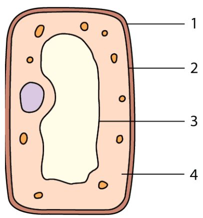


Figure 1.26

A 1 and 2
B 1 and 4
C 2 and 3
D 3 and 4

Section B: Structured Questions

1 Name the structure in the cell that:
(a) controls the movement of substances in and out of the cell;
(b) contains genetic information;
(c) is involved in cell respiration;
(d) stores and modifies substances made by the ER for secretion out of the cell.

2 Look at the list of cell structures:
cell membrane, large central vacuole, cytoplasm, nucleus, chloroplasts, mitochondria, endoplasmic reticulum, Golgi body, ribosomes

Which of the structures listed above are:
(a) present in both plant and animal cells?
(b) present in plant cells only?

3 Figure 1.27 shows three different cells seen under the microscope. Which is a plant cell? Explain your answer.

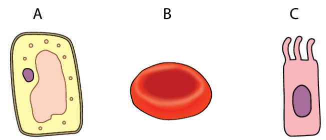


Figure 1.27

Section C: Free-response Question

1 Describe how proteins synthesised by ribosomes are transported out of the cell.

CHAPTER 02

Movement of Substances

What You Will Learn

- What is diffusion?
- What is osmosis?
- What is active transport?

Think like a chef and act quickly! Two chefs are cooking potatoes. Each potato needs to be cut into four pieces. Each potato also needs to be soaked in water before cooking.

Chefs Nurul and Faridah took a potato each and scraped off its skin.

Chef Nurul cut the potato into four pieces before soaking it in water for one hour. Chef Faridah soaked the potato in water for one hour before cutting it into four pieces.

Which chef will need to exert more strength to cut the potatoes? Why do you think so? What role does the potato skin play?

2.1 What Is Diffusion?

Learning Outcomes

- Define diffusion and describe its role in nutrient uptake and gaseous exchange in plants and humans.
- Describe the factors that affect the rate of diffusion.

Diffusion

Imagine that you are sitting in the living room reading a book. Your sister accidentally spills a bottle of perfume in the living room. Gradually, you become aware of a pleasant scent spreading through the living room.

Figure 2.1 illustrates how diffusion takes place.

Figure 2.1 Diffusion of perfume particles

1. Perfume, like all matter, is made up of particles such as atoms, molecules or ions.
2. Individual particles of perfume evaporate from the surface of the spill, that is, they become a gas.
3. The gas particles have kinetic energy and are constantly moving in all directions. They bump into one another and move about randomly.
4. This causes the gas to spread throughout the house, until it reaches your nose and you smell it. The gas spreads outwards through a process called *diffusion*.

What Is a Concentration Gradient and How Is It Related to Diffusion?

In Figure 2.1, point A represents the location where the bottle of perfume was spilled. Point B represents you in the living room, some distance away. Concentration refers to the amount of a substance within a fixed volume. The concentration of gas particles is higher at A than at B. Thus, there is a difference in concentration between points A and B. This concentration difference can be shown on a graph (Figure 2.2) and is referred to as the concentration gradient.

Link

Physics
We learn that the random movement of microscopic particles is known as Brownian motion.

In Figure 2.2, the height of the blue line shows the concentration at each point. If we join the concentrations at A and B, we get a straight line, which is sloped or has a gradient. This red dotted line is the *concentration gradient* between A and B.

Concentration gradient is the difference in concentration between two regions.

The particles of fluids (liquids and gases) possess movement (kinetic) energy. They are continuously moving about. As their movement is random, the particles will move (diffuse) down the concentration gradient and become evenly spaced out after some time (Figure 2.3).

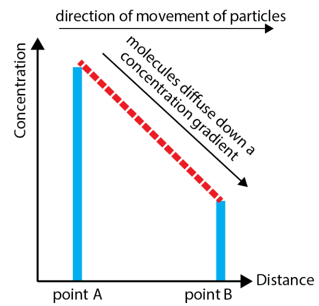


Figure 2.2 Graphical representation of diffusion

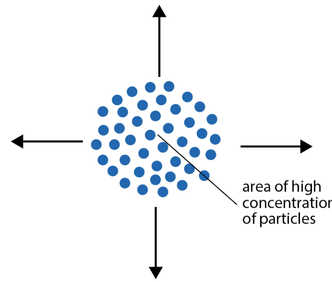


Figure 2.3 Arrows showing direction of movement of particles as they space out

In Figure 2.1, the smell of perfume diffuses throughout the house.

- *Diffusion* can thus be described as the net movement of particles down a concentration gradient.
- *The steeper the concentration gradient for a substance, the faster the rate of diffusion for that substance.*

Diffusion is the net movement of particles (atoms, molecules or ions) from a region where they are of higher concentration to a region where they are of lower concentration, that is, down a concentration gradient.

Link

Chemistry
We learn that all matter is made up of tiny particles that are in constant random motion. These moving particles have kinetic energy.

Helpful Note

Net movement refers to the overall movement of particles. Net movement of particles occurs when the movement of particles in one direction is greater than the movement of particles in the opposite direction.

When the two regions have the same number of particles per unit volume, the movement of the particles between the two regions will be the same in both directions. Thus, there will be no net movement.

Let's Investigate 2.1

Aim
To investigate the diffusion of a dissolved substance in water

Procedure
1. Drop a copper(II) sulfate crystal into a gas jar full of water as shown in Figure 2.4. Cover the jar and allow it to stand for a few days.
2. Observe the changes in the colour of the water.

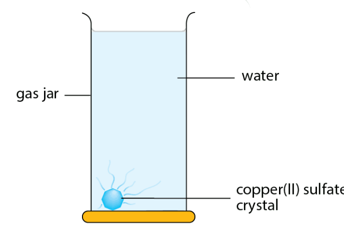


Figure 2.4 Experimental set-up to demonstrate diffusion

Observation and Discussion
1 Using the concept of concentration gradient, explain why the blue colour of copper(II) sulfate gradually spreads throughout the water in the jar.
2 When does diffusion stop?

As you saw in Let's Investigate 2.1, the particles of copper(II) sulfate moved from a region of higher concentration to regions of lower concentration in the surrounding water. In other words, the solute particles diffused evenly throughout the liquid to form a solution.

If there is more than one substance dissolved in the same liquid, then the dissolved particles of one substance will diffuse independently of the others.

Diffusion Across a Membrane

Figure 2.5 illustrates the process of diffusion through a permeable membrane. A permeable membrane allows both the solvent (water) and the solutes (the dissolved substances) to pass through it.

As a result:
- The dissolved particles of copper(II) sulfate will diffuse across the membrane to the left side of the beaker.
- The dissolved particles of potassium nitrate will diffuse across the membrane to the right side of the beaker.

Eventually, there will be equal concentrations of all particles on both sides of the membrane.

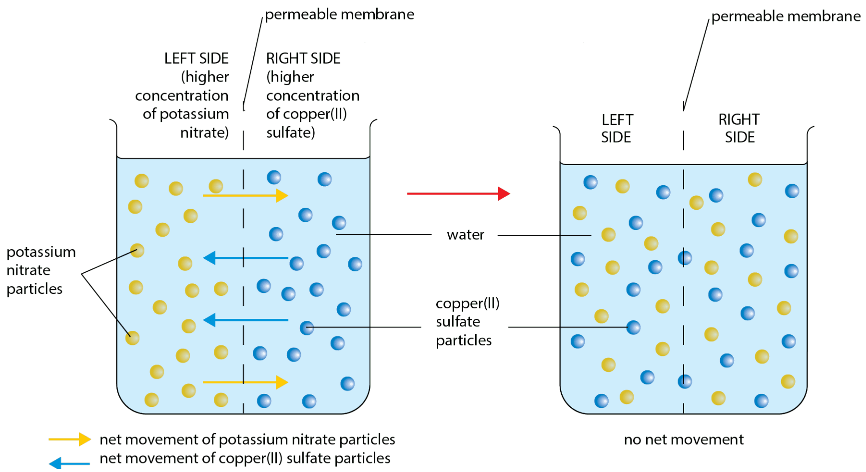


Figure 2.5 Diffusion of potassium nitrate and copper(II) sulfate particles through a permeable membrane

Factors That Affect the Rate of Diffusion

The rate of diffusion can be affected by factors such as:
- concentration gradient
- diffusion distance
- surface area-to-volume ratio

How concentration gradient affects the rate of diffusion has been discussed on page 21.

Diffusion Distance

The time taken for a substance to move from one point to another depends on the distance between the two points. The distance through which a substance diffuses is called the diffusion distance. The shorter the diffusion distance, the less time is needed for the substance to travel, and hence the rate of diffusion is higher.

In living organisms, the cell membrane is not like the membrane in Figure 2.6. It allows some substances to pass through but not others. For example, oxygen and carbon dioxide can pass through the cell membrane but proteins cannot. *Diffusion is an important way by which oxygen and carbon dioxide move into and out of cells.*

Exchange of oxygen and carbon dioxide in the lungs takes place by diffusion (Figure 2.6(a)). Plant cells such as root hair cells also take in oxygen and remove carbon dioxide by diffusion (Figure 2.6(b)). In both these scenarios, the diffusion distance is short, allowing diffusion to occur at a higher rate.

Link
How do humans carry out gas exchange? Read about it in Chapter 7.
How do plants carry out gas exchange? Read about it in Chapter 12.

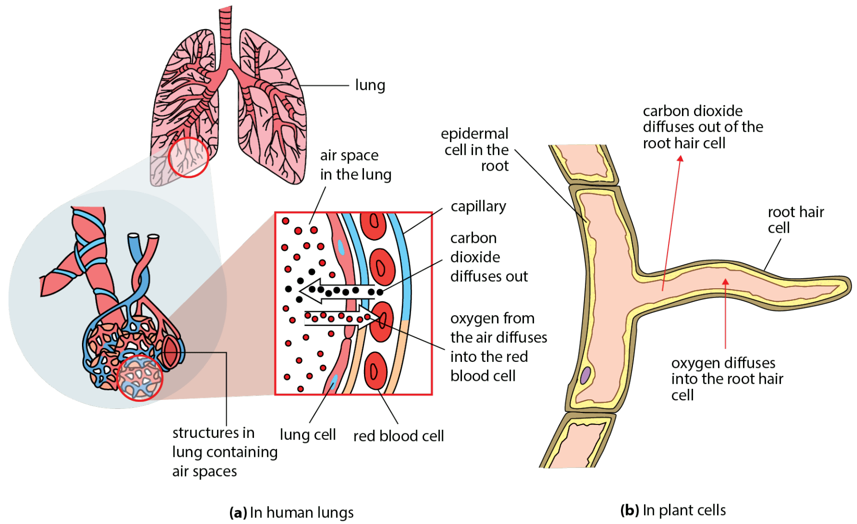


Figure 2.6 Gas exchange of oxygen and carbon dioxide via diffusion

Disciplinary Idea
Systems
Living organisms rely on diffusion to facilitate the exchange of gases with the environment needed for survival.

Solutes can also diffuse, for example, in the small intestine when dissolved amino acids and glucose are absorbed by diffusion into the blood capillaries. A solute is a substance that has been dissolved in another substance.

Surface Area-to-volume Ratio

What does surface area-to-volume ratio mean to a cell?

Why are cells typically small? Why do all large organisms always have bodies made up of many small cells and not just one large cell?

The answers to these questions are related to the rate at which materials move across the cell membrane. Cells need to move oxygen, nutrients and waste materials across their cell membrane fast enough to stay alive.

The rate of movement of a substance across a cell membrane depends on how large the cell membrane is (i.e. the surface area of the cell). For two cells of the same volume, the one with the larger surface area allows for a higher rate of diffusion. The ratio between the surface area and volume of a cell is called surface area-to-volume ratio, and is an essential concept in biology. The greater the surface area-to-volume ratio of a cell, the higher the rate at which substances move in and out of it.

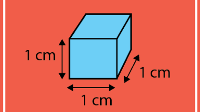
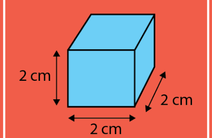
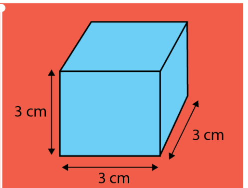
The following investigation will help you better understand surface area-to-volume ratios.

Let's Investigate 2.2

Calculating Surface Area-to-volume Ratios

1 Consider three cubes of sides 1 cm, 2 cm, and 3 cm respectively. We use three cubes to represent cells of different sizes.
2 Complete Table 2.1.

Table 2.1 Surface area-to-volume ratio of three cubes representing cells of different sizes

Cube	 sides 1 cm	 sides 2 cm	 sides 3 cm
Surface area	Area of one face = 1 cm × 1 cm = 1 cm^2 Surface area = number of faces × area of one face = 6 × 1 cm^2 = 6 cm^2		
Volume	Volume = 1 cm × 1 cm × 1 cm = 1 cm^3		
Surface area-to-volume ratio	6 cm^2 : 1 cm^3		

From our calculations, we can observe that as the cube becomes bigger, the surface area does not increase in the same proportion as the volume. The cube of sides 1 cm has 6 cm^2 of surface area to 1 cm^3 volume. But the cube of sides 3 cm has only 2 cm^2 of surface area to 1 cm^3 volume. The largest cube has the smallest surface area-to-volume ratio. The rate of movement of substances across the largest cube is the slowest. Thus, as a cell grows, the rate of movement of substances across a cell will decrease.

Helpful Note

A cube has six square faces. To find the surface area of a cube, find the area of one face and multiply by six.

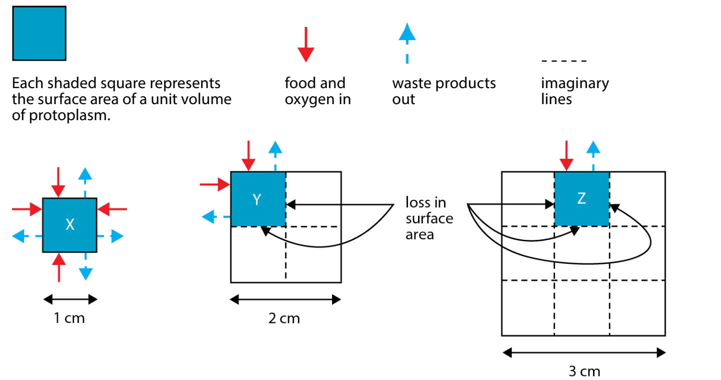
Let's explore the efficiency of diffusion in three types of cells using the models in Figure 2.7.

