

Part I

Unit 1: Cells and multicellular organisms

Topic 1

Cells as the basis of life

1.1 Prokaryotic and eukaryotic cells

1.1.1 Cells: a general overview

KEY POINT :

Note that the first part of the syllabus (cell membrane) is located after our introduction to prokaryotic and eukaryotic cells. It just fits better to talk about what the cell needs, *then* learn how cells obtain these things through the cell membrane!

Probably one of the most fundamental aspects of biology is the study of **cells**.

The **cell theory** states three key principles, which will help you to gain an understanding and appreciation for cells.

1. All living things are composed of cells.
2. Cells are the smallest living organisational units.
3. All cells come from pre-existing cells (this is known as **biogenesis**).

You should memorise these three key points, as they are foundational pieces of information which will be built upon as you further your knowledge of biology.

SCIENCE AS A HUMAN ENDEAVOUR :

The study of cells is called **cytology** and often involves the use of microscopes in order to identify types of cells and observe the various cellular structures within them. Over centuries of using microscopes to observe cells, scientists have been able to slowly develop the three key ideas that make up the cell theory through the advancement of microscopy. For example, the concept of biogenesis could only have been discovered by observing cell division under a microscope! So, essentially everything we know about cytology is thanks to the advancement of microscopy!

All cells have a variety of different functions, thus, they each require different resources for survival. In general, however, there are **five main requirements** for cell survival that apply to almost every cell.

These are:

1. **Energy source**
 - Light energy: energy obtained from sunlight
 - Chemical energy: energy attained from consumption
2. **Matter**
 - Gases such as oxygen (O_2) and carbon dioxide (CO_2)
3. **Nutrients**
 - Simple nutrients (i.e. monosaccharides, disaccharides, polysaccharides)
 - Complex nutrients (i.e. amino acids, fatty acids, glycerol, ions, water, and nucleic acids such as DNA and RNA)
4. **Removal of wastes**
 - Urea, ammonia, uric acid, CO_2 , O_2 , water, ions, metabolic heat (body heat), etc.
5. **Favourable environmental conditions**
 - Tolerance ranges: all cells have tolerance ranges, only within which they can survive (i.e. temperature, pH, etc.)
 - Availability of resources

All cells contain a variety of specialised **organelles**, each of which perform critical biochemical processes which allow for the maintenance and survival of the cell.

Organelle	Function
Nucleus	Contains the cell's DNA (genetic code), surrounded by a double-layered membrane called the nuclear envelope . Within the nucleus is the nucleolus , which is where ribosomes are assembled.
Ribosomes	Sites of protein synthesis whereby mRNA is translated into proteins. Ribosomes are either bound to RER (see below) or floating free in the cytoplasm.
Endoplasmic reticulum (ER)	Network of intracellular membranous sacs (called cisternae) and tubules which link with the cell membrane and other membranous organelles, including the nucleus. There are two types of ER, smooth ER (SER) and rough ER (RER) . <ul style="list-style-type: none"> – SER contains enzymes involved in the synthesis of molecules other than proteins, such as phospholipids and steroids. – RER is studded with ribosomes which produce proteins. Once the proteins are made, enzymes in the ER add sugar molecules to form glycoproteins. Then, from the RER, proteins move into the Golgi apparatus for export out of the cell.
Golgi apparatus	Stack of flattened cisternae which, unlike the RER, are unconnected. Transport vesicles form at each cisternae to transport proteins made by the RER into the cytosol or out of the cell via a process called exocytosis .
Mitochondria	Double membrane-bound organelles which are the sites of aerobic respiration, whereby ATP is produced.
Lysosomes (only animal cells)	Specialised vesicles which contain enzymes that digest (break down) waste or unwanted materials.

1.1.2 Comparing prokaryotic cells and eukaryotic cells

All cells can be sorted into two main types: **prokaryotic** cells (called **prokaryotes**) and **eukaryotic** cells (called **eukaryotes**). Both prokaryotic and eukaryotic cells share similar characteristics, which points to a past common evolutionary relationship. However, there are also key differences between both, which are important to grasp.

MEMORY PROMPT :

What are the key similarities and differences between eukaryotic and prokaryotic cells?

Prokaryotic cells	Eukaryotic cells
No nuclear membrane (circular DNA)	Nucleus-bound DNA
Organelles free in cytoplasm	Membrane-bound organelles
Small size and less complex	Generally larger and more complex
Large surface area: volume ratio	Smaller surface area: volume ratio
Can only be unicellular (composed of a single cell)	May be unicellular or multicellular (composed of a single cell or many cells)

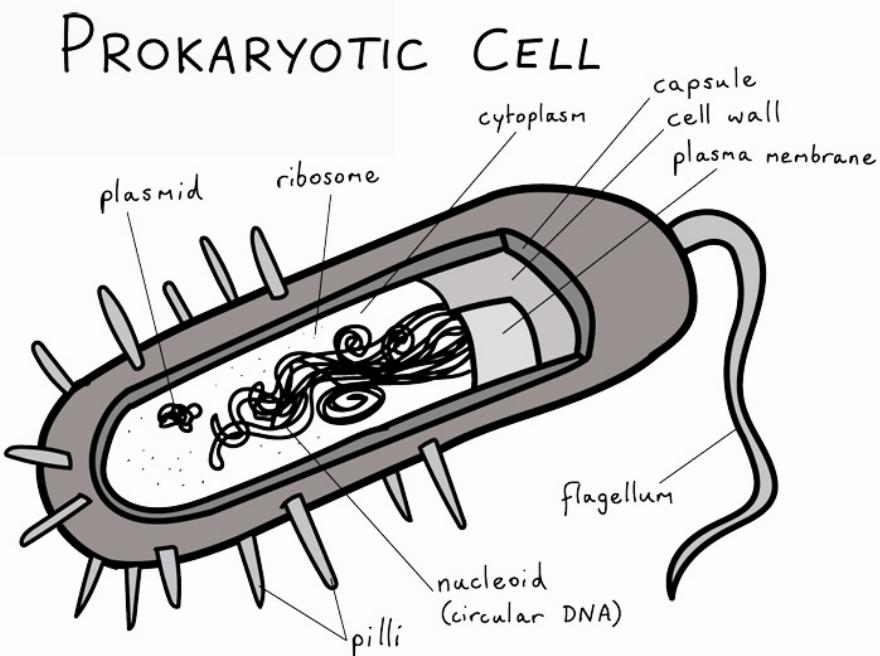
1.1.3 Prokaryotic cells

Prokaryotic cells are different from eukaryotic cells in that they are **less complex** and generally require **fewer resources** and perform **fewer functions**.

MEMORY PROMPT :

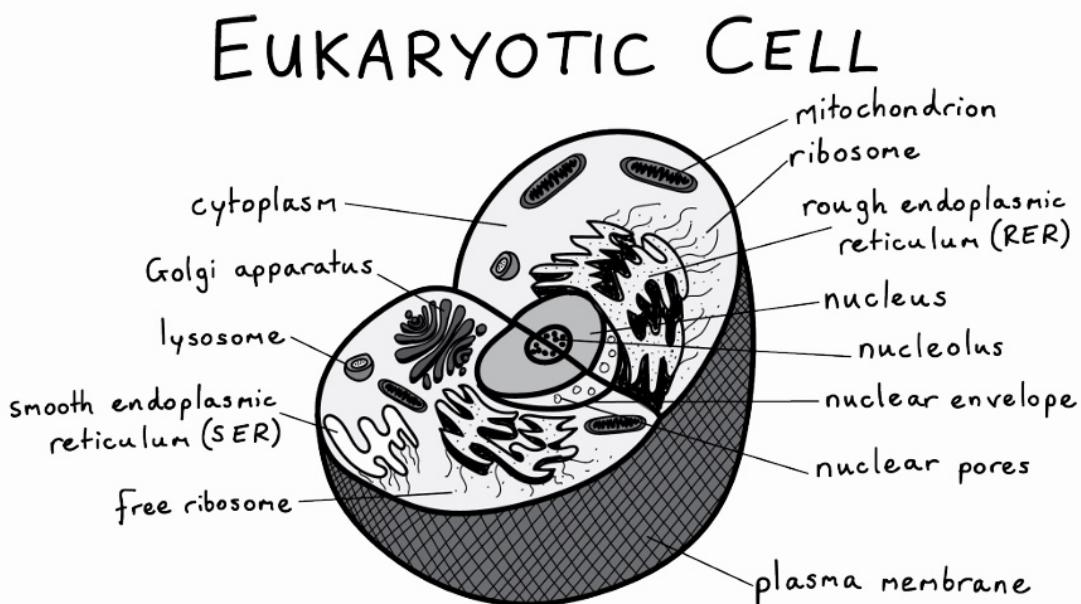
The key elements of a prokaryotic cell are:

- No nucleus; DNA usually contained in a circular chromosome or nucleoid (within cytoplasm)
- Organelles, like plasmids, reside in cytoplasm, and are not membrane-bound
- Cell wall and plasma membrane
- Ribosomes
- Flagellum (for locomotive purposes)



1.1.4 Eukaryotic cells

Eukaryotic cells are generally **larger and more complex** than prokaryotic cells. This complexity also means that eukaryotes are capable of **more advanced processes**, so it is expected that eukaryotes would have more **highly specialised organelles** to facilitate more advanced biochemical processes.



Some of these important biochemical processes that eukaryotes must be able to perform are as follows:

Biochemical process	Area of occurrence	Microscopic picture of organelle
Photosynthesis (plants only)	Chloroplasts (plants only)	
Cellular respiration	Mitochondria	
Synthesis of proteins	Rough endoplasmic reticulum (ribosomes)	
Synthesis of carbohydrates, lipids and steroids	Smooth endoplasmic reticulum	
Synthesis of pigments, tannins and polyphenols	Plastids (plants only)	
Removal of cellular products and waste	Lysosomes	

Image sources:

Chloroplast: Yuv345 / Wikimedia Commons / CC BY-SA 4.0 https://upload.wikimedia.org/wikipedia/commons/e/e0/Lettuce_Chloroplast_STEM.jpg

Mitochondria: University of Toronto Biochemistry <http://biochemistry.utoronto.ca/wp-content/uploads/2014/09/mitoEM.jpg>

Rough endoplasmic reticulum: Peter Takizawa, Yale Department of Medical Studies [http://medcell.med.yale.edu/histology/cell_lab/ rough_endoplasmic_reticulum_em.php](http://medcell.med.yale.edu/histology/cell_lab/rough_endoplasmic_reticulum_em.php)

Smooth endoplasmic reticulum: University of Leeds https://www.histology.leeds.ac.uk/cell/cell_organelles.php

Plastids: Source: Dr. phil.nat Thomas Geie / Wikimedia Commons / CC BY-SA 3.0 <https://commons.wikimedia.org/wiki/File:010-Sol-tub-40xHF-Gewebe.jpg>

Lysosomes: Source: The McGraw-Hill Companies, Inc © 2006 <http://dehistology.blogspot.com/2011/06/lysosomes.html>

MEMORY PROMPT :

The key elements of a eukaryotic cell are:

- Larger and more complex
- Nucleus
- DNA encased in chromosomes inside nucleus
- Mitochondria
- Membrane-bound organelles

1.2 Cell membrane

1.2.1 Plasma membrane

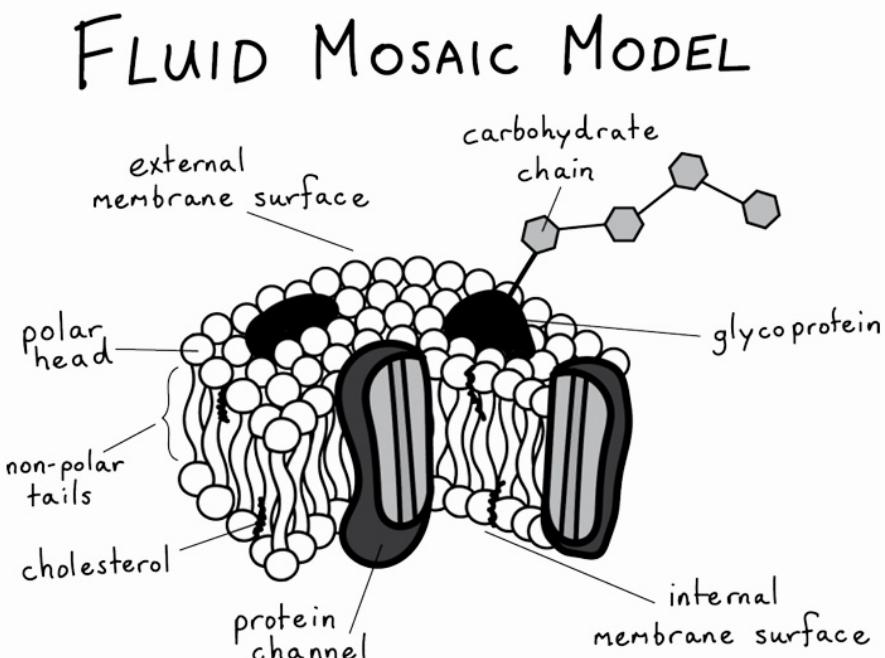
Cells exist in a watery environment called **extracellular fluid**, which is in constant contact with the membrane surrounding the cell, called the cell's **plasma membrane**. This membrane is **semi-permeable** in nature, which means it can allow certain materials to pass through it and into the cell's **intracellular fluid** (also called **cytosol**), and waste products to pass out of the cell, into the extracellular fluid. This **plasma membrane** provides a crucial connection between the intracellular and extracellular environment of the cell itself, without completely isolating the cell. Thus, the cell membrane is a semi-permeable, flexible covering around the cell which protects it and contains its organelles, while simultaneously facilitating the movement of materials into and out of the cell via various channels studded throughout the membrane.

KEY POINT :

Cytosol shouldn't be confused with cytoplasm:

- **Cytoplasm:** encompasses all the contents inside the cell membrane (i.e. cytosol and organelles), besides the nucleus.
- **Cytosol:** is the liquid portion of the cytoplasm; the intracellular fluid.

A great way to visualise the cell membrane and all of its components is to use the **fluid mosaic model**, which denotes a dynamic membrane composed of two distinct layers and studded with proteins. I would recommend practising drawing a simplified version of this model, since you will most likely be asked to recall several components of the cell membrane during exams, so using a visual aid like this is great for prompting your memory.



Key features of the fluid mosaic model

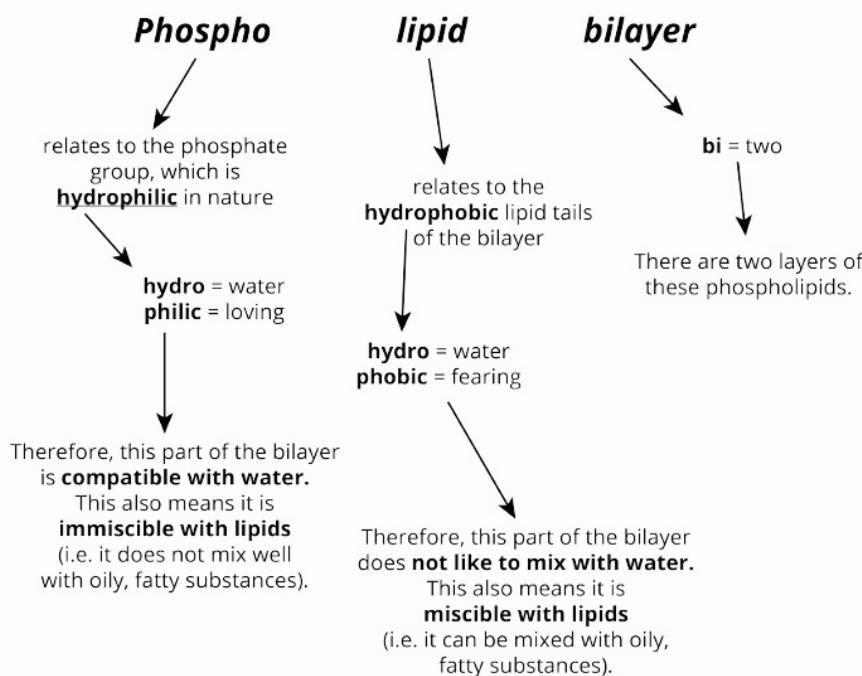
- **Phospholipid bilayer:** two layers of phospholipid molecules (clearly showing the polar, hydrophilic heads and non-polar, hydrophobic tails) which forms what's known as the phospholipid bilayer.
- **Proteins:** (see page 16 for a comprehensive list of these).
- **Carbohydrates:** when carbohydrates are linked to protruding proteins, they are called **glycoproteins**. When they are linked to lipids in the membrane, they are called **glycolipids**. These both play a role in recognition and adhesion between cells, and in the recognition of antibodies, hormones, and viruses.
- **Cholesterol:** a type of fatty molecule existing between the molecules of the phospholipid bilayer. Its role is to stabilise the membrane without affecting its overall fluidity, and reduce the permeability of the membrane to small water-soluble molecules.

SCIENCE AS A HUMAN ENDEAVOUR :

In 1972, **Singer and Nicolson** were first responsible for describing the **fluid mosaic model** of the phospholipid bilayer, and established that it was not rigid but rather dynamic and complex, embedded with protein channels and floating particles, and capable of allowing diffusion to occur through it. Now widely accepted in the scientific community, research of this model is ongoing in order to better understand its components, such as the structure of protein channels.

Now that we know what the fluid mosaic model is about, let's break down the term **phospholipid bilayer** into its substituent parts, so that it doesn't sound so complicated.

Simply, the phospholipid bilayer is a semi-permeable barrier made up of *two layers* of phospholipid molecules, each consisting of a **hydrophilic head** and **two hydrophobic tails**. Again, sounds complicated, but we'll break it down.



So, now we know that we have two main sections of the bilayer, which both interact with water and lipids differently. This is critical information because the materials that cells need to survive come in a variety of different forms; some may interact better with the hydrophilic heads, and others may interact only with the hydrophobic tails.

Therefore, suppose your cells required a substance that was hydrophilic in nature, for example, a hydrophilic hormone. This would be problematic since it would be unable to cross through the water-fearing tails of

the bilayer, right? Luckily, your cells have systems in place to avoid such a predicament. This is where the various **proteins** that stud the phospholipid bilayer come into play.

These have a variety of names depending on their individual function and relative size.

Integral proteins: are proteins whose position is permanently fixed in the cell membrane. You can think of these as 'full-time employees' of your cell membrane!

- When integral proteins span both layers of the phospholipid bilayer (passing through the hydrophobic tails and peeking atop the hydrophilic heads), they are also called **transmembrane proteins**.
- Transmembrane proteins are super important because they provide a direct travel route between the intracellular and extracellular environment of your cells.

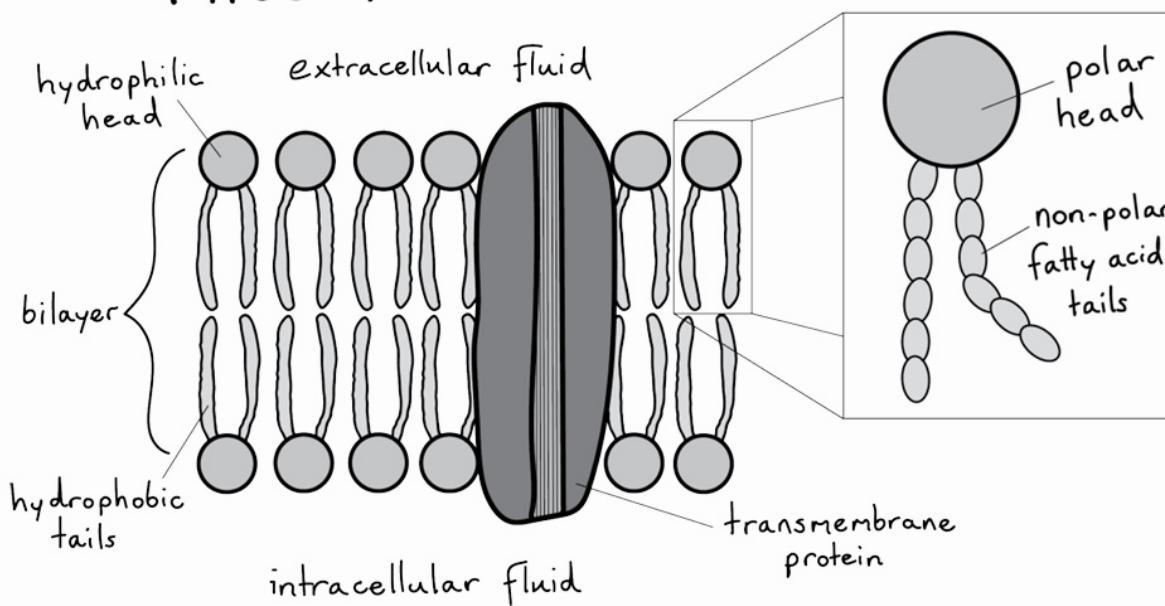
Transmembrane proteins have a variety of critical functions:

- Transport:** they can act as transport channels to transport molecules and ions through the membrane. For example, a hydrophilic molecule or one that is too big to fit through the membrane can use these protein channels as a mode of entry.
- Enzymatic activity:** they can act as **enzymes**, meaning they can catalyse reactions and cause specific reactions to occur.
- Signal transduction:** this means that a transmembrane protein can act as a receptor that can interact with signalling molecules to transmit signals from outside the cell to the inside.
- Cell-cell recognition:** they can function in cell–cell recognition, allowing a cell to distinguish one type of neighbouring cell from another.
- Intercellular joining:** they can connect cells to each other.
- Attachment to the cytoskeleton and extracellular matrix:** this means they can increase the structural integrity of the cell by anchoring it to the cytoskeleton and extracellular matrix.

Peripheral proteins: are proteins that are only a temporary part of the cell membrane. You can think of these as 'part-time or casual employees' of your cell membrane!

- The purpose of these proteins is to bind to integral proteins or penetrate into either the intracellular surface or extracellular surface of the cell membrane.

PHOSPHOLIPID BILAYER



1.2.2 Crossing the plasma membrane

As mentioned before, the semi-permeable plasma membrane provides a point of access for important materials to enter and exit the cell via transmembrane proteins. This occurs through a variety of methods, depending on the molecule's properties, such as **size, charge, polarity, and solubility**.

There are two main types of transport across the plasma membrane: **passive** and **active transport**. These differ by whether or not energy is required as an input for the process to occur.

