



STEMpathy

OCR A Level Biology

A (H420)

Revision Notes for Year 1

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Microscopy

The properties of a microscope are determined by its **magnification** and **resolution**:

- **Magnification:** How many **times larger** an image appears **compared** to the original object's size.
- **Resolution:** The level of **detail** which can be seen in an image.

The table below outlines the different types of microscopes:

| Microscope Type | Key Features | Limitations |
|--|---|---|
| Optical Microscope | <ul style="list-style-type: none"> - Cheap, portable, easy to use - Can view live specimens - Stains increase contrast | <ul style="list-style-type: none"> - Low resolution - Limited magnification |
| Confocal Microscope | <ul style="list-style-type: none"> - High-resolution 2D and 3D images - Depth selectivity on thick specimens - Can view live cells | <ul style="list-style-type: none"> - Expensive - Requires fluorescent tagging |
| Transmission Electron Microscope (TEM) | <ul style="list-style-type: none"> - Very high resolution and magnification - Reveals internal structure | <ul style="list-style-type: none"> - Specimens must be dead - Thin sectioning needed - Requires staining and vacuum |
| Scanning Electron Microscope (SEM) | <ul style="list-style-type: none"> - 3D surface images - High magnification and detail | <ul style="list-style-type: none"> - Specimens must be dead - Requires coating with conductive material - Vacuum environment |

Properties of Microscopes

The table below provides an overview of the key properties of each type of microscope:

| Type | Magnification* | Resolution | Wavelength | Cost | Ease of Use |
|--------------|----------------|------------|--------------|-----------|--------------------------|
| Optical | x1500 | 200 nm | 400 - 700 nm | Cheap | Portable and easy |
| Confocal | x2000 | 200 nm | 400 - 700 nm | Moderate | Less portable and medium |
| Scanning | x100,000 | 0.2 nm | 0.004 nm | Expensive | Bulky and difficult |
| Transmission | x500,000 | 0.2 nm | 0.004 nm | Expensive | Bulky and difficult |

*These are approximate values most commonly cited in examination materials.



Module 2: Microscopy



Microscopy

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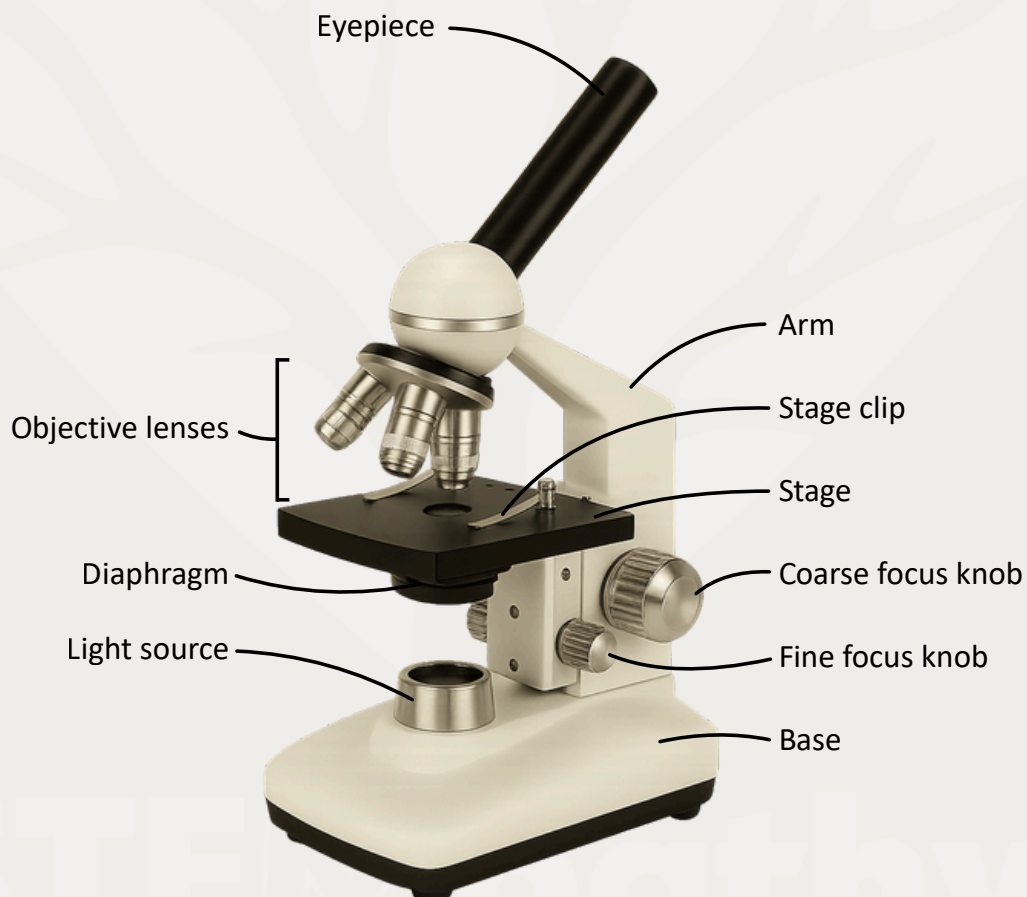
Microscopy Calculations

When using a microscope to look at samples, it is useful to know the:

- **Total magnification:** The overall **magnifying power** of a microscope.
- **Magnification:** The factor by which the **image of an object is increased** compared to its actual size.
- **Actual size:** The **true size** of the object being observed.
- **Image size:** The **measured size** of the magnified object in the image.

Total Magnification (of a Microscope)

If you know the magnification of the **eyepiece lens** and the **objective lens** on your (optical) microscope, then you can calculate its **total magnification**.



Formula:

$$\text{Total Magnification} = \text{Eyepiece Magnification} \times \text{Objective Magnification}$$

Where:

- **Eyepiece Magnification:** The magnification of the ocular lens.
- **Objective Magnification:** The magnification of the objective lens.





Magnification (of an Image)

If you have an **image** produced by a microscope and know the **actual size** of the object, then you can calculate the **magnification**.

Formula:

$$\text{Magnification} = \text{Image Size} \div \text{Actual Size}$$

Where:

- Image Size: The measured size of the image.
- Actual Size: The real size of the object.

A common mistake, or misunderstanding, is to measure the whole picture, rather than **just** the object of interest within it.

Actual Size

If you know **how many times** an image has been **magnified** and can measure the image of the object, then you can calculate what its **actual size is**.

Formula:

$$\text{Actual Size} = \text{Image Size} \div \text{Magnification}$$

Where:

- Image Size: The measured size of the image.
 - Magnification: The magnification factor used.
-

Image Size

If you lack the actual image produced by a microscope, but know the **magnification** and the **actual size** of the object of interest, then you can calculate **how big it appears** in the image.

Formula:

$$\text{Image Size} = \text{Actual Size} \times \text{Magnification}$$

Where:

- Actual Size: The real size of the object.
- Magnification: The magnification factor used.

Module 2: Preparing Microscope Slides



Preparing Microscope Slides

The table below outlines the key steps for the 3 main types of **slide samples**:

| Sample Type | Key Steps |
|-----------------------|---|
| Bacterial smear | Air dry → heat fix → Gram stain → rinse → blot dry → apply cover slip |
| Thin section or smear | Place on slide → add stain → cover slip at angle → blot excess |
| Living organism | Water drop → add specimen → lower cover slip at angle → avoid bubbles |

Staining

Staining enhances **contrast**, making cell structures easier to **identify**.

The table below outlines examples of stains you may encounter:

| Stain | Function |
|----------------|---|
| Methylene blue | General-purpose stain for making specimens more visible. |
| Acetic orcein | Binds to DNA and stains chromosomes dark red. |
| Eosin | Stains cytoplasm. |
| Sudan red | Stains lipids. |
| Iodine | Stains cellulose in plant cell walls yellow and starch granules blue/black (appearing violet under the microscope). |

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Bacteria: Gram Staining

Gram staining is a **differential staining** technique; it **distinguishes** between Gram-positive and Gram-negative bacteria based on **differences** in their cell wall structure.