In Figure 2.7, the larger cell B has more surface area than cell A, but it has less surface area for every unit volume of protoplasm compared to A. The rate of intake of food and oxygen per unit volume is therefore slower in cell B than in cell A.

The cells in root tips and shoot tips are small and actively growing. As a cell continues to grow in size, its growth slows down and stops once it reaches its optimum size. This is because as the cell grows larger, the rate of oxygen and food intake slows down. Thus, it will not be beneficial for a cell to grow too big.

Word Alert

Optimum: best or most favourable



Cell A with sides of 1 cm
This cell can obtain food and oxygen from all its sides.

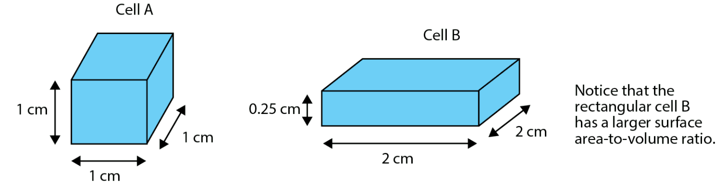
Cell B with sides of 2 cm
Portion Y has the same volume of protoplasm as X. However, its surface area has been reduced by half. It can only obtain half the amount of food and oxygen per unit time compared to X. Thus, the whole cell B can only be half as active as cell A.

Cell C with sides of 3 cm
Portion Z has as an even smaller surface area per unit volume. Therefore, it gets less food and oxygen per unit time compared to Y. The whole cell C is even less active than the other two cells.

Figure 2.7 Models to explain what surface area-to-volume ratio means to a cell of increasing size

How do cells adapt their surface area-to-volume ratios?

Consider the two shapes in Figure 2.8. Each represents a cell. Cells A and B have the same volume of 1 cm^3 but have different surface areas. What is the surface area-to-volume ratio for cells A and B?



Cell A: Surface area = 6 cm^2
Volume = 1 cm × 1 cm × 1 cm
= 1 cm^3

Cell B: Surface area = 10 cm^2
Volume = 2 cm × 2 cm × 0.25 cm
= 1 cm^3

Figure 2.8 Models to explain how cells of the same volume can have different surface areas

Link

How is the root hair cell adapted to its function? Recall what you have learnt in Chapter 1.

Word Alert

Protrusions: things that stick out from the surrounding surface
Lumen: hollow space of a tubular structure

Some cells are specifically adapted to absorb substances, for example, root hair cells and the epithelial cells, which line the small intestine (Figure 2.9). Such cells often have long narrow protrusions or folds in their membranes. These greatly increase the surface area-to-volume ratio of the cell membrane through which materials can be absorbed into the cell. You will learn more about this in Chapter 5.

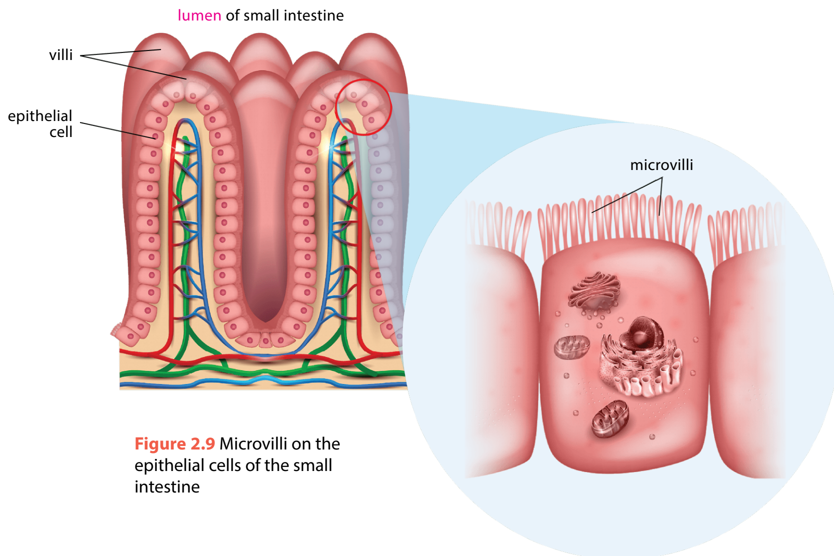


Figure 2.9 Microvilli on the epithelial cells of the small intestine

Let's Investigate 2.3

Aim

To investigate the relationship between surface area-to-volume ratio and absorption

Procedure

1. Use a knife and cut out three blocks of agar (stained with bromothymol blue) with the dimensions (in cm) shown in Figure 2.10.
2. Completely immerse the three agar blocks in dilute hydrochloric acid and note the time.
3. As the acid diffuses into the blocks, the blocks gradually turn from blue to yellow. Examine the blocks regularly. Record how long it takes for each block to turn completely yellow.

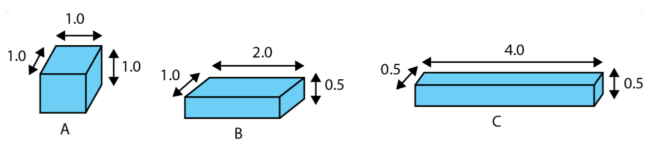


Figure 2.10 Three agar blocks with the same volume but different surface area

Link

Practical Workbook
Experiment 2A

Observation and Discussion

1. What can you say about the relationship between surface area-to-volume ratio and the rate of absorption of the acid?
2. How can you relate the shape of the agar blocks to cells in the body?

Now, look at Figure 2.11. What do you notice? What do you think is taking place? Comment on the statements made by the three persons about the movement of molecules.

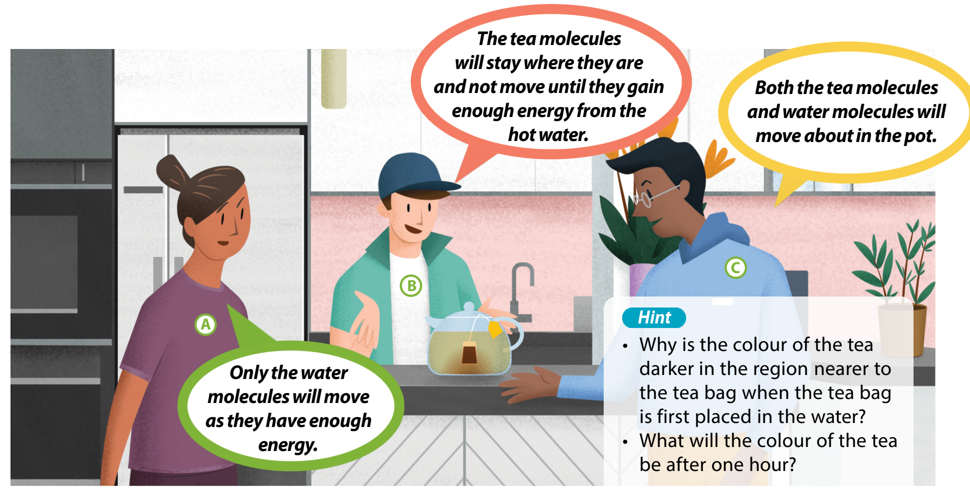


Figure 2.11 Three persons are discussing the movement of molecules. Comment on their statements.

Link

Chemistry

We learn that moving particles have kinetic energy. As temperature increases, particles gain more energy and move faster. The rate of diffusion increases as the temperature of the solution increases.

Let's Practise 2.1

1. (a) What is a concentration gradient?
   (b) Define the term *diffusion*. What factor(s) affect the rate of diffusion?
2. Explain why actively growing cells are usually small in size. Why do cells **not** grow beyond a certain size?
3. (a) How are the root hair cell (Figure 2.12), the epithelial cell of the small intestine (Figure 2.13) and the red blood cell (Figure 2.14) adapted for absorption of materials?

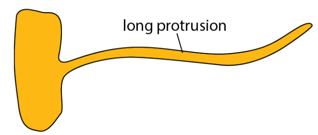


Figure 2.12 Root hair cell

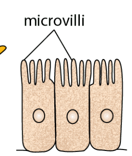


Figure 2.13 Epithelial cell

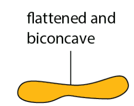


Figure 2.14 Red blood cell

   (b) What feature(s) do the three cells have in common?

Link

Theory Workbook
Worksheet 2A

2.2 What Is Osmosis?

Learning Outcomes

- Define osmosis, investigate and describe the effects of osmosis on plant and animal tissues.
- Discuss the factors that affect the rate of osmosis.

Osmosis

The cell membrane is a **partially permeable membrane**. *It allows some substances to pass through but not others.* Figure 2.15 shows the two arms of a U-tube separated by a partially permeable membrane. This membrane is permeable to water molecules but not to sucrose molecules. Sucrose is cane sugar, also known as table sugar.

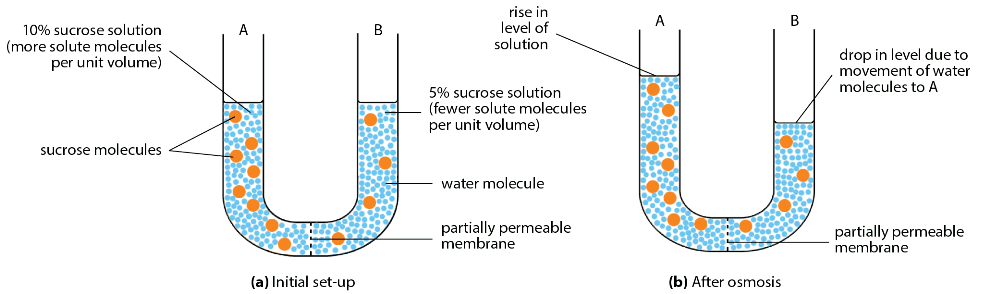


Figure 2.15 Experimental set-up to demonstrate osmosis

Compared to arm B, arm A contains:
- More sucrose molecules per unit volume
- Fewer water molecules per unit volume

After some time, the level of solution in arm A rises, while that in arm B falls.

What do you think has happened?
- Sucrose molecules cannot diffuse from arm A to B because the molecules are too big to pass through the pores of the membrane.
- Water molecules move from B to A because solution B has more water molecules per unit volume than solution A. A dilute solution has more water molecules per unit volume than a concentrated solution of the same volume.

Net result: Both arms A and B have the same solute concentration (*same number of solute molecules per unit volume*).

The diffusion of water molecules across a partially permeable membrane is called *osmosis*.

Link

Chemistry
We learn that the concentration of a solution is given by the amount of a solute dissolved in a unit volume of the solution.

Let's Investigate 2.4

Aim
To demonstrate osmosis

Procedure
1 Tie a knot at one end of a piece of dialysis tubing.
2 Half-fill a boiling tube with distilled water.
3 Use a pipette to half-fill the dialysis tubing with sucrose solution. Carefully rinse the outside of the dialysis tubing with distilled water if any sucrose solution is spilled.
4 Set up the apparatus as shown in Figure 2.16. Make sure the levels of the liquid inside and outside the tubing are the same. Use a paper clip to hold the dialysis tubing in place. Mark the level on the outside of the boiling tube.
5 Set up a second experiment in a similar way but with distilled water in both the dialysis tubing and the boiling tube.
6 After 20 minutes, observe and note the level of liquid inside and outside the tubing in each experiment.

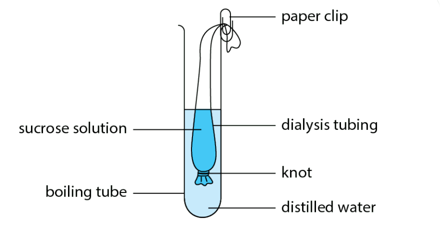


Figure 2.16 Experimental set-up to demonstrate osmosis

Observation and Discussion
1 What can you say about the dialysis tubing? How do you account for your observation in step 6?
2 What is the purpose of the second experimental set-up?

Link

Practical Workbook
Experiment 2B

What Is Water Potential and How Is It Related to Osmosis?

- The term '**water potential**' is always used in connection with osmosis. *Water potential is a measure of the tendency of water molecules to move from one place to another*. A dilute solution (solution with lower concentration of solute) would have a higher water potential than a concentrated solution. Hence, water molecules would move out of the dilute solution and into the concentrated solution through osmosis.
- When a partially permeable membrane separates two solutions of different water potentials, a water potential gradient is established (Figure 2.17). Water molecules move from a region with higher water potential to a region with a lower one, that is, down a water potential gradient.

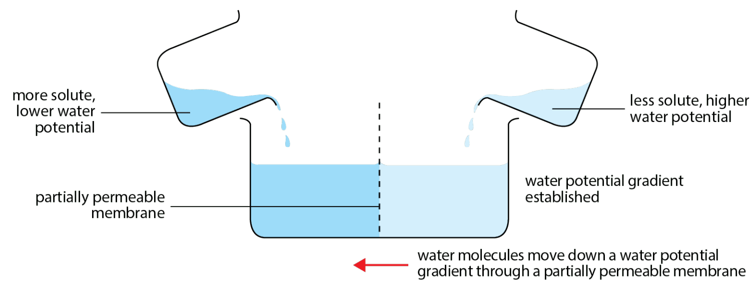


Figure 2.17 Water potential gradient set up in the container

Figure 2.18 represents graphically how water potential is associated with osmosis.

Osmosis is the net movement of water molecules from a region of higher water potential to a region of lower water potential, through a partially permeable membrane.

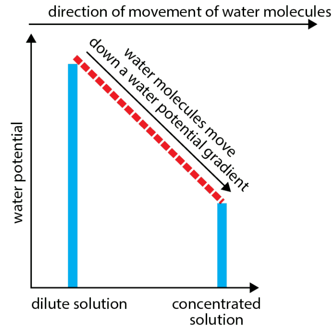


Figure 2.18 Graphical representation of water potential gradient

Tech Connect

In Singapore, there are five NEWater plants that supply Singapore with up to 40% of its water needs.

The NEWater process involves recycling treated used water into ultra-clean, high-grade reclaimed water. One of the stages of the NEWater production process is reverse osmosis. Similar to osmosis, this process involves a partially permeable membrane. However, pressure is applied to move water molecules across the membrane in a direction that is opposite to that of osmosis.

Figure 2.19 Reverse osmosis water treatment system

Reverse osmosis can remove toxins from water. By this method, very small particles can be removed by using an electric pump to force water under high pressure through a membrane (Figure 2.19). The membrane is partially permeable and has very tiny pores, which allow only very small molecules such as water molecules to pass through. The water is passed through the membrane several times until pure water is obtained.