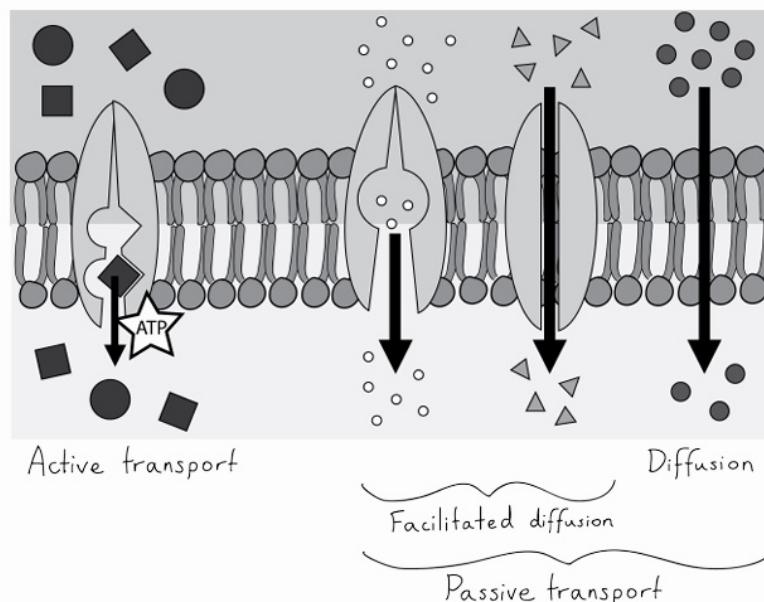
Passive transport

This occurs when **no input of energy** is required for the molecule to pass across the membrane. We'll go through the three main types of passive transport here: **diffusion**, **facilitated diffusion**, and **osmosis**.

- **Diffusion:** is the process whereby particles in a solution move from an area of *high* concentration to an area of *low* concentration (i.e. along/with the concentration gradient). There are three main factors that affect the rate of diffusion:
 - Concentration: the rate of diffusion *increases* as the difference in concentration *increases*.
 - Temperature: the rate of diffusion *increases* as the temperature *increases* (because the particles move faster with greater *kinetic energy*).
 - Particle size: the rate of diffusion *increases* as the size of the particles *decreases*.
- **Facilitated diffusion:** is the type of diffusion whereby proteins channels are used by the cell (without expending energy) to allow certain molecules to travel across the membrane which would otherwise have been impermeable to such materials. There are two main types of membrane transport proteins used in facilitated diffusion:
 - Channel proteins: act like pores in the membrane, which open and close to encase specific substances – usually water-soluble (hydrophilic) polar particles, such as ions.
 - Carrier proteins: change their shape to conform and bind to the molecules being transported across the membrane, after which they return to their original shape.
- **Osmosis:** is the diffusion of **water molecules** across a semi-permeable membrane, whereby water moves from an area of *high* to *low* water concentration (or from *low* solute concentration to an area of *high* solute concentration, thus diluting the concentrated solution). Diffusion occurs down water's concentration gradient (known as the **osmotic gradient**) using pressure known as **osmotic pressure**.

Active transport

In contrast to passive transport, active transport across the plasma membrane **requires an input of energy** to occur. Molecules move against the concentration gradient, from an area of *low* to *high* concentration, requiring the expenditure of energy.



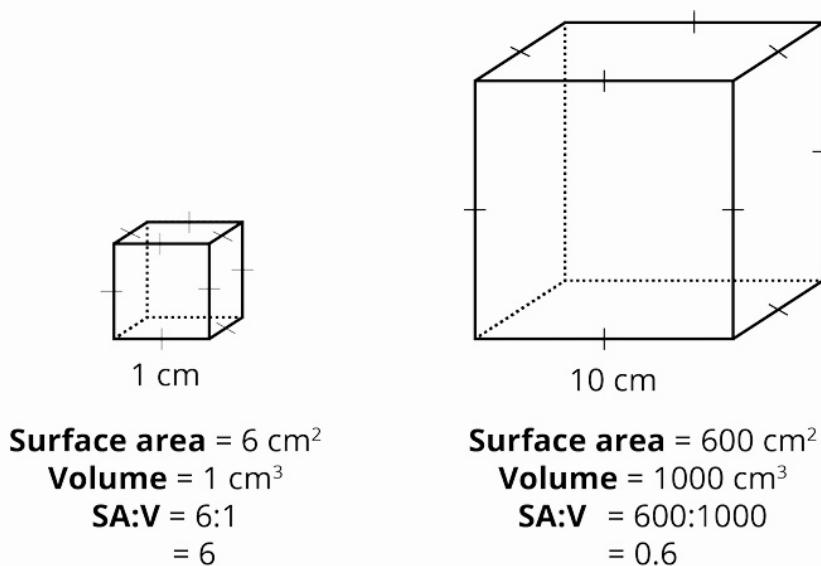
Bulk transport

- **Exocytosis:** refers to the movement of substances **out** of the cell, from the cytoplasm to the extracellular fluid. This requires the use of a **transport vesicle**, which encloses the waste material, fuses with the membrane, and then breaks down to release the materials outside the cell.
- **Endocytosis:** is the reverse of exocytosis, and is the movement of substances **into** the cell, from the extracellular fluid into the cytoplasm.
 - **Pinocytosis:** the entry of small-substances contained in extracellular fluid, carried by a vesicle.
 - **Phagocytosis:** the entry of large particles engulfed by a vesicle

As we've explored already, the cell membrane has a special design which equips it with the crucial ability to transport materials between the internal and external environment of a cell. Specifically, the *rate* at which these materials are exchanged is heavily influenced by the *surface area* of the surrounding membrane.

For instance, larger cells, which have greater metabolic needs, will obviously have a greater capacity for exchanging nutrients and waste into and out of the cell, respectively.

However, the **surface area to volume (SA:V)** relationship dictates that exchange will actually occur at a slower rate due to the large size of the cell, which is disproportionate to its volume. This may be a difficult concept to wrap your head around, but if you think about it using a model it will become much simpler.



A 1 cm cube will have a surface area of 6 cm^2 ($1 \text{ cm} \times 6$ sides), while still retaining a volume of 1 cm^3 ($1 \text{ cm} \times 1 \text{ cm} \times 1 \text{ cm}$). Thus, the surface area to volume ratio is 6:1 or simply 6.

Conversely, a 10 cm cube will have a surface area of 600 cm^2 ($10 \text{ cm} \times 6$ sides), and a volume of 1000 cm^3 ($10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$). Therefore, the surface area to volume ratio is 600:1000 or 0.6, which is much smaller than the SA:V ratio of the smaller cube.

Thus, as the surface area to volume ratio increases, such as in smaller cells, the rate of exchange (such as via diffusion) also increases. The way larger cells can combat these challenges is by changing their shape – through elongation or small projections and folding, such as the villi in the lining of your small intestines.

1.3 Internal membranes and enzymes

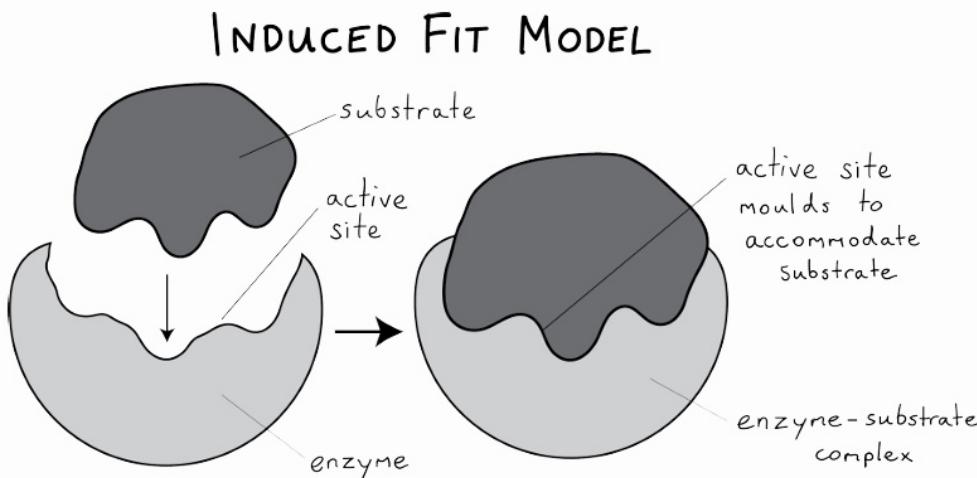
Now we know that the external membrane of the cell can be arranged to increase the surface area to volume ratio. However, organelles and the arrangement of **internal membranes** in the cell are also extremely important for dealing with the surface area to volume ratio problem. Organelles have their own membranes, some of which are also highly folded to increase the reactions that can occur across them helping with the survival of the cell. A good example of this is the **mitochondria** (or powerhouse of the cell!) in eukaryotic animal cells. The mitochondria contain **double-layered cristae** folded upon themselves, which increase the area available for the critical production of energy in the cell. As larger cells have higher needs, this is extremely important. Smart, right?

1.3.1 Enzymes

Enzymes are complex globular proteins with pocket(s) along their surface called **active sites**. These active sites are what molecules (called **the substrate**) bind to in order to initiate a chemical reaction.

There are some important key features of enzymes that are worth remembering:

- Enzymes have **unique active sites** which are **highly specific**, meaning they usually only interact with certain substrates. Enzymes are really fussy, you might say!
- When the substrate binds to the active site, this is called an **enzyme–substrate complex**. Enzymes are kind of pushovers in the sense that they bind to substrates using the **induced fit model**, meaning the active site actually changes its own shape once in contact with the substrate to accommodate it!

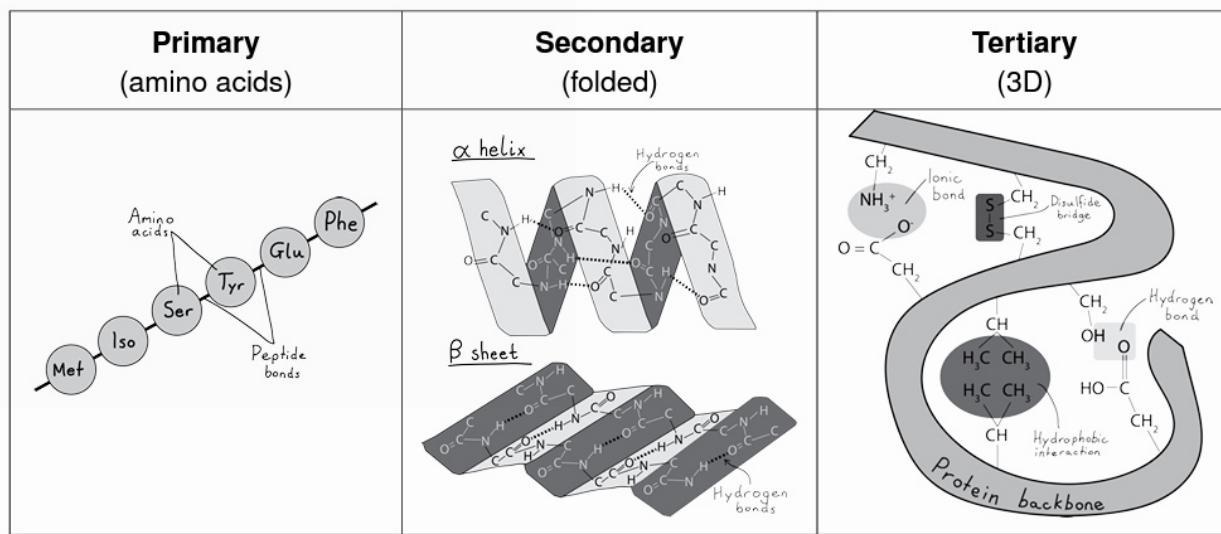


- Enzymes are unchanged during reactions, and thus, they may be reused over and over again.
- Enzymes can usually be identified by their **suffix**, which almost always ends in -ase. Furthermore, enzymes are generally named after the substrate they interact with (which often ends in the suffix -ose). Therefore, can you guess what the enzyme *lactase* would be responsible for? Lactase is an enzyme which breaks down *lactose*, which you find in dairy products! Fun fact: lactose intolerant people don't have the enzyme *lactase*, and for that reason, they are unable to break down or digest foods which contain *lactose*.

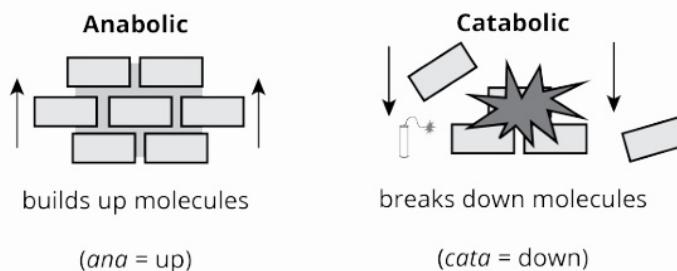
SCIENCE AS A HUMAN ENDEAVOUR :

Before the induced fit model was established as fact, scientists once believed that enzymes were rigid, and substrates fit into them as a key fits into a lock! This is not the case however, as we now know that enzymes change their shape to fit the substrate, before changing back to their original state for the next reaction to occur.

Like all proteins, enzymes are composed of chains of **amino acids**. These long chains make up what we call the **primary structure** of the enzyme. This is then *folded* into either alpha helices or beta sheets, forming the **secondary structure**. You can see in the diagram below what each of these secondary structures look like! The protein is then coiled into a 3D shape known as the **tertiary structure**. It is at this point that the enzyme takes on its characteristic 'globular' protein shape.

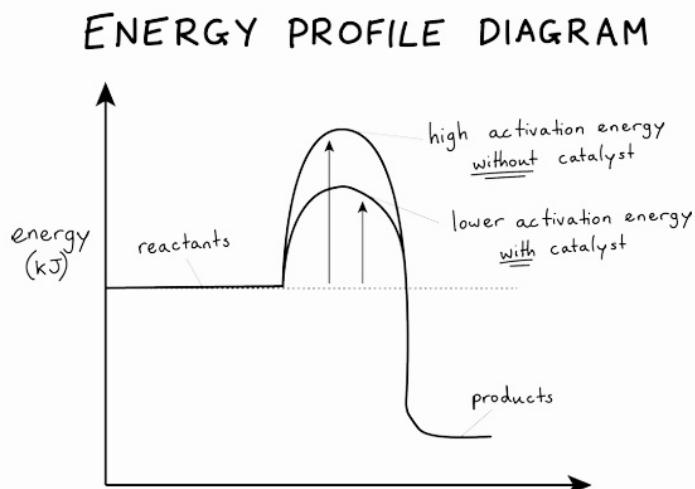


Enzyme reactions fall under two main categories, **anabolic** and **catabolic**. These might sound confusing but, by looking at the Greek prefixes of each word, you can easily distinguish between the two.



As with every chemical reaction, enzyme reactions require an initial input of **activation energy** to occur. However, enzymes have a special superpower that allow them to **lower the activation energy** required for biochemical reactions! There are several ways this superpower works to lower the required activation energy of the reaction – such as positioning of the substrates, mechanical stress on the substrates, chemical environment, etc.

You can see this represented visually in an **energy profile diagram** like the one below. I definitely recommend you become familiar with these, as you may be asked to interpret them, or identify their key components.



Enzymes, powerful as they may be, still require certain conditions in order for them to operate optimally. Thus, enzymes have specific **tolerance ranges** which must be adhered to. If these favourable conditions are not present, enzyme function can suffer significantly, or cease altogether.

There are five main factors that affect enzyme function: **temperature, pH, enzyme inhibitors, the concentration of reactants and products, and the presence of cofactors**.

- **Temperature:** since enzymes are made of proteins, an increase in temperature (which exceeds the tolerance range of the enzyme) may cause the 3D structure of the protein to unravel, thus, it is said to have **denatured**, whereby the active site becomes permanently altered and can no longer interact with the substrate. Conversely, lower temperatures will not denature the active site, but will greatly slow the reaction rate.
- **pH:** if conditions are too acidic or too alkaline, this means that there is either a high concentration of H^+ or OH^- ions, respectively. This negatively interferes with the positive-to-negative interactions of the amino acid side chains because these side chains may be charged, which would interfere with the electrostatic attractions between them, pulling the folded structure apart and causing the protein to denature.
- **Enzyme inhibitors:** since the active site is where all the action happens, should this site be impeded in any way – like say binding with molecules that have the **same active site configuration** – this would cause the enzyme to be rendered ineffective. This circumstance is called **competitive inhibition**.
- **Concentration of reactants and products:** the relative concentrations of enzymes and substrates has a direct effect on the reaction rate, until a point of saturation is achieved whereby the reaction rate is at peak efficiency and cannot improve further.
 - Increasing the concentration of enzymes would increase the reaction rate until the point of saturation is reached.
 - Increasing the concentration of substrate ensures that a sufficient quantity of reactants are available for the reaction to continuously proceed.
- **Presence of cofactors:** some enzymes may require the presence of a cofactor in order to be successfully activated. These cofactors may be organic molecules called **coenzymes**, or inorganic ions. Cofactors may need to be permanently bound to the enzyme, or may only attach in the event of a specific circumstance.

1.4 Energy and metabolism

Energy is required for all processes on earth, and may come in many forms, such as solar energy from the sun, thermal (heat) energy, kinetic energy (such as that which is involved in movement), and chemical energy (the potential energy that is stored in chemical bonds between molecules and which must be broken for it to be released). Cells break down molecules – such as glucose, which is a popular choice for many organic biochemical processes – and use the resultant chemical energy to reconstruct a new type of universal transport energy molecule called **ATP**.

MEMORY PROMPT :

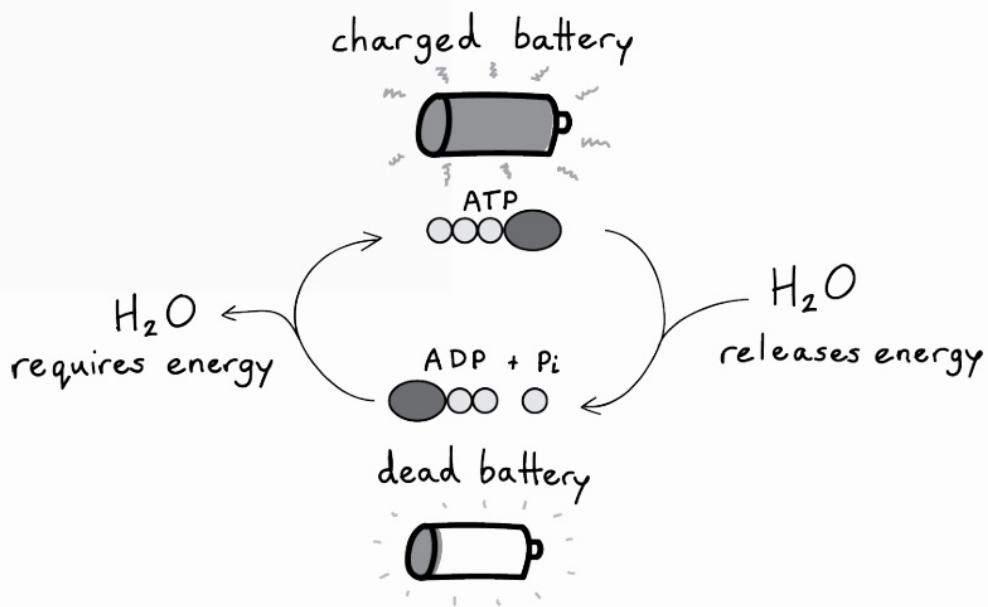
This molecule, **ATP**, stands for **adenosine triphosphate**, and its name gives clues that can help you remember its components:

- **Adenosine:** is made up of a nitrogenous base (adenine) + a sugar molecule (ribose). Therefore, adenine + ribose = adenosine.
- **Triphosphate:** is made up of three (tri) inorganic phosphate groups. Therefore, $3 \times$ phosphate = triphosphate.

So, by looking at the constituent words that make up ATP, we can find memory prompts and clues as to its structure.

The reason why ATP is such a desirable commodity for cells is because the bonds between the phosphate groups contain a high amount of energy, and these bonds can be broken during **cellular respiration** to release a burst of chemical energy which can be used for all sorts of energy-dependent cellular processes.

When the ATP molecule is broken to release its energy, it breaks into one molecule of ADP and one molecule of phosphate. ADP is adenosine diphosphate, which means it has lost a molecule of phosphate, from *tri* (3) to *di* (2). Therefore, as you can see, we haven't lost any molecules, but they have simply been split up into another form. As such, all the ingredients are there for ATP to be remade, as long as another reaction occurs to remake it. So, we can clearly see that this is a **reversible reaction**.



Different organisms and cells have differing energy needs. There are two categories – autotrophs and heterotrophs – with which we can categorise organisms according to how they obtain energy.

- **Autotrophs:** are organisms which can synthesise their own energy by converting inorganic matter (such as O₂ and H₂O) into organic substances (such as glucose, C₆H₁₂O₆).
 - **Photoautotrophs** obtain solar energy from the sun.
 - **Chemoautotrophs** obtain energy for **carbon fixation** from inorganic reactions known as chemosynthesis, such as by the oxidation of inorganic molecules.
- **Heterotrophs** are known as 'consumers' because they aren't able to synthesise their own organic compounds (like autotrophs) and thus, heterotrophs must attain energy by 'consuming' other organisms or their products.

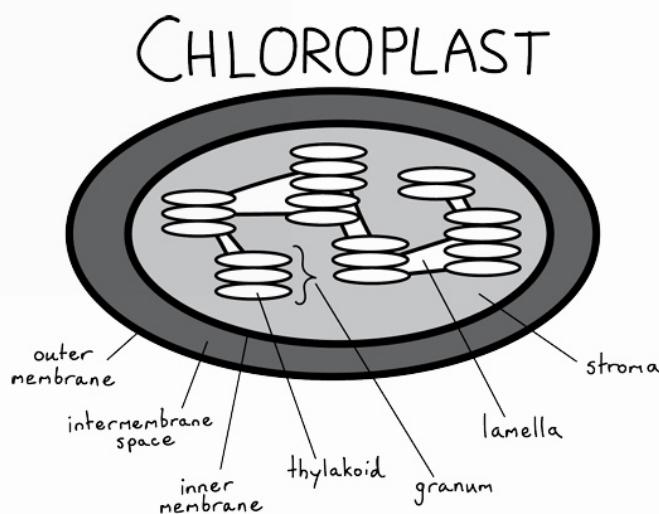
MEMORY PROMPT :

You can think of heterotrophs as a stereotypical lazy teenager who isn't capable of cooking for themselves, and instead waits for their parents to provide food for them!