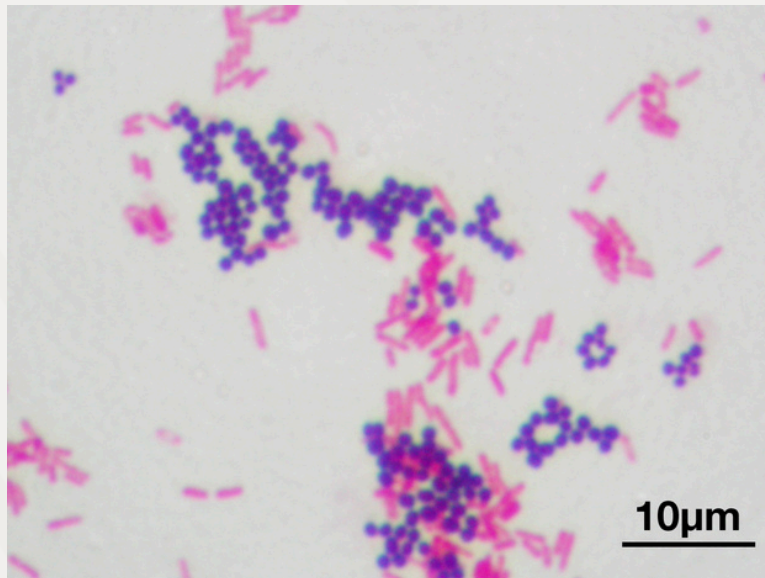


Photo by Y tambe - Y tambe's file, CC BY-SA 3.0

Tissues: Samples and smears

Preparing Smears and Thin Sections:

1. Place the sample directly onto a clean slide.
2. If needed, stain the edge of the sample before applying the cover slip.
3. Lower the cover slip at an angle to prevent air bubbles.
4. Blot away excess stain if required.

Preparing a Microscope Slide for Living Organisms

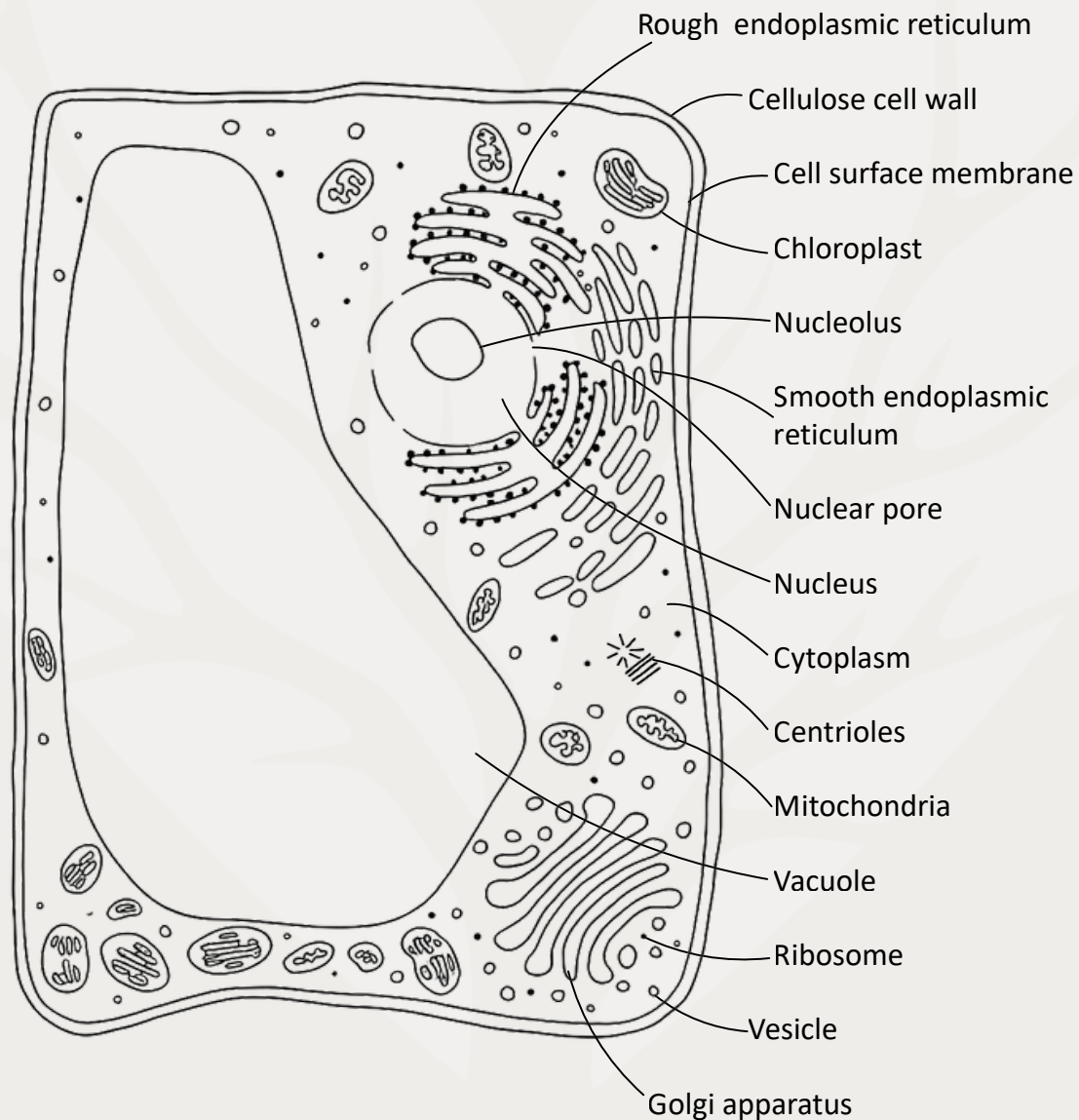
Preparing Living Samples (e.g. Amoeba):

1. Add a drop of water to the slide.
2. Add the living organism gently.
3. If appropriate (for small prokaryotic organisms), place the cover slip on carefully and gently to avoid damaging the specimen and prevent air bubbles.



Eukaryotic Cell Structure

The diagram below illustrates generic eukaryotic cell structure.



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Membrane-Bound Organelles

The table below outlines the structure and function of **membrane-bound organelles**:

| Organelle | Structure | Function |
|-------------------|---|--|
| Nucleus | Double membrane (nuclear envelope) with nuclear pores. Contains nucleolus (RNA & proteins). | Stores DNA as chromatin. Controls protein synthesis via mRNA. Nucleolus makes ribosomes. |
| Rough ER (RER) | Flattened sacs (cisternae) with ribosomes on the surface. | Folds proteins. Transports them via cisternae. Sends them in vesicles to the Golgi. |
| Smooth ER (SER) | Flattened sacs without ribosomes. | Synthesises lipids, cholesterol, phospholipids, steroid hormones |
| Golgi Apparatus | Stack of membrane-bound sacs. | Modifies proteins/lipids. Packages them into vesicles for transport. |
| Mitochondrion | Double membrane. Inner membrane folds to form cristae. Fluid interior is called the matrix. | Does Aerobic respiration to make ATP. Contains its own mDNA. Can self-replicate. |
| Chloroplast | Double membrane. Stacks of thylakoids (grana). Stroma with enzymes. | Does photosynthesis: Thylakoids: light-dependent*. Stroma: Calvin cycle*. Contains its own cpDNA. |
| Permanent Vacuole | Large fluid-filled sac (cell sap). Tonoplast membrane. | Maintains turgor pressure for structural support. |
| Lysosome | Membrane sac with hydrolytic enzymes. | Digests old organelles, pathogens or debris via enzyme breakdown. |

*Stages of photosynthesis studied in A2.

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Organelles Without A Membrane

The table below outlines the structure and function of **organelles without membranes**:

| Organelle | Structure | Function |
|-------------------------|--|--|
| Cilia | Short projections from the cell membrane. Made of microtubules from centrioles. | Move substances across the cell surface. Some act as receptors in cell signalling. |
| Undulipodia | Long cilium. | Moves the whole cell (e.g. sperm). |
| Ribosome (80s) | Made of RNA & protein. Made of two subunits. | Synthesises proteins from mRNA. Free in the cytoplasm or attached to the RER. |
| Centrioles / Centrosome | Two microtubule cylinders at a right angle. Centrosome is the centriole & surrounding matrix. | Forms a spindle during cell division. Forms cilia. |
| Cytoskeleton | Network of protein filaments (microtubules, actin, etc.). Has motor proteins which move along microtubules. | Supports shape and strength. Enables movement of organelles, vesicles and entire cells. Used in cytokinesis. Stabilises tissues. Involved in cell signalling. |
| Cellulose Cell Wall | Rigid outer layer made of cellulose fibres. | Provides support; maintains shape. Prevents lysis when the cell is turgid. |
| Chitinous Cell Wall | Rigid outer layer of chitin and proteins. | Provides support; maintains shape. Prevents lysis when the cell is turgid. |

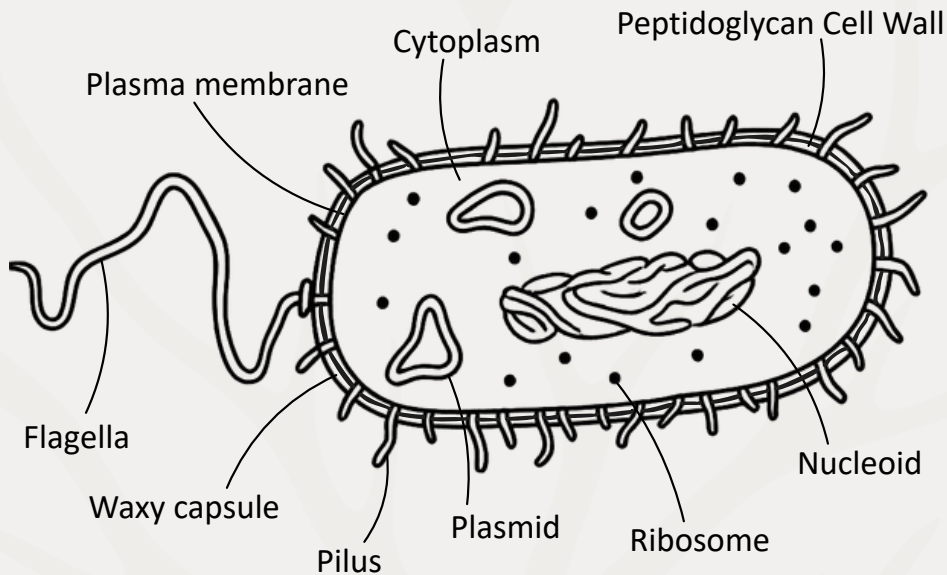
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Module 2: Prokaryotic Cell Structure



Prokaryotic Organisms

Prokaryotic organisms are defined by their **lack of membrane-bound organelles**, such as a nucleus. Their DNA, typically in the form of a **single circular chromosome**, is free-floating in the **cytoplasm** in a region called the **nucleoid**.