Why do you think NEWater is an important source of water for Singapore?

Similar to diffusion, the rate of osmosis can be affected by factors such as:
- water potential gradient
- distance over which water molecules need to move
- surface area-to-volume ratio

How Does Osmosis Affect Living Organisms?

A cell is surrounded by a living, partially permeable cell membrane. Enclosed within the cell membrane are the nucleus, cytoplasm and a mixture of various substances.

Note that the cell wall of plants is permeable and allows most dissolved substances to pass through. A plant cell behaves differently from an animal cell when placed in solutions with differing water potentials. This is due to the presence of the cell wall in plant cells.

What Happens to a Cell in a Solution With Higher Water Potential?

When a cell is placed in a solution with a higher water potential, water molecules will move from a region of higher water potential (outside the cell), into a region of lower water potential (inside the cell).

A plant cell will expand or swell. This is because plant cells are protected by an inelastic cell wall (Figure 2.20). Plants are supported by the pressure of water inside the cells pressing outwards on the cell wall.

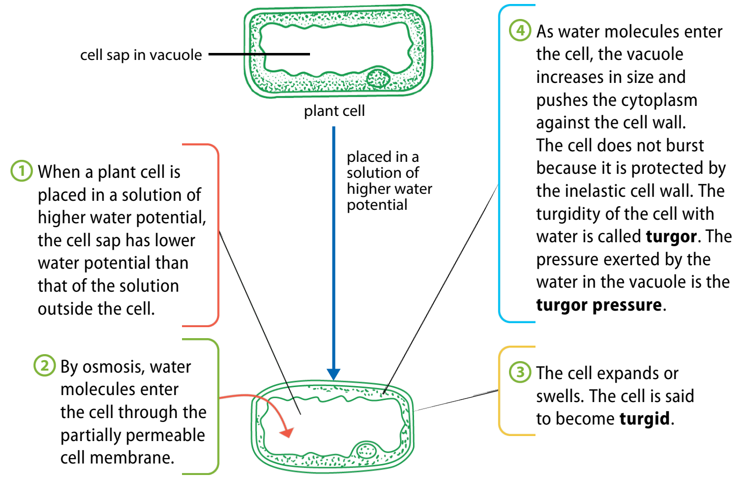


Figure 2.20 A plant cell in a solution with higher water potential

Link

Human cells must be surrounded by fluid in relatively constant water potential. Read more about how this is done in Chapter 9.

An animal cell will swell and may even burst in a solution of higher water potential than its cytoplasm (Figure 2.21). This is because, unlike plants, it does not have a cell wall to protect it.

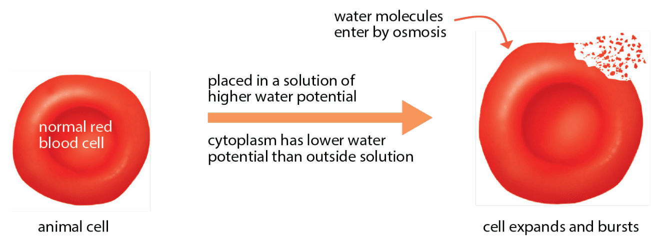


Figure 2.21 An animal cell in a solution with higher water potential

What Happens to a Cell in a Solution of the Same Water Potential?

Cells immersed in a solution with the same water potential as their cytoplasm will not change their size or shape. The movement of water molecules is the same in both directions. Hence, there is no net movement of water molecules in or out of the cell.

Disciplinary Idea

Homeostasis, Co-ordination and Response

Through the processes of diffusion, osmosis and active transport, the internal environments of living organisms are kept constant to provide the optimal conditions for cells to survive.

What Happens to a Cell in a Solution With Lower Water Potential?

When a cell is placed in a solution with a lower water potential, water molecules will move from a region of higher water potential (inside the cell), into a region of lower water potential (outside the cell).

A plant cell will decrease in size and become limp (Figure 2.22).

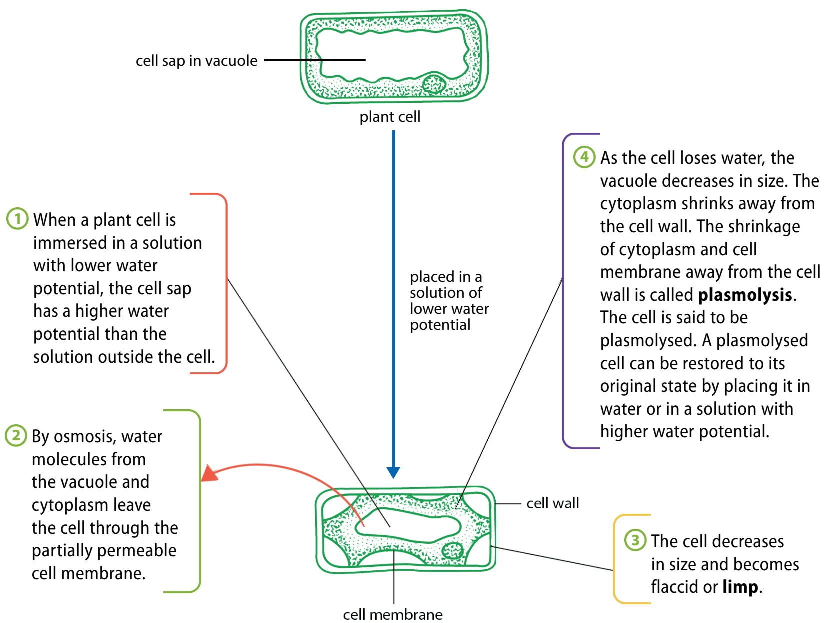


Figure 2.22 A plant cell in a solution with lower water potential

Placing an animal cell in a solution with lower water potential will cause it to lose water. The cell shrinks and spikes appear on the cell (Figure 2.23). This process is called **crenation**. An animal cell will become dehydrated and eventually die when placed in a solution with a low water potential.

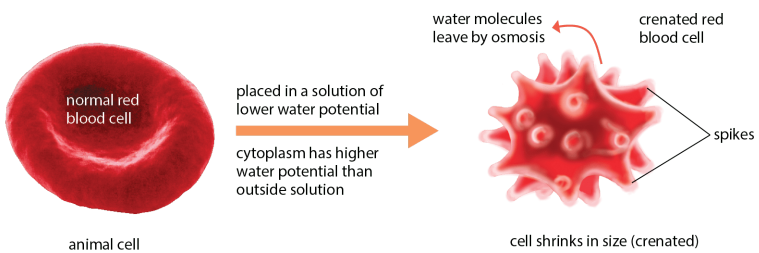


Figure 2.23 An animal cell in a solution with lower water potential

Why Is Turgor Important in Plants?

Turgor, or how turgid cells are, plays an important role in maintaining the shape of soft tissues in plants. The young stems and leaves of herbaceous and non-woody plants are able to remain firm and erect. This is because of the turgor pressure within their cells. When there is a high rate of water loss from the cells, they lose their turgidity and the plant wilts.

The movements of certain plant parts are due to changes in turgor. For example, changes in the turgor of the guard cells cause the opening and closing of the stomata (Figure 2.24).

Link

How do the stomata of plants open and close? Read more about it in Chapter 12.

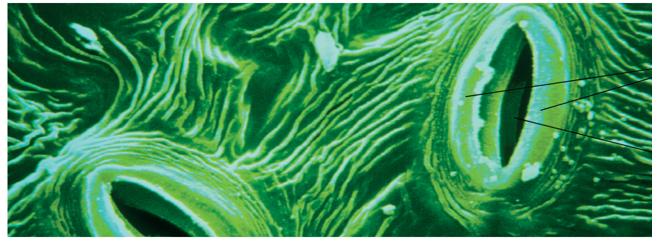


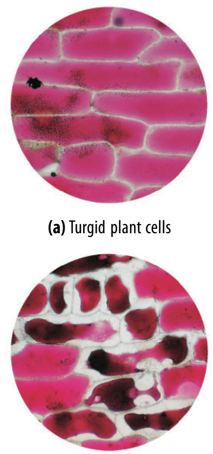
Figure 2.24 Electron micrograph of stomata

Plasmolysis causes cells to become flaccid or limp (Figure 2.25). Cells will be killed if they remain plasmolysed for too long. Thus, it is not advisable to add too much fertiliser around the roots of plants because the soil solution will become very concentrated and water molecules will move out of the roots by osmosis.

Inability of the roots to absorb water, together with continued evaporation of water from the leaves, will cause the plant to wilt. Unless sufficient water is added to dilute the soil solution, the plant will eventually die (Figure 2.26).

Helpful Note

Soil solution is a thin film of water that surrounds individual soil particles. It usually contains dissolved mineral salts or ions.



(a) Turgid plant cells

(b) Flaccid and plasmolysed plant cells

Figure 2.25 Cells of onion leaf epidermis (stained)

(a) Turgor pressure in the cells of the plant helps to keep this plant firm and upright.

(b) Loss of turgor due to excessive water loss may cause a plant to wilt.

Figure 2.26 Effects of turgor pressure on plants

Link

Practical Workbook
Experiment 2C

Let's Investigate 2.5

How can we show osmosis in living tissues (potato)?
Potato strips are commonly used in experiments to show osmosis in living tissues. The dimensions of the strips used are shown in Figure 2.27. For instructions on how to set up this experiment, refer to Experiment 2C of the Practical Workbook.

If the potato strips decrease in length, does this relate to water molecules leaving the strips? How can this experiment be extended to estimate the concentration of cell sap in the cell?

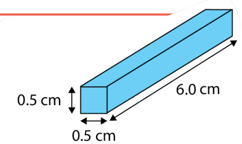


Figure 2.27 A potato strip used in osmosis experiments

Word Alert
Cuticle: a thin protective outermost layer

Link

Practical Workbook
Experiment 2D

Let's Investigate 2.6

How can we show osmosis in living tissues (scape)?
A scape (leafless flower stalk), e.g. Chinese leek, can also be used to demonstrate osmosis in living tissue. Figure 2.28(a) shows a section of a scape. A scape has two main layers of cells; the outer epidermal cells and the cortical cells. Only the outer epidermal cells are covered by a waterproof cuticle that protects the plant tissue against water loss.

One cut strip is placed in water and another in concentrated sucrose solution (Figure 2.28(b)).

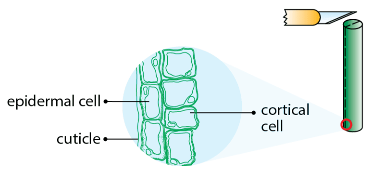


Figure 2.28(a) Layers of cells in a scape

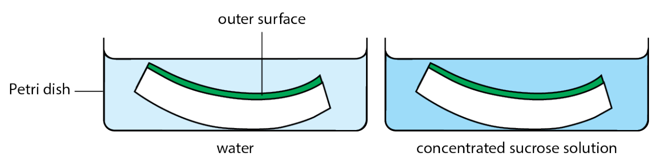


Figure 2.28(b) Cut scape in water and a concentrated solution

Predict what happens to the strip in each solution. Carry out Experiment 2D in the Practical Workbook to find out more.

Let's Investigate 2.7

You are given an experiment to determine the relative concentrations of three sugar solutions A, B and C. You are provided with a spinach stem, 3 cm long, and a scalpel/sharp knife.

1 **The problem**
How to determine the relative concentrations of the three solutions

2 **Some points to consider**
- The different water potentials of the solutions
- The water potential of cell sap
- The skin (epidermis) of the plant material is waterproof.
- Water molecules move from a solution of higher water potential to a solution of lower water potential.

3 **Method**
Describe how you would carry out your investigation.

4 **Results**
Enter your results/observations (including any drawings) below:

Solution A	Solution B	Solution C

5 Determine the relative concentrations of the solutions.

Relative Concentration	Very Dilute	Dilute	Very Concentrated
Solution A			
Solution B			
Solution C			

(Put a tick in the appropriate box.)

6 Explain your answer.

Table 2.2 summarises the key differences between diffusion and osmosis.

Table 2.2 Differences between diffusion and osmosis

Diffusion	Osmosis
Net movement of particles (atoms, molecules, ions)	Net movement of water molecules
Movement of particles from a region of higher concentration to a region of lower concentration, down a concentration gradient	Movement of water molecules from a solution of higher water potential to a solution of lower water potential, down a water potential gradient
Partially permeable membrane not required	Partially permeable membrane required

Let's Practise 2.2

1 Humans store food to see them through times when food is in short supply. Unfortunately, bacteria and fungi attack stored food and make it go bad. One way of preventing this is to store food in strong salt solutions (brine) or sugar solutions (syrups) (Figure 2.29). Suggest with reasons why brine or syrups are used in food preservation.

Figure 2.29

2 An animal cell is placed in a concentrated solution of sugar. Which substance will leave the cell and which will move into the cell? What processes are involved?

Link

Theory Workbook
Worksheet 2B

Disciplinary Idea

Energy
Energy is required during active transport to ensure that substances can be transported against a concentration gradient, which is critical for many biological processes.

2.3 What Is Active Transport?

Learning Outcome

- Define active transport and discuss its importance as an energy-consuming process by which substances are transported against a concentration gradient, as in ion uptake by root hairs and uptake of glucose by cells in the villi.

Living cells are able to absorb certain substances even though these substances are of higher concentration inside the cell than they are in the external environment. This means that the cells are absorbing substances against a concentration gradient (Figure 2.30). Such a process requires energy and is called *active transport*.

Active transport is the process in which energy is used to move the particles of a substance across a membrane against its concentration gradient, that is, from a region where the particles are of lower concentration to a region where they are of higher concentration.

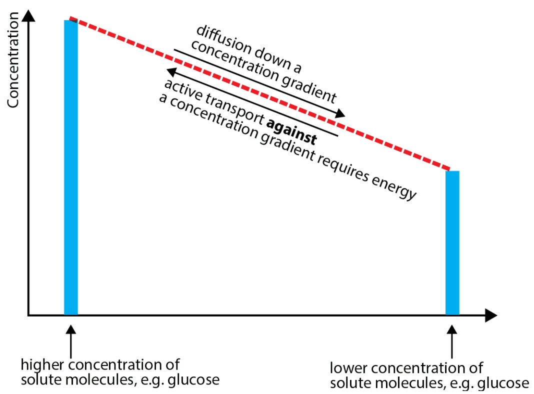


Figure 2.30 Difference between active transport and diffusion

Table 2.3 summarises the key differences between diffusion and active transport.