Carbon fixation is the process whereby inorganic carbon (usually carbon dioxide, CO₂) is converted to organic compounds (such as glucose, C₆H₁₂O₆). It is this glucose which is often used for a quick burst of energy to make ATP which can be stored and used for cellular processes such as growth and repair.

1.4.1 Photosynthesis

Photosynthesis is an enzyme-controlled series of chemical reactions that occurs in the **chloroplast** within plant cells. **Light** (solar) energy is used (along with carbon dioxide and water) to synthesise organic compounds such as **glucose**. You should also recognise that **photosynthesis is a form of carbon fixation** which ‘fixes’ carbon from the atmosphere (from CO_2) into organic molecules (glucose). There are multiple stages involved, which occur in different parts of the chloroplast. To understand these processes, I highly recommend referring to this illustration of a chloroplast below to match all the processes with their respective regions in the organelle.



Light dependent reactions

As the name suggests, the reactions involved in this stage require light to proceed. **Photosystems I and II** are light-dependent reactions that occur in the thylakoid membranes, where chlorophyll and enzymes are located. Stacks of thylakoid disks are called granum (plural = grana).

During this stage:

1. Light energy is absorbed by chlorophyll.
2. This energy is then used to split water (H_2O) to produce oxygen (O_2).
3. This energy is also used to form NADPH and ATP, using inputs of NADP^+ (nicotinamide adenine dinucleotide phosphate), ADP (adenosine diphosphate) and P_i (inorganic phosphate).

Light independent reactions

This stage has opposite prerequisites to the light-dependent stage, in that light is not required for these reactions to proceed. This phase occurs in the **stoma** of the chloroplast, where **coenzymes** provide energy to drive the reactions.

During this stage:

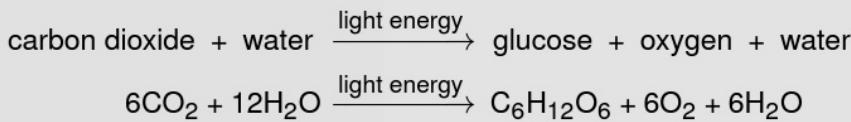
1. The NADPH and ATP that were produced in the light-dependent reactions are used in a process called the **Calvin cycle**.
2. Carbon dioxide (CO_2) from the atmosphere is incorporated into the Calvin cycle, whereby enzymes catalyse reactions which use up the ATP and NADPH from the light dependent reactions.
3. The product of this cycle is 2 G3P molecules, each containing 3 carbon atoms, which are combined to form a molecule of glucose ($\text{C}_6\text{H}_{12}\text{O}_6$).

The Calvin cycle is undergoing many rounds simultaneously, and thus, reactants are being fed through multiple cycles to produce the final products.

So, essentially, both light dependent and light independent phases occur in different parts of the chloroplast to produce glucose via the biochemical process of photosynthesis.

KEY POINT :

To summarise, the main inputs of photosynthesis are carbon dioxide (CO_2), water, and the presence of light energy, and the products are glucose, oxygen and water. This information can be easily summarised in a simple chemical equation, which are important to understand (and you should be able to write at least one of these for your assessments!):



Furthermore, photosynthesis is just like all other biochemical processes in the sense that its rate can be affected by many factors. The four main ones you need to know are: **the number of chloroplasts, stomata, reactants (inputs), and temperature.**

- **Number of chloroplasts:** obviously, a plant cell which contains more chloroplasts means that more rounds of photosynthesis can occur simultaneously, thus producing a higher volume of product (glucose).
- **Stomata:** leaves contain stomata, which are little openings that control the entry of carbon dioxide into the cell, and the loss of water via **transpiration** (or the evaporation of water out of the leaves). Therefore, the number of stromata affect the quantity of chemical reactants or inputs that are available.
- **Reactants (inputs):** this includes light energy, carbon dioxide, and water. However, water has an indirectly negative effect on the rate of photosynthesis. This is because although plants usually have enough water for photosynthesis, if the plant suffers from water stress, stomata close to prevent further water loss, thus restricting the amount of carbon dioxide that can be absorbed from the environment and thereby limiting the rate of photosynthesis.
- **Temperature:** remember how I said that photosynthesis is controlled by enzymes? And do you remember how, earlier in these notes, we learnt that enzymes are made of proteins (see page 7), and can denature or be rendered inefficient depending on high or low temperatures, respectively? From this, you should be able to understand why temperature affects the rate of photosynthesis.
 - Photosynthesis occurs optimally at a certain temperature range (remember, this relates to tolerance ranges). High temperatures could cause the protein enzymes to denature, whereas low temperatures slow the reaction rate of photosynthesis.

Even if you aren't taking Chemistry as a subject this year, you should know that one of the main influences of any chemical reaction is the **availability of reactants**. You can think of it as a recipe; if you don't have the ingredients, you can't make the final product. Or if you don't have enough ingredients, you'll only end up with a small amount of your final dish. This can be applied to any chemical reaction, including photosynthesis; the amount of light, carbon dioxide, and water greatly affects how much (or if any) of the final products, glucose and oxygen, are produced at the end.

1.4.2 Cellular respiration

The glucose that is produced in photosynthesis in autotrophs, or that is consumed by heterotrophs, is used in a process called **cellular respiration**.

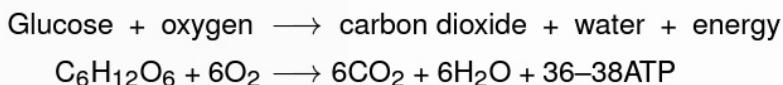
According to the syllabus, you need to understand that cellular respiration is an “enzyme-controlled series of chemical reactions and that the reaction sequence known as aerobic respiration (glycolysis, Krebs cycle and electron transfer chain) requires oxygen.” Therefore, the **design of mitochondria** optimises it for all these enzyme-controlled reactions, given that the folded double-membranes allow for a **much greater surface area**, which you'll remember works to **increase the reaction rate** of biochemical processes.

Simply, cellular respiration is yet another enzyme-controlled series of chemical reactions, involving a number of steps, in this instance; three. When thought of as a sequence, these three steps, **glycolysis**, **Krebs cycle**, and **electron transfer chain**, are known as **aerobic respiration**. As you can tell by the name, aerobic respiration **requires oxygen**.

However, cellular respiration is a process that is very resourceful, and it can even continue in conditions where oxygen is unavailable. You may be able to guess that this version of cellular respiration is known as **anaerobic** respiration, meaning that air or oxygen is not needed to proceed. Although, keep in mind that **less energy is produced** at the end of this process in comparison with aerobic respiration.

In a nutshell, the inputs or reactants required for cellular respiration (aerobic) are glucose and oxygen, and the products are carbon dioxide, water and energy in the form of ATP (remember that big molecule called adenosine triphosphate?).

This can be summarised in yet another chemical equation! Try to remember at least the worded version of this equation.



You should be able to see a link between photosynthesis and cellular respiration. In terms of autotrophs, photosynthesis directly produces the energy (glucose) for ATP to be formed, which can then be utilised by the cell for all sorts of processes such as building new molecules, and for general growth and repair. In terms of heterotrophs, glucose and ATP are used in the same way, except the means by which glucose is attained is different, since heterotrophs can't synthesise their own glucose like autotrophs can. Thus, heterotrophs actually rely on autotrophs either directly or indirectly as a source of energy. For example, herbivores feed on plants, which synthesise glucose themselves, and thus directly provide the animal with energy. These animals may also be eaten by other animals such as humans or other predatory mammals in order to obtain glucose indirectly from the plants that sustained those herbivores. See how biology builds upon itself, layer by layer?

There are three main steps involved in **cellular respiration**. These are:

- **Glycolysis** – produces a net yield of 2 ATP molecules
 - Occurs in the cytosol
 - Breaks down glucose into 2 molecules of **pyruvate**
 - Releases 2 ATP and 2NADH molecules
 - **Overall products:** 2 pyruvate + 2ATP + 2NADH
- **Krebs cycle** – produces a net yield of 2 ATP molecules
 - Occurs in the **mitochondrial matrix** (inside the double-membrane of the mitochondria)
 - Uses the ATP produced in glycolysis to move the pyruvate into the inner membrane of the mitochondria via **active transport** (which, you'll remember, uses energy to occur)
 - Several enzyme-catalysed reactions occur, which transfers energy to coenzymes such as NADH, FADH₂, and ATP
 - **Overall products:** each cycle produces 2 ATP and a total of three molecules of CO₂ for every pyruvate molecule metabolised, and six molecules of CO₂ for every molecule of glucose metabolised (i.e. 3CO₂ per pyruvate + 6CO₂ per glucose molecule + 2 ATP)
- **Electron transport chain** – produces a net yield of 26–28 ATP
 - Occurs in the **cristae and matrix** of the mitochondria
 - During this phase, electrons and protons are moved along the mitochondrial membranes to generate ATP
 - Energy carrying molecules from the Krebs cycle such as NADH and FADH₂ are fed back into the electron transport chain where they are converted back into their original forms of NAD⁺ and FAD, respectively (therefore, you can see how this process is renewable, and the cycle of cellular respiration can restart)
 - **Overall products:** water and 26–28 ATP molecules

Both the Krebs cycle and electron transport chain stages require oxygen to proceed, however, glycolysis can occur without the presence of oxygen in the process of **anaerobic respiration**.

MEMORY PROMPT :**How is anaerobic respiration different from aerobic respiration?**

- Less efficient than aerobic respiration: only 2 ATP are produced (compared to 36–38 ATP in aerobic respiration).
- Occurs faster than aerobic respiration: this is because only one step is required.
- Only the first stage (glycolysis) is initiated; the products of glycolysis are the same as in aerobic respiration, however:
 - In plants, the 2 pyruvate molecules are used in **ethanol fermentation**, which produces ethanol + CO₂.
 - In animals, the 2 pyruvate molecules are used up in **lactic acid fermentation**, whereby lactic acid is produced.

Think about when you exercise and your muscles feel really tight – this is because you don't take in as much oxygen when your breathing becomes erratic during exercise, so, rather than prioritising the efficiency of aerobic respiration, anaerobic respiration is occurring to supply your muscles with quick bursts of ATP to get you through your workout session.

KEY POINT :

Remember, for photosynthesis and cellular respiration, the syllabus wants you to be able to summarise where they occur in the cell, their inputs and outputs, and how these processes are related to one another.

As always, there are several factors which can affect the rate of cellular respiration. These are:

- **Temperature:** you may be able to guess why temperature is a limiting factor, judging by some of the previous enzyme-controlled reactions. But to summarise, enzymes are composed of proteins, and thus, they have specific tolerance ranges in which they can function optimally.
 - If the temperature exceeds this optimum range, the proteins can denature, causing the active site of the enzyme to become distorted, thus rendering it ineffective and ultimately decreasing the reaction rate of cellular respiration as a result.
 - If the temperature falls below the range, the reactant molecules do not possess an adequate amount of kinetic energy to react quickly with one another, thus slowing the overall reaction rate.
- **Glucose availability:** much like how baking a cake relies on the initial availability of ingredients, so too are all chemical reactions limited by the concentration of reactants. Thus, since glucose is the substrate for glycolysis – the first stage in cellular respiration – its availability will affect the overall reaction rate.
- **Oxygen concentration:** oxygen is an essential reactant for aerobic respiration, especially since it is the final reactant for the electron transfer chain which is the main producer of ATP in comparison with all the other stages. Therefore, increased or decreased concentrations of oxygen will either increase or decrease the reaction rate, respectively.

Topic 2

Multicellular organisms

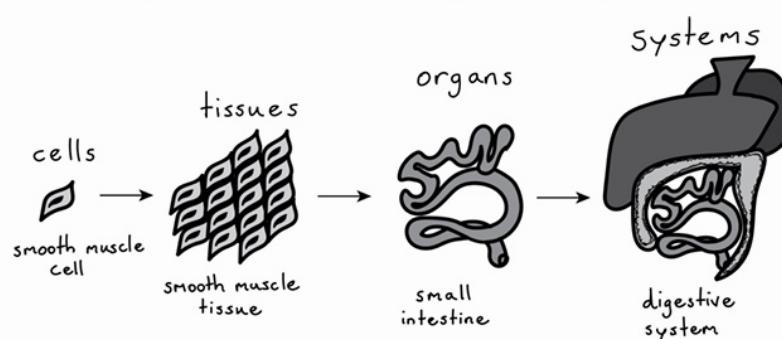
Multicellular organisms like you and I differ from unicellular organisms in a number of ways. This is because multicellular organisms have greater energy requirements than unicellular organisms, which means that they need more cells to carry out their functions. This, in turn, means that multicellular organisms have specialised cells to carry out more complex functions.

	Unicellular	Multicellular
Number of cells	One	Many
Prokaryotes or eukaryotes?	Prokaryotes and some eukaryotes are unicellular	Eukaryotes only
Functions	One cell and its organelles are responsible for all the functions for cell survival	Many cells are specialised and work together in a hierarchy of levels (cells > tissues > organs > systems) to perform all the life-sustaining functions for cell survival
Size	Very small; usually microscopic	Macroscopic (results in larger body size due to greater number of cells)
Lifespan	Short	Long
Reproduction	Rapid, and usually asexual, clonal reproduction (i.e. binary fission), resulting in genetically identical offspring	Slower, and usually sexual reproduction, resulting in genetically diverse offspring

2.1 Cell differentiation and specialisation

Since multicellular organisms are much more complex than unicellular organisms, they also need to employ more sophisticated strategies to equip their cells to become capable of performing such intricate tasks. You can think of this as an employer of a large, reputable company which invests in the best available training to ensure his employees are well-equipped for performing complex tasks in all different departments in the company's overall workforce hierarchy.

Similarly, multicellular organisms have a hierachal structure of **specialised cells** (cells which are optimised for a specific function) which compose special tissues, organs, and systems for specific functions.

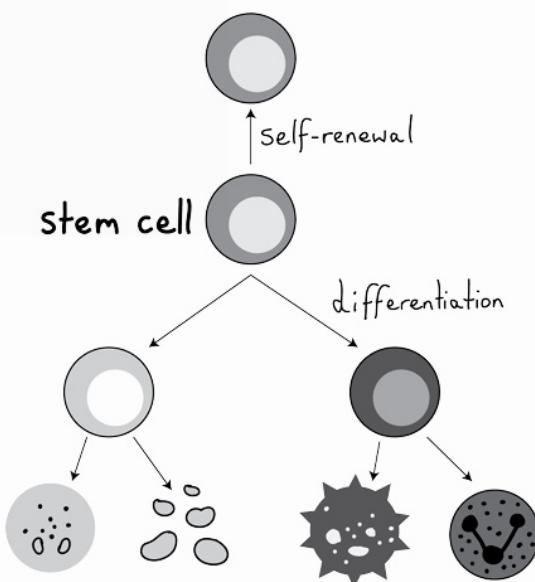


In this example, the hierarchical structure of **cell > tissue > organ > system** is demonstrated using smooth muscle cells, which form the tissue of the small intestine, which is a vital organ within the digestive system.

2.1.1 Stem cells

To truly understand and appreciate cell specialisation, it helps to think of how humans reproduce. Reproductive cells called **gametes** – a male sperm and a female egg – fuse together to form a single cell called a **zygote**. This cell then proliferates into the many trillions of cells that make up your entire being. But how does a single cell generate trillions more by itself? This question can be answered by understanding **stem cells**.

Stem cells are unspecialised cells which are yet to undergo **cell differentiation** (whereby they become **specialised cells**). They are full of untapped potential, capable of transforming into an array of new cells, depending on their **potency**.



There are four types of stem cell **potencies** which basically determines the limits of their differentiation capacities. Stem cells are vital for the composition of a fully complete multicellular organism, and their potencies allow for the renewal and growth of specialised cells at different stages in the multicellular organism's life cycle. Without these stem cells, multicellular organisms would be much the same and would be unable to carry out highly specific functions.

Thus, there are four different **potencies** of stem cells, in order of decreasing potency.

1. **Totipotent** stem cells are capable of differentiating into **any cell type**. They have the highest level of potency. Only the zygote, and its divisions up to the 16-cell morula,¹ are totipotent.
2. **Pluripotent** stem cells are those which are capable of differentiating into any of the three germ layers (during embryonic development), listed below. These stem cells are present in the blastocyst and cannot give rise to an entire organism.
 - (a) Endoderm (can form parts of the body, such as the lungs and gut lining).
 - (b) Mesoderm (contributes to parts such as muscle, bone and blood).
 - (c) Ectoderm (gives rise to tissues such as the skin and nervous system).
3. **Multipotent** stem cells are those which can give rise to several cell types, however they are limited to a certain range only. For example, epithelial stem cells can differentiate into a variety of cells which make up various membranes (such as the lungs or gut lining), but they are restricted to these and cannot, for example, give rise to red blood cells or anything else.
4. **Unipotent** stem cells can only differentiate into a single cell type, but are largely renewable and can divide repeatedly. These are generally used for self-renewal/repair. For example, skin cells are constantly being replenished, and are unipotent since they obviously cannot spawn any other cells such as neurons or blood cells, for example.

¹This is the name given to a very early embryo that has divided into 16 cells (called a 'morula' after the Latin word for mulberry, since at this stage the cluster of cells resembles a berry) before becoming a blastocyst, at which point it is no longer totipotent.

SCIENCE AS A HUMAN ENDEAVOUR :**Stem cell research**

One of the most hotly debated topics within the scientific community is the use of stem cells in medical technology. Objectively, the use of stem cells – especially embryonic stem cells – could allow scientists to culture fully-functioning tissues and organs, which can be used to save lives. However, there are unfortunately a variety of ethical drawbacks to stem cell therapy, such as the tendency to harm or even destroy growing embryos during the process of harvesting embryonic stem cells at the blastocyst stage.

Bioartificial organs

Instead of relying on donor organs and tissues, scientists can manufacture bioartificial organs and tissues using cells from a patient or stem cell bank.

Organ transplantation and issues surrounding it

The procedure of transplanting an organ from a person who no longer needs it to one who may be in dire need of it is a life-saving treatment, and is one of the many phenomenal advancements of modern medicine. However, there are risks involved which make this procedure a tricky one. There are many factors that can affect the success of the procedure, and may negatively harm the patient instead of aiding them. For example, a donor organ may be *rejected* by the patient's body if the human leukocyte antigen system (HLA) markers on the organ are recognised as non-self by the patient's immune system, which happens if the patient's HLA markers don't match those of the donor's. This is why it's so critical that organ donors are correctly matched to the recipient patient.

Further advancements in science have led to the development of antirejection drugs to combat the risk of rejection in patients, however, the downsides to suppression of the patient's immune system is that it can cause them to become prone to other diseases such as cancer. Even though much is now known about the adaptive immune response to organ transplants, further research into the innate immune system is required to more effectively combat organ rejection issues in the health field. Additionally, one highly disputed social issue with regards to organ donation is whether or not countries should employ an opt-in system (whereby the public remain off the organ donor list unless they choose to be on it), or an opt-out system (whereby the public are automatically placed on the organ donor list until they opt out). Some argue that an opt-out system would result in a greater volume of available donor organs, but there are ethical concerns regarding this system.

2.2 Gas exchange and transport

The purpose of transport systems is to allow nutrients into cells, and to expel waste materials. This goal is achieved through several body systems: the circulatory system, lymphatic system, respiratory system, digestive system, and excretory system. Not all of these exist in invertebrates, but there are some commonalities that exist for the same purpose of exchanging nutrients and wastes, whether in mammals or any other animal.

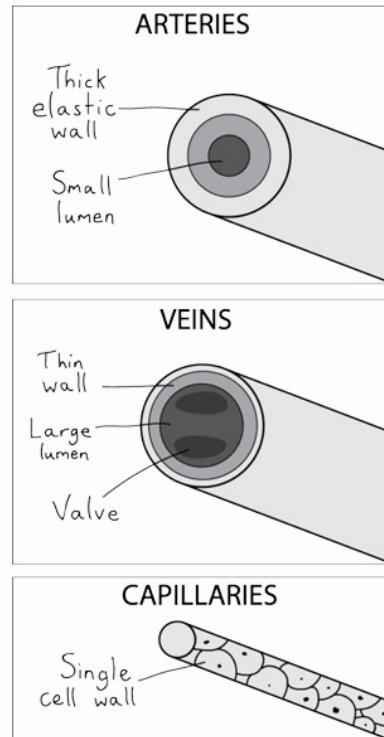
2.2.1 Circulatory system

The circulatory system is a major body system involved in the transport of nutrients and wastes for multicellular organisms. The circulatory system can be divided into two components:

- **Open circulatory system:** has a heart or heart-like structure, but the blood-like fluid (called haemolymph) is not contained within blood vessels. Invertebrates use this type of system, since they have less complex requirements.
- **Closed circulatory system:** more complex, and usually employs the use of a multi-chambered heart and enclosed blood vessels to carry blood away from and back to the heart. Specialised **capillaries** are also used for the purpose of exchanging substances between blood and its nearby tissues. This type of circulatory system is what we humans use, as do all other vertebrates, as they have more sophisticated needs than invertebrates.

The blood vessels involved in the mammalian circulatory system are:

- **Arteries:** these lead blood away from the heart. You can remember this as the arteries lead away from the heart. There are also **arterioles**, which are smaller arteries that lead to capillaries.
- **Veins:** these lead blood back to the heart. Veins contain valves to prevent blood from flowing backwards which would strain blood vessels and may result in arrhythmias or other health problems. There are also **venules**, which are smaller veins that lead to capillaries.
- **Capillaries:** the smallest, microscopic blood vessels, which are optimised for exchanging materials such as oxygen, carbon dioxide and other nutrients via diffusion and filtration between blood and interstitial spaces, tissues, and cells.