The table below outlines the cell structures that can be found in prokaryotic cells:

| Cell Structure | Structure | Function |
|-----------------|--|---|
| Cell Wall | Made of peptidoglycan in bacteria, it varies in Archaea. | Provides mechanical support and protection. Prevents lysis when the cell is turgid. |
| Cytoplasm | Gel-like substance with dissolved solutes. | Site of metabolic reactions. |
| Ribosomes (70S) | Made of RNA. | Synthesises proteins from mRNA. |
| Nucleoid | Region of the cytoplasm with a circular chromosome (naked, no histones). | Contains genes. Controls cell activity via mRNA for protein synthesis. |
| Plasmids | Small circular DNA loops in the cytoplasm. | Carry extra genes that can be shared via conjugation. |
| Flagella | Long whip-like structure. | Moves the cell. Enables chemotaxis. |
| Pili | Short, needle-like protein projections. | Attach to surfaces or other cells. Share plasmids by conjugation. |
| Capsule | A thick waxy layer outside the cell wall. | Prevents drying out. |

Module 2: Organelle Involvement in Protein Synthesis



Protein Synthesis and Organelles

Protein synthesis assembles **amino acids into a polypeptide chain**, which is then **folded and modified into a protein**.

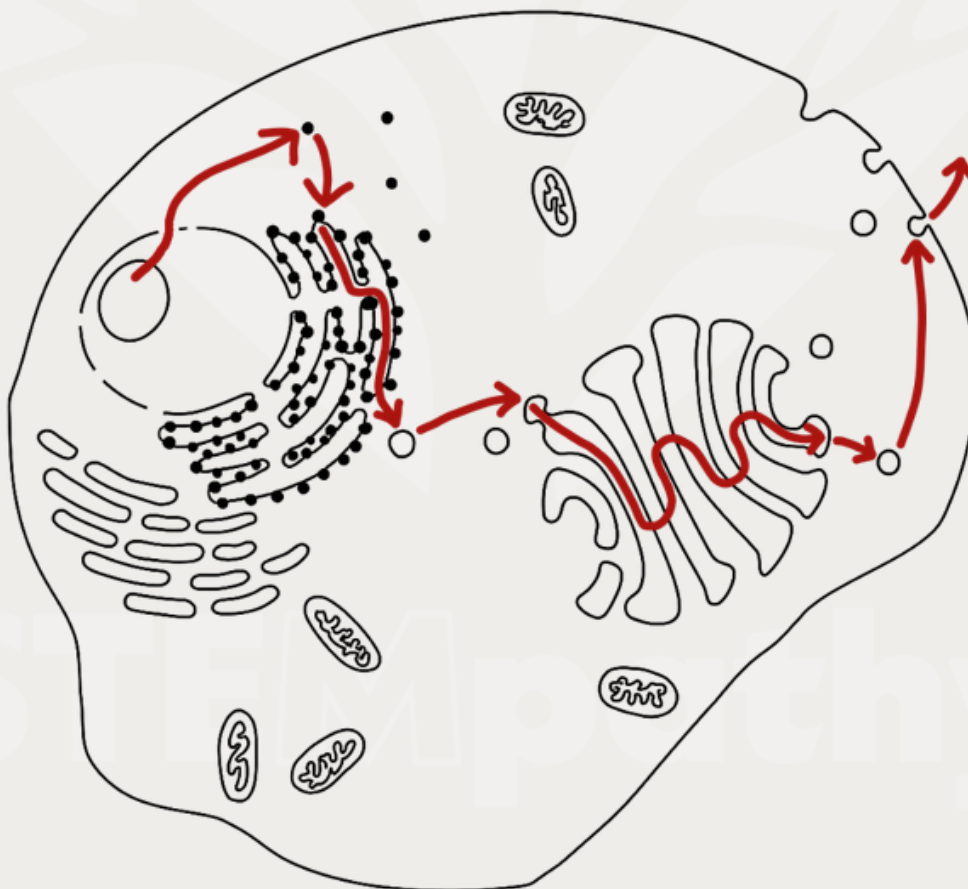
It consists of two phases, **transcription** and **translation**:

- **Transcription** is when a gene is transcribed (copied) to **produce mRNA** (messenger RNA).
- **Translation** is when **ribosomes** make a polypeptide (protein) chain by 'reading' the bases on mRNA to **assemble amino acids** in the correct order.

However, it takes many organelles working together to produce a fully functioning protein.

The order of **organelles involved** (usually) is:

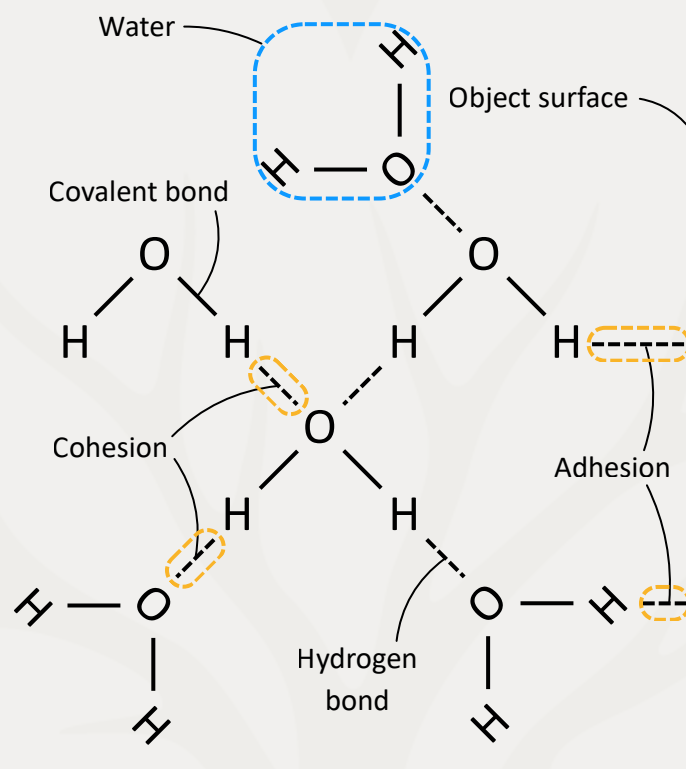
Nucleolus → Nuclear Membrane → Ribosome → Rough Endoplasmic Reticulum → Vesicle → Golgi Apparatus → Secretory Vesicle → Cell Surface Membrane





The Biological Importance of Water

Water is **essential** to life as we know it, with unique **properties** arising from its structure. Water molecules are **polar**, which allows them to **form hydrogen bonds** with each other and other important molecules.



Cohesion is where water molecules form hydrogen bonds **among themselves**.

Adhesion is where water molecules form hydrogen bonds with **other molecules**.

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The table below outlines the important **properties of water** and their **importance** in biology:

| Property | Description | Biological Importance |
|----------------------------------|--|---|
| Density | Ice is less dense than liquid water. | Ice floats, forming an insulating layer, allowing aquatic organisms to survive in stable temperatures. |
| Solvent | Polar molecule that dissolves ionic and polar substances. | Allows solutes to dissolve in the cytoplasm. Enables transport and metabolic reactions. |
| High specific heat capacity | Absorbs lots of heat before the temperature rises due to hydrogen bonding. | Stabilises temperature in organisms and environments. |
| High latent heat of vaporisation | Requires lots of energy to evaporate. | Evaporation removes heat (e.g. sweat, transpiration). Helps cool organisms and regulate body temperature. |
| Cohesion and adhesion | Water sticks to itself (cohesion) and surfaces (adhesion). Due to hydrogen bonds. | Supports capillary action in xylem. Enables surface tension – lets small organisms walk on water. |
| Role in metabolism | Reactant in hydrolysis and photosynthesis. Product of condensation reactions and respiration. | Involved in anabolic and catabolic reactions. Medium for reactions and solvent for transport. |

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Macromolecules

Macromolecules are **large biomolecules**, important to the structure and function of living organisms, made up of **covalently bonded monomers**.