Table 2.3 Differences between diffusion and active transport

Diffusion	Active Transport
Net movement of particles from a region of higher concentration to a region of lower concentration, down a concentration gradient	Net movement of particles from a region of lower concentration to a region of higher concentration, against a concentration gradient
Energy from respiration not required	Energy from respiration required
Cell membrane not required	Cell membrane required

Link

How do cells of the small intestine carry out nutrient uptake? Read Chapter 5 to find out.

Why is active transport an important process in the kidneys? Read more about it in Chapter 8.

How do root hair cells carry out the uptake of mineral salts? Read Chapter 12 to answer the question.

Where Does Active Transport Occur?

Active transport occurs only in living cells because living cells respire. It is during respiration that energy is released, and part of this energy is used in active transport.

In the human body, examples of active transport include the uptake of glucose by the microvilli of epithelial cells in the small intestine, and from the kidney tubules into the blood capillaries.

In plants, root hair cells can take in mineral salts from the soil solution by diffusion or active transport, depending on the concentration of mineral salts in the soil solution (Figure 2.31).

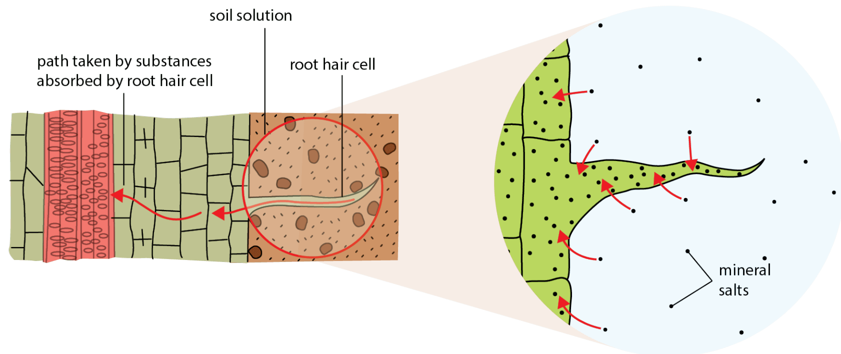


Figure 2.31 Root hair cells take in dissolved mineral salts through diffusion as well as active transport.

Let's Practise 2.3

1 Why does active transport **not** take place in dead cells?
2 Name **three** characteristics that are different between diffusion and active transport.

Link

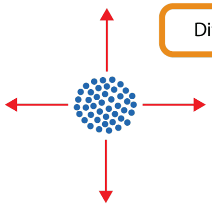
Theory Workbook
Worksheet 2C
Let's Assess
Let's Reflect

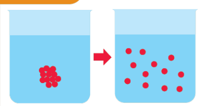
Let's Map It

Movement of Substances Into or Out of Cells

achieved by

Diffusion





which is defined as the

Net movement of atoms, molecules or ions from a region where they are of higher concentration to a region where they are of lower concentration

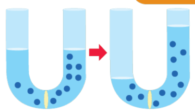
and is different from osmosis as it

- Refers to any substance, gas or liquid
- Does not require a partially permeable membrane

which share similarities as they

- Do not require energy from respiration
- Involve movement of substances down a concentration or water potential gradient

Osmosis

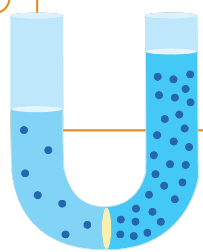


which is defined as the

Net movement of water molecules across a partially permeable membrane, from a region of higher water potential to a region of lower water potential

and is different from diffusion as it

- Refers only to water (solvent molecules)
- Takes place across a partially permeable membrane



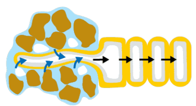
Active transport

which is defined as the

Movement of particles through a cell membrane, from a region of their lower concentration to a region of their higher concentration (against a concentration gradient), using energy from respiration

and is different from diffusion as it

- Requires energy from respiration
- Involves movement of substances against their concentration gradient
- Takes place across a partially permeable membrane



Let's Review

Section A: Multiple-choice Questions

1 Strips of potato tissue were placed in sugar solutions of different concentrations. The percentage change in length of the potato strips is shown in the graph in Figure 2.32.

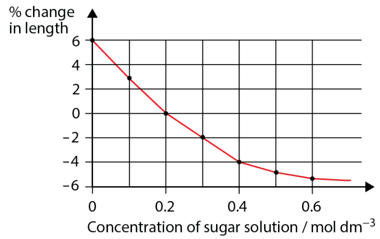


Figure 2.32

Which solution has the same water potential as the cell sap?

A 0.05 mol dm^{-3} **B** 0.1 mol dm^{-3}
C 0.2 mol dm^{-3} **D** 0.4 mol dm^{-3}

2 An apparatus was set up as shown in Figure 2.33. After a few hours, the level of solution in the thistle funnel rose. The water in the beaker turned red.

Which process caused the water in the beaker to turn red?

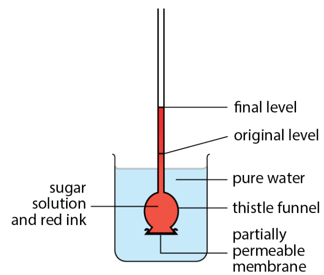


Figure 2.33

A active transport
B diffusion
C gravitational pull
D osmosis

Section B: Structured Question

1 Arrange set-ups X, Y and Z in decreasing order of their water potential gradients between sucrose solutions A, B, C and D in the beakers shown in Figure 2.34.

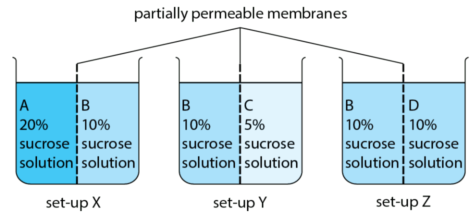


Figure 2.34

Section C: Free-response Questions

1 Define the terms *diffusion*, *osmosis* and *partially permeable membrane*.

2 How does diffusion differ from osmosis?

3 Why do sports drinks have the same water potential as the cells in our body? Suggest what would happen if body cells were in an environment that had:
(a) significantly higher water potential;
(b) significantly lower water potential.

CHAPTER

03 Biological Molecules

What You Will Learn

- What are carbohydrates?
- What are fats?
- What are proteins?

Do you know that marathon runners need to eat a lot of carbohydrates two days before a race? This may include sugary foods. We know that eating too much sugary foods can cause obesity, sometimes even for people who exercise regularly. Why do you think marathon runners still eat these foods?

3.1 What Are Carbohydrates?

Learning Outcomes

- List the chemical elements that make up carbohydrates.
- State that cellulose, glycogen and starch are synthesised from glucose.
- State the main role of carbohydrates as an immediate source of energy in living organisms.
- Describe and carry out tests for starch (using iodine in potassium iodide solution) and reducing sugars (using Benedict's solution).

The Need for Food and Water

All living organisms need food. The food we eat contains nutrients that are essential for us. Nutrients include water, carbohydrates, fats and proteins. Carbohydrates, fats and proteins are three major types of biological molecules found in living organisms. Water is an essential component of all body tissues. About 70% of our body weight is water. Hence, water is extremely important to life.

Helpful Note

Water has several important functions. It dissolves substances for chemical reactions that take place in living things. In plants, water is essential for photosynthesis, to keep cells turgid or firm, and to transport mineral salts. In humans, water helps to regulate body temperature and transport dissolved substances within the body. Drinking enough water is important for various body functions.

Carbohydrates

Figure 3.1 shows food rich in carbohydrates.

Carbohydrates are organic molecules made up of the elements carbon, hydrogen and oxygen. The hydrogen and oxygen atoms are present in the ratio 2 : 1.

For example:

- glucose has the formula $C_6H_{12}O_6$ (ratio of hydrogen to oxygen is 12H : 6O = 2H : 1O)
- sucrose (cane sugar) has the formula $C_{12}H_{22}O_{11}$ (ratio of hydrogen to oxygen is 22H : 11O = 2H : 1O)

Carbohydrates may be classified as single sugars, double sugars or complex carbohydrates (Figure 3.2).

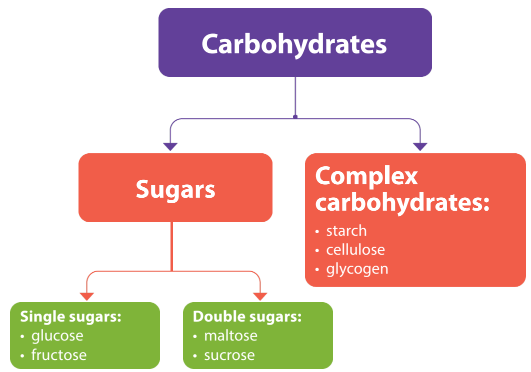


Figure 3.2 Classification of carbohydrates

Figure 3.1 Food rich in carbohydrates

Link
What is water potential? Recall what you have learnt in Chapter 2.

Sugars

Sugars are sweet and soluble in water. When dissolved in water, they will lower the water potential of the solution. Sugars provide us with energy to do work and carry out activities (Figure 3.3).

Figure 3.3 Sugars provide us with energy to do sports.

Single Sugars

A single sugar is the basic unit of carbohydrate. It can pass through cell membranes and be absorbed into the cells.

The common single sugars are **glucose** and **fructose** (refer to Table 3.1). They both have the same chemical formula, $C_6H_{12}O_6$, but their atoms are arranged differently within the molecules. These different arrangements give the sugars different chemical and biological properties.

Table 3.1 Occurrence of single sugars

Single Sugar	Occurrence
Glucose	Found in plants and animals
Fructose	Common in plants, but rare in animals

Glucose is found in plants and animals. Fructose is common in plants but rare in animals. The structure of glucose and fructose can be represented by the diagrams shown in Figure 3.4.

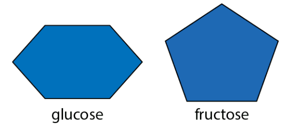


Figure 3.4 Structures of glucose and fructose

Double Sugars

A double sugar is formed when two single sugars are joined together. Common double sugars are **maltose** and **sucrose**.

Maltose (malt sugar) occurs in germinating grains. Maltose consists of two glucose molecules bonded together.

The equation below shows how a maltose molecule can be produced from two glucose molecules.

A sucrose molecule is made up of one glucose molecule and one fructose molecule joined together.

glucose + fructose → sucrose

The structure of sucrose can be represented in a diagram as shown in Figure 3.5.

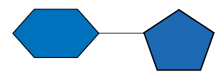


Figure 3.5 Structure of sucrose

A double sugar can be split into two single sugar molecules by using an organic molecule called an enzyme. For example, when a solution of maltose is mixed with the enzyme maltase, glucose molecules are produced.

Link
What are enzymes? Read more about them in Chapter 4.

Link

Chemistry
We learn that a redox reaction is a chemical reaction which involves the oxidation of a substance and the reduction of another substance.

Helpful Note

For a solid food sample, e.g. a peanut, break the sample up to release the cell contents. This can be done by crushing the sample in water using a mortar and pestle. The sample can then be tested.

How Can We Test for Reducing Sugars?

Glucose, fructose and maltose are also known as **reducing sugars**. Reducing sugars will produce a red precipitate when boiled with Benedict's solution (refer to Let's Investigate 3.1). Sucrose is a non-reducing sugar and will not give a red precipitate with this test.

Let's Investigate 3.1

Aim
To test for the presence of reducing sugars in different food samples using Benedict's solution

Procedure
1 Place 2 cm^3 of each food sample into a test-tube (Figure 3.6).
2 Add 2 cm^3 of Benedict's solution to the food sample (Figure 3.7).
3 Shake the mixture and place the test-tube in a boiling water-bath for 2–3 minutes (Figure 3.8).
4 Record the colour of the solution.

Observation
Table 3.2 shows the colour changes observed when carrying out the Benedict's test with increasing amounts of reducing sugar.


Figure 3.6

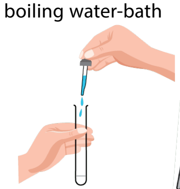


Figure 3.7

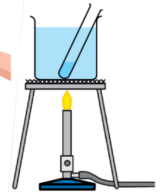


Figure 3.8

Table 3.2 Colour changes with different amounts of reducing sugar

Observation	Amount Present
Solution remained blue	No reducing sugar
Benedict's solution turned from blue to green	Traces of reducing sugar
Benedict's solution turned from blue to yellow or orange	Moderate amount of reducing sugar
Benedict's solution turned from blue to red / Red precipitate formed	Large amount of reducing sugar

Figure 3.9 shows the colour change from blue to red indicating an increasing amount of reducing sugar present in the solutions.


Figure 3.9

Link

Practical Workbook
Experiment 3A

Complex Carbohydrates

What Are Complex Carbohydrates?

A complex carbohydrate is made up of many similar molecules of single sugar joined together to form a large molecule.

Starch, glycogen and cellulose are complex carbohydrates made up of numerous glucose molecules. The glucose molecules are linked in different ways, giving rise to different structures. Hence, starch, glycogen and cellulose have different chemical and biological properties. They also have different roles as shown in Table 3.3.

Table 3.3 Types of complex carbohydrates

Complex Carbohydrate	Structure	Role	Occurrence
Starch	A starch molecule is made up of several thousand glucose molecules joined together.	It is a storage form of carbohydrates in plants. When needed, it can be digested to glucose to provide energy for cell activities.	Found in storage organs of plants, e.g. potato tubers and tapioca
Cellulose	A cellulose molecule is made up of many glucose molecules joined together. The bonds between glucose units are different from that in starch.	The cellulose cell wall protects plant cells from bursting or damage. Cellulose cannot be digested in our intestines. They serve as *dietary fibre* that prevents constipation.	Present in cell walls of plants
Glycogen	Glycogen is a branched molecule. It is made up of many glucose molecules joined together.	It is a storage form of carbohydrates in mammals. When needed, it is digested to glucose to provide energy for cell activities.	Stored in the liver and muscles of mammals

Link

Chemistry
We learn that a polymer is a type of macromolecule formed by many small units called monomers linked together.

Helpful Note

Complex carbohydrates such as starch, cellulose and glycogen have different structures (Figure 3.10).

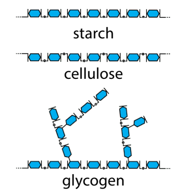


Figure 3.10

Tech Connect

Fibre is found in vegetables and fruits. Fibre cannot be digested and we often find food high in fibre difficult to chew. This poses a problem for the elderly, who may not be able to chew food effectively.