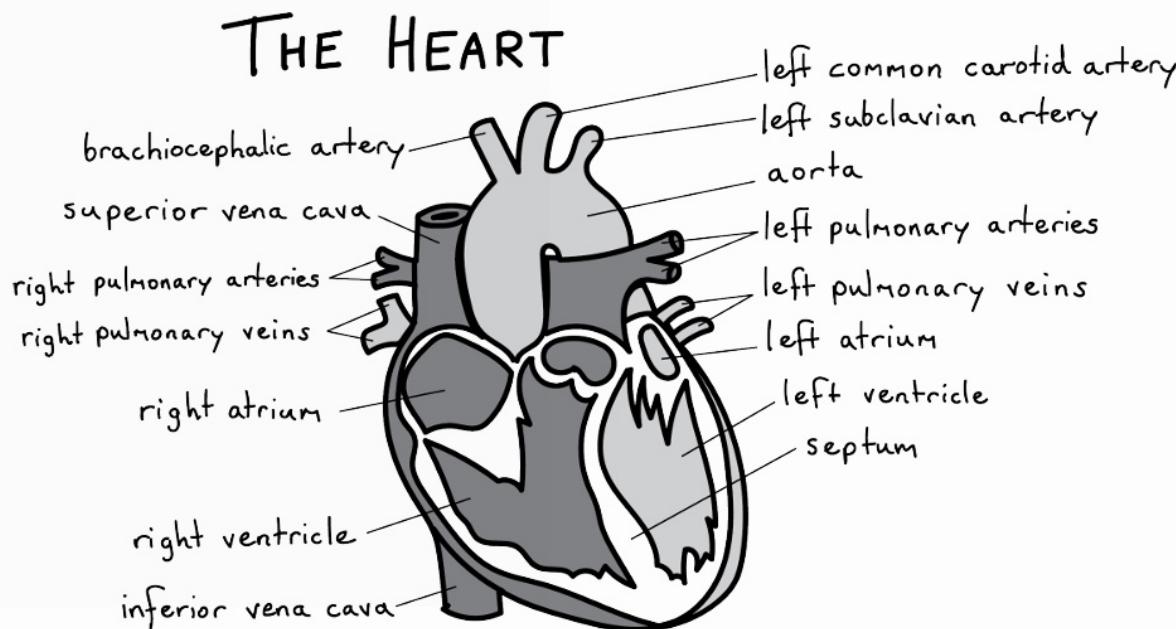


MEMORY PROMPT :

Why are capillaries useful for exchange of materials?

- Small size
- Thin, porous membrane (one cell thick)
- Exist in a large, branching network; hence there is a large surface area for exchange

The heart



Circulation pathways

- **Pulmonary circulation:** transports blood to and from the lungs.
 - Deoxygenated blood is pumped from heart to the lungs (via arteries) where it can then be oxygenated.
 - Oxygenated blood is supplied back to the heart from the lungs (via veins).
- **Systemic circulation:** circulates blood to and from the rest of the body.
 - Oxygenated blood is pumped from the heart to the organs (remember, it becomes oxygenated from the lungs first).
 - Next, once the oxygenated blood expends its oxygen, deoxygenated blood returns to the heart where it can be pumped to the lungs for oxygenation.

2.2.2 Lymphatic system

The second mammalian transport system is the lymphatic system.

Occasionally, due to the porous nature of capillaries, it is natural for proteins to occasionally leak out. However, it is the job of the lymphatic system to return this protein-filled extracellular fluid back into the capillaries, via a complex branched system of lymph vessels, lymph nodes and organs such as the thymus and spleen.

When this extracellular fluid enters the lymphatic system, it is now called '**lymph.**' Lymph is transported in a single direction, from the tissues to the heart.

2.2.3 Respiratory system – gas exchange in animals

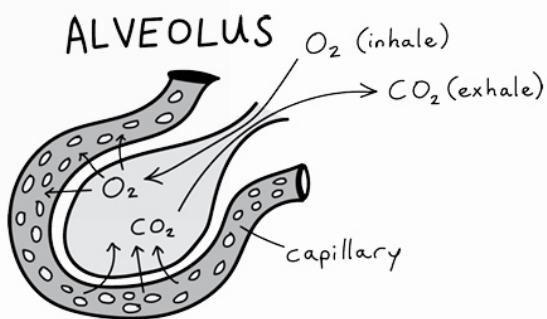
You should remember from earlier that the exchange of oxygen and carbon dioxide is fundamental in the process of cellular respiration. Thus, the respiratory system is critical for allowing the exchange of these important gases. The role of the respiratory system is to absorb much-needed oxygen from the environment and transport it to the cells via the circulatory system. As such, you should understand that the respiratory and circulatory systems work hand-in-hand.

Gas exchange is **most efficient** when:

- The surface area to volume ratio is as *high* as possible.
- The membrane or barrier is as *thin* as possible.
- The respiratory surface is *adequately supplied with the gas* being exchanged.
- There is efficient *removal* of the substance once the exchange has occurred.
- As the gas is efficiently supplied and removed from the respiratory surface, a *high concentration gradient* can therefore be maintained, thus resulting in *increased diffusion rate*.

In mammals, the lungs tick all these boxes perfectly. Firstly, the membranes in the lungs are super thin, and surface area is maximised due to the incredible branching structure that exists inside the lungs, which are each made up of a single bronchus, which branches into bronchioles, which branch again into clusters of alveoli. Each alveolus is covered with a webbing of capillaries. Therefore, as air enters the lungs and filters into the alveoli, the oxygen from the air efficiently makes use of the large surface area and thin membranes and quickly diffuses into the nearby capillaries, thus quickly supplying the blood with oxygen. This system is quick and efficient and allows deoxygenated blood to be supplied with oxygen, while oxygenated blood cycles back around to the heart (see how this all ties into the circulatory system)?

Below is a single alveolus diagrammatic representation of how gases are exchanged to and from the circulatory and respiratory systems via diffusion



Partial pressure and diffusion

Now, let's dive deeper into exactly *how* these gases are transported into the bloodstream from the alveoli. They don't magically move, but instead, the **oxygen diffuses** through the thin membrane because of the difference in **partial pressure** of the gas present in the blood of the capillaries compared to the alveolus/tissues, which forces the gases to be exchanged. Thus, gas exchange occurs because the **gases always diffuse down the partial pressure gradient**, meaning they diffuse from an area where the gas is at a higher pressure to an area where the gas is at a lower pressure.

So, since oxygen has a partial pressure of approximately 104 mm Hg² in the alveoli but only 40 mm Hg in the blood of the pulmonary capillaries, oxygen will move down its partial pressure gradient to enter the blood. Carbon dioxide follows the same process but in the opposite direction – from the blood to the lungs. The partial pressure of carbon dioxide in the blood is 45 mm Hg and 40 mm Hg in the alveoli, so it will diffuse from the deoxygenated blood and into the lungs. It is also the same process for moving into tissues, the partial pressure of oxygen/carbon dioxide is different in the blood to the tissues so it can move down the gradient and into/out of the tissues.

MEMORY PROMPT :

Why does oxygen diffusion occur?

- The branching structure of lungs means they have a large surface area to allow for diffusion.
- Thin membranes facilitate diffusion.
- The difference in partial pressure between alveoli and blood means O₂ will diffuse between them.

KEY POINT :

Whilst the syllabus doesn't specify that you need to remember these *exact* pressures, it does ask that you understand the **relationship between the structural features of the alveoli and the function of gaseous exchange surfaces** in the exchange of gases, and partial pressure is an extremely important part of this. Including the pressures makes it much easier to see how the diffusion gradient works to help with the exchange of gases across these surfaces. But as long as you can remember which direction these gases are going because of the partial pressure gradient, you should be fine for your assessments.

²'Hg' is a unit of measurement for pressure. It is denoted as Hg because it is measured in relation to the pressure generated by an inch of mercury, as Hg is the symbol for the element mercury. You likely won't need to know these units – just remember that it's related to pressure!

Haemoglobin

Another way that oxygen diffusion is made more efficient is through the presence of the protein **haemoglobin** in the blood. Oxygen doesn't just diffuse entirely by itself through the membrane, but is instead carried by these proteins, which greatly increase the oxygen-carrying capacity of blood.

Haemoglobin contains four subunits, and each of these subunits contain an **iron molecule** capable of binding to oxygen – so four oxygen molecules can be carried per haemoglobin molecule. The compound formed when haemoglobin binds to oxygen is known as **oxyhaemoglobin**.

Haemoglobin has a high affinity for oxygen when concentrations are high (e.g. in the lungs) but has less affinity towards oxygen when concentrations are low (e.g. in the tissues), so it can release the oxygen into these areas with less oxygen. Without haemoglobin's help, gas exchange would be far less efficient!

Up until this point in the 'animal respiratory systems' sub-topic, I've only discussed mammals. But insects, reptiles, fish, amphibians, and birds all follow suit, with structural differences depending on their body type, features, and environment. However, your syllabus only focuses on the mammalian respiratory system, so I'm not going to overload you with irrelevant information about other types of respiratory systems. However, feel free to look up descriptions and diagrams of other types of respiratory systems, if you're curious!

2.3 Exchange of nutrients and wastes

2.3.1 Digestive system

Digestion is the act of breaking down food into a form that can be readily absorbed and **metabolised** into energy. This process of digestion involves both physical and chemical breakdown.

KEY POINT :

Food that is not absorbed passes out of the intestine through a process called **egestion**. This term shouldn't be confused with **excretion**, which involves the removal of substances that were produced by the body (such as urine), which we will discuss in more depth later.

Physical breakdown

The purpose of this phase is to increase the surface area of food particles so that can be better absorbed in the next phase. This occurs through mechanisms such as chewing. If you think about it, you can't swallow a whole apple and expect its nutrients to be well-absorbed by your body, right? First, you would need to chew it to increase the surface area of each piece to allow digestive enzymes to come into contact with as much of the outside surface as possible in order to break it down (which is where the next phase comes in).

Chemical breakdown

It is during this phase that **digestive enzymes** come into play and actually initiate digestion. Thus, digestive enzymes interact with the surface of the now broken-down food molecules, causing them to become chemically changed, as they are being broken apart into more simpler molecules that can be absorbed into the bloodstream (again, notice how the circulatory system is linked to this system).

The process most enzymes use to split these molecules is called **hydrolysis** (*hydro* meaning water, and *lysis* meaning to split), which involves a chemical reaction that splits the target food molecule by the addition of a water molecule. Chemical digestion can occur inside the cell (intracellular) as well as outside the cell (extracellular).

There are three main types of digestive enzymes:

Type of enzyme	→ what it breaks down
Amylases	→ carbohydrates
Proteases	→ proteins
Lipases	→ lipids

Process of digestion

1. **Mouth:** where mastication (chewing) occurs to mechanically break up food into pieces.
2. **Epiglottis:** the flap at the entrance of the larynx which prevents food from entering the trachea, thus directing it down the oesophagus.
3. **Oesophagus:** the tube that carries food to the stomach, aided by peristalsis (muscle contractions).
4. **Stomach:** where enzymes and acidic gastric juices are secreted to aid digestion. More muscle contractions continue to break up food and pushes it further into the digestive system.
5. **Liver:** plays a role in regulating metabolism, toxin removal, and processing nutrients. The liver also stores excess glucose as glycogen which can be stored and converted back into glucose when needed for energy, and it produces bile for the digestion of fats.
6. **Gall bladder:** stores bile.
7. **Pancreas:** produces and activates digestive enzymes when food reaches the first part of the small intestine. The pancreas also produces insulin and glucagon (which regulates blood glucose levels), and sodium hydrogen carbonate (which neutralises stomach acids in food).
8. **Small intestine:** digestion primarily occurs in this organ. The small intestine absorbs nutrients and minerals from the food particles, which have been broken down already by all the previous steps and enzymes. The small intestine contains many blood vessels, allowing them to directly absorb the digested materials and transport them throughout the circulatory system.
9. **Large intestine:** water is absorbed with soluble compounds such as vitamins and minerals. Undigested food is removed as faeces through egestion.

It is important to note that other types of animals will have different components involved in digestion. For example, carnivores and herbivores have different jaws and teeth which are optimised for chewing/tearing meat, or grinding plant matter, respectively. Furthermore, there are some details that are specific to herbivores which are worth discussing.

Herbivore digestive processes

Cellulose is a large organic molecule which primarily composes plant cell walls, and is too large to be absorbed without digestion. Thus, to digest cellulose, an enzyme called cellulase is required, which is rarely produced in herbivores, and is usually obtained from a mutually beneficial relationship with gut bacteria which produce the enzyme.

Furthermore, depending on the species of herbivorous mammal, **fermentation** is utilised in different parts of the intestine. Thus, these herbivores can usually be separated into two groups depending on where fermentation takes place.

For **hindgut fermenters**, fermentation can occur in the caecum (an enlarged pouch which joins the small and large intestines) or the first part of the large intestine, or both. Absorption mostly occurs in the small intestine. Such an arrangement means that the advantage obtained from the symbiotic relationship is limited, since the products of digestion are not fully absorbed (which is why many hindgut fermenters such as horses contain many undigested material within their faeces).

For **foregut fermenters**, the fermentation chamber is located before the stomach which is called the **rumen** in animals such as cattle and sheep (ruminants). This process allows food to be regurgitated into the mouth for further chewing, and returned to the rumen for bacterial chemical digestion. More nutrients can be absorbed in this process, but it takes longer than hindgut fermentation.

2.3.2 Metabolism

Basal metabolic rate is the baseline amount of energy a resting, unstressed animal requires per unit of time in order to carry out the most basic of functions. In animals and other mammals, metabolic rate is affected by a number of factors such as age, gender, level of activity, and body composition (i.e. the ratio of body fat or bone to muscle).

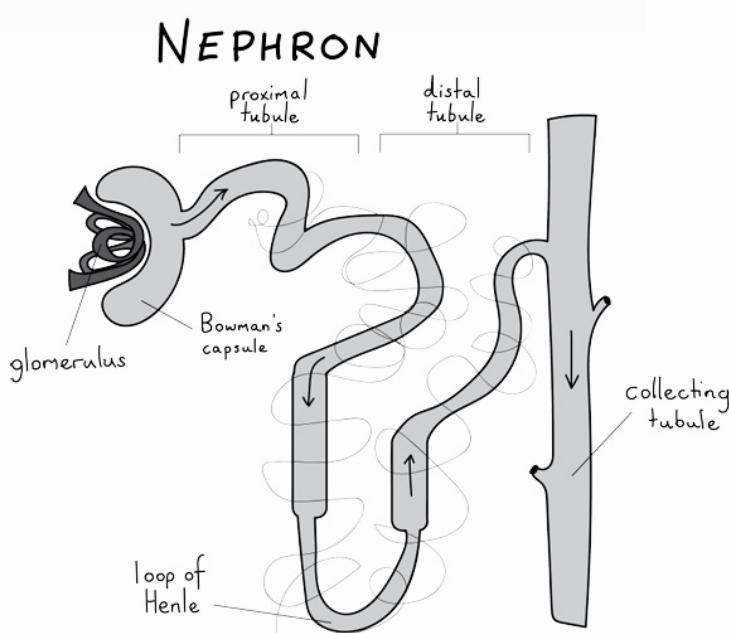
We will look at metabolism in more detail in Unit 2.

2.3.3 Excretory system

The purpose of the excretory system is to rid the body of toxic or unwanted waste products (such as carbon dioxide and nitrogenous wastes) that are produced by the organism itself as by-products of other biochemical processes.

For example, to rid the body of **nitrogenous wastes** such as **ammonia**, which is produced as a result of digesting proteins, the body converts ammonia into one of two forms: **urea** (in mammals) or **uric acid** (in birds and reptiles). Then, in the mammalian kidney, **urine** is produced which contains the urea and is then safely excreted by the body. Unsurprisingly, this process also ties into the circulatory system, as waste products are filtered from the bloodstream into the urine.

The **kidney** is an incredibly important organ associated with the **excretory system**, and it works closely with the circulatory system as waste products are filtered out of the bloodstream and into the urine, produced by the kidneys. The **nephron** (of which there are about one million in each normal adult kidney) is the functional unit of the kidney, meaning all of the kidney's functions occur here. There are many important components of the nephron, each of which play an important role in the production of urine.



- **Glomerulus:** network of tightly-knit looping capillaries embedded inside the Bowman's capsule, carrying blood under high pressure.
- **Bowman's capsule:** surrounds the glomerulus and collects the primary filtrate forced into the capsule by the high pressure in the glomerulus.
- **Proximal tubule:** site of selective reabsorption of useful substances (i.e. water, glucose, amino acids, salts).
- **Loop of Henle:** enhances water reabsorption by establishing salt concentration gradient via active transport.
- **Distal tubule:** reabsorbs some substances such as sodium by active transport, facilitated by active transport.
- **Collecting tubule:** reabsorbs water via osmosis, further concentrating the urine.

The functions of the nephron that are associated with the production of urine include:

- **Passive filtration:** from the bloodstream into the nephrons of the kidney. High blood pressure in the glomerular capillaries forces small molecules and water to filter into the Bowman's capsule, this fluid is called the primary filtrate.
- **Secretion of salts:** ammonium, potassium, and hydrogen ions are secreted into the distal tubules via active transport.
- **Selective reabsorption and passive removal of water:** occurs along the length of the nephron:
 1. Glucose and amino acids are reabsorbed by the proximal tubules by active transport against the concentration gradient.
 2. Meanwhile, water is passively reabsorbed from the urine, along its osmotic gradient.
 3. The urine becomes concentrated as sodium chloride (salt) is pumped out of the loop of Henle and into the medullary region to create a high salt concentration in that region.
 4. When the urine reaches the collecting tubule, which is permeable to water but not to salt, water passes out of the collecting tubule and back into the blood vessels, thus, concentrating the urine inside the collecting tubule even further.

This is because, (remember the laws of osmosis) the collecting tubule is located in the medulla, which has a very high salt concentration (thanks to the loop of Henle). Therefore, water inside the collecting tubule attempts to dilute the salt concentration on the outside by diffusing out, thus, leaving more concentrated urine inside the tubule.

2.4 Plant systems – gas exchange and transport systems

Before we cover gas exchange and transport systems in plants, it is important to understand that there are both vascular and nonvascular plants.

- **Vascular plants** are those which exchange gases and transport water and mineral ions.
- **Nonvascular plants** (for example, moss or some algae) are those which lack roots, stems, or leaves. They reside in moist habitats and reproduce with spores. Gas exchange is easy because their ‘leaves’ are usually very thin, so gases can be exchanged directly at the surface.

Therefore, in **vascular plants**, the sites of gas exchange are the leaves, stems and roots, and transport of nutrients (water, mineral ions and sugars) occurs via closed vessels (like a closed circulatory system) of **vascular bundles**, containing **vascular tissue** (xylem and phloem).

Features of **vascular bundles** include:

- **Xylem** (\uparrow): vessels which transport **water and mineral ions upwards** from the roots to the leaves.
- **Phloem** (\downarrow): vessels which transport **sugars (from photosynthesis) downwards** from the leaves (the sites of photosynthesis) to the rest of the plant.
- **Lignin sheath**: strengthens and supports the vascular tissue.
- **Vascular tissue** is present in the leaves, stems, and roots, and allows for the transport of all the reactants or products of photosynthesis. For example, this allows water to be transported all the way from the roots to the leaves.

To make this easier to remember, I will split the process of gas exchange and transport in plants into three sections: the **leaves, stems, and roots**.

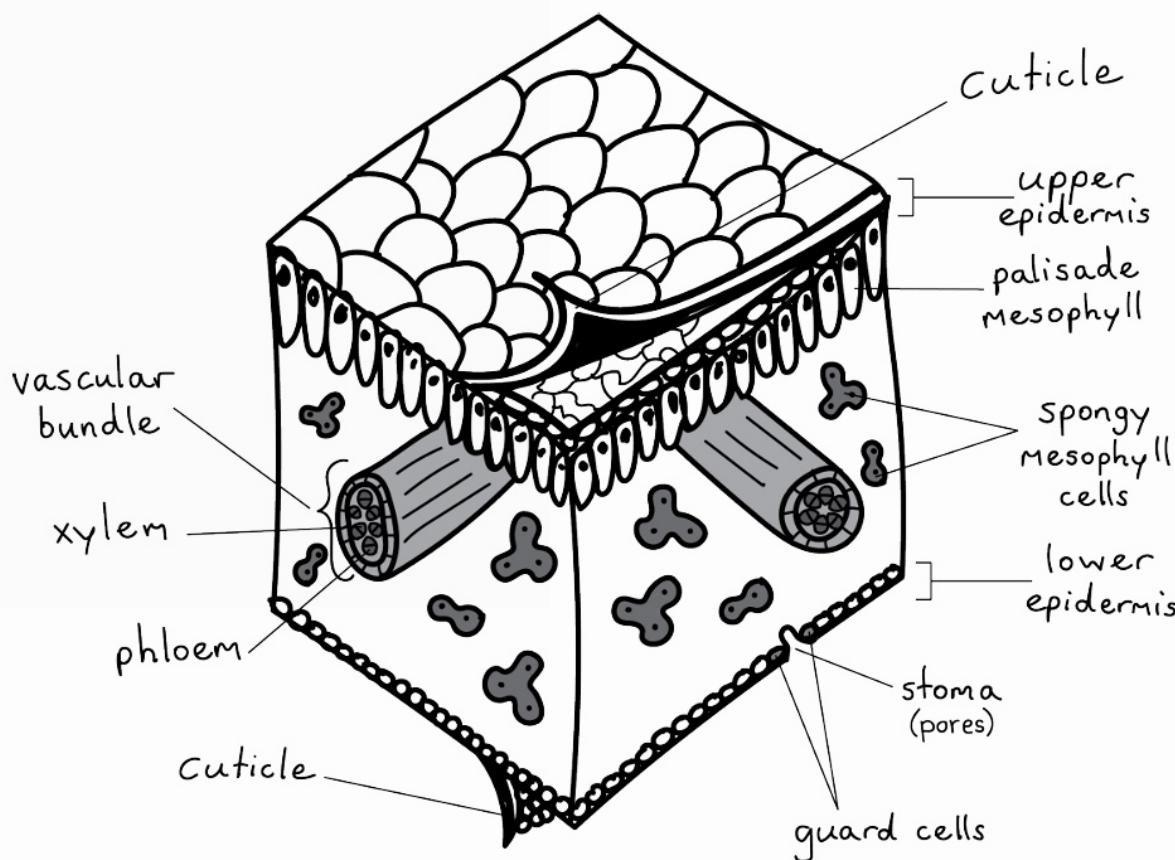
2.4.1 Leaves

Leaves are the sites of photosynthesis, and thus require light, water, and gases such as carbon dioxide and oxygen to be exchanged. Therefore, in vascular plants, these gases are exchanged through tiny ‘pores’ in the leaves’ epidermis called **stomata** (singular *stoma*), which open and close to regulate the movement of gases into and out of the leaves.