The table below gives an overview of these four groups of biomolecules.

| Biomolecule | Elements Present | Monomer | Polymer(s) | Examples |
|---------------|---------------------|------------------------|------------------------------|--|
| Carbohydrates | C, H, O | Monosaccharides | Polysaccharides | Maltose, Sucrose, Lactose, Starch, Glycogen, Cellulose |
| Lipids | C, H, O | Fatty acids & Glycerol | Triglycerides, Phospholipids | Phospholipids, Cholesterol, Steroids |
| Proteins | C, H, O, N, S**most | Amino acids | Polypeptides, Proteins | Collagen, Enzymes, Antibodies |
| Nucleic Acids | C, H, O, N, P | Nucleotides | DNA, RNA | mRNA, tRNA, rRNA |

Monomers are **small molecules** which, when joined to other molecules of the same type, form a **polymer**.

A **polymer** is a large molecule made from **many monomers** joined together in **condensation reactions**.

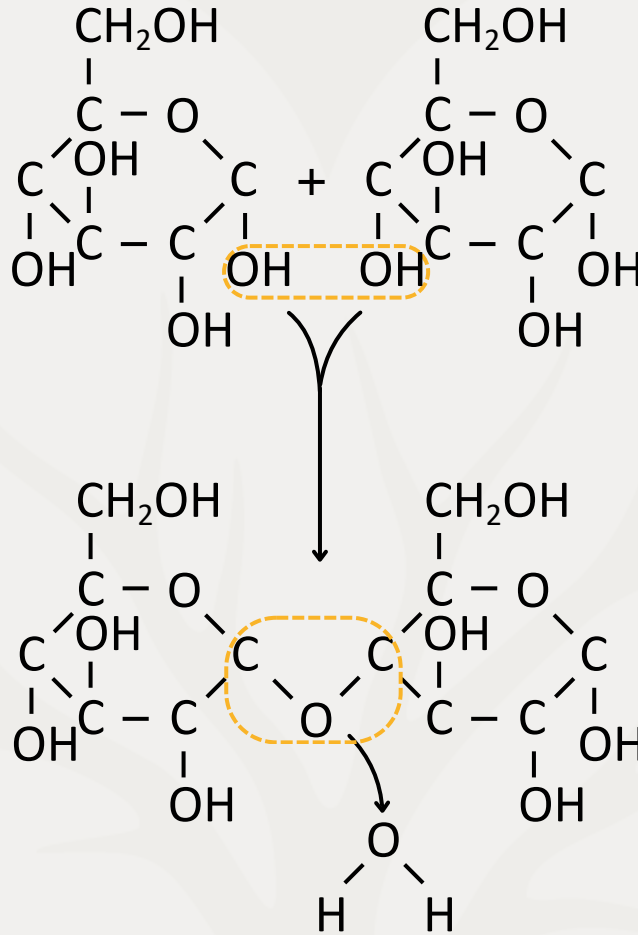
A **condensation reaction** is when two molecules are **joined** together with a **covalent bond**, forming (and releasing) a **water molecule** in the process.

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The diagram below shows a covalent bond (a glycosidic bond) being formed from a reaction between the hydroxyl groups on two different molecules:



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Module 2: Introduction to Macromolecules



The table below gives an overview of the bonds in biological molecules formed by condensation reactions.

| Biomolecule | Monomer | Bond Type | Image |
|---------------|------------------------|----------------|-------|
| Carbohydrates | Monosaccharides | Glycosidic | |
| Proteins | Amino acids | Peptide | |
| Lipids | Glycerol & Fatty acids | Ester | |
| Nucleic Acids | Nucleotides | Phosphodiester | |

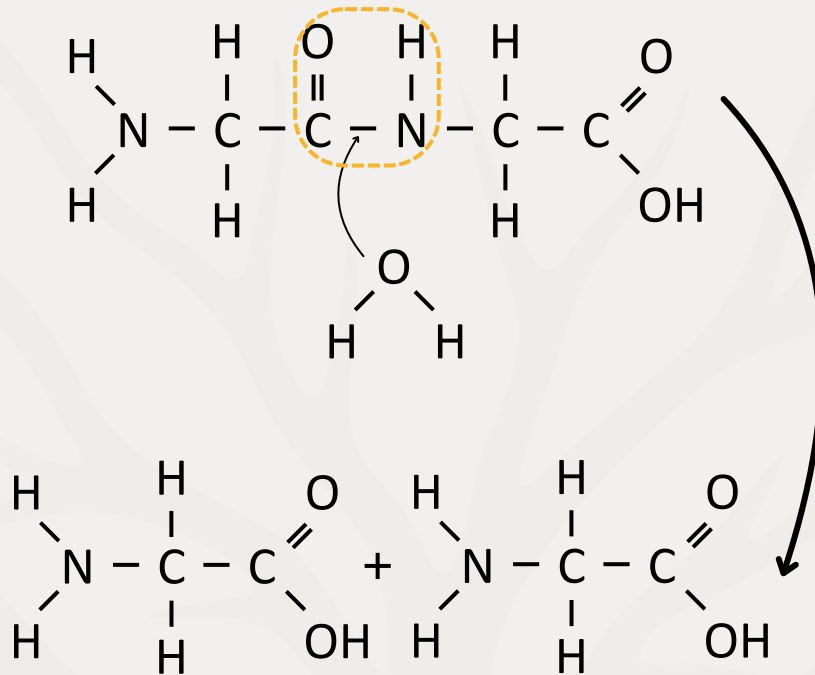




Polymers can be **broken down** (digested) into monomers again in **hydrolysis reactions**.

A **hydrolysis reaction** is when a water molecule is used to **break** a **covalent bond**, producing two molecules from one.

The diagram below shows a covalent bond (specifically a peptide bond) being broken in a dipeptide to produce two amino acids.

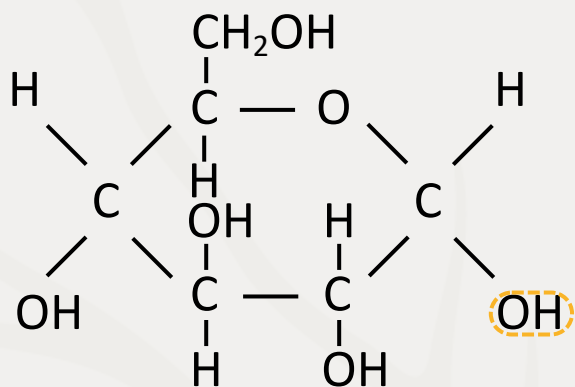


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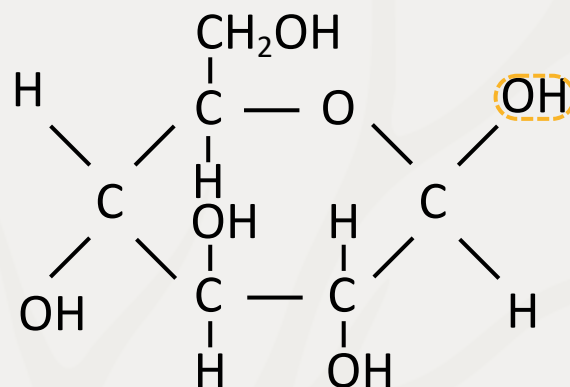


Carbohydrates

Carbohydrates are a group of biological molecules that are a key source of **energy** and have structural roles in both animals and plants; **glucose** is one of the most important. **Glucose** comes in **two forms** (isomers) called α (alpha) glucose and β (beta) glucose.



Alpha-glucose



Beta-glucose

Monosaccharides

Monosaccharides are individual **sugar monomers**, such as glucose.

The table below outlines some of the most **common monomers** used to build larger carbohydrates:

| Monosaccharide | Molecular Formula | Type | Use |
|-------------------|-------------------|---------|---|
| α -Glucose | $C_6H_{12}O_6$ | Hexose | Energy source and primary respiratory substrate. |
| β -Glucose | $C_6H_{12}O_6$ | Hexose | Energy source, a component of glycolipids and glycoproteins |
| Ribose | $C_5H_{10}O_5$ | Pentose | A component of nucleotides (e.g. ATP, RNA) |

All of these monosaccharide monomers are reducing, so they test positive in a Benedict's test.