Figure 3.11 Supplement powders of chlorella, wheatgrass and moringa leaf

Enter the technology of soluble fibre supplements! Engineers have applied their knowledge of what roughage can do for our digestive system. They also understand how roughage can exist as fibres that are soluble in water. The result of this is a powdery substance that we can dissolve in water, or even mix with food or with soup and drink down (Figure 3.11). Some supplements are tasteless and odourless, which makes them highly suitable for the taste-conscious consumer.

This is a good example of how engineers create a piece of technology out of what was originally a solution to a problem. The technology comes in the form of an industrial product that is available to the average consumer.

Disciplinary Idea

Energy
Complex carbohydrates are one of the energy stores used by plants and animals.

Glycogen and Starch Are Stores of Glucose

Plants store glucose in the form of starch. Animals cannot make or store starch in their bodies. We get most of our carbohydrates from plants in the form of starch.

In animals, the main store of glucose is glycogen. Hence, glycogen is sometimes called 'animal starch'. In mammals, glycogen is stored mainly in the liver and the muscles (Figure 3.12).

Figure 3.12 Glycogen and starch as stores of glucose

Glycogen and starch are suitable as storage materials in cells because:
- They are insoluble in water, so they do not change the water potential in the cells.
- They are large molecules that cannot diffuse through cell membranes, so they will not be lost from the cell.
- They can easily be easily broken down to glucose when needed, for example, in tissue respiration.
- Their molecules have compact shapes, so they occupy less space than all the individual glucose molecules that make up a glycogen or starch molecule.

Link
How is starch broken down in the gut? Read about it in Chapter 5.

Breakdown of Starch

Starch in the foods we eat may be digested in our alimentary canal. When starch is digested, the bonds within the polysaccharide are broken and the glucose molecules are released.

The enzyme amylase digests starch to form the sugar maltose. Amylase cannot break maltose down to glucose. Maltose is hydrolysed to glucose by another enzyme, maltase. Note that complete digestion of starch gives glucose molecules (Figure 3.13).

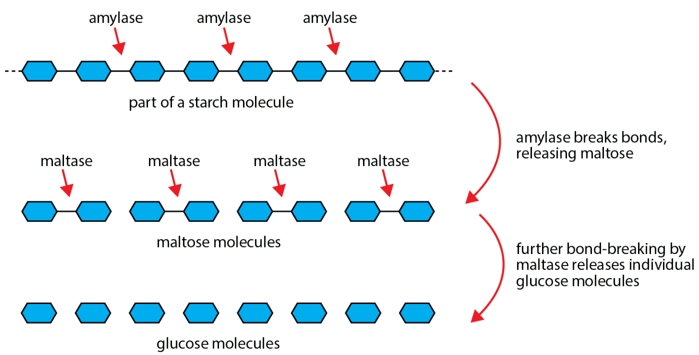


Figure 3.13 Digestion of starch

What Are the Functions of Carbohydrates?

Carbohydrates are needed:
- as a substrate for respiration, to provide energy for cell activities;
- to form supporting structures, for example, cell walls in plants;
- to be converted into other organic compounds such as amino acids and fats;
- for the formation of nucleic acids, for example, DNA;
- to synthesise lubricants, for example, mucus, which consists of a carbohydrate and a protein; and
- to synthesise the nectar in some flowers. **Nectar** is a sweet liquid that plants produce to attract insects.

Link
What is respiration? How are carbohydrates involved in the formation of DNA? Read more about these in Chapters 7 and 14 respectively.

How Can We Test for Starch?

Starch can be detected by the iodine test. A few drops of *iodine solution* to any substance containing starch will produce a blue-black colour.

Let's Investigate 3.2

Aim
To test for the presence of starch in a food sample using iodine solution

Procedure
1 Add a few drops of iodine in potassium iodide solution to a food sample.
2 Record your observations.

Observation
Iodine solution on the potato turns from brown to blue-black upon contact with starch in the food sample (Figure 3.14).

Figure 3.14 Iodine solution on the food sample turns from brown to blue-black.

Link
Practical Workbook
Experiment 3A

Let's Practise 3.1

1 Describe how you would test for reducing sugars in a food sample.
2 Describe how you would test for starch in a food sample.
3 Outline the role of carbohydrates in the life of an organism.
4 What do you think will happen if you add some amylase to a starch solution and test the resulting solution with Benedict's solution after five minutes?

3.2 What Are Fats?

Learning Outcomes

- List the chemical elements that make up fats.
- State that lipids such as fats are synthesised from glycerol and fatty acids.
- State the main roles of fats for insulation and long-term storage of energy in living organisms.
- Describe and carry out tests for fats (using ethanol).

Have you ever put a bowl or pot of soup in the refrigerator and seen the oil on the surface harden into solids? These are oils or fats (Figure 3.15). Where do they come from, and what does the body do with them?

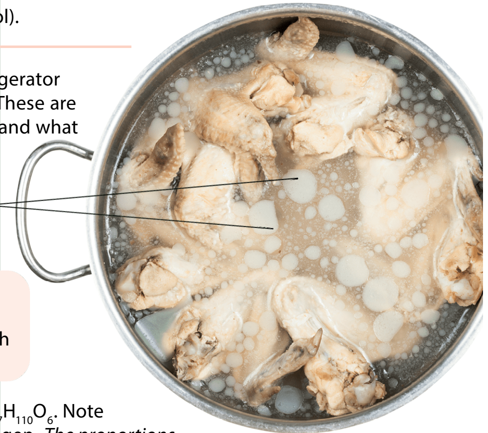


Figure 3.15 The oil on the surface changes from liquid to solid when placed in the refrigerator.

Fats

Fats are a type of lipid.

Fats, like carbohydrates, are organic molecules made up of the elements carbon, hydrogen and oxygen. But unlike carbohydrates, fats contain much less oxygen in proportion to hydrogen.

For example, tristearin (beef fat) has the formula $C_{57}H_{110}O_6$. Note how little oxygen it contains in proportion to hydrogen. *The proportions of the elements that make up fats are not fixed, so there is no general formula for fats.*

Fats can be animal fats or plant fats. Fats are commonly used as a store of energy, especially by animals.

Fats Can Be Broken Down into Fatty Acids and Glycerol

Fats can be broken down into simpler compounds such as fatty acids and glycerol. Refer to the general equation shown in Figure 3.16.

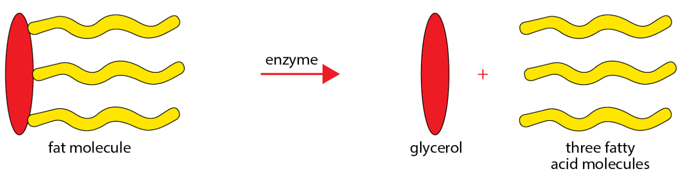


Figure 3.16 A fat molecule breaks down into glycerol and fatty acid.

The reaction involves an enzyme. For example, when tristearin is broken down by the enzyme lipase, stearic acid and glycerol are produced:

$$\text{tristearin} \xrightarrow{\text{lipase}} \text{glycerol} + \text{three stearic acid molecules (an example of fatty acid)}$$

What Are the Sources of Fats?

- Foods that are rich in fats include butter, cheese, fatty meat, olives, many nuts, peas, beans, seeds of castor oil and palm oil (Figure 3.17).
- The meat of most fishes and 'white meats' have relatively less fats. However, some fishes such as herring and salmon have lots of fats.

Figure 3.17 Examples of food rich in fats

What Are the Functions of Fats?

How are some animals able to survive in cold climate, while others are not able to? What are the features common to these animals? How do these features help them to survive in the cold?

Fats function as:

- A source and a long-term storage of energy.
  - They are a suitable long-term storage material because fats have a higher energy value compared to carbohydrates.
- An insulating material that prevents excessive heat loss. For example, animals such as seals have a thick layer of fat (blubber) beneath the skin, which helps to reduce loss of body heat (Figure 3.18).
- A solvent for fat-soluble vitamins and many other vital substances such as hormones.
- An essential part of cells, especially in cell membranes.
- A way to reduce water loss from the skin surface. Glands in the skin secrete an oily substance.
  - This oily substance forms a thin layer over the skin surface, reducing the rate of evaporation of water.
  - The oily substance also reduces the rate of heat loss from the skin.

Disciplinary Idea

Energy

Fats are one of the energy stores of animals. They are required by living organisms to carry out life processes.

Link

How does the body control heat loss? Read more about it in Chapter 9.

Figure 3.18 Seals and polar bears have a thick layer of fat beneath their skin, which helps reduce heat loss.

How Can We Test for Fats?

The *ethanol emulsion test* is a test for the presence of fats. A white emulsion is formed when ethanol and water are added to fats. An *emulsion* is a suspension of small drops of a liquid in another liquid.

Let's Investigate 3.3

Aim
To test for the presence of fats in food samples using the ethanol emulsion test

Procedure
1 On samples in liquid state (e.g. coconut oil):
   (a) Add 2 cm^3 of ethanol to a drop of liquid sample in a test-tube and shake the mixture thoroughly.
   (b) Add 2 cm^3 of water to the mixture and shake the mixture.
   (c) Record your observation.
2 On samples in solid state (e.g. peanut):
   (a) Crush the solid sample into small pieces using a mortar and pestle and place the pieces in a test-tube.
   (b) Add 2 cm^3 of ethanol into the test-tube and shake thoroughly.
   (c) Allow the solid particles to settle. Carefully decant the ethanol (pour off the top layer of ethanol) into another test-tube containing 2 cm^3 of water and shake the mixture.
   (d) Record your observation.

Observation
The white emulsion produced indicates the presence of fats (Figure 3.19).

Figure 3.19 A white emulsion formed indicates the presence of fats. In the absence of fats, the solution will remain clear.

Link
Practical Workbook
Experiment 3A

Let's Practise 3.2

1 List the chemical elements that make up fats.
2 List **three** functions of fats.
3 Describe how you would test for fats in a food sample.

Past to Present

How has our opinion of eating eggs changed over time? In the past, eggs were considered bad for our health and we were discouraged from eating more than two per week. Now, eggs are considered by some nutritionists as the "perfect food". They are believed to contain all the necessary nutrients that are good for our growth and maintenance of the body (Figure 3.20). Eggs also contain cholesterol, which is a type of lipid.

What about the discussion on cholesterol intake? Is the amount of cholesterol found in our blood determined by how much cholesterol we take in from food? Or is cholesterol manufactured by our bodies from other types of nutrients? Are all forms of cholesterol bad for our health?

Our knowledge of nutrients, and the roles they play in our lives, keeps maturing as we gain a better understanding of how our bodies function.

What attitudes should we embrace as we continue to explore this topic and discover more insights on food and nutrients? How should we behave when these insights from the latest research studies contradict what we thought we knew about the topic?

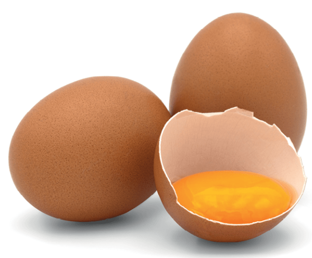


Figure 3.20 Eggs contain protein, healthy fats and many nutrients like vitamins A, D and E, iron and folate.

3.3 What Are Proteins?

Learning Outcomes

- List the chemical elements that make up proteins.
- State that polypeptides and protein are synthesised from amino acids.
- State the main roles of proteins for growth and repair of cells in living organisms.
- Describe and carry out tests for protein (using biuret solution).

Vegetarians are people who choose not to eat meat. Instead of consuming meat as a source of protein, they eat a lot more dairy (milk-based) or soy products. This is because proteins are essential nutrients and so alternative sources of protein must be consumed to ensure a healthy and balanced diet.

Proteins

Proteins are organic molecules made up of the elements carbon, hydrogen, oxygen and nitrogen. Another element, sulfur, may also be present.

Proteins are always present in all cells. Their molecules are the largest and most complicated of all the food substances. Proteins are commonly found in the meat of animals (Figure 3.21).

Amino Acids — the Building Blocks of Proteins

A protein molecule is built up from simpler compounds known as amino acids. An *amino acid* is made up of an amino group (–NH_2), an acidic group (–COOH) and a *side chain* (denoted by R, which may sometimes contain sulfur). The general formula for an amino acid can be written as:

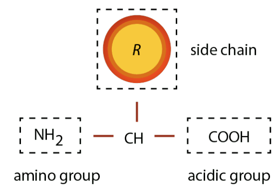


Figure 3.21 Fish meat contains proteins.

There are 20 different naturally occurring amino acids, for example, methionine and valine. They differ because of their different *R* groups. Amino acids are combined in various ways to form millions of different protein molecules, just as the 26 letters of the alphabet can be used to form a very large number of words.

Disciplinary Idea

Structure

Proteins are composed of multiple molecules of amino acids arranged in different ways.

Long Chains of Amino Acids Fold to Give Proteins a Three-dimensional Shape

Many amino acid molecules are joined in a linear manner to form a polypeptide. Polypeptides in turn may be linked up to form an even longer chain of amino acids. A protein molecule is made up of one or more such chains folded together (Figure 3.22). In most proteins, the polypeptide chains are folded into a more complex, three-dimensional shape.

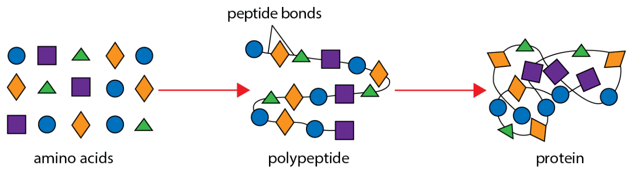


Figure 3.22 Amino acids are joined to form polypeptides, which link up to form even longer chains of amino acids.

Link

Chemistry

We learn that a polymer is a type of macromolecule formed by many small units called monomers linked together.

What Are the Sources of Proteins?

Proteins can be found in both animal and plant foods. Milk, eggs, seafood and meat, such as chicken and lean beef, are some animal foods rich in proteins (Figure 3.23). Plant foods rich in proteins include soya beans, nuts, grains and vegetables such as French beans.

What Are the Functions of Proteins?

Proteins are used in the:
- synthesis of new cytoplasm, for growth and repair of worn-out body cells;
- synthesis of enzymes and some hormones; and
- formation of *antibodies* to combat diseases.