Stomata are ‘guarded’ or bordered by two **guard cells** which contract or relax to open or close the stoma, respectively. But how do these guard cells know when to open and close the stomata? The answer relates to **turgor pressure**, which is the guard cell’s internal fluid pressure. Thus, when water enters the guard cells, their turgor pressure rises, causing them to contract and open the stoma to allow water vapour to escape and thus, partially relieve the turgor pressure. When water evaporates from the stomatal openings in the leaves, this is known as **transpiration**. Favourable conditions for the opening of stomata (related to the reactants and products of photosynthesis) are:

- Abundant water
- Abundant light
- Low internal carbon dioxide concentrations

Internal structure of a leaf



- **Upper epidermis:** protects the leaf by secreting a waxy cuticle, allows sunlight to reach the chloroplasts below, and prevents excessive water loss.
- **Mesophyll:** made up of palisade and spongy mesophyll cells. This layer houses the chloroplasts for photosynthesis.
 - **Palisade mesophyll cells:** tightly packed with chloroplasts.
 - **Spongy mesophyll cells:** loosely packed with chloroplasts to leave room for air spaces to allow for gas exchange.
 - **Vascular bundles:** xylem and phloem.
- **Lower epidermis:** this layer contains the stomata and guard cells.

2.4.2 Stem

The stem connects the roots and the leaves, and thus provides a means of transport of materials from the roots to the leaves to be used for photosynthesis. Just like the leaves, the epidermis of green stems also contain stomata for gas exchange. In woody stems, however, stomata are replaced by loosely packed groups of cork cells, through which air can pass. A group of these cork cells are called a **lenticel**.

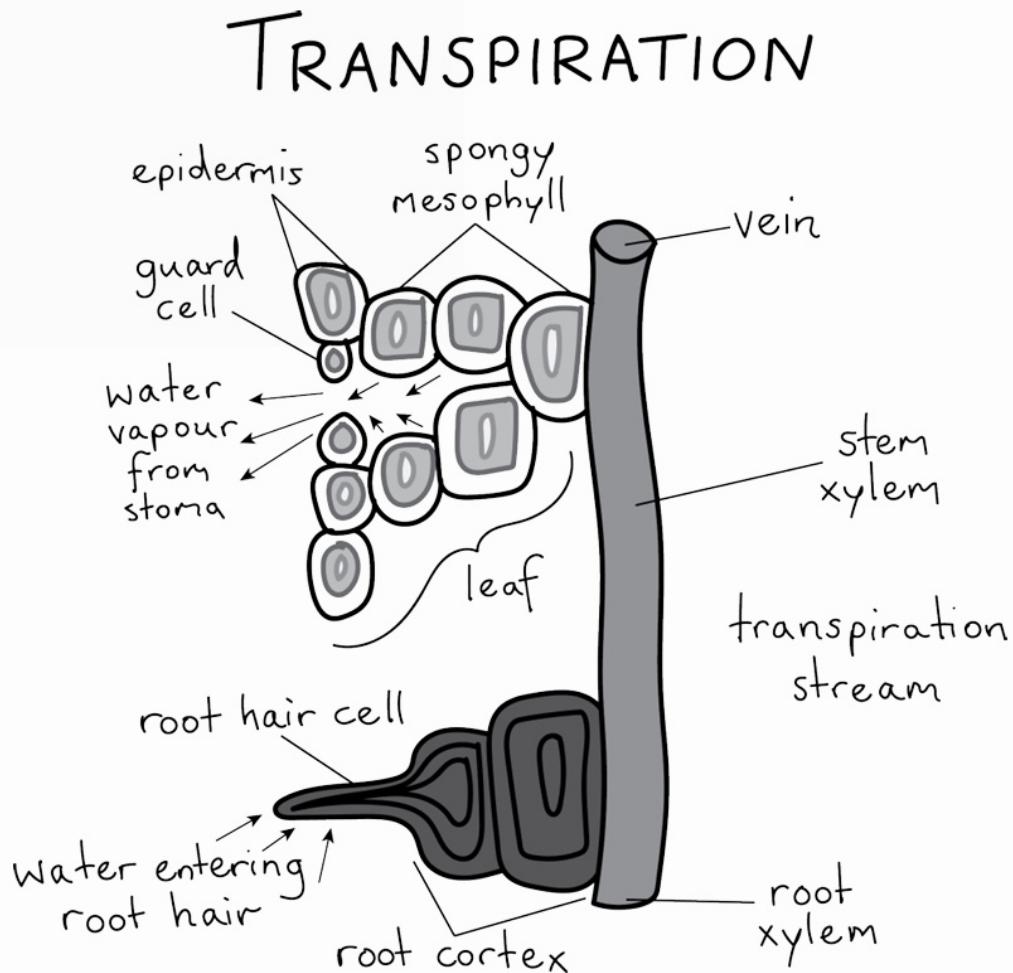
2.4.3 Roots

The purpose of the roots is to uptake water and nutrients from the soil and transport it to the leaves via the stem. The branching structure of roots increases their surface area and thus, their capacity for absorption of water and minerals from the surrounding soil. Furthermore, since soil contains air spaces, **root hairs** also allow oxygen to diffuse into them and then into the roots themselves. If soil becomes waterlogged, the air spaces become filled with water, and an insufficient amount of oxygen will diffuse into the roots, thus, causing the plant to wilt.

Substances may enter the roots by either the extracellular or cytoplasmic pathway:

- **Extracellular:** most water and some mineral ions cross through or between cell walls.
- **Cytoplasmic:** some water and most mineral ions cross through the cytoplasm of living root cells. This means crossing the plasma membrane of the root hairs, which may occur through active transport, osmosis and diffusion.

Whatever pathway water chooses, there will be a barrier between the roots and the xylem called the **Caspary strip**. This regulates which substances enter the xylem tissue by forcing water travelling via the extracellular pathway into the cytoplasm. The passive movement of water into the roots and up to and out of the leaves through the stomata is called **transpiration**. This process requires **no energy** and is catalysed by the heat energy in sunlight which breaks the **cohesive bonds** in water molecules, causing water to escape through the stomata via evaporation. The pathway that water takes is called the **transpiration stream** and allows water to travel from the roots all the way to the leaves and out of the stomata.



The rate of transpiration is affected by:

- **Humidity:** ↑ humidity = ↓ transpiration rate
 - This is due to the high level of moisture in the air, resulting in a decreased water concentration gradient between the outside air and the inner leaf.
- **Temperature:** ↑ temperature = ↑ transpiration rate
 - Greater heat energy means that more cohesive bonds are broken, thus, increasing the rate of evaporation of water.
- **Wind:** ↑ wind speeds = ↑ transpiration rate
 - Higher wind speeds force water vapour away from the stomata.

2.4.4 Vascular tissue – in detail

As we've already learned, vascular tissue is contained in vascular bundles and is present in the leaves, stem, and roots. It allows for the transport of all the materials discussed previously, whether they are the reactants or products of photosynthesis. A more detailed comparative summary of both forms of tissues can be found below.

Xylem tissue	Phloem tissue
Transports water and inorganic mineral ions upward from the roots to elsewhere in the plant.	Transports organic solutes such as sugars from sources (e.g. leaves) to sinks (e.g. roots, stems, flowers, fruits) in a process called translocation .
Composed of xylem vessels and tracheids .	Composed of sieve tubes, companion cells, parenchyma cells, and sclerenchyma cells.
As xylem matures, its walls become strengthened with lignin and the cytoplasm and nucleus disintegrate (so essentially, mature xylem can be thought of as being 'dead')	Mature phloem sieve tubes are living and contain strands of cytoplasm (plasmodesmata) but no nucleus – plasmodesmata also connect sieve cells with companion cells, which do contain a nucleus

Think of mature xylem cells as hewn out, mature bamboo sheathes, which are hollow and joined end to end like a straw. Just like a straw, water can easily pass through this mature xylem tissue, making it effective for transport. **Tracheids** are similar to xylem, except, when mature, water is transported *horizontally* through adjoining pits.

Part II

Unit 2: Maintaining the internal environment

Topic 1

Homeostasis

1.1 Homeostasis

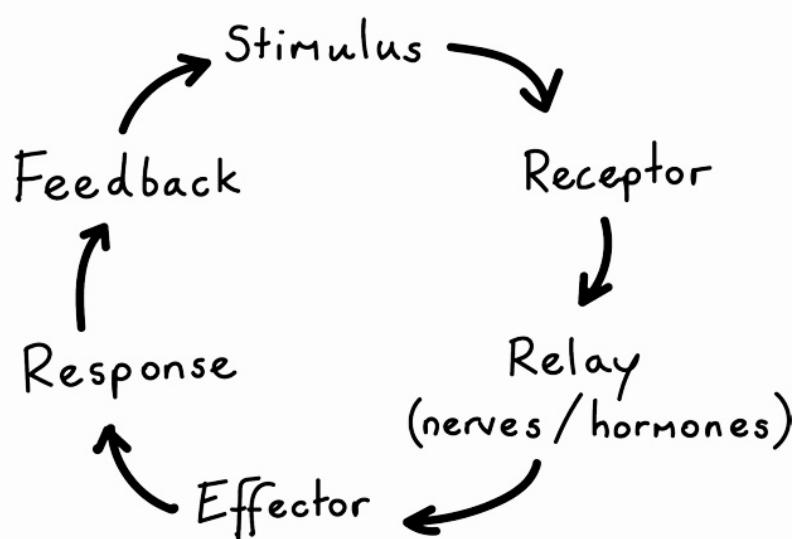
In order for all the aforementioned biological processes to occur, it is crucial that an organism remains in a state of **homeostasis**. This means an organism is in a relatively stable physiological state where all internal conditions are regulated within an organism's **tolerance range** when either the internal or external environment changes. This means the organism is able to react to external or internal stimulus and adequately adjust to compensate – thus maintaining a state of **equilibrium** known as homeostasis.

This task of detection and reacting to compensate, is achieved by **feedback loops** and is generally referred to as the stimulus-response model, because the body detects a change (stimulus) and reacts through feedback loops (response).

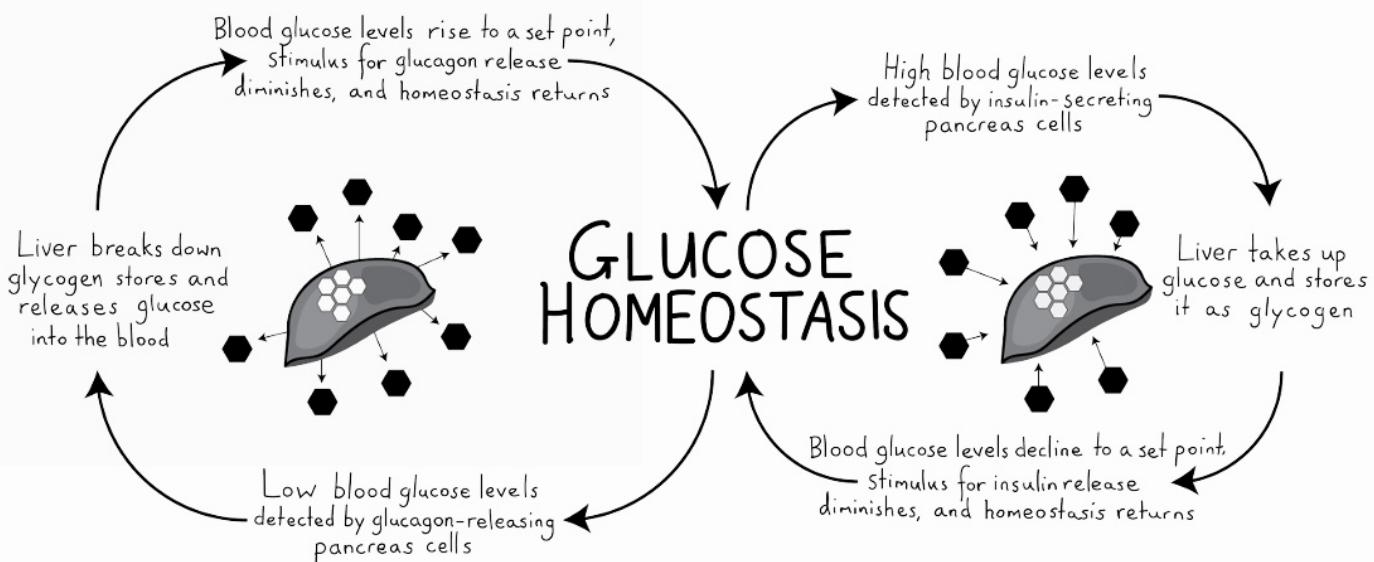
Having said that though, how does an organism detect environmental changes, whether internal or external? This is achieved by **sensory receptors**, which come in a wide variety of different forms to maintain homeostatic equilibrium.

1.1.1 Feedback loops

Homeostasis is maintained via a series of steps which make up **negative feedback loops**. These feedback loops may involve both the **nervous system** and the **endocrine system**. Within these feedback loops, changes in the internal or external environment are detected (by **sensory receptors**) and a **counter response** is initiated (via **effectors**) in order to reduce the effect of the change imposed. Effectors respond to stimuli and may be either **muscles** or **glands**, where muscles contract in response to neural stimuli, and glands produce secretions.

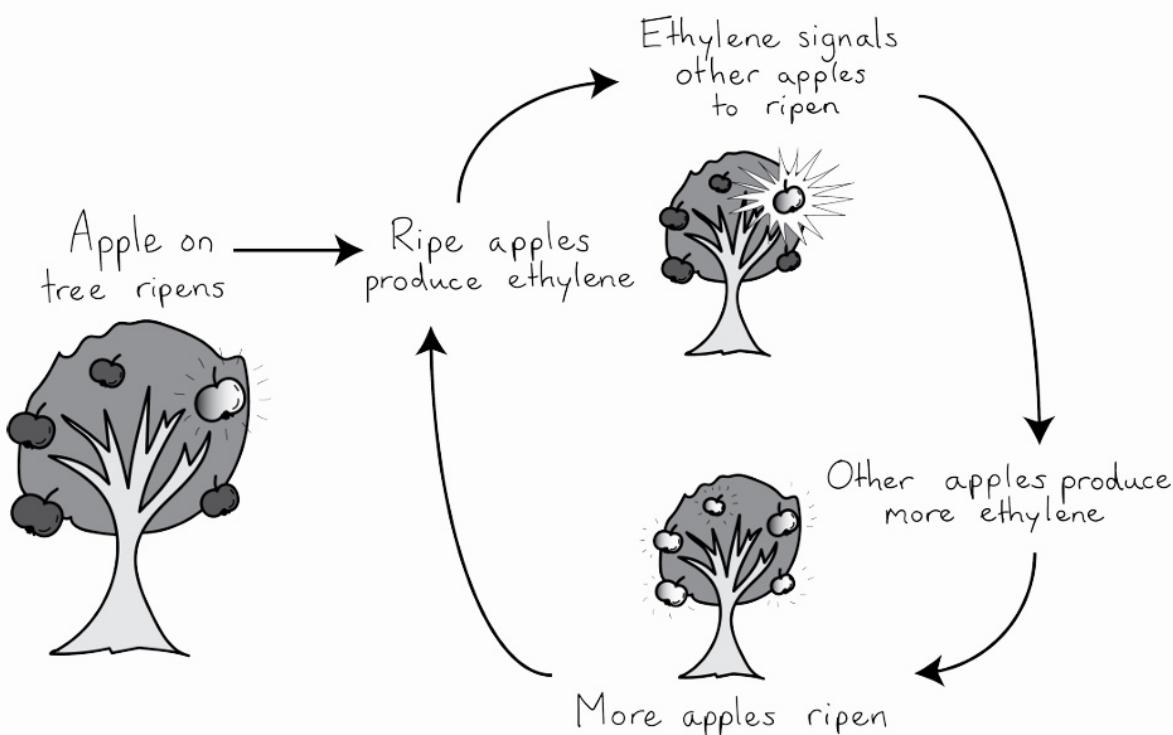


An example of a **negative feedback loop** ('negative' because something in the body is *reduced* to return to homeostasis, not because it is 'bad'!) is how blood glucose levels are regulated by insulin and glucagon. In this case, the stimulus is an increase/decrease in blood sugar levels, the receptor is beta cells in the pancreas, and the effector is insulin/glucagon which is secreted by the pancreas.



Feedback loops are not always negative, however. While negative feedback loops work to partially reverse the change imposed on the system, thus maintaining equilibrium, **positive feedback loops** are the opposite in that they work to maintain or enhance the direction of the stimulus, to force the body out of homeostasis. For example, during childbirth, uterine contractions are continuously initiated by the secretion of oxytocin by the endocrine system, thus pushing the baby into the birth canal in order for the baby to be born.

Another example of a positive feedback loop is the process by which fruit trees ripen and prompt neighbouring fruits and trees to ripen, as shown below.



1.1.2 Sensory receptors

Sensory receptors detect change. In animals, these may be **interoreceptors** (which detect internal stimuli such as blood pressure and blood chemistry) or **exteroreceptors** (which detect external stimuli such as pain and pressure). Plants have special sensory receptors to respond to light, gravity, touch, temperature, and water.

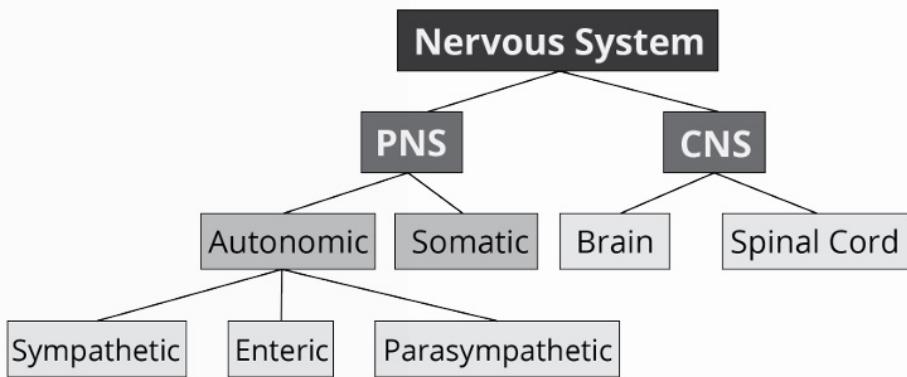
Animals		
Receptor	Stimuli detected	Location of receptor
Chemoreceptors	Specific chemical compounds	Taste buds, olfactory epithelium, etc.
Thermoreceptors	Heat	Skin and tongue, etc.
Mechanoreceptors	Pressure (touch)	Blood vessels, skin
Photoreceptors	Light	Eye spots, rod and cone cells in retina, etc.
Nocireceptors	Pain	Body tissues
Electroreceptors (fish only)	Electric currents in water	Organs in the skin of some fish

Plants				
Receptor	Stimuli detected	Location of receptor	Response initiated	Example
Phytochromes	Light	Stems, leaves, root tips, flowers, seed coats	Phototropism: hormones secreted which cause the plant to grow towards/away from light, or cause flower buds or stomata to open in response to light.	Leaves face upwards towards the sun, and roots grow down into the soil
Amyloplasts	Gravity and pressure (touch)	Roots and storage tissues	Gravitropism: dictates the direction that shoots and roots grow in.	Downward root growth, upward shoot growth
			Thigmonasty: dictates the plant's response to touch or vibration by initiation of an action potential .	Venus flytrap: traps prey when detected by sensors

1.2 Neural homeostatic control pathways

The nervous system (along with the endocrine system) is integral in maintaining homeostasis by sending signals via sensory receptors to respond to environmental changes.

The nervous system can be divided into the **central nervous system** (which I will refer to as **CNS** from now on) and the **peripheral nervous system (PNS)**.



- **CNS:** encompasses the brain and spinal cord.
- **PNS:** encompasses all the afferent (sensory) and efferent (motor) nerves that communicate with the CNS and effector organs, respectively. The motor section is composed of the **somatic** (voluntary) and **autonomic** (involuntary) systems.
 - **Somatic (voluntary) system:** controls conscious body movement.
 - **Autonomic (involuntary) system:** subdivided into **sympathetic**, **parasympathetic**, and **enteric** systems.
 - * **Sympathetic:** prepares the body for an emergency (e.g. increased heart rate and metabolism).
 - * **Parasympathetic:** enhances bodily activities which conserve energy (e.g. slowed metabolism, decreased heart rate).
 - * **Enteric:** coordinates intestinal control (e.g. gut function and digestion).

The functional unit of the nervous system is the **neuron**, of which there are three basic classes.

Neuron class	Function/message pathway	Diagram
Afferent (sensory) neurons	Sends signals from tissues and organs (effector cells) to the CNS	
Efferent (motor) neurons	Sends signals from CNS to tissues and organs (effector cells).	
Interneurons	'Middle men' which connect other neurons within the nervous system.	

The basic structure of the neuron consists of three main segments; the **dendrites** (the ‘listening’ end), the **cell body** (soma), and the **axon** (the transmission cable). However, the neuron is more complicated than this, and so contains other components which are all linked to these main sections, such as the **nucleus**, **nodes of Ranvier**, **myelin sheath**, **axon terminals**, and **synaptic terminals**.

- **Dendrites:** allows the neuron to receive and process incoming information and conduct an action potential along the axon.
- **Soma (cell body):** contains the **nucleus**.
- **Axon:** an action potential is conducted along this section.
- **Nodes of Ranvier:** gaps in the myelin sheath which contain channels for Na^+ (sodium) ions involved in action potentials.
- **Myelin sheath:** prevents leakage of Na^+ ions which would otherwise slow down the action potential during conduction.
- **Axon terminals:** connects the axon to target cells, allowing action potential to transmit.
- **Synaptic terminal:** contains vesicles containing neurotransmitters which causes Ca^{2+} (calcium) ions to enter the cells and thus release neurotransmitters into the synaptic cleft via exocytosis.

1.2.1 Signal transduction

In order for a signal to be passed from one neuron to a neighbouring neuron or target cell, neural signal transduction must occur, which utilises both electrical and chemical signalling.

Firstly, dendrites detect a stimulus and gated sodium (Na^+) and potassium (K^+) ion channels are opened, thus forming an **action potential**. This is a wave of electrical change that passes along an **axon membrane**.