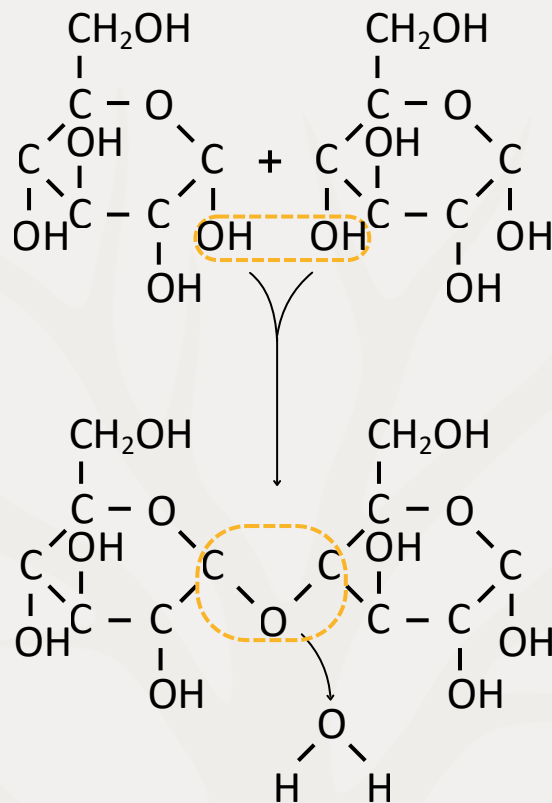




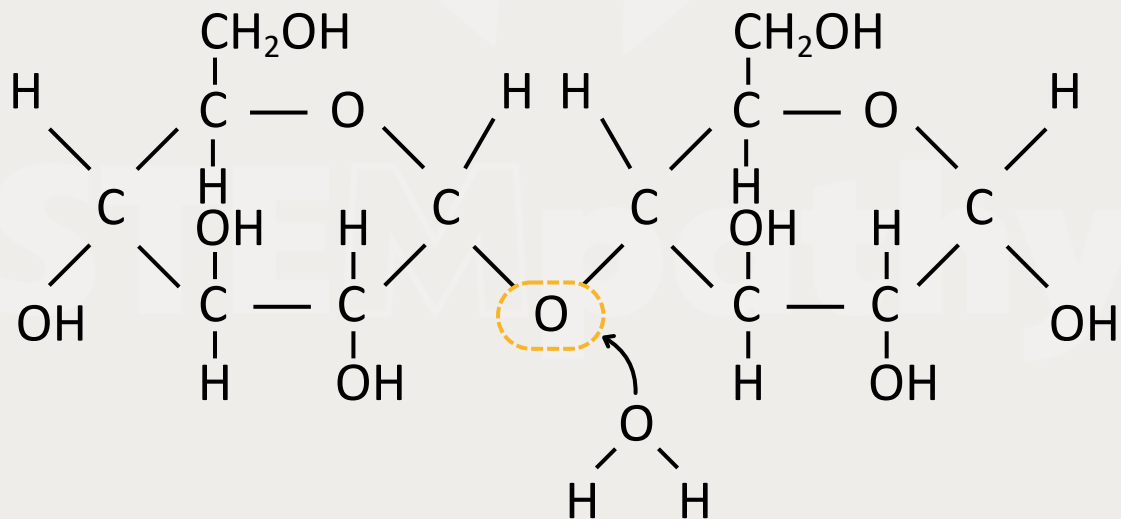
Disaccharide and Polysaccharide Formation

Carbohydrates like disaccharides and polysaccharides are made by joining monosaccharides using **glycosidic bonds**.

Glycosidic bonds form through **condensation reactions** between the **hydroxyl groups** of two monosaccharides, releasing a water molecule as a byproduct.



When carbohydrates are **hydrolysed** (digested), **enzymes** (e.g. amylase or maltase) break the **glycosidic bonds** using water, releasing smaller sugars or monosaccharides.



Maltose



Disaccharides

Disaccharides are two sugar molecules joined together with a **glycosidic bond**.

The table below outlines the most common **disaccharides** formed from monosaccharides:

| Disaccharide | Monomers joined | Use |
|--------------|--|-------------------------------------|
| Cellobiose | β -Glucose + β -Glucose | Intermediate in cellulose breakdown |
| Lactose | α -Glucose + β -Galactose | Sugar in milk and an energy store |
| Maltose | α -Glucose + α -Glucose | Intermediate in starch digestion |
| Sucrose | α -Glucose + Fructose | Transport sugar in plants |

Of these disaccharides, **only sucrose is non-reducing**, so it gives a **negative result** in a **Benedict's test**.

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Polysaccharides

Polysaccharides are long chains of **sugar monomers** joined by **glycosidic bonds**.

The table below outlines the structure of the 4 main **polysaccharides**:

| Polysaccharide | Monomers | Image | Glycosidic Link | Structure | Compact? |
|----------------|---------------------------------------|-------|-----------------|---|----------|
| Cellulose | β -Glucose + β -Glucose | | 1-4 | Straight chain with many hydrogen bonds between and within chains. | |
| Glycogen | α -Glucose + α -Glucose | | 1-4 and 1-6 | Coiled (less than starch) and highly branched. | |
| Amylose | α -Glucose + α -Glucose | | 1-4 | Coiled into a spiral, held together by hydrogen bonds. | |
| Amylopectin | α -Glucose + α -Glucose | | 1-4 and 1-6 | Coiled into a spiral held together by hydrogen bonds, but with branches (less than glycogen). | |

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Module 2: Carbohydrates



The table below outlines how structure relates to the function of each polysaccharide's use:

| Polysaccharide | Use(s) | How Structure Supports Function |
|----------------|---|--|
| Cellulose | Structural support in plant cell walls | Many hydrogen bonds between fibres provide tensile strength and rigidity. |
| Glycogen | Energy storage in animals | Compact spiral to store many glucose molecules. 1-6 glycosidic bonds create branches providing many access points for enzymes to release glucose molecules quickly. |
| Amylose | Long-term (slow-release) energy storage in plants | Compact spiral to store many glucose molecules. |
| Amylopectin | Energy storage in plants | Compact spiral to store many glucose molecules. 1-6 glycosidic bonds create branches providing many access points for enzymes to release glucose molecules quickly. |

Polysaccharides are **broken down** into monomers and disaccharides during **digestion** by **enzymes**, typically to release monomers, which can then be used to **release energy** in respiration.

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Lipids

Lipids are a group of molecules with a wide variety of structures and functions in organisms, but most importantly, they are used in cell **plasma membranes** and for **energy storage** and **thermal insulation**.

| Lipid Type | Components | Ester bonds? | Image |
|--------------|--|--------------|--|
| Triglyceride | Glycerol + 3 fatty acids | Yes | <p>The diagram shows a glycerol backbone on the left, consisting of three carbon atoms in a vertical chain. Each carbon is bonded to a hydrogen atom (top), another hydrogen atom (bottom), and an oxygen atom (right). Each oxygen atom is part of an ester linkage to a fatty acid chain. Each fatty acid chain consists of a carbonyl group (C=O) bonded to a four-carbon alkyl chain. All carbons in the alkyl chains are saturated with hydrogen atoms.</p> |
| Phospholipid | Glycerol + 2 fatty acids + phosphate group | Yes | <p>The diagram shows a glycerol backbone on the left. The top carbon is bonded to a hydrogen atom (top), a hydrogen atom (bottom), and an oxygen atom (right) that is part of a phosphate group. The phosphate group is shown as a phosphorus atom double-bonded to an oxygen atom above it and single-bonded to two hydroxyl groups (OH) to its right. The middle and bottom carbons of the glycerol backbone are each bonded to a hydrogen atom (top and bottom) and an oxygen atom (right) that is part of an ester linkage to a fatty acid chain. Each fatty acid chain consists of a carbonyl group (C=O) bonded to a four-carbon alkyl chain. All carbons in the alkyl chains are saturated with hydrogen atoms.</p> |
| Steroid* | Four fused carbon rings | No | <p>The diagram shows the skeletal structure of cholesterol. It features four fused carbon rings: three six-membered rings and one five-membered ring. A hydroxyl group (OH) is attached to the first ring. A methyl group is attached to the second ring. A double bond is present in the second ring. A hydrocarbon side chain is attached to the fifth ring, consisting of a branched alkyl chain.</p> |

*The OCR A level Biology specification uses cholesterol to represent all steroids.

Lipids are (mostly) **non-polar**, so they are (usually) **insoluble** in water; however, they do dissolve in alcohol.





Fatty acids

Fatty acids are one of the components that make up **triglycerides** and **phospholipids**, the other being glycerol.

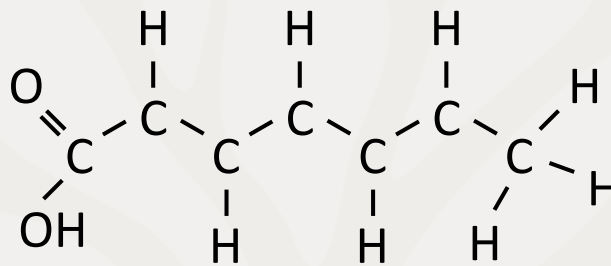
Fatty acids are **not lipids**, but are instead used to make them.

Fatty acids are **long-chain hydrocarbons** with a carboxyl group on one end.