Figure 3.23 Examples of plant and animal proteins

Helpful Note

Children who do not get enough protein may suffer from a protein deficiency disease called kwashiorkor. Such children usually have a pot-belly appearance with scaly, cracked skin.

How Can We Test for Proteins?

Proteins can be detected by the biuret test. The *biuret solution* is a blue solution made up of sodium hydroxide and copper(II) sulfate. It turns violet (deep purple) when proteins are present.

Let's Investigate 3.4

Aim

To test for the presence of proteins in a food sample (e.g. egg white) using biuret solution

Procedure

1 To 2 cm^3 of liquid food sample (e.g. egg white), add an equal volume of biuret solution.
2 Shake well and allow the mixture to stand for five minutes.
3 Record your observation.

Figure 3.24 A violet (deep purple) colour indicates the presence of proteins. In the absence of proteins, the solution will remain blue.

Observation

A violet colour indicates the presence of proteins (Figure 3.24).

Question

What colour changes do you observe when the egg white is mixed with biuret solution?

Link

Practical Workbook

Experiment 3A

Let's Practise 3.3

1 (a) List the chemical elements that make up proteins.
(b) List **three** functions of proteins.
2 Describe how you would test for proteins in a food sample.
3 Food tests were carried out on three different foods, labelled A, B and C. The results of the tests are given in Table 3.4.

Table 3.4 Results of food tests

Test	A	B	C
Add iodine solution	Iodine remains brown	Iodine remains brown	Blue-black colour observed
Heat with Benedict's solution	Red precipitate formed	Red precipitate formed	Solution remains blue
Add biuret solution	Solution remains blue	Violet colour observed	Violet colour observed

(a) Using the results from the table, state what substances are present in each food.
(b) Describe how you would test for fats in a piece of skin from an orange.
(c) Outline the role of proteins in the life of an organism.

Link

Theory Workbook

Worksheets 3A–3B
Let's Assess
Let's Reflect

Biology Connect

Scan the QR code to explore a simulation on testing for nutrients.

How Can We Identify the Different Nutrients Present in Our Food?

You can carry out food tests on a variety of foods, for example, peanut, cucumber, onion, tomato and banana in order to find out what nutrients they contain. The following points in Let's Investigate 3.5 are worth noting.

Let's Investigate 3.5

1 To test a food for presence of reducing sugars or proteins, cut the food into small pieces or grind up the food with a pestle and mortar (Figure 3.25). This helps to break the cells and release the food substances so as to make a concentrated solution for testing.
(a) Place some crushed pieces of food in a test-tube. Add 2 cm^3 of water to the test-tube to dissolve the sugars and proteins in the food.
(b) Decant the solution into another test-tube.
(c) Perform Benedict's or biuret test with the solution. (Refer to Let's Investigate 3.1 and 3.4 respectively.)
2 To test for starch, use the iodine test in Let's Investigate 3.2.
3 To test for fats, use the ethanol emulsion test in Let's Investigate 3.3.

Figure 3.25

Link

Practical Workbook
Experiment 3B

Cool Career

Nutrition Coach

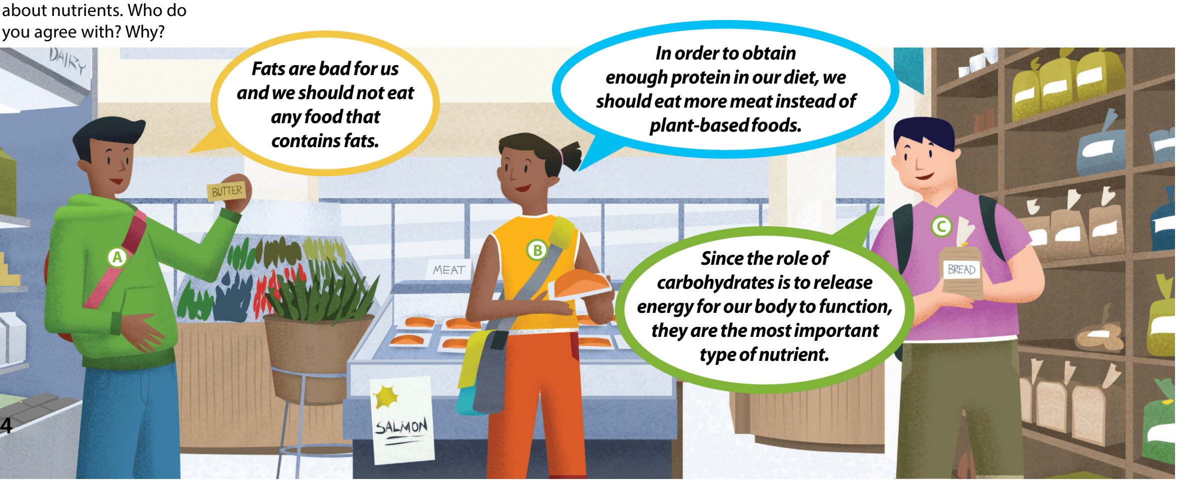
Nutrition coaches work with their clients to guide them towards a healthy lifestyle (Figure 3.26). They help their clients to incorporate healthy eating behaviours into their lifestyle.

To be successful at this, nutrition coaches need to have a good knowledge of what nutrients can do for our health. They must have a good understanding of human behaviour, especially when people are faced with changes in life. They can incorporate healthy diets into the programmes to build the physical fitness of their clients.


Figure 3.26 Nutrition coach and a patient discussing a diet plan

Now, look at Figure 3.27. Do you agree with what is said here? Why or why not?

Figure 3.27 Three friends are having a discussion about nutrients. Who do you agree with? Why?



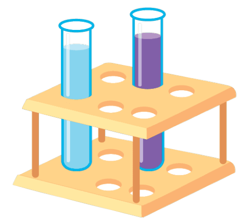
Let's Map It

Biological Molecules

Carbohydrates
- Organic compounds made up of carbon, hydrogen and oxygen, with hydrogen and oxygen atoms present in the ratio 2:1.
- which can be
  - Single sugars
    - Include glucose and fructose
  - Double sugars
    - Include maltose and sucrose
  - which can be identified using → Benedict's test
    - Remains blue in the absence of reducing sugar
    - Turns green, yellow, orange or red, depending on amount of reducing sugar present.
    - Note: Sucrose is a non-reducing sugar.
  - Complex carbohydrates
    - Are made from glucose molecules (e.g. starch, cellulose and glycogen)
    - which can be identified using → Iodine test
      - Remains brown in the absence of starch
      - Turns blue-black in the presence of starch

Fats
- Organic compounds made up of carbon, hydrogen and oxygen, but contain much less oxygen in proportion to hydrogen.
- Fats are synthesised from fatty acids and glycerol.
- which can be identified using → Ethanol emulsion test
  - Remains clear in the absence of fats
  - Forms white emulsion in the presence of fats

Proteins
- Organic compounds made up of carbon, hydrogen, oxygen and nitrogen. Sulfur may also be present.
- Proteins consist of one or more folded polypeptides, each made up of a chain of amino acids.
- which can be identified using → Biuret solution test
  - Remains blue in the absence of proteins
  - Turns violet in the presence of proteins



Let's Review

Section A: Multiple-choice Questions

1 Benedict's test was carried out on four solutions. The colour of the reaction at the end of the test is shown in Table 3.5.

Table 3.5

Solution	Colour
1	Turns green
2	Remains blue
3	Turns brick-red
4	Turns yellow

What is the best interpretation of the results?

	Solution 1	Solution 2	Solution 3	Solution 4
A	0.05% glucose	0.5% starch	1.5% glucose	0.1% glucose
B	1.0% glucose	1.0% starch	1.5% glucose	0.5% glucose
C	0.5% starch	0.05% glucose	0.1% glucose	1.5% glucose
D	1.0% starch	0.5% glucose	0.5% starch	0.1% starch

2 Which of the four substances listed below will give a violet colour when tested with biuret solution?

A butter **B** cellulose
C lean meat **D** glycogen

3 Which nutrient in a person's diet is used to make new enzyme molecules in his body?

A carbohydrate **B** fat
C protein **D** water

Section B: Structured Questions

1 Soldiers in the Arctic, who experience sub-zero temperatures, are recommended a diet rich in a certain nutrient. Such a diet is different from typical diets in tropical regions.
(a) Which nutrient is the Arctic diet rich in?
(b) Give a reason for your answer in (a).

2 (a) State the names of the chemical elements that make up carbohydrates and proteins.
(b) State the basic molecules that are used to make these substances.
(i) starch
(ii) glycogen
(iii) proteins
(iv) fats
(c) State the importance of the following in our diet.
(i) carbohydrates
(ii) fats
(iii) proteins

Section C: Free-response Question

1 Players are advised to eat bananas during long matches in a competition. Why?

CHAPTER

04 Enzymes

What You Will Learn

- What are enzymes?
- What are the characteristics of enzymes?

Isn't it amazing how the toughest stains can be removed from your favourite T-shirts after washing? It is not done with the aid of special powers. It is through "special powders". A lot of washing powders available in the market contain biological catalysts called enzymes. What are enzymes?

4.1 What Are Enzymes?

Learning Outcome

- Describe enzymes as biological catalysts, which are made of proteins and are involved in all metabolic reactions.

Biological Catalysts

Biological catalysts are large biological molecules called enzymes. Most enzymes are found in living organisms.

A **catalyst** is a substance that can speed up a chemical reaction, without itself being chemically changed at the end of the reaction.

For example, potassium chlorate(VII) naturally breaks down (decomposes) to water and oxygen. This reaction occurs very slowly and at a high temperature.

$$\text{potassium chlorate(VII)} \xrightarrow{\text{strong heat}} \text{potassium chloride} + \text{oxygen}$$

When potassium chlorate(VII) is heated strongly in a test-tube, oxygen is given off. Gentle heating only melts the potassium chlorate(VII), and no oxygen is produced. If a little manganese(IV) oxide is added to the melted substance, the reaction is speeded up and oxygen is rapidly given off. Manganese(IV) oxide:
- allows the reaction to be carried out at a lower temperature; and
- speeds up the reaction.

At the end of the reaction, the same mass of manganese(IV) oxide remains, showing that it has not been changed in the reaction. Manganese(IV) oxide is an inorganic catalyst (Figure 4.1). Inorganic catalysts are not destroyed by boiling or by changes in the pH of the solution.

In the same way, complex apparatus and high temperatures are required to break down carbohydrates, fats or proteins in the laboratory. However, cells can carry out these same reactions quite rapidly without having to raise the body temperature. Cells carry out these reactions using catalysts called *enzymes*.

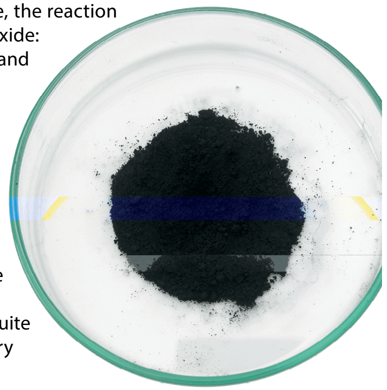


Figure 4.1 Manganese(IV) oxide is an inorganic catalyst.

Enzymes Are Biological Catalysts

Enzymes are proteins that function as biological catalysts. They catalyse or speed up the rate of chemical reactions. They remain chemically unchanged at the end of the reaction.

Enzymes are made up of protein molecules that are folded to take on three-dimensional globular shapes.

Link

What are proteins? Recall what you have learnt in Chapter 3.

Enzymes Lower Activation Energy

Fat in a peanut seed can be broken down by oxidation into carbon dioxide and water. This reaction can take place when the peanut is burnt. In other words, energy in the form of heat must be supplied to start breaking down the fat in the peanut seed.

The energy needed to start a chemical reaction is called **activation energy** (Figure 4.2).

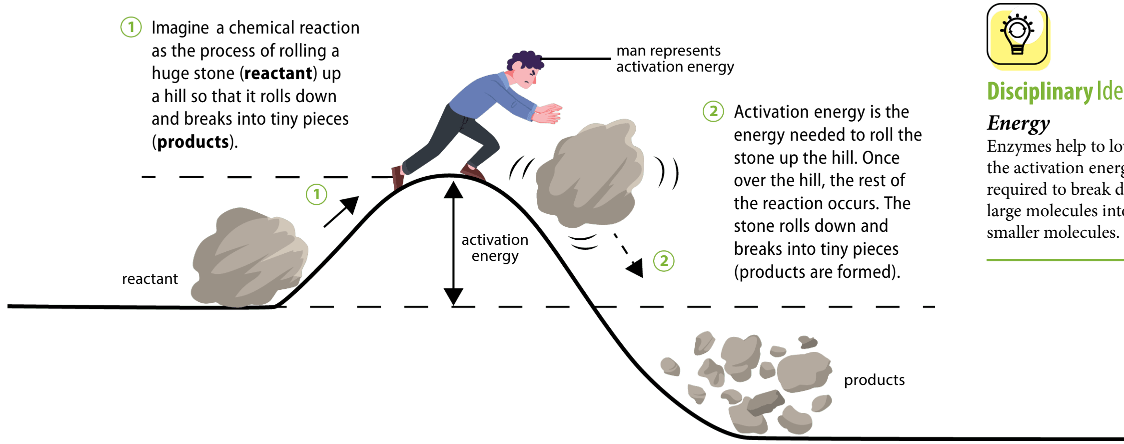
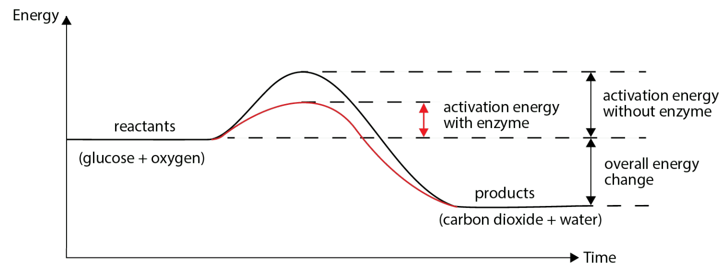


Figure 4.2 Activation energy is needed to start a chemical reaction.

Enzymes provide an alternative pathway with lower activation energy required to start a chemical reaction. They lower the 'height' of the 'hill'. This is shown in the graph in Figure 4.3. Enzymes catalyse chemical reactions. They speed up the rate of chemical reactions by lowering the activation energy.

For example, enzymes speed up the breakdown of glucose to carbon dioxide and water (Figure 4.3) at body temperature (37 °C).



Note: If the overall energy change is negative, there is a decrease in energy content (as shown in graph). If the overall energy change is positive, there is an increase in energy content.