KEY POINT :

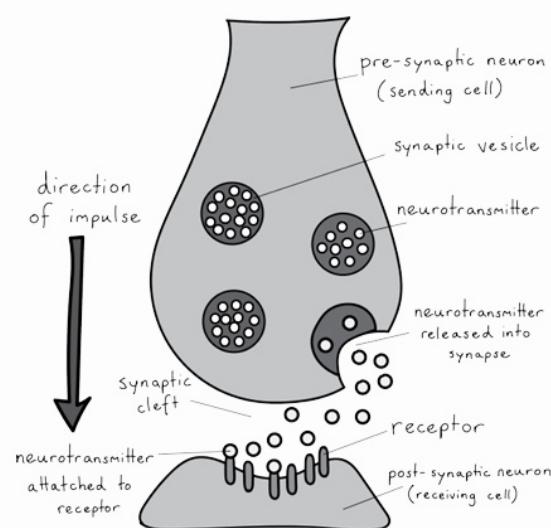
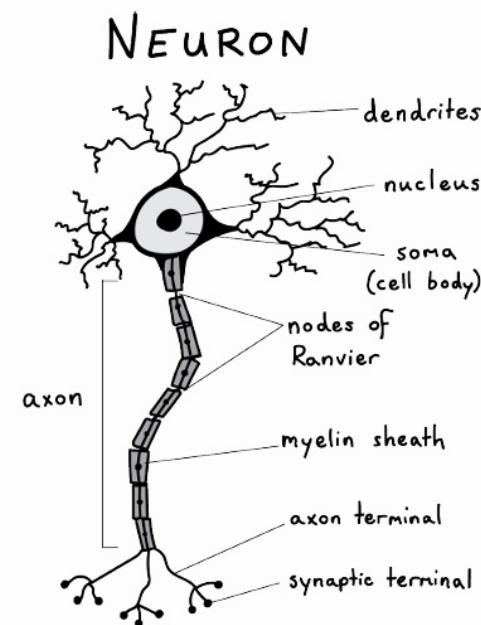
The action potential being passed along the axon ‘wiring’ of the neuron is the **electrical component** of signal transduction. The release of chemical neurotransmitters is the **chemical component**.

This action potential is passed along the axon membrane and is carried to **synaptic terminals** at the end of the axon, which form **synapses** with other cells.

Synapses consist of three components:

- **Pre-synaptic cell:** such as the axon terminal, which contains neurotransmitters contained in vesicles.
- **Synaptic cleft:** the ‘valley’ that the neurotransmitters must cross.
- **Post-synaptic cell:** the target cell or the recipient of the neurotransmitters, which contains receptors.

Now that the action potential has reached the synaptic terminal, Ca^{2+} (calcium) ions are released into the cell which causes vesicles containing **neurotransmitters** to be released into the **synaptic cleft** via **exocytosis**, whereby the neurotransmitters then bind to the **receptors** on the **post-synaptic cell**.



1.3 Hormonal homeostatic control pathways

Now that we've covered the nervous system's role in maintaining homeostasis, we must now begin to explore how the **endocrine system**, in conjunction with the nervous system, plays a critical role in maintaining equilibrium within the body.

Rather than nerve impulses, the endocrine system uses tiny signalling molecules called **hormones** which regulate the growth and activity of cells, and may affect the target cells over a short or long-lasting period of time. Hormones are also very powerful in the sense that they can affect just a single target cell, or may cause different responses in multiple target cells simultaneously.

The endocrine system is composed of glands and organs that synthesise and secrete these hormones into the bloodstream or lymphatic system, whereby either the circulatory system or lymphatic system circulates these 'chemical messengers' to target cells and tissues. It is important to note, however, that hormones are very 'picky' – they can only act on target cells which contain that hormone's *specific* receptor proteins.

Furthermore, a cell's receptivity to a hormone depends on the number of receptors that a cell carries for that specific hormone. As such, an increase in receptors is known as **upregulation**, and a decrease in receptors is called **downregulation**.

The endocrine system is linked with the nervous system, not only in the activities that it is involved in, but also in that the nervous system stimulates the production of hormones.

Animal hormones can be sorted into three main classes:

- **Lipid hormones:** these are **hydrophobic** in nature, and are derived from either fatty acids (**eicosanoids**) or cholesterol (**steroids**).
 - Eicosanoids: play a role in cell growth, fever and inflammation (e.g. prostaglandins).
 - Steroids: play a role in regulating metabolism, salt/water balance, inflammation and sexual function (e.g. testosterone, progesterone, oestrogen, cortisol).
- **Peptide and protein hormones:** these are **hydrophilic** in nature.
 - Peptide hormone (e.g. insulin).
 - Protein hormone (e.g. growth hormone, which is essential for healthy growth and development).
- **Amino-acid-derived hormones:** these are small hormones derived from the amino acids tyrosine and tryptophan, and can be either hydrophilic (**catecholamines**) or hydrophobic (**thyroid hormones**).
 - Catecholamines (e.g. adrenaline and dopamine).
 - Thyroid hormones (e.g. thyroxine).

SCIENCE AS A HUMAN ENDEAVOUR :

Use of bovine growth hormones in the dairy industry (rBST)

As briefly mentioned above, growth hormone is important for regulating growth and development in animals. Therefore, farmers can 'hack' the effects of this hormone by adding synthetic bovine growth hormones or other types of hormones in dairy cattle to stimulate milk production. Although this results in improved efficiency and cost-effectiveness, the exact risks associated with implementing these synthetic hormones is unclear, and thus, further research is required to reach a definitive answer.

In addition to animal hormones, there are five main types of **plant hormones** (or **phytohormones**):

- **Abscisic acid:** affects seed/bud dormancy, drought tolerance, and apical dominance, whereby the main stem dominates all other side-branching stems.
- **Auxin:** allows shoots to bend towards the light (phototropism) and roots to grow downwards into the soil (gravitropism).
- **Cytokinins:** affects the growth of lateral (side) branches.
- **Ethylene:** affects ripening (e.g. increasing sugar content in fruit and influencing fruit and leaf drop).
- **Gibberellins:** affects elongation of stems, leaf expansion, seed germination, and flower maturation.

Just as in neural homeostatic control pathways in the nervous system, the endocrine system utilises **signal transduction** to convert a stimulus signal into a response. However, with regards to hormones, the signal may undergo some form of chemical or physical change, such as by changing the signalling molecule itself, or by converting the signal from one type to another (i.e. chemical to electrical signal).

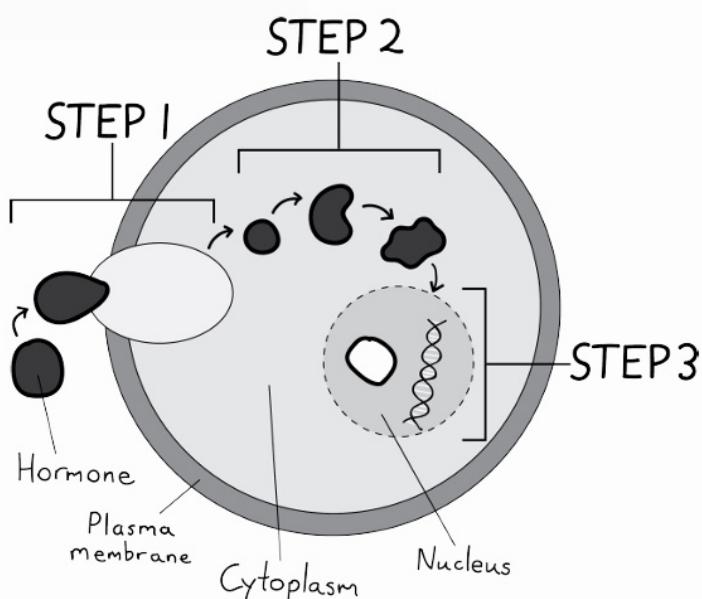
There are three steps involved in the stimulus-response model:

Step 1 – Reception: detection of the signalling molecule via a receptor. The hormone binds to a receptor displayed on the outside of the cell.

Step 2 – Transduction: involves converting the signal into a form that can be relayed to the target cell.

This process may be **single step**, such as by binding the molecule to one receptor to create a cellular response, or **multi-step**, whereby the molecule binds to a receptor which causes a **transduction cascade**, involving a sequence of steps in which several different molecules are sequentially activated.

Step 3 – Cellular response: the activation of a cellular activity or process, usually in the form of gene transcription within the nucleus.



This generalised model becomes altered when applied to either hydrophobic or hydrophilic hormones.

Hydrophobic hormones (such as steroids) are lipid-soluble, and thus, can easily diffuse through the fatty acid tails of the phospholipid bilayer. Therefore, these hormones bind to **intracellular receptors** in the nucleus or cytosol to form a complex [reception]. Once in the nucleus, this complex **acts as a transcription factor**, which activates certain genes by binding to DNA sequences [transduction]. The activated form of the receptor complex, after entering the nucleus, elicits a cellular response through the activation of genes which will initiate a cellular activity or process [cellular response].

Hydrophilic hormones are water-soluble and thus, are unable to diffuse through the phospholipid bilayer. As a result, these hormones must bind to receptors on the **outside of the cell**, such as **transmembrane proteins** [reception]. The fact the protein is **intracellular** allows the signal to be transferred to the inside of the cell from the outside, through changes to the shape of the intracellular binding site. This triggers a **transduction cascade** whereby second messengers (those which result from the initial change in shape of the protein) are produced [transduction]. This transduction cascade causes several molecules to be activated which activates a cellular response [cellular response].

KEY POINT :

Note that signal transduction may **activate** or **inhibit** cellular functions in the target cell, but these are cellular responses nonetheless.

1.4 Thermoregulation

Thermoregulation can simply be defined as an organism's ability to maintain its body temperature within an optimal range required for homeostasis. For example, in humans, the optimal body temperature range is 35.6–37.8°C. Thus, **thermoregulatory mechanisms** are in place in order to ensure this range is not exceeded.

Animals can be grouped into two broad categories depending on how they regulate their body temperature:

- **Endotherms:** generate their own body heat.
 - This is achieved internally through negative feedback loops, containing sensory inputs and effector responses to detect and adjust to temperature changes, allowing endotherms to maintain their body heat within a narrow tolerance range.
 - You can think of endotherms as being 'warm-blooded.'
 - Most mammals and birds are endotherms
- **Ectotherms:** unable to generate their own body heat and thus rely on external heat sources.
 - Ectotherms may adopt behavioural mechanisms (such as by laying on warm rocks or sand) to absorb heat. As a result, ectotherms' internal body heat is subject to external influences, and will fluctuate based on environmental temperatures.
 - You may think of ectotherms as being 'cold-blooded.'
 - Most reptiles, fish, amphibians, and invertebrates are ectotherms.

KEY POINT :

The syllabus mainly focuses on how *endotherms* regulate their body temperature, but I've added the above information on ectotherms for completion's sake, and so you could compare how they differ. From here on, I will only focus on *endotherms*.

There are a variety of thermoregulatory mechanisms or features which endotherms employ in order to maintain heat exchange, whether they be to warm up or cool down.

1.4.1 Structural features

- **Insulation:** fur, feathers, skin, blubber.
- **Vascular body parts:** long ears or tails which are highly vascular, thus, allowing heat exchange to occur close to the surface of the skin via the blood.
- **Brown adipose tissue:** contains a high number of mitochondria, which affects metabolic rate, and thereby aids the organism in transitioning from a state of torpor (state of physiological inactivity) to an awakened state of normal metabolic function.
- **High number of mitochondria within cells:** greater number of mitochondria increases metabolic rate, which in turn generates more heat via cellular respiration at the cost of a larger input of nutrients.

1.4.2 Behavioural responses

- **Kleptothermy:** sharing body heat through huddling.
- **Torpor:** conservative state in which the metabolism is lowered to conserve energy.
 - **Hibernation:** prolonged state of torpor during winter.
 - **Brumation:** similar to hibernation but occurs in reptiles, and is triggered by low air temperatures and short daylight hours.
 - **Aestivation:** prolonged state of torpor under hot and dry conditions.
- **Evaporative cooling/heat exchange:** physiological mechanism which is initiated by behaviours such as licking, panting, spraying water on the body, wallowing in water/mud, etc.

There are also other behavioural **adaptations** which aid in thermoregulation, such as seeking shelter or adopting nocturnal behaviour.

1.4.3 Physiological mechanisms

- **Vasomotor control:** controls how blood vessels constrict or dilate to promote or inhibit heat exchange.
- **Vasoconstriction:** blood vessels in the skin become tighter and limit heat loss.
- **Vasodilation:** blood vessels in the skin expand and heat is lost to the environment as blood moves close to the surface to release heat.
- **Evaporative heat exchange/cooling:** capillaries close to the surface of the skin allow a cooling effect to occur as heat is exchanged from warm blood to cool blood.
- **Countercurrent blood flow:** process which cools the blood entering the brain as the cooled blood in the veins passes in the opposite direction to the warmer blood from the arteries, thus, allowing heat to be lost from the warm blood to the cool blood. The blood from veins is cooler because it undergoes **evaporative cooling** within the nostrils.
- **Piloerection** ('goosebumps'): constriction of muscles around hair follicles in the skin, causing the hairs to stand erect and form an insulating barrier against the cold.
- **Thermogenesis:** increased metabolic activity from organs/tissues/cells to generate heat through:
 - **Shivering thermogenesis:** increases heat production through involuntary muscle contractions which generates metabolic heat.
 - **Non-shivering thermogenesis:** produces metabolic heat without the act of muscle contractions due to brown adipose tissue, which contains a high number of mitochondria.

1.4.4 Homeostatic mechanisms

Note that the name 'homeostatic mechanisms' is somewhat misleading, since all these mechanisms work to maintain homeostasis!

- **Misalignment detectors:** sensory cells in the hypothalamus detect when blood temperatures drop below or exceed the optimal range, and activate homeostatic mechanisms in order to urgently 'realign' the body to maintain homeostasis, either by enhancing heat production (to increase body temperature) or heat exchange (to decrease body temperature).
- **Disturbance detectors:** temperature receptors in the skin that are tuned to sense and react to changes in **environmental temperatures**, which are *external* to the body. These work to prevent a change in core body temperature.
- **TRH (thyrotropin releasing hormone):** acts on the thyroid gland to release hormone messengers which regulate metabolism and increase heat production and body temperature.

Human response to heat	Human response to cold
<ul style="list-style-type: none"> – Vasodilation – Slowing metabolic rates – Evaporative cooling (sweating, spraying water on skin, bathing/swimming) – Countercurrent heat exchange – Seeking shade – Removing clothes 	<ul style="list-style-type: none"> – Vasoconstriction – Increasing metabolic rate to generate heat (e.g. TRH) – Shivering thermogenesis – Piloerection (goosebumps) – Seeking shelter – Wearing warm clothes

SCIENCE AS A HUMAN ENDEAVOUR :

In certain professions where cooling systems inside clothing is essential, these cooling systems can be modelled on the human thermoregulatory response, such as by using liquid cooling, counter-current cooling, and dispersal of heat to the surrounding environment. However, more research is required to optimise these clothing options as there are drawbacks to manufacturing these types of clothing due to the great design complexities and concerns regarding overall efficiency and wearability.

1.5 Osmoregulation

1.5.1 Osmoregulation in animals

Osmoregulation can be defined as the regulation of water balance, which is necessary for controlling salt concentration. Much like thermoregulation is achieved by endotherms and ectotherms, osmoregulation can be achieved by both **osmoregulators** and **osmoconformers**.

- **Osmoregulators:** can regulate their own internal osmotic concentration regardless of external concentration changes. Thus, the internal osmotic concentration is irrespective of the external conditions
- **Osmoconformers:** are those whose internal osmotic concentration conforms to that of their surroundings. Thus, their internal osmotic concentration is *the same* as the outside concentration. Most marine invertebrates are osmoconformers.

Osmoregulation involves the movement of water into and out of cells via **osmosis**. The amount of water that moves into or out of the cell, however, depends on the solute concentration.

Remember that according to the laws of osmosis, if the salt concentration on the outside of the semipermeable membrane is higher than on the inside, this would cause water to move out of the cell to dilute the external salt concentration. Thus, water moves from low solute (salt, in this case) concentration to high solute concentration. Conversely, if the salt concentration was lower on the outside of the cell, water would move from the outside to the inside of the cell. Again, water moves from low to high solute concentration.

Factors affecting the solute concentration, and therefore the amount of water lost throughout the day, are **exercise, temperature, humidity, and diet** (including food and fluid intake).

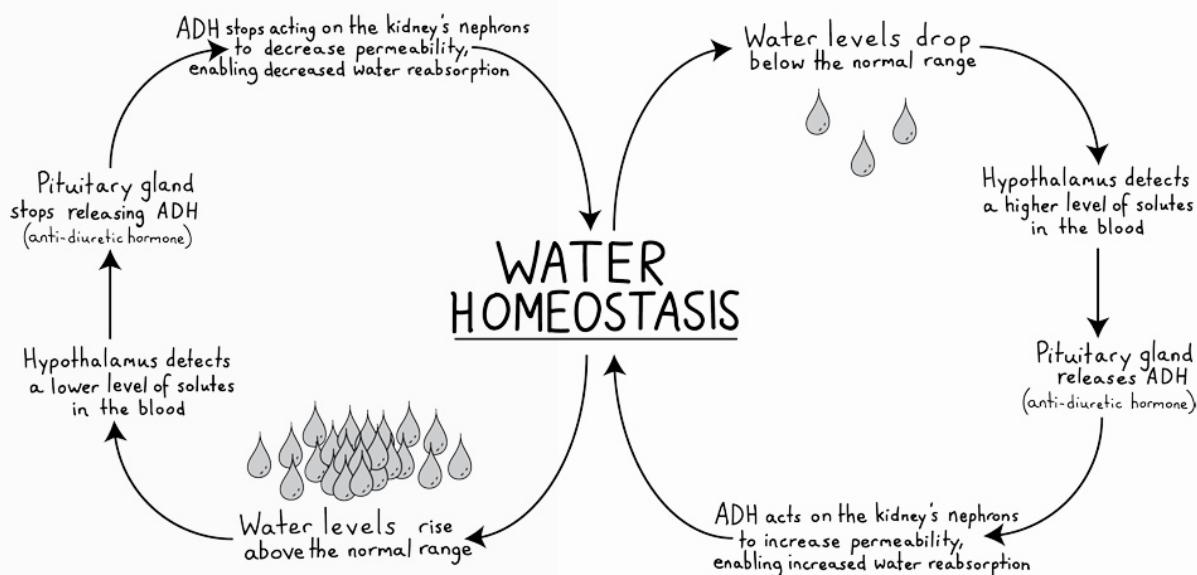
In order to detect changes in water and solute concentrations, two types of receptors are involved:

- **Osmoreceptors:**
 - Exist in the hypothalamus of the brain
 - Detect blood solute concentrations
- **Baroreceptors:**
 - Exist in the atria of the heart
 - Detect changes in blood pressure which indicates blood volume

You could say that both these receptors work together to monitor an organism's **osmolality**, which is a measure of the concentration of the particles (sugars such as salt) that affect osmosis. As you read through the mechanisms, remember that negative feedback systems are in place, and are working to detect changes and recorrect by triggering responses.

A key hormone involved in regulating osmolality is **antidiuretic hormone (ADH)**, which regulates water reabsorption by signalling the kidneys to increase or decrease the nephron's permeability to water.

- If osmolality is low, this means that too much water has been taken into the body.
 - This is detected by osmoreceptors.
 - In response, the release of antidiuretic hormone (ADH) is decreased, so that less water is reabsorbed by the kidney and more is left in the nephron.
 - As a result, urine volume increases, becoming more dilute and pale.
- If osmolality is high, not enough water has been absorbed by the body.
 - Again, this is detected by osmoreceptors.
 - In response, the release of ADH is increased and more water is reabsorbed by the kidneys, leaving the urine more concentrated in the nephron.
 - As a result, urine volume decreases, becomes more concentrated, and turns a darker yellow as more salts are contained within.



Conversely, just as osmoreceptors detect changes in blood solute concentrations to dilute or concentrate the urine, baroreceptors are equally important in maintaining osmolality, by detecting changes in blood pressure. A key enzyme involved in the detection of blood pressure changes is **renin**.

Renin, secreted by the kidneys, triggers the release of a hormone called **aldosterone** from the adrenal glands. Aldosterone regulates sodium and potassium levels by causing more water to be drawn into the blood by osmosis, thus **increasing blood volume and pressure**.

1.5.2 Osmoregulation in plants

Plants use specialised structural features as well as homeostatic hormonal systems to regulate their water balance. Factors that affect water balance are **salinity**, **heat**, and **wind**.

Before examining the various features which carry out osmoregulation in plants, it is important to recognise that **different types of plants** exist which determine the adaptations with which they are equipped, since different plants exist in different environments and are exposed to different external conditions.

- **Xerophytes** (*xeros* = dry, *phyton* = plant): plants which grow in dry, hot environments, such as cacti. Xerophytes contain structural adaptations focused on reducing water loss.
- **Halophytes** (*halos* = salt, *phyton* = plant): salt-tolerant plants which grow in highly saline soils or waters, such as mangroves. Halophytes utilise physiological adaptations to withstand high salinity.
- **Mesophytes** (*meso* = middle/moderate, *phyton* = plant): plants which thrive in moist environments with well-aerated soil, such as meadow clovers (terrestrial plants with moderate water). Mesophytes contain structural features such as fibrous roots and food storage adaptations.
- **Hydrophytes** (*hydro* = water and *phyton* = plant): plants which live in water, such as water lilies. Hydrophytes have structural adaptations to facilitate CO_2 and light absorption needed for photosynthesis, including stomata on upper sides of leaves, reduced root system, and small cuticles.

Xerophytes minimise water loss (e.g. cacti, aloevera)	Halophytes tolerate salt water (e.g. mangroves, marshes)	Mesophytes thrive in moist environments (e.g. clovers, daisies)	Hydrophytes live atop or submerged in water (e.g. water lilies, hornwort)

Structural features of plants affecting osmoregulation	Leaf surface area
	Rolled leaves
	Leaves oriented away from the sun
	Number of stomata (generally on the underside of leaves to optimise gas exchange, but also found on the upper sides of aquatic plants)
	Sunken/protected stomata
	Stomatal hairs (form a humid microclimate for the stomata to live in, which decreases the rate of transpiration)
	Thick, waxy cuticle
Physiological mechanisms to adapt to high salinity	Extensive root systems
	Compartmentalisation of ions within cells and tissues, through which excess salt is transported to vacuoles or old tissue to prevent accumulation in the cytoplasm
Homeostatic mechanisms (plant hormones) involved in abscission*	Excluding salt at the roots and leaves, such as by shedding leaves that are overloaded with salt
	Abscisic acid
	Auxin
	Ethylene

*Abscission is the loss of plant organs such as leaves, which reduces the surface area exposed to dry air and thus, slows water loss in the plant

Topic 2

Infectious disease

2.1 Infectious disease

Despite all the lengths that your body goes to in order to prevent the disruption of homeostasis, disease can still occur.

We define **disease** as a condition which **impairs the normal function of an organism**.