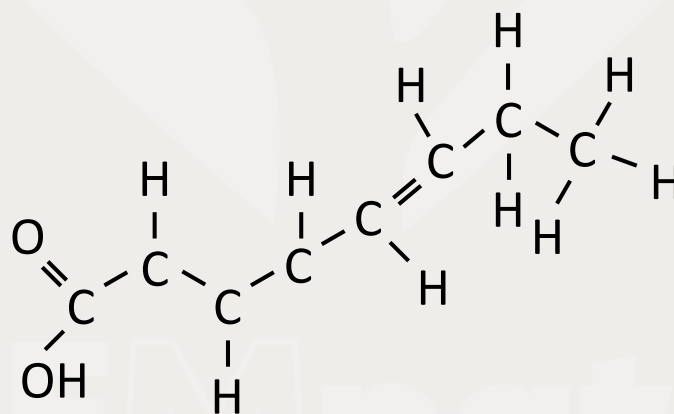
They can either be **saturated** or **unsaturated**.

Saturated fatty acids have no **C=C bonds**, and are a **straight chain**.

Unsaturated fatty acids have at least one **C=C bond**, which causes a **kink in the chain**.



Saturated fatty acid



Unsaturated fatty acid

The **more** C=C bonds an unsaturated fatty acid has, the **lower** its melting point.

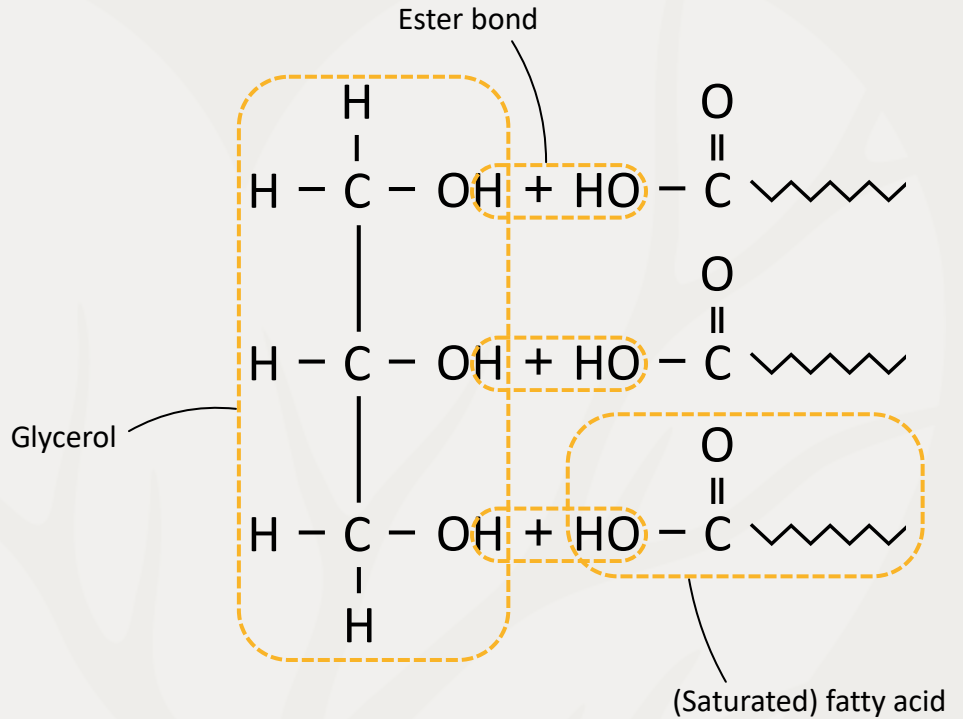




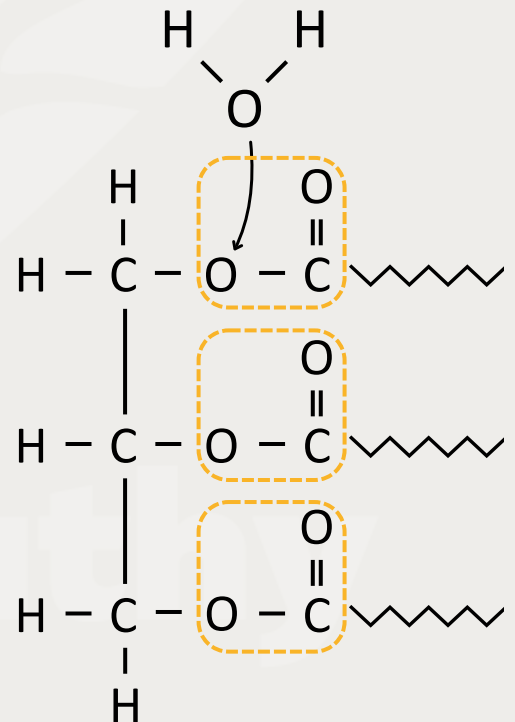
Triglyceride Synthesis

Triglycerides are made by joining **glycerol** to **three fatty acids** using **ester bonds**.

Ester bonds are formed in **condensation reactions** between the **hydroxyl** ($-OH$) group on glycerol and the **carboxyl** group on a fatty acid. This produces a molecule of water as waste.



When lipids are **hydrolysed** (digested), enzymes such as **lipase** break the ester bonds using water, releasing **glycerol** and **fatty acids**.



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Biological Functions of Lipids

The table below outlines how **structure** relates to the **function** of each **lipid** type's use:

| Lipid Type | Use(s) | How Structure Supports Function |
|--------------|--|---|
| Triglyceride | Energy storage, insulation, protection | Hydrophobic and compact. Stores large amounts of energy. |
| Phospholipid | Forms membranes, emulsifier | Amphipathic: hydrophilic phosphate head and hydrophobic fatty acid tails allow bilayer formation and emulsification of fats in water. |
| Steroid | Hormones, membrane stability | Small, flat, mostly hydrophobic molecules, so they can diffuse through membranes. Cholesterol fits between phospholipid tails to stabilise membranes. |
| Wax | Waterproofing and protection | Hydrophobic and solid at room temperature, so it forms protective barriers against water loss or microbial entry. |

Lipid **insolubility** is important because they do **not affect water potential**, allowing energy-rich molecules to be stored without significant changes in osmotic balance.

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Proteins

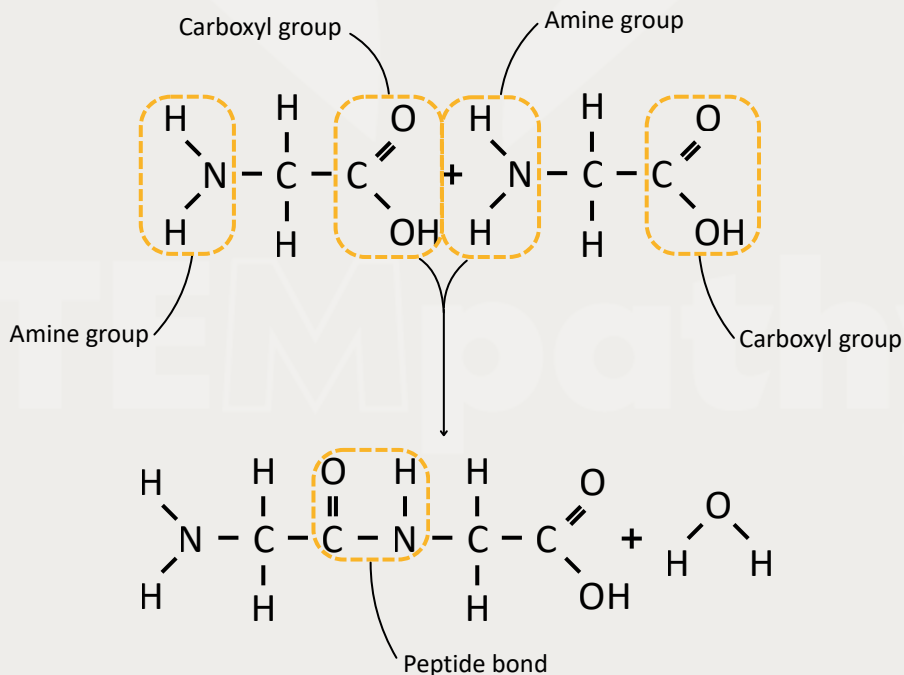
Proteins are important biological molecules with structural and metabolic roles determined by their structure. They can be **enzymes, hormones, antibodies**, structural scaffolds or transport molecules.

The table below outlines the **structural levels** of a protein:

| Level | Definition | Structural Bonds |
|------------|--|---|
| Primary | Order of amino acids in a polypeptide chain | Peptide bonds |
| Secondary | Coiling and folding of the polypeptide chain into α -helix or β -pleated sheets (zig-zag) | Hydrogen bonds (between different amino acids' -NH and -CO groups) |
| Tertiary | The 3D shape of the protein, stabilised by interactions between R-groups | <ul style="list-style-type: none"> - Hydrogen bonds* - Ionic bonds* - Disulfide bridges* - Hydrophobic and hydrophilic interactions |
| Quaternary | Two or more polypeptide chains associating | <ul style="list-style-type: none"> - Hydrogen bonds - Ionic bonds - Disulfide bridges - Hydrophobic and hydrophilic interactions |

*between different amino acids' R groups.