Figure 4.3 Activation energy for an enzyme-catalysed reaction

Disciplinary Idea

Energy

Enzymes help to lower the activation energy required to break down large molecules into smaller molecules.

Link

Chemistry

We learn the effects of catalysts on the rate of reactions. Catalysts provide pathways with lower activation energies that increase rate of reactions. Enzymes are biological catalysts.

What Reactions Do Enzymes Catalyse?

Some food molecules are large and insoluble in water. These molecules cannot diffuse through the cell membrane.

Enzymes are required to break these large molecules into simpler and smaller substances so that they are:
- soluble in water
- small enough to diffuse through the cell membrane (Figure 4.4)

Enzymes that are involved in digestion are known as **digestive enzymes**. Examples of digestive enzymes are:
- amylase — digests starch to maltose
- maltase — digests maltose to glucose
- protease — digests proteins to polypeptides, then to amino acids
- lipase — digests fats to fatty acids and glycerol

Link

What is digestion? Read more about it in Chapter 5.

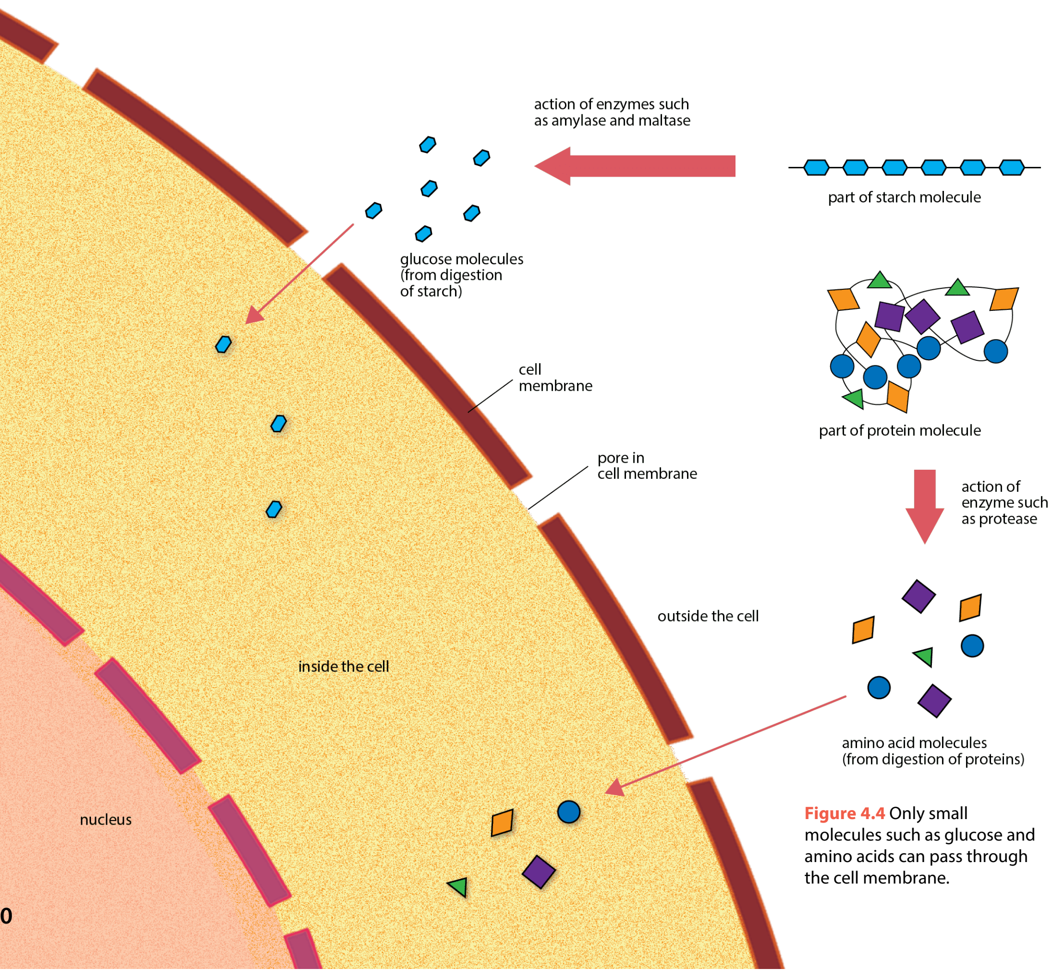


Figure 4.4 Only small molecules such as glucose and amino acids can pass through the cell membrane.

Enzymes Either Build Up or Break Down Complex Substances

Enzymes are also involved in biological reactions. Enzyme-catalysed reactions can be classified into:
- reactions that build up complex substances (anabolic reactions)
- reactions that break down complex substances (catabolic reactions)

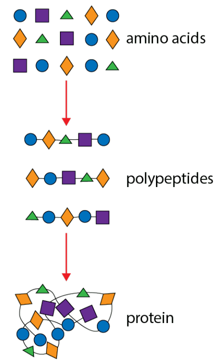
Figure 4.5 shows examples of processes in which enzymes are involved.

Enzymes

Build up complex substances

Cells build up or synthesise complex substances from simpler ones.

For example:
- Amino acids taken into the cells may be used to build up proteins. The cytoplasm contains special enzymes to catalyse such reactions.



Proteins being built up from amino acids

- In photosynthesis, glucose is synthesised from carbon dioxide and water. The chemical reactions involved in photosynthesis are controlled by enzymes.

Break down complex substances

Cells break down complex substances to simple substances.

For example:
- Large molecules in food are broken down into smaller molecules by digestive enzymes.
- In cell respiration, glucose is broken down to release energy and form carbon dioxide and water. This process involves a series of chemical reactions, each catalysed by a different enzyme. The enzymes act together to completely break down glucose.
- Hydrogen peroxide is sometimes produced during chemical reactions in the cells. This substance is toxic to the cells. Both plant and animal cells produce the enzyme catalase to break down hydrogen peroxide to water and oxygen, hence removing the toxic effect. Catalase is especially abundant in blood and the liver of mammals.

Figure 4.5 Two types of enzyme-catalysed reactions

From the above functions of enzymes, it is important to note that *enzymes catalyse practically all the chemical reactions that occur in an organism*. However, enzymes are produced only when they are needed. For example, digestive enzymes are produced only when there is food to digest in the alimentary canal.

How Are Enzymes Named?

Previously, enzymes were simply named by the persons who discovered them. For example, pepsin (a type of protease) was discovered and named by a scientist, Theodor Schwann (Figure 4.6), who was studying digestive processes. 'Pepsin' means 'to digest' in Greek.

However, naming enzymes this way led to a lot of confusion. Nowadays, enzymes are named according to a scientific system. The name of each enzyme:
- shows the substance on which the enzyme acts
- ends in 'ase'

For example, lipase refers to an enzyme that acts on lipids.

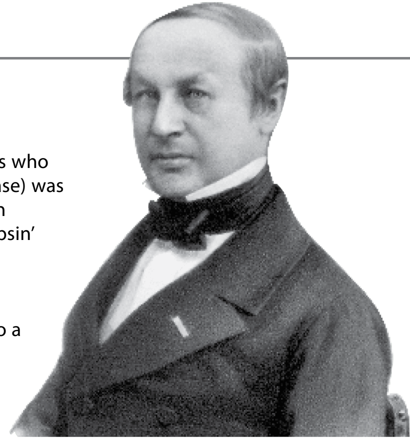


Figure 4.6 Theodor Schwann, German physician and physiologist

How Are Enzymes Classified?

Enzymes are classified according to the chemical reactions they catalyse. For example:
- **carbohydrases** are enzymes that digest carbohydrates
- **proteases** are enzymes that digest proteins
- **lipases** are enzymes that digest fats (lipids)

Let's Practise 4.1

1 (a) What is an enzyme?
(b) What are the **two** types of reactions that enzymes catalyse?
2 The unripe fruit of the papaya tree contains a particular type of digestive enzyme that is often used to soften meat.
(a) Infer the kind of organic molecule that this enzyme acts on.
(b) Suggest how the enzyme may cause the effect of softening of meat.
3 Red blood cells contain a common enzyme known as catalase. What do you think would happen if a drop of blood was added to a solution of hydrogen peroxide?

Link
Theory Workbook
Worksheet 4A

4.2 What Are the Characteristics of Enzymes?

Learning Outcomes
- Explain the mode of action of enzymes in terms of an active site, enzyme–substrate complex, lowering of activation energy and enzyme specificity using the 'lock-and-key' hypothesis.
- Investigate and explain the effects of temperature and pH on the rate of enzyme-catalysed reactions.

Washing clothes in hot water is a traditional way of getting them very clean as the hot water helps in removing grease and dirt from soiled clothes. However, if you are using a biological washing detergent (Figure 4.7), which contains enzymes, it is recommended that you use lukewarm water instead of hot water. Why is this so? It is related to the nature of enzymes and how they function.

Figure 4.7 Enzyme-based biological detergent

How Does an Enzyme Work?

Enzymes are highly specific in their action. For example, amylases only act on starch, and not on proteins or fats. Similarly, proteases act only on proteins, and lipases only on fats. This **enzyme specificity** means that each chemical reaction inside a cell is catalysed by a unique enzyme.

Disciplinary Idea

Structure and Function

The structure of biological molecules affects their functions. For example, the structure of enzymes affects the substrates that can fit into the active site. This affects the reactions they catalyse.

An enzyme is specific in its action due to its three-dimensional shape. The 'lock-and-key' hypothesis explains how the shape of an enzyme affects the way it functions.

'Lock-and-key' Hypothesis

The substances on which enzymes act are called **substrates**. For example, protein is the substrate on which a protease acts.

According to the 'lock-and-key' hypothesis, enzyme reactions depend on the presence of **active sites** (Figure 4.8). Active sites are grooves (depressions) or 'pockets' on the surface of an enzyme molecule into which the substrate molecule(s) with the matching shape can fit — just like a lock and key. The enzyme is the lock, and the substrate is the key.

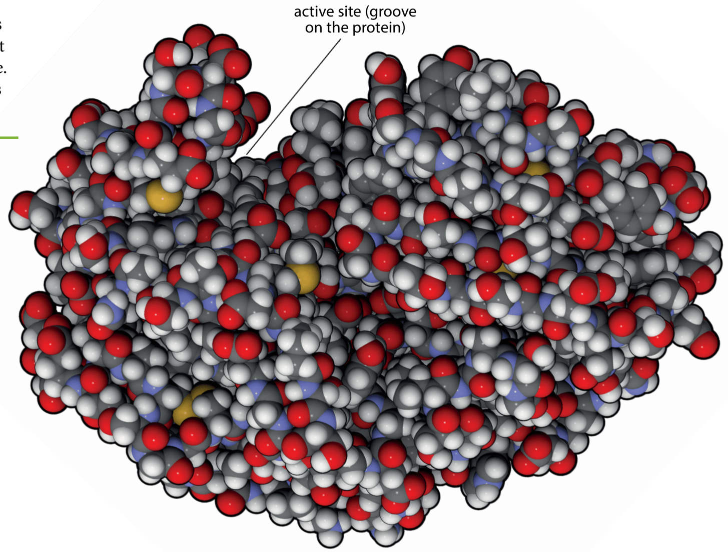


Figure 4.8 Three-dimensional model of enzyme pepsin with its active site

When the substrate binds to the active site of the enzyme, an **enzyme–substrate complex** is formed. It is a temporary molecule formed when substrates bind to the enzyme. Reactions take place at the active site to convert the substrate molecule(s) into product molecule(s). The product molecule(s) separate(s) from the enzyme. The enzyme molecule remains unchanged and is free to combine again with more substrate molecules.

The general equation is: $\mathbf{E + S \rightleftharpoons ES \rightleftharpoons E + P}$

where **E** = enzyme
S = substrate(s)
P = product(s).

The specific nature of an enzyme for its substrate is described in Figure 4.9.

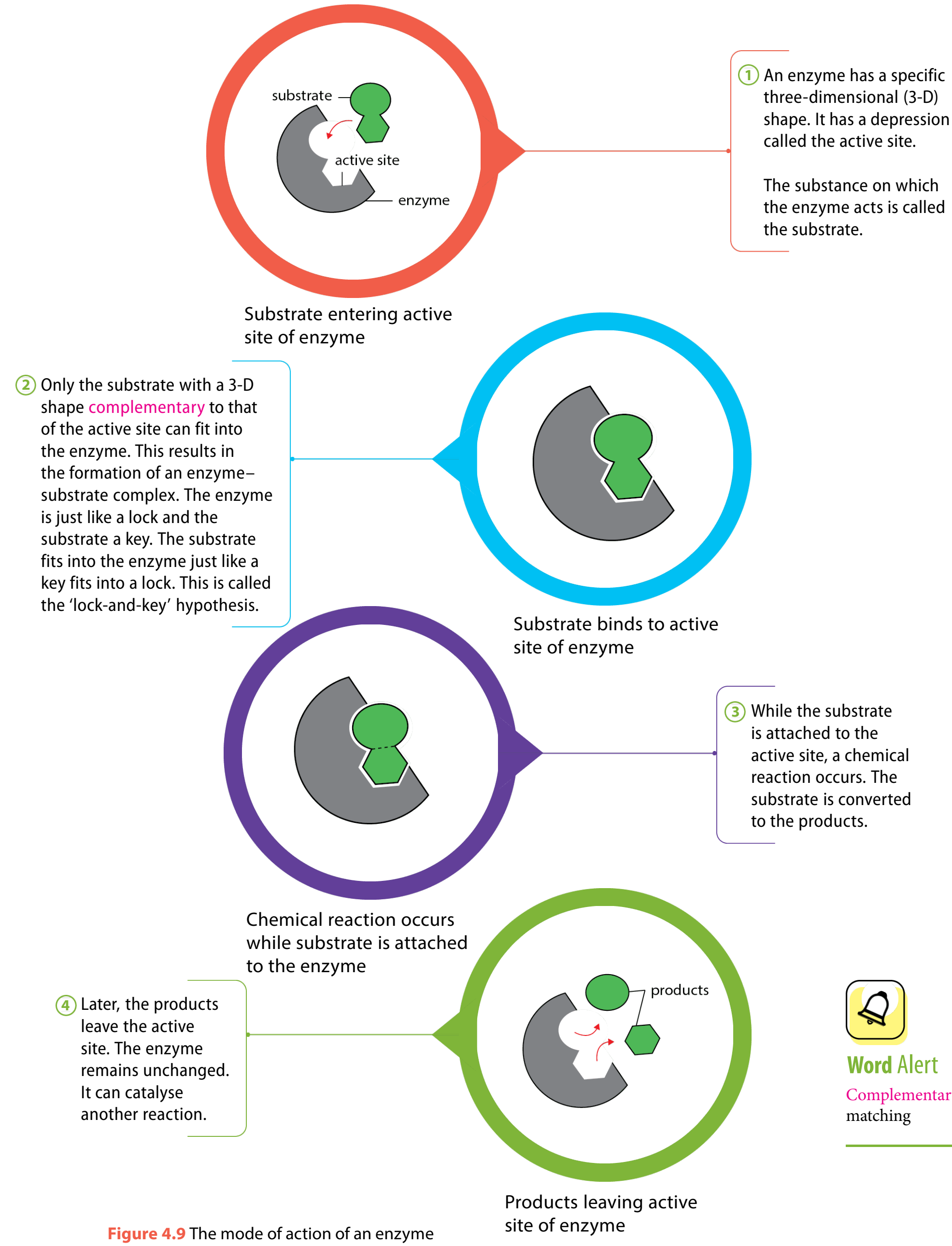


Figure 4.9 The mode of action of an enzyme

Word Alert

Complementary: matching

Characteristics of Enzymes

Enzymes Speed Up Chemical Reactions

Enzymes alter the rates of chemical reactions that occur in a cell. Enzymes speed up a chemical reaction by lowering the activation energy needed to start the reaction.