Diseases can be classified as either **infectious** (caused by a pathogen) or **non-infectious** (such as genetic or lifestyle diseases), where an infectious pathogen is not involved. We'll first discuss infectious diseases before returning to non-infectious ones and a comparison of both.

2.1.1 Types of infectious pathogens

Pathogens may be primary or opportunistic.

- **Primary pathogens:** are able to infect a healthy host at any time.
- **Opportunistic pathogens:** are only able to infect an immunosuppressed host during a window of weakness, such as by poor nutrition, stress or infection by another pathogen.

There are **six** types of infectious pathogens: **parasites, protozoa/protists, fungi, prokaryotes/bacteria, viruses, and prions**.

Cellular (living)				Acellular (non-living)	
Parasites (e.g. tapeworm)	Protozoa (e.g. malaria)	Fungi (e.g. tinea)	Prokaryote (e.g. leprosy)	Virus (e.g. HIV/AIDS)	Prion (e.g. CJD)

- **Parasites:**

- Organisms which derive their own nutrients from the host, thus, harming the host.
- Examples include helminths (worms) and nematodes (roundworms, hookworms, threadworms, or pinworms).

- **Protozoa/protists:**

- A diverse group of organisms that can be pathogenic to animals or plants.
- Animals pathogenic protists include zooflagellates, sarcodines, and sporozoans (such as plasmodium which causes malaria and are transmitted by the mosquito as the vector).
- Plant pathogenic protists include oomycetes (water mold) that can cause seedling blights, root rot, and mildew.

- **Fungi:**

- A diverse kingdom of organisms which can secrete digestive enzymes and other chemicals into the environment to break down organic matter so that it can be absorbed.
- These secretions can act as agents of disease in the host.
- Examples include molds, true yeasts, and fungi-like yeasts.

- **Prokaryotes/bacteria:**

- Bacteria are cellular, and thus, can be treated via **antibiotics** (unlike viruses). They can be identified by a variety of different characteristics:
 - * Shape: cocci (spherical), bacilli (rods), spirochetes (spirals)
 - * Organisation: single, pairs, clumps, chains
 - * Presence or absence of a capsule
 - * Mobility: flagella or cilia
 - * Requirement for oxygen: aerobic, obligate anaerobic, facultative anaerobic
 - * Nutritional requirements
 - * Gram-staining characteristics: gram-positive bacteria are purple when stained, and secrete exotoxins into their environment; gram-negative bacteria are pink when stained and produce endotoxins which only release when the bacteria ruptures

- **Viruses:**

- Non-living intracellular parasites that can only replicate inside cells. They are ‘non-living’ in the sense that viruses are not made out of cells, and thus need to use host cells to replicate.
- The structure of a virus is made up of genetic material encased in a **capsid** protein coat. This genetic material may contain either DNA or RNA (these are called **retroviruses**).
- Since viruses are non-cellular, they cannot be treated by antibiotics (unlike bacteria).

- **Prions:**

- Pathogens made of protein which don’t contain genetic material.
- Function as a pathogen by causing the host to **misfold its own normal prion proteins** (PrP) into abnormal prions which have detrimental effects on the nervous system. The accumulation of these abnormal prions forms **harmful plaques** in the brain.
- An example of a prion disease is Creutzfeldt-Jakob disease (CJD), a neurodegenerative disease caused by prions.
- Unfortunately there are currently no treatment options available for prions.

2.1.2 Virulence factors

How effective a pathogen is against an organism’s defences depends on the pathogen’s **virulence**, which is the degree to which it can cause disease. The greater the virulence, the easier it is for the pathogen to infect its host.

Several **virulence factors** exist which aid the pathogen in infecting the host. If pathogens are like infantry, think of these virulence factors as special artillery or defences which equip them to more effectively infiltrate enemy forces and/or evade capture.

- **Capsule:** coating which surrounds the cell wall of bacterium, making it far less vulnerable to elimination by the host’s immune system. This may be a factor in acquired antibiotic resistance.
- **Adhesins:** proteins or carbohydrates on the surface of the pathogen which allow it to better adhere to host cells. For example, **pili** are hair-like structures which can help the pathogen adhere to proteins on the cell’s surface.
- **Invasion factors:** surface components that allow the bacterium to invade host cells.
- **Toxins:** include endotoxins and exotoxins. For example, bacteria can secrete harmful toxins which interfere with normal cellular functions, and can affect the host even after the bacteria have died.
- **Lifecycle changes:** some pathogens have the ability to change forms throughout their lifecycle, which can make them much harder to be treated. Pathogenic **fungi and protozoa** are two examples of pathogens which can do this, with some fungi being able to change between unicellular and multicellular forms.

2.1.3 Modes of transmission

- **Direct contact:** for example, through poor hygiene such as not washing hands after touching infected surfaces.
- **Coming into contact with bodily fluids:** pathogens can be carried within fluids such as saliva, blood, semen, and vaginal secretions.
- **Food or water contamination:** sources of food and water can transmit infections as a result of chemicals, pesticides, animal waste, industrial waste, etc.
- **Vectors:** some organisms can act as carriers of pathogens without being infected themselves. Vectors therefore act like a free ‘public transport’ service for certain pathogens, such as the plasmodium, which is a protist that causes malaria, and is transmitted within the saliva of mosquitoes. So, in this example, the vector is the mosquito, the pathogen is the plasmodium, and the disease is malaria.

2.1.4 Antigenic shift and drift in viruses

By now, hopefully you can appreciate that pathogens are very good at what they do, and that they employ a variety of clever measures to infect the host. However, the host is also well-equipped to fight back. By this, I mean that the host’s immune system detects specialised proteins called **antigens** on the surface of the pathogen, which are like a barcode, allowing the immune system to recognise it as a foreign entity which must be targeted and destroyed.

Once again, however, the pathogens are also equipped to deal with such an attack, especially when viruses are concerned. The antigens on viruses have the special ability to undergo certain changes in an attempt to evade being caught and remain one step ahead of the host’s immune system. It’s kind of like how undercover agents change their hairstyle or clothing to mask their identity! However, instead of changing appearances, viral antigens can undergo **antigenic drift or antigenic shift** to avoid detection, the latter being more effective than the former.

- **Antigenic drift:** a process whereby small, random genetic changes cause minor alterations to the shape of the antigens. These changes are really small, but over time, can prove to be reasonably effective at masking the pathogen from being detected.
- **Antigenic shift:** a more drastic change to the genetic code of a virus, which results in completely new antigens. This occurs as two viral strains swap genes, forming a new genetic code (hence why this is typically more effective).

2.1.5 Non-infectious disease

There are three main types of non-infectious diseases:

Genetic diseases	Transmitted genetically during reproduction
Nutritional diseases	Caused by inadequate diet
Environmental diseases	Caused by environmental factors (e.g. exposure to chemical mutagens)

Genetic diseases

Genetic diseases are those that can be inherited during sexual reproduction due to **mutations** that occur on chromosomes which carry hereditary information in the form of DNA. These mutations can occur as ‘copying errors’ during chromosomal duplication, and result in **chromosomal diseases**. A normal human contains 46 chromosomes in total, and when these chromosomes are displayed as a picture, it is called a **karyotype**. Karyotypes are incredibly useful for determining if chromosomal abnormalities or errors in duplication have occurred.

To correctly read a human karyotype, it is helpful to remember that:

- Chromosomes exist in pairs. Although each pair of chromosomes may differ in size, each chromosome should be similar in length to its counterpart (with the exception of the sex chromosomes in males – see below). If an individual is missing one chromosome from a pair, they will have a monosomy (e.g. conditions such as Turner syndrome). If an individual has an extra copy of one chromosome, they will have a trisomy (e.g. conditions such as Down syndrome).
- The 23rd pair of chromosomes are the two sex chromosomes.
 - Females will have **two equally sized** sex chromosomes (i.e. two X chromosomes).
 - Males will have two **unequally sized** sex chromosomes (i.e. one X and one Y chromosome).

Therefore, should you be asked to read a karyotype, look out for these key points, and you will quickly be able to spot any abnormalities.

Lastly, the mechanism by which genetic diseases are inherited is through inheritance of a mutated **allele** during the fusion of gametes (sperm and egg cell) during sexual reproduction. **Alleles** are just variations of genes which code for particular traits.

If an organism contains two of the same copies of an allele for a particular gene, they are **homozygous** for that trait. If an organism contains one different copy of each allele for a particular gene, they are **heterozygous** for that trait.

An example of a genetic disease is **sickle cell anaemia**. To be affected, one must be homozygous for the allele which carries sickle-cell anaemia. One who is heterozygous (carrying only one allele) will not be directly affected but will be a carrier who can pass the disease to their children.

Nutritional diseases

Nutritional diseases are caused by inadequate or excessive nutrient intake. The most common nutritional disease varies country to country depending on population densities, such as in the case of developing countries which are more prone to nutritional diseases caused by inadequate nutrient intake, whereas developed countries tend to face nutritional diseases that are caused by excessive intake of nutrients.

Examples of nutritional diseases are vitamin D deficiency and obesity

Environmental diseases

Environmental diseases are those which are caused by external factors such as exposure to toxic chemicals, radiation, stress, or pollutants.

2.1.6 Comparing infectious and non-infectious disease

Infectious disease	Non-infectious disease
<ul style="list-style-type: none"> – Caused by a pathogen (agent of disease) – Pathogens are passed between organisms to spread the disease – Pathogens include viruses, bacteria, fungi, protists, prions, and parasites 	<ul style="list-style-type: none"> – Caused by external circumstances rather than by infectious pathogens – Generally not able to be transmitted between organisms – May be either genetic or lifestyle (i.e. nutritional or environmental) diseases

2.2 Immune response and defence against disease

Realising how well-equipped pathogens are to break down the body's defences may seem frightening, until we learn about how equally well-equipped the immune system is at counteracting the forces of pathogens. Basically, the immune system is like a lighthouse with a giant spotlight which detects and destroys any foreign particles which it recognises to be different from its own. This 'lighthouse' identifies these foreign molecules via detection of **antigens**.

Antigens are molecules, such as proteins or carbohydrates, that elicit an immune response. They are studded on all cells, acting as 'tags' which allow the immune system to identify them as **self** or **non-self** (i.e. legit or imposter!). Obviously, if all antigens were seen as harmful, this would be bad news for your own body, since it would attack its own antigen-lined cells. This does still happen however, but it's not normal and leads to what we call **autoimmune diseases**. Otherwise, it is expected that your body has **self-tolerance** towards its own antigens. Each type of cell exhibits a certain antigen (all antigens have slightly different shapes) by which they are recognised. The body is able to recognise foreign pathogens as 'non-self' by their antigens. Antibodies bind specifically to antigens, allowing for a number of immune responses.

But before pathogens even reach the 'lighthouse,' the host has several lines of defence to prevent the pathogen from breaching the organism. These are **physical** defence strategies (first) and **chemical** defence strategies (second).

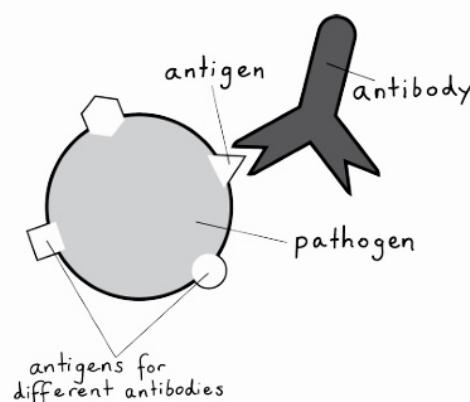
2.2.1 Physical barriers to infection – first-line defences

In plants, these first-line defences come in the form of bark, cell walls, thick waxy leaf cuticles, the ability to close stomata against incoming pathogens, and even the orientation of leaves.

In animals, physical barriers to infection are things such as unbroken skin and body secretions. Unbroken skin, such as the thin epithelial membrane which lines the skin, respiratory, gastrointestinal and urogenital tracts, form a continuous barrier against pathogens. Body secretions trap incoming pathogens in sticky mucus and drive them away using hair-like cilia.

2.2.2 Chemical barriers to infection – second-line defences

If the first line defences (the physical barriers) fail to keep out unwanted pathogens, the aid of chemical barriers are called in as reinforcements. **Plants** make use of toxic chemicals to fend off pathogens.



Chemical barrier	Description of function in plants
Saponins	Soap-like chemical which acts to break down lipids, thus, working to disrupt the phospholipid membrane of pathogens.
Terpenes	Compose many of the essential oils in plants.
Phenolics	Class of plant chemicals which include those that disrupt cellular metabolism in pathogens, have antibiotic properties, etc. Include flavonoids, tannins and phytoalexins.
Alkaloids	Highly toxic to many organisms including fungi, bacteria and insects.
Cyanogenic glycosides	Compounds that decompose to form hydrogen cyanide which is extremely toxic because it disrupts ATP production in the mitochondria of eukaryotic cells, thus, resulting in cell death.

Animals also utilise chemical barriers to infection, which come in several forms.

Chemical barrier	Description of function in animals
Secretions	Defend the body from infection by destroying bacterial cell walls (e.g. tears, sweat, and saliva).
Stomach acid and digestive enzymes	Powerful enough by themselves to kill many pathogens.
Fluid in the lungs	Acts as a detergent-like substance which is antimicrobial and coats pathogens.

2.2.3 Innate immune response

If the host is unable to defend itself through either its physical or chemical barriers, it now has to employ the use of its **innate immune response**, which summons defending cells and molecules to attack invading pathogens. This type of immune response occurs in both plants and animals, and is non-specific, meaning specific antigens are not targeted. However, as well as the innate response, animals also utilise the **adaptive immune response** which provides long-term immunity to pathogens through creation of immunological memory. This type of immunity is specific, unlike in innate immunity.

The key differences between the innate and adaptive immune response are summarised below:

Innate immune response	Adaptive immune response
Non-specific – does not target specific antigens	Specific – targets specific antigens
Rapid response	Slower response
Present in all animals	Only present in vertebrates after exposure to pathogens
Fixed response – does not adapt	Adapts in response to foreign antigens
Does not create immunological memory	Results in immunological memory which produces a more potent immune response after subsequent exposures to the pathogen

Innate immune response in plants

In plants, several proteins are produced which elicit immune responses to protect themselves from attacking pathogens. However, there must be a trigger which lets the plant know when to make these proteins. There are certain patterns called **microbe-associated molecular patterns (MAMPs)** within the cell walls of pathogens which are detected by **pattern recognition receptors (PRRs)**, which in turn trigger the immune response by making one or several of the following proteins, depending on the imminent danger. Important plant proteins include:

- **Defensins:** small proteins which have a range of defensive actions, including the inhibition of digestive enzymes in insects or microorganisms.
- **Protease inhibitors:** proteins which can inhibit certain types of enzymes.
- **Digestive enzyme inhibitors:** proteins which impede normal digestion.
- **Hydrolytic enzymes:** proteins which digest cell walls of pathogens.

Innate immune system in vertebrates

In vertebrates, the innate immune response encompasses the following:

- Surface (physical) barriers, such as skin, mucus, and cilia
- Inflammatory system
- Complement system

The **complement system** encompasses over 30 **complement proteins** which are found in the blood-stream. Their purpose is to eliminate cells that are foreign or ‘non-self.’ When one of these complement proteins becomes triggered in response to a foreign antigen on a pathogen, a cascade effect is initiated which leads to a string of all the other complement proteins being activated one-by-one.

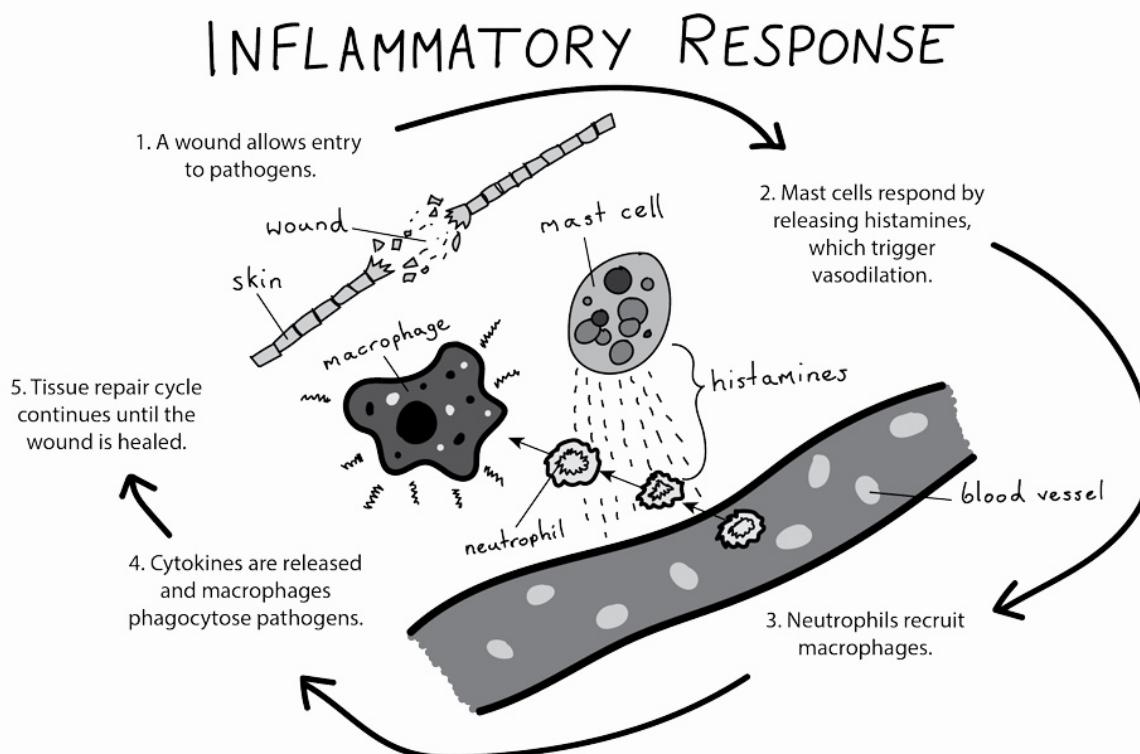
These complement reactions have a few purposes:

- Attracting and enhancing the activity of phagocytic cells which enhances the ability to recognise and engulf foreign material
- Forming attack complexes to destroy bacteria directly by perforating bacterial membranes and causing them to **lyse** (split and release their contents)
- Contributing to inflammation by increasing local permeability of capillaries and attracting phagocytes

Cytokines are small signalling molecules involved in the immune system which are released by cells in response to cell damage or the presence of pathogens. Cytokines may trigger non-specific or specific reactions. **Interferons** are a type of cytokine, which are produced by and act on a host cell infected by a virus, which essentially work by interfering with viral RNA to limit the replication of the virus. They also attract natural killer cells, which we will discuss later. **Chemokines** are another example of a cytokine, which attract leukocytes to the sites of infection and inflammation.

2.2.4 Inflammatory response

The **inflammatory system** involves increasing blood flow to an area of damaged or infected tissue by summoning complement plasma proteins, leukocytes (i.e. macrophages) and platelets to the wound. This response is triggered when cells become damaged, and cytokines are released, stimulating **mast cells** and **platelets** which in turn releases **histamines**. Histamines trigger **vasodilation**, which allows **neutrophils** to escape from blood vessels and recruit **macrophages** which help **phagocytose** (engulf) foreign pathogens. This cycle continues until the tissue is repaired. The following information can be briefly summarised in the following diagram.



As a result of this inflammatory response, it is normal for the body to experience symptoms such as fever, redness, swelling, etc.

Another important point to mention is the role of **prostaglandins** in the inflammatory response. These are a group of lipid compounds with hormone-like effects which stimulate vasodilation and constriction during inflammation. If you refer to the diagram above, you can match prostaglandins to step 2 of the inflammatory response.

2.2.5 Adaptive immune response in vertebrates

If both the first-line defences *and* the non-specific innate immune response is not enough to counteract the pathogen, this is when vertebrates resort to their adaptive immune response.

KEY POINT :

Adaptive immunity differs from innate immunity as it is *specific* and results in *immunological memory*.

How is this immunological memory formed, you may ask? This is thanks to **B lymphocytes**, **T lymphocytes**, and **antibodies** working together to prepare the host's immune system not only to defend against invading pathogens the first time, but boost it to be even more prepared should a subsequent attack occur. Essentially, memory cells hold a grudge against pathogens, meaning should they return, they will be more aggressive and kill them even faster than before.

We can see this demonstrated in the example of **vaccines**. Some vaccines, such as the influenza vaccine, require 'booster shots' in periodic doses. This is because the artificial active immunity depreciates over time as immunological memory starts to fade. This happens because of antigenic shift and antigenic drift, causing the viral strain to change over time, thus making it increasingly harder for your immune system to detect the virus from previous memory. As such, these booster vaccines allow your body to build up new immunological memory and stay ahead of the game at all times.

B lymphocytes	T lymphocytes
Produce antibodies (immunoglobulins)	Regulate the immune response, directly kill infected host cells, activate other immune cells, and produce cytokines
Produced in humoral immunity	Produced in cell-mediated immunity

In vertebrates, the adaptive immune response involves humoral and cell-mediated immunity, and is regulated by cytokines (such as **interleukins**).

Although humoral and cell-mediated immunity are different, it is important to remember that the purpose that is achieved by *both* of these scenarios is that **immunological memory** is created.

2.2.6 Humoral immunity

Humoral immunity involves **B lymphocytes**, which are studded with antigen-specific antibodies that can bind with free antigens. Alternatively, B lymphocytes can secrete antibodies as well.

Identification of antigens occurs by **clonal selection**, whereby a particular lymphocyte is activated which is specifically equipped to deal with the target antigen. Then, **clonal expansion** allows the lymphocyte to clone itself rapidly. These clones can either differentiate into plasma cells or memory B lymphocytes.

If plasma cells are chosen, such as during a first exposure, the clones essentially put out a ‘rush order’ whereby tons of antibodies are produced to counter the antigens. Alternatively, after a second exposure, memory B lymphocytes may be produced to form immunological memory. These cells can become plasma cells in the instance of re-infection, when more antibodies are required once again.

Antibodies

Antibodies are specific to certain types of antigens, and are produced as part of **humoral immunity** by **B lymphocytes** in response to these antigens. Thus, they are designed to be effective against antigens after even a single exposure. Antibodies essentially function by interfering with the normal function of pathogens without killing them directly. Antibodies are a Y-shaped protein, consisting of short **light chains** which make up the arms, and long **heavy chains** which compose the stem. Antibodies may directly bind to the sites on antigens (**agglutination**) or activate phagocytes and the complement cascade to destroy antigens (**antigen-antibody complexes**), or may cause soluble antigens to become insoluble and thus precipitate out of solution (known as **precipitation**), among other methods.