Proteins are formed in condensation reactions between **amino acids**, forming **peptide bonds** between an amine group on one amino acid and a hydroxyl group on the other.





Conjugated Proteins

A **conjugated protein** is a protein that is associated with a **prosthetic group** – a non-protein component that is permanently included in the final functioning protein.

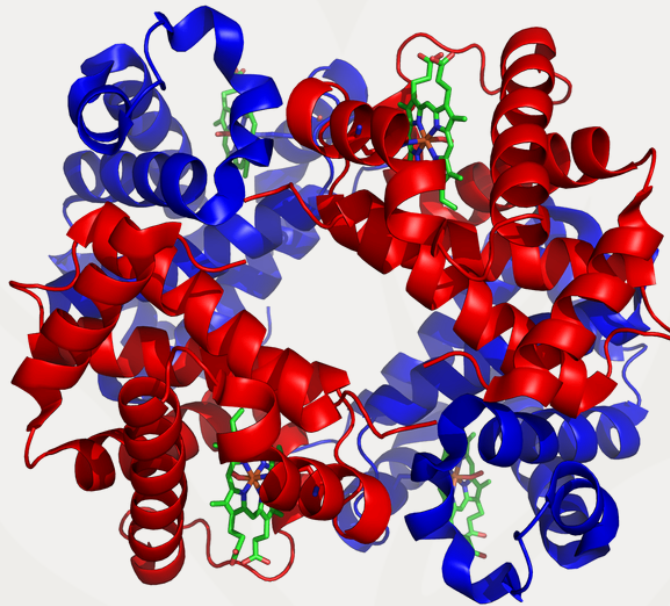


Image By [Zephyris at the English-language Wikipedia](#), CC BY-SA 3.0

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Inorganic Ions

Inorganic ions are **essential** to the maintenance of physical structures and physiological mechanisms in organisms. A **lack** of an inorganic ion can result in **deficiency symptoms** or **diseases**.

Positive ions are called **cations**, and **negative** ions are called **anions**.

The table below lists the common cations:

| Name | Symbol |
|-----------|-------------------|
| Calcium | Ca^{2+} |
| Sodium | Na^{+} |
| Potassium | K^{+} |
| Hydrogen | H^{+} |
| Ammonium | NH_4^{+} |

The table below lists the common anions:

| Name | Symbol |
|-------------------|--------------------|
| Nitrate | NO_3^{-} |
| Hydrogencarbonate | HCO_3^{-} |
| Chloride | Cl^{-} |
| Phosphate | PO_4^{3-} |
| Hydroxide | OH^{-} |

These inorganic ions will appear throughout the biological processes studied throughout the AS and A level course. You are expected to recognise and recall their symbols.





Chemical Tests for Biomolecules

Biochemical **tests** can either be **qualitative** or **quantitative**.

Qualitative tests only give a **positive or negative** response, allowing you to **identify** a substance.

Quantitative tests allow you to **determine the concentration** of a substance in a solution.

Qualitative Tests

The table below provides an overview of the different qualitative tests for identifying biological molecules:

| Chemical | Reagent(s) Used | Positive Result | Negative Result |
|---------------------------------------|--|-------------------------------------|--------------------------|
| Biuret Test (Proteins) | Biuret reagent (or NaOH → CuSO ₄) | Lilac | Stays blue |
| Benedict's Test (Reducing Sugars) | Benedict's reagent (+ 80°C heat) | Green → Yellow → Orange → Brick-red | Stays blue |
| Benedict's Test (Non-Reducing Sugars) | HCl (hydrolysis) + NaHCO ₃ → Benedict's reagent (+ 80°C heat) | Green → Yellow → Orange → Brick-red | Stays blue |
| Iodine Test (Starch) | Iodine solution | Blue-black color | Yellow-brown (no starch) |
| Emulsion Test (Lipids) | Ethanol → Water | Cloudy white emulsion | Solution remains clear |

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Colorimetry

Colorimetry is a **quantitative** method used to determine the **concentration** of a coloured solution by measuring how much **light** is **absorbed** (or transmitted) through a solution.

A **colorimeter** measures how much light (of a specific wavelength) passes through a solution placed in a cuvette.

A blank (usually distilled water) is used to **calibrate** the colorimeter to zero absorbance (or 100% transmission) for **comparison** with the solution being tested.



Colorimetry for reducing sugars

Procedure:

1. Add excess Benedict's reagent to your sample and heat it to 80°C.

The more reducing sugar present, the more precipitate that forms, and the fewer copper(II) ions remain in solution.

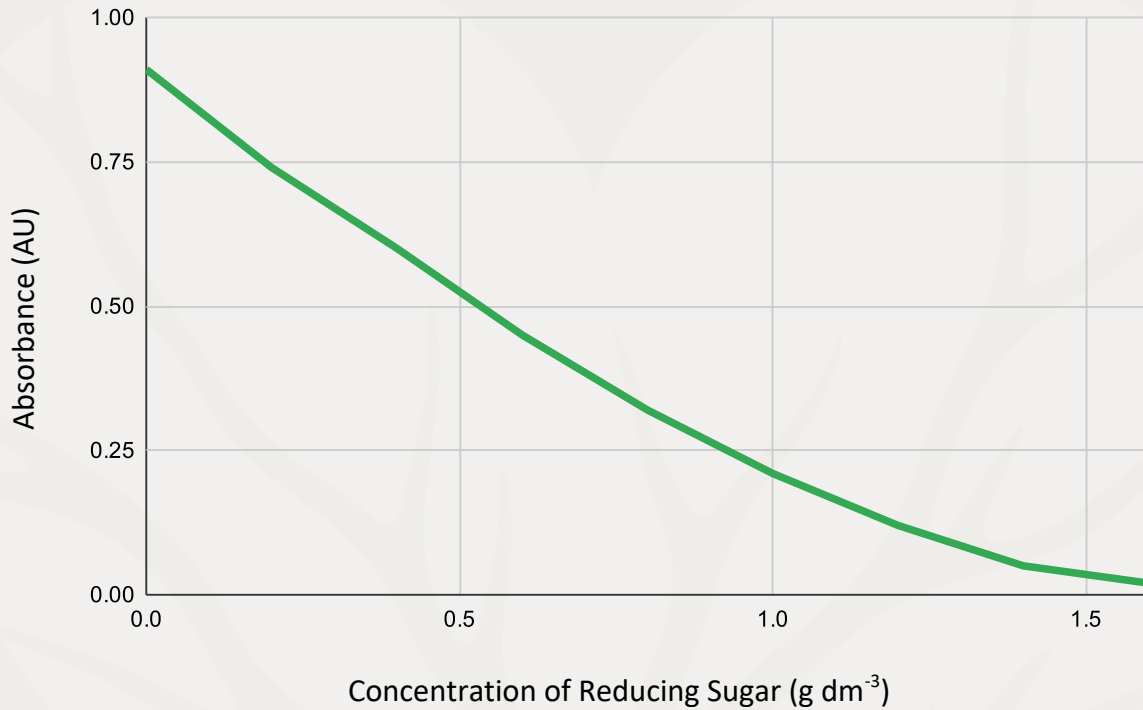
2. Centrifuge the mixture to remove the precipitate.
3. Collect the supernatant (the clear liquid) and place into a cuvette.
4. Calibrate a colorimeter with distilled water (for comparison).
5. Use a colorimeter to measure the absorbance of the supernatant.

Use a red filter (blue Benedict's solution absorbs red light).

6. Compare absorbance readings to those from solutions of known concentration to create a calibration curve by plotting absorbance vs concentration.