Enzymes Are Specific in Action

Enzymes have active sites. Only substrates with a shape complementary to the active site can fit into the enzymes. When an enzyme binds to its substrate, it forms an enzyme–substrate complex. However, high temperature, acids and alkalis can affect the shape of an enzyme and consequently its function.

Enzymes Are Required in Minute Amounts and Remain Unchanged at the End of Reactions

Enzymes are very efficient molecules. Since they remain unchanged in the reactions they catalyse, the same enzyme molecules can be used over and over again. Thus, a small amount of an enzyme can catalyse the reaction for a large amount of substrate. For example, just a spoonful of washing powder containing enzymes is enough to wash a large load of clothing.

Enzymes Are Affected by Temperature

Figure 4.10 shows the effect of temperature on the rate of enzyme reaction.

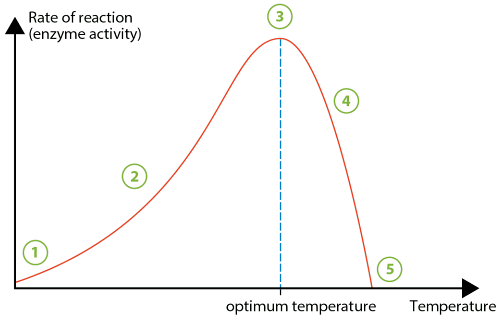


Figure 4.10 Effect of temperature on the rate of enzyme reaction

1 **An enzyme is less active at low temperatures.**
At low temperature, the kinetic energy of molecules is low. Enzyme and substrate molecules move slowly. The rate of the substrate molecules colliding with the enzyme is very low.

2 **As the temperature increases, the rate of enzyme reaction increases.**
Increasing the temperature increases the kinetic energy of molecules. The rate of effective collision (i.e. the rate of substrate molecules colliding and fitting into the active site of the enzyme) is increased. This increases the rate of enzyme-substrate complex formation.

3 **This is the optimum temperature, where the enzyme is most active.**
For most human enzymes, the optimum temperature is about 40–45 °C.

Word Alert
Optimum: most favourable

4 **Increasing the temperature above the optimum causes a rapid decrease in the rate of enzyme reaction.**
The active site of the enzyme molecule begins to lose its original shape and is no longer complementary to the shape of substrate molecules.

5 **At this temperature all the enzyme molecules have been denatured.**
Most enzymes are denatured.

Denaturation is the change in the three-dimensional structure of an enzyme or any other soluble protein, caused by heat or chemicals such as acids or alkalis.

Denaturation results in the loss or alteration of the enzyme's active site (Figure 4.11). The substrate can no longer fit into the enzyme's active site, and no reaction will occur. Hence, when an enzyme is denatured, it can no longer act as a catalyst.

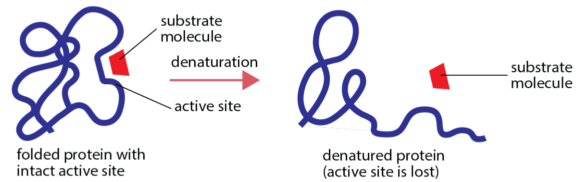


Figure 4.11 At temperatures above optimum, some enzymes are denatured. Enzymes lose their active sites when they are denatured.

Let's Investigate 4.1

Aim
To find out how temperature affects enzyme action

Procedure
1 Label and fill test-tubes A_1, B_1, C_1 and D_1 with 5 cm^3 of starch solution respectively.
2 Label and fill test-tube D_2 with 3 cm^3 of distilled water, and test-tubes A_2, B_2 and C_2 with 3 cm^3 of amylase solution respectively.
3 Set up the experiment (see Figure 4.12 on the next page) by placing the test-tubes into water-baths of varying temperatures as shown in the table below.

Test-tubes	A_1, A_2	B_1, B_2	C_1, C_2	D_1, D_2
Temperature / °C	0	37	100	37

4 After 5 minutes, pour the contents of test-tubes A_2, B_2, C_2 and D_2 into test-tubes A_1, B_1, C_1 and D_1, respectively. Shake to mix the contents in each test-tube. Return the test-tubes to their respective water baths.
5 After 1 minute, remove one drop from each solution with a dropping pipette and put it in the well in the plate provided. Then test it with a drop of iodine solution. (The solution turns blue-black if starch is present.)
6 Continue step 5 at 1-minute intervals until the iodine solution remains brown. This shows that all the starch has been digested.
7 Record the total time (*T*) taken (in minutes) for the starch in each test-tube to be completely digested.

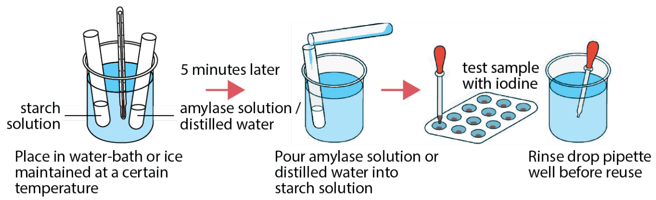


Figure 4.12 Experimental set-up to show how temperature affects enzyme action

Observation

1 The iodine solution turned blue-black when test-tube A_1 was tested for starch at the various 1-minute intervals.
2 The iodine solution remained brown when test-tube B_1 was tested for starch after T minutes.
3 The iodine solution turned blue-black when test-tube C_1 was tested for starch at the various 1-minute intervals.
4 The iodine solution turned blue-black when test-tube D_1 was tested for starch at the various 1-minute intervals.

Conclusion

1 The less time taken to digest starch, the more active the enzyme is. In this investigation, enzyme activity is measured by calculating $\frac{1}{T}$ (the reciprocal of the time taken to digest starch). What can you conclude about the effect of temperature on the activity of amylase from the graph of $\frac{1}{T}$ against temperature?

Link

Practical Workbook
Experiments 4A–4B

Helpful Note

Optimum pH values of some enzymes:
- amylase (a carbohydrase) in saliva: pH 7
- protease in stomach: pH 2
- protease in small intestine: pH 8

Disciplinary Idea

Structure and Function

Enzymes are proteins, and hence are affected by all the conditions that affect proteins, such as temperature and pH. They have optimal ranges of temperature and pH.

Biology Connect

Scan the QR code to explore a simulation on the effects of temperature and pH on the rate of enzyme reaction.

Enzymes Are Affected by pH

Enzymes are affected by the acidity or alkalinity of the solutions in which they act. Some work best in acidic solutions (for example, protease in the stomach), others require alkaline solutions (for example, intestinal enzymes). When enzymes are placed in pH conditions that vary from the optimum, they start to denature. Extreme changes in the acidity or alkalinity of the solutions denature the enzymes.

In Figure 4.13, point M indicates maximum activity of amylase at a pH of about 7 (optimum pH). As the solution becomes acidic (from pH 7 to 5) or alkaline (from pH 7 to 9), its activity decreases. At pH 4 or above pH 9, the enzyme is completely denatured.

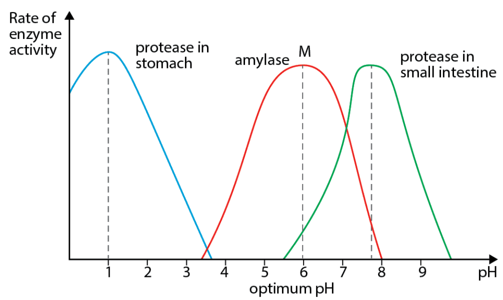


Figure 4.13 Effect of pH on the rate of reactions catalysed by different enzymes

Tech Connect

Some COVID-19 vaccines need to be stored at low temperatures for them to be effective. In some instances, the vaccines need to be stored at temperatures as low as −70 °C.

At this very low temperature, enzymatic reactions that could break down the mRNA (a type of genetic material) in the vaccine are literally frozen to a halt. Scientists and engineers thus need to design, construct and use special freezers that have the ability to maintain such sub-arctic temperatures. They also need to design and construct containers that can store and transport large quantities of the vaccines across the world, from the place where it is manufactured to reach different countries.

These special freezers and containers are examples of technology in action. Engineers apply their knowledge in cooling systems to design and build machines that work to prevent enzymatic reactions on the vaccine ingredients during storage and transport (Figure 4.14).

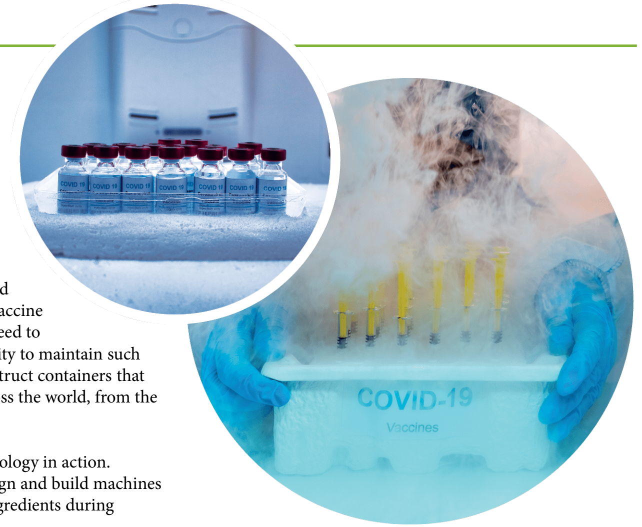


Figure 4.14 Storage of Covid-19 vaccine in freezers

You have learnt how enzymes break down large molecules in food into smaller molecules. Now look at Figure 4.15. What are your views on the statements made by the three people?

Figure 4.15 Three people are discussing the effect of enzymes on silk clothing. What is your view?

The experiment in Let's Investigate 4.2 is based on the fact that egg albumen (egg white) contains protein. Protease is a protein-digesting enzyme produced by the stomach. This experiment is designed to test how pH affects the activity of pepsin.

Let's Investigate 4.2

Aim

To investigate how pH affects enzyme action

Procedure

1 Label four test-tubes A, B, C and D, respectively.

2 Fill the four test-tubes as follows:

Table 4.1

Test-tube	Contents
A	a piece of boiled egg white + 10 drops dilute hydrochloric acid + 3 cm^3 protease found in the human stomach
B	a piece of boiled egg white + 10 drops dilute hydrochloric acid + 3 cm^3 distilled water
C	a piece of boiled egg white + 10 drops dilute sodium carbonate + 3 cm^3 protease found in the human stomach
D	a piece of boiled egg white + 10 drops distilled water + 3 cm^3 protease found in the human stomach

Observation and Discussion

1 Which test-tube is protease active in? What would be observed in this test-tube?

2 What are the purposes of test-tube B and test-tube D?

Link

Practical Workbook
Experiments 4C–4D

Let's Practise 4.2

1 Figure 4.16 represents the action of an enzyme.

(a) Name **two** properties of enzymes that are illustrated in the figure.
(b) State **two** other features, not necessarily shown in the figure.

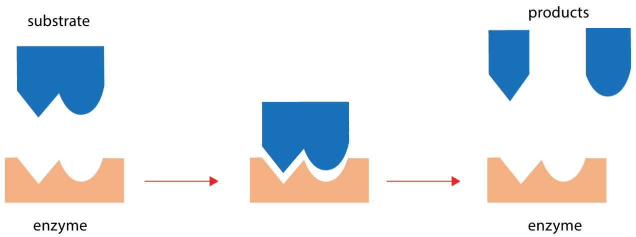


Figure 4.16

2 What is the process of denaturation in enzymes?

Link

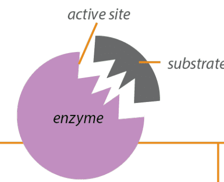
Theory Workbook
Worksheet 4B
Let's Assess
Let's Reflect

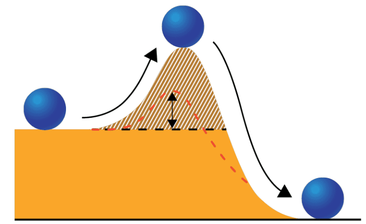
Let's Map It

Enzymes

are

Biological catalysts





with **Functions** *which include*
- Digesting large food molecules into smaller molecules
- Breaking down food substances in cells to release energy (cellular respiration)
- Building up or synthesising complex substances
- Breaking down toxic substances in cells

with **Characteristics** *which include*
- Speeding up chemical reactions without being chemically changed
- Being required in small amounts
- Being highly specific
- Working best at an optimum temperature and pH
- Catalysing reversible reactions

with a **Mode of action** *which includes*
- Providing an alternative pathway with lower activation energy required for a reaction
- Interacting with the substrate according to the 'lock-and-key' hypothesis to form an enzyme-substrate complex

classified by the **Type of reaction catalysed** *which includes*
- Carbohydrases that digest carbohydrates
- Proteases that digest proteins
- Lipases that digest fats (lipids)

that can be affected by

Changes in temperature or pH
- Increasing the temperature increases the rate of enzyme reaction until the optimum temperature is reached.
- Increasing or decreasing the pH from the optimum decreases enzyme activity.
- Enzyme denaturation takes place when there are extreme changes in pH and at a temperature above the optimum.