2.2.7 Cell-mediated immunity

Firstly, the key type of cell involved in **cell-mediated immunity** are **T lymphocytes**. As suggested by the name, these originate from the lymphatic system, and they are able to differentiate into a variety of different cells which each have roles to play in cell-mediated immunity.

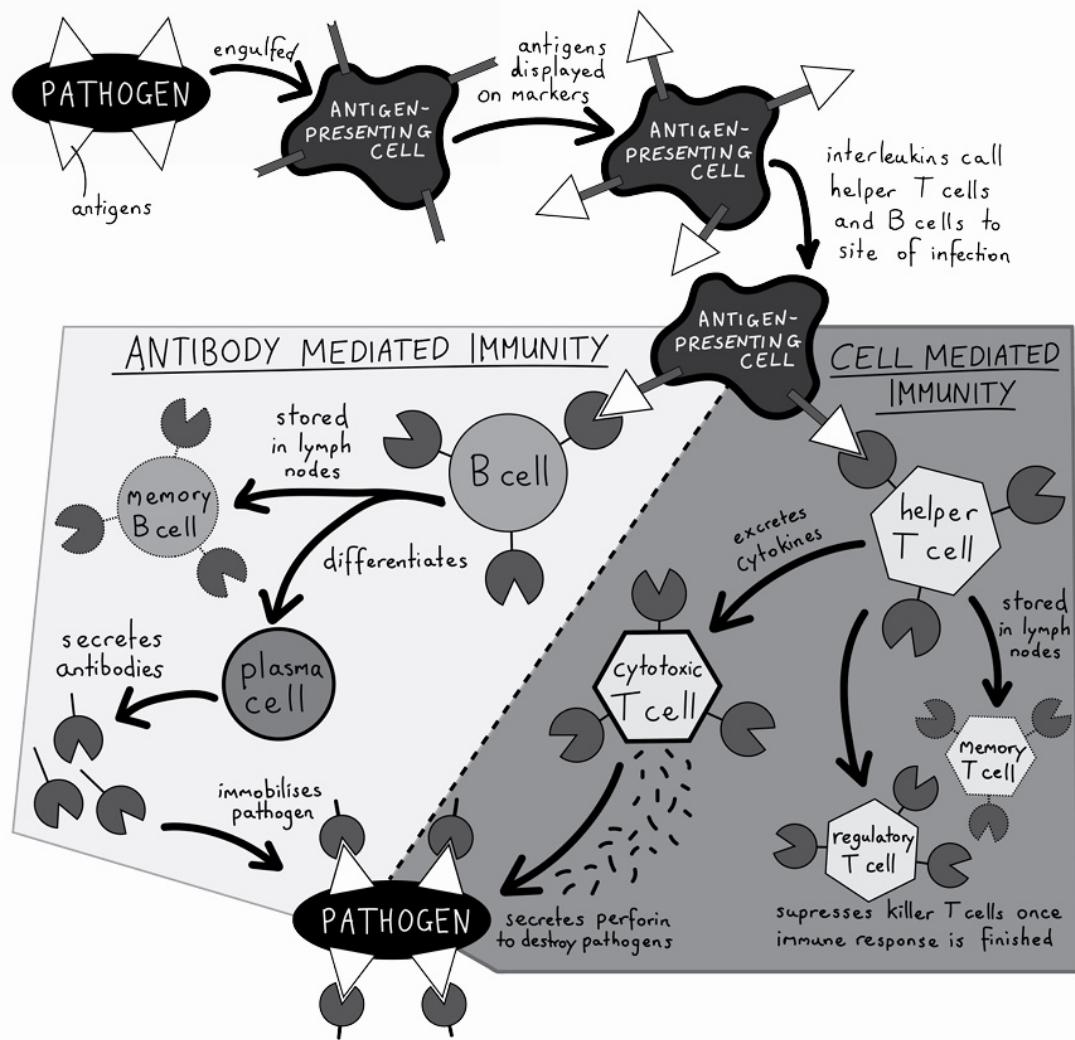
If you think about the word ‘cell-mediated’ you can infer that this type of immune response places a certain type of cell in the position of ‘mediator,’ which controls and regulates the entire process and all the cells involved. This role is assumed by the **T cell receptors (TCRs)**. Like antibodies, these have both a variable and a constant region, but unlike antibodies, they have only one antigen-binding site and only bind to fragments of antigens that are presented on the surface of antigen-presenting cells.

Cell-mediated immunity involves T lymphocytes. There are four types you should become familiar with.

Type of lymphocyte	Function
Helper	Secretes cytokines which promote inflammation and activate macrophages and B lymphocytes.
Cytotoxic	Release toxins to kill foreign, infected or abnormal host cells.
Memory	Become antigen-specific lymphocytes and are thus responsible for immunological memory.
Regulatory	Suppresses the immune response and allow the body to return to its normal functions once infection has been successfully dealt with.

All of these cells work together in tandem to destroy pathogens.

1. T cells mobilise when they encounter a cell (e.g. a dendritic cell, macrophage, or B cell) that has digested an antigen and displays antigen fragments on its MHC molecules.
 - MHC stands for the **major histocompatibility complex**, which are peptides on the surface of the cell that serve as warning lights indicating to T cells that a particular cell has an antigen.
2. TCRs mediate the immune response by binding to fragments of antigens on antigen-presenting cells.
3. This triggers signal transduction in helper T cells.
4. Helper T cells proliferate and release cytokines which activate cytotoxic T cells and attract macrophages and neutrophils to the scene.
5. Cytotoxic T cells attack the infected or pathogenic cell. This results in cell death.
6. Regulatory T cells inhibit the immune response once the antigen has been dealt with.



2.2.8 Immunological memory

Now that we've covered how both humoral and cell-mediated immunity attacks pathogens, let's move onto how immunological memory is created.

Simply, after a first exposure, B and T lymphocytes respond to antigens in what is known as the **primary immune response**, by producing B and T memory lymphocytes which contribute to immunological memory. The primary immune response primarily produces antibodies known as IgM (immunoglobulin) antibodies to fight infection. However, should lymphocytes have a second exposure to the same antigens encountered in the primary immune response, a **secondary immune response** is initiated, which works faster and more effectively due to the presence of pre-existing memory lymphocytes. This type of immune response primarily uses IgG antibodies instead of IgM antibodies (a different type of immunoglobulin).

2.2.9 Types of immunity

While we have already discussed the mechanisms by which immunity is activated, it is important to understand that there is more than one type of immunity that can be formed (some of which you have had since you were born!). The types of immunity in a host can be categorised into a branching hierarchical structure, each requiring the use of different cells and mechanisms, and each with different strengths. We've already established the fact that innate immunity refers to first line physical and chemical defences, so now let's just focus on categorising adaptive immunity.

Adaptive immunity can be categorised as either passive or active. Furthermore, both passive and active immunity can be attained either naturally or artificially.

	Mode of acquisition	Effectiveness	Example
Natural passive	Antibodies produced in one organism are transferred naturally to another individual.	Temporary immunity is attained, since no immunological memory is formed (as the adaptive immune system doesn't get a chance to respond with its own lymphocytes). However, this doesn't last as long as active immunity because antibodies have a shorter life span once in another organism.	Maternal antibodies are transferred from mother to foetus in placenta or through breastfeeding.
Natural active	Natural exposure to a pathogen allows a host to manufacture its own antibodies and memory B and T lymphocytes, thus, becoming ill and recovering .	Very strong, long-term immunity is attained. Even a single exposure can provide long-term immunity. Subsequent exposures are dealt with even faster and more effectively due to memory B and T lymphocytes already present.	A primary exposure to chickenpox causes the host to become sick and produce its own antibodies, resulting in the formation of long-term immunological memory.
Artificial passive	Antibodies produced in one organism are transferred <i>artificially</i> to another individual (usually via an antiserum injection).	Temporary immunity is attained.	Administering IgG antibodies to mothers of Rh-incompatible babies in order to stifle a potential immune response occurring in the mother.
Artificial active	Artificial exposure to a pathogen (such as via injection of a vaccine) allows host to manufacture its own antibodies and memory B and T lymphocytes without contracting the disease .	Very strong, long-term or short-term immunity is attained. A single vaccine may provide long-term immunity, or may require booster shots. Either way, this is still stronger than both forms of passive immunity.	Smallpox vaccination exposes host to a live poxvirus similar to smallpox, causing the host to form its own antibodies and immunological memory without suffering from the actual smallpox virus.

SCIENCE AS A HUMAN ENDEAVOUR :**Snake antivenom production**

A potential alternative option to ‘milking’ venomous snakes to obtain antivenoms is producing artificial antivenoms via synthetic DNA and thus simulate the same antibody response that would be initiated if real antivenom antibodies were injected.

Prevention and eradication of disease through vaccination

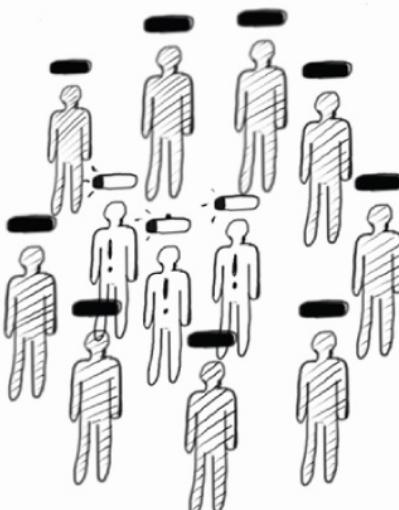
Vaccination can be useful for both the prevention and complete eradication of certain diseases, by introducing antigens to the host in a less concentrated form, in order to elicit an immune response. Vaccines may provide long-lasting immunity or may provide short-term immunity and require booster shots. This depends on how long the memory lymphocytes last. For example, smallpox is a disease that has been completely eradicated worldwide thanks to vaccination. This type of vaccine generally provides long-term protection for up to five years before a booster shot is required. However, the influenza vaccine – although effective at preventing the flu and providing long-term memory cells – does require frequent seasonal booster shots because the influenza virus tends to undergo antigenic shift and antigenic drift which requires new antigens to be introduced to the host in order to maintain immunity.

Let's just clear up why immunological memory is not formed during passive immunity, even though it is a type of adaptive immunity. Think of it as receiving a pre-made piece of furniture. You didn't receive the instruction manual, nor did you figure out how to put it together yourself; it simply showed up on your doorstep. Although you would happily use this piece of furniture until it broke, you wouldn't be equipped to make another piece of furniture for yourself once this occurs, since you were never taught. Thus, similarly during passive immunity, when receiving pre-made antibodies from another organism, either maternally (naturally) or artificially (via an injection), the host has never been exposed to the original antigen and thus, doesn't have an instruction manual for how to deal with subsequent attacks. This is why, although it is part of the adaptive immune system, immunological memory can only be formed via active immunity, whereby the host is exposed to the antigens (the ‘instruction manual’) rather than the antibodies, thus allowing it to manufacture its own antibodies and create immunological memory (whether naturally, through exposure, illness, and recovery, or artificially through immunisation/vaccination).

2.2.10 Herd immunity

Artificial active immunity via immunisation is a very effective and convenient method for attaining strong immunity, since immunological memory can be effectively established without actually becoming ill such as when attaining active immunity through natural exposure. Realistically, a large portion of the population may be able to avoid vaccination and still be able to successfully fight off many illnesses, thus attaining natural active immunity that way. However, there is a smaller segment of the population, including the elderly, infants, and pregnant women, who are known to be **immunosuppressed**, meaning they are more susceptible to getting sick. Thus, the same pathogen that may cause minor discomfort and still build immunity in a healthy person could *severely harm* an immunocompromised person. It is for this reason the concept of **herd immunity** exists. Quite literally, herd immunity protects those that are immunocompromised like a herd of elephants would protect the weak – by surrounding them with the strong and healthy to defend them against incoming predators.

HERD IMMUNITY



Based on this concept, and depending on the virulence and transmissibility of each particular pathogen (more on this in a moment), a certain majority percentage of the population must be immunised before the smaller immunocompromised population can be protected *without* being vaccinated. Thus, the vaccinated population acts as a buffer to protect those who are unable to withstand the vaccination, even in its weakened, attenuated form. Although a simple concept, it is only effective if this percentage majority is reached in order to make the chances of an immunocompromised person getting the pathogen negligible, despite not being immunised themselves.

Now, you may be wondering how scientists can determine the exact proportion of the population that must be vaccinated in order to establish herd immunity. This figure is mathematically calculated based on factors such as:

- The length of time an individual is infectious
- The probability of transmitting the infection to a susceptible individual during a single contact
- The rate of new individuals contacted

The calculated figure is called the **reproduction number (R_0)** (pronounced 'R naught') and is an indication as to how easily a disease can be transmitted and thus indicates the potential risk that an outbreak will occur. The higher the R_0 value, the easier it is for the disease to spread, thus increasing the chance of an outbreak.

- If $R_0 < 1$, this means that each case of an infection causes less than one new infection. Therefore, over time, the disease will decline and die out.
- If $R_0 = 1$, this means each case of an infection causes one new infection. Therefore, over time, the disease will stay alive and stable, but there won't be an outbreak or an epidemic.
- If $R_0 > 1$, this means each case of an infection causes more than one new infection. Therefore, over time, the disease will be transmitted to more and more people, and there may be an outbreak or epidemic.

KEY POINT :

R_0 numbers aren't taught to you until the next syllabus section on transmission and populations, but I wanted to bring this in now so we can connect this concept to herd immunity!

Having said that, we now have an answer to our earlier question: scientists can calculate and use this R_0 value to determine what percentage of the population must be immunised before herd immunity can be achieved. This percentage also depends on other factors besides the R_0 such as the susceptibility of the population to the disease as well as the mechanism of transmission. For example, diseases that spread via direct touch will not spread as far as diseases that travel via airborne transmission, as we will look at in more detail in the next section.

2.3 Transmission and spread of disease (epidemiology)

2.3.1 Carriers and agents of disease

The **spread of disease** actually refers to the spread of the **disease-causing pathogen**. Disease transmission can be categorised by the way the pathogen is transmitted, either through direct or indirect contact.

Direct contact transmission (via physical contact)	Person-to-person contact	Pathogens requiring a moist environment will enter via broken skin, mucous membranes, or an orifice, such as through skin-to-skin and fluid transfer.
	Droplets	Droplets usually travel between 1–2 metres; for example they can be sprayed when sneezing, coughing, or speaking.
Indirect contact transmission (no physical contact)	Airborne transmission	Classed as airborne if pathogens remain airborne for greater distances than 1–2 metres. Some pathogens can remain on surfaces for extended periods of time and contaminate them. Objects or materials likely to carry pathogens are called fomites (e.g. clothes, utensils, door handles).
	Contaminated food and water/ environmental reservoirs	Sources of food and water can transmit infections as a result of chemicals, pesticides, animal waste, or industrial waste contaminating supplies that are then consumed or used by humans. An example of this might be contaminated water reservoirs which have the potential to form localised clusters for disease.
	Animal-to-person contact	Pathogens that can cause disease in both humans and animals can be transferred from animal-to-human such as via a bite or scratch.
	Vectors	Certain organisms may act as carriers for disease (that are not directly affected by the disease itself) that transfer the pathogen to susceptible individuals. Mosquitoes are one example which carry the plasmodium pathogen which is responsible for causing malaria. Note that not all vectors are animals or insects. Humans are highly effective vectors of disease, due to their ability to spread disease over vast distances. Furthermore, humans which tend to cluster together, coupled with poor hygiene, such as in developing countries with poor sanitation, greatly amplifies the chances of an outbreak.

SCIENCE AS A HUMAN ENDEAVOUR :

Although you are probably familiar with how the spread of disease can be facilitated by poor hygiene in dense populations, in the past, basic sanitary measures were by no means common knowledge. Even something as simple as hand washing was not discovered to be effective at killing germs until 1847 when Hungarian scientist Ignaz **Semmelweis** noticed a pattern of patients dying after doctors moved to the maternity ward without washing their hands between patients after performing autopsies. It was this observation which led to the establishment of rules which required doctors to wash their hands after autopsies and before attending the maternity ward. It may seem strange that you would have to tell doctors to wash their hands in between touching the dead and the living, but even something as simple as this had to be learned through trial and error.

Another scientist who became influential in the development of our knowledge of disease transmission was the German physician Robert Koch, who formulated **Koch's postulates** – a set of scientific criteria for establishing whether a specific microorganism was the cause of a particular disease. Koch and Semmelweis made great contributions to further the field of **epidemiology** which deals with the study of diseases in populations to determine cause-and-effect relationships between disease and populations.

Keep in mind that in this modern age, it is so much easier for humans to travel and thus, potentially carry with them a host of pathogens. Think about the interconnectedness and vastness of travel routes, whether by plane, train, tram, car, boat, and many more. It is therefore even more critical for humans to employ safety measures through maintaining good hygiene and avoiding contact with susceptible persons when sick.

KEY POINT :

Transmission of disease is facilitated by both **regional** and **global** movement of organisms.

Disease outbreaks that are localised to a particular region or community are known as **epidemics**, whereas those that span multiple countries or across large regions (e.g. the Black Death which wiped out a third of the population of Europe in the 1300s) are known as **pandemics**.

Environmental factors that affect the rate of infection and transmissibility are:

- Temperature and humidity
- Precipitation
- Airflow and ventilation
- Hygiene
- Human behaviour

2.3.2 Strategies for controlling the spread of disease

During this part of your studies of Biology, you may be expected to **analyse data** relating to disease transmissibility and evaluate effective measures for controlling infection. As such, a crucial factor to consider when determining how easily a disease can spread is the **persistence of pathogens**. This refers to how long pathogens can lurk within the host before becoming activated, or how long the infected host remains infectious. This can be due to a number of factors such as:

- Reproduction rates (R_0)
- Toxicity
- Virulence

There's that R_0 value again – I told you it was important! The R_0 number is really useful for allowing us to very quickly evaluate how potentially dangerous a particular disease could be to certain populations. Remember what it means and how to interpret it as you are likely going to be asked to analyse this sort of data in exams. If you know what you're doing and understand how all these factors are interrelated, you can gain easy marks!

Now, let's go over the strategies which can be employed to prevent the transmission and spread of disease.

- **Personal hygiene measures:** washing with soap and water, practising hygiene etiquette around others when sick, and maintaining general cleanliness.
- **Travel hygiene:** including receiving vaccinations relevant to regional pathogens.
- **Community safety measures:** contact tracing allows tracing back to the origin of infection. Its purpose is to identify a list of all those who were in contact with that person, thus, limiting further infections.
- **Quarantining:** effective strategy to isolate infected individuals from uninfected individuals by physical separation to stop transmission in its tracks. Quarantining occurs for a set period of time, which is determined by how long the incubation period is for the particular disease. This strategy becomes more critical as the R_0 value rises, meaning the disease is highly infectious.
- **Closing schools and workplaces and restricting mass gatherings:** by limiting the cluster behaviour of humans, the potential for an outbreak becomes limited.
- **Temperature screening:** often used at global borders in ports and airports to detect even asymptomatic diseases by measuring temperature increases. If you think back to when we studied the immune response, you'll remember that when your body is fighting an infection, the inflammatory response often causes the core body temperature to rise as antibodies and B and T lymphocytes are hard at work.
- **Travel restrictions:** limiting the movement of populations in and out of areas experiencing an outbreak.

SCIENCE AS A HUMAN ENDEAVOUR :

Quarantine and biosecurity

Due to how easy it is for disease to spread across vast global regions via air travel, it is crucial that countries monitor and control the spread of disease by putting in place certain systems which detect disease before it can spread any further. The risk of disease transmission overseas is further amplified especially in cases where the incubation period is extended, meaning that many travellers may not physically appear to be ill, and yet, still be capable of transmitting the pathogen to others. Furthermore, should a disease be transmitted overseas, this could potentially be very dangerous since the foreign strain could be completely unfamiliar to the population and therefore they would be entirely susceptible. Therefore, security measures must be put in place such as by placing infrared thermal image scanners at airports to detect fevers, and/or, by implementing appropriate quarantine measures to isolate the infected persons and stop the spread of disease. The entry of agricultural pests across borders can also be a significant issue as they can potentially damage agricultural crops or act as vectors for disease for foreign pathogens. Security measures such as baiting, luring and trapping pests such as flies provides useful information as to the prevalence of specific types of pests (e.g. fruit flies) which indicates if further control is necessary, such as in the case of a suspected outbreak. More research is required to further understand the behaviour of pests such as fruit flies, and how to best combat them.

Modelling disease outbreak and spread

Mathematical modelling can be useful for predicting potential communicable disease and projecting outbreaks, which can help facilitate the success of vaccination programs by ensuring they are well-informed and adequately planned. Disease outbreak modelling can help give an understanding as to the implications for attendees of at-risk mass gatherings, as well as how health service personnel and infrastructure may be affected as a resulting of an outbreak.

Part III

Assessment tips

Section 1

Advice for exams and assessments

1. Read the question and re-read the question... don't get excited as soon as perusal time is over and start writing your answer before really understanding the question. That may get you some marks, but you will almost certainly omit key pieces of info. If you are really eager to get started and afraid you might forget something, write dot points related to that question on a separate piece of paper. This will free up some brain space and allow you to approach each question with a clear mind and without feeling cluttered with points you must not forget to mention.
2. Don't get overwhelmed by the whole paper. Even if you don't know something, or a lot of things, stay calm, breathe, and take it one question at a time. During perusal time, find at least one question you are fairly confident with, or that you think is easiest, and start with that one when perusal time is up. This strategy will help you gain confidence after successfully completing a question you find easy, which will help you tackle the harder components of the exam with more confidence.
3. Start revising well before the exam date. Cramming is stressful and only gets you short-term results. It's always better for your grades and your mental health to begin revising before that stressful exam-period even begins, so that you can gain a deep understanding of the course material instead of just memorising quick facts the night before the test.
4. Pay attention to the time, and ideally, leave yourself enough time (even if it's only 10 minutes) to go over the exam at the end and fill in any blanks or correct any errors. These last crucial minutes, if spent well, could earn you just a few more marks which may push your grades just that little bit further.
5. Do practice exams. I can't stress this enough. You can read all the textbooks/study notes/class notes you want, but if you don't do practice questions, you'll never truly know if you are actually *understanding* everything you're taking in. Don't be fooled by all your pretty aesthetic notes, you have to put your knowledge to the test and gain 'test' confidence. This will really help you to stay calm during exams after feeling more prepared.