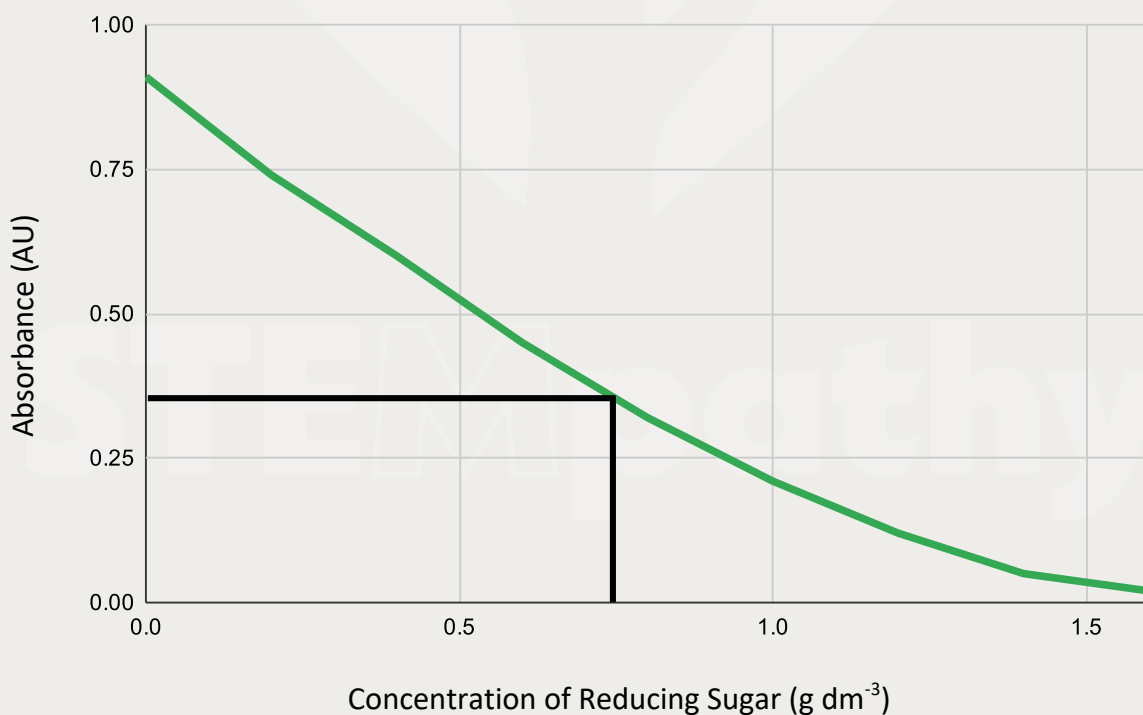
Absorbance (AU) vs Concentration of Reducing Sugar (g dm^{-3})



Less absorbance = higher concentration of reducing sugar.

Then use the graph to find the concentration of unknown samples by interpolation.

Absorbance (AU) vs Concentration of Reducing Sugar (g dm^{-3})





Chromatography

Chromatography is a technique used to **separate** and identify **biological molecules**.

Substances which are **highly soluble** and have a **low affinity** towards the material will travel at a **greater rate** than those with a lower solubility and/or higher affinity.

Larger molecules also move **more slowly** than smaller molecules (of the same solubility and affinity).

The two components used are:

- **Stationary phase:** A paper (cellulose) or TLC plate (plastic covered in silica or aluminium hydroxide).
- **Mobile phase:** A solvent in which the biological molecule is dissolved.

The table below outlines example molecules that can be separated:

| Molecule Separated | Use in Biology |
|------------------------|---|
| Amino acids | Identify components in proteins (e.g. protein digestion analysis) |
| Carbohydrates (sugars) | Detect the presence and type of sugars in a sample |
| Vitamins | Separate and identify different vitamins in food samples |
| Nucleic acids | Used in genetic research to analyse DNA/RNA fragments |
| Hormones/Drugs | Athletic anti-doping tests |

Practical method:

1. A sample is spotted onto a pencil line (used to measure how far substances have travelled) on chromatography paper or the TLC plate.
2. The plate/paper is placed in a solvent (the mobile phase) with the pencil line above the solvent.
3. The solvent moves up the stationary phase via capillary action, coming into contact and dissolving the sample molecules.
4. Sample molecules move upwards and separate out, based on their affinity and solubility.
5. Once the solvent front reaches the top, the chromatogram is removed and dried.
6. Calculate each molecule's R_f value (how much it dissolves into the mobile phase).

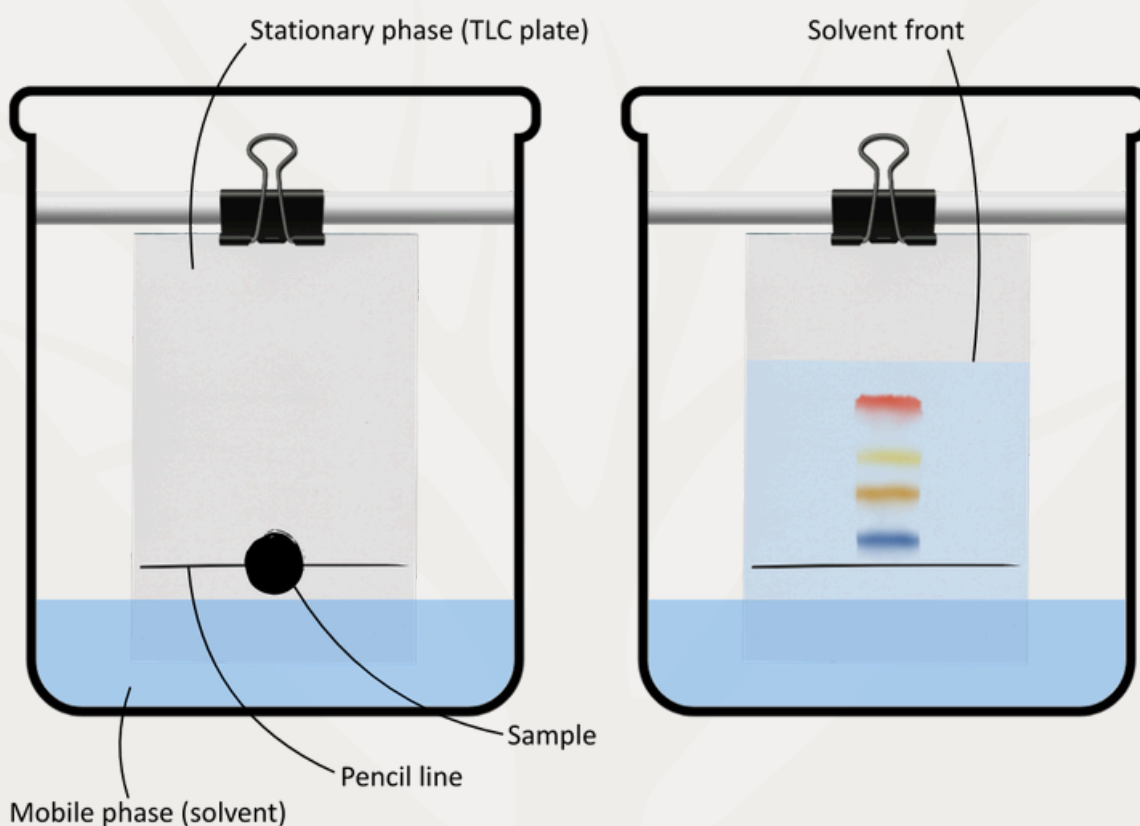




Calculating Rf Values:

$R_f = \text{Distance moved by the solute} \div \text{Distance moved by the solvent front}$

- Distance moved by solute: Measure from the baseline (pencil line) to the centre of the spot.
- Distance moved by solvent: Measure from the baseline to the solvent front (before it dries!).
- Compare Rf values with known standards to identify molecules.



Detecting Colourless Molecules

In GCSE practicals, coloured pigments are typically used to observe the separation of substances, but many biomolecules do **not** have a discernible **colour**.

The following treatments make them **visible**:

- **Iodine vapour**: Iodine binds to **organic** molecules, staining them **brown**.
- **Ninhydrin spray**: Reacts with **amino acids**, turning them **brown** or **purple**.
- **Ultraviolet (UV) light**: TLC plates may have a UV-reactive coating. Molecules block fluorescence, revealing **dark spots**.

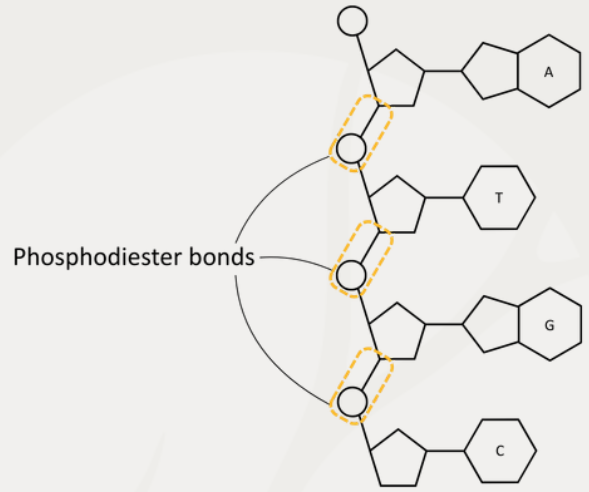




Nucleic Acids

Nucleic acids are **DNA** and **RNA**, polymers involved in the encoding and transmission of information in biological life.

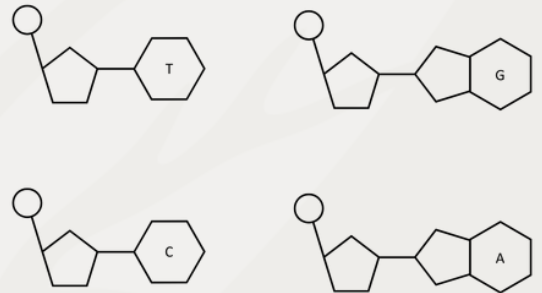
Nucleic acids are made up of many **nucleotide monomers** joined together by **phosphodiester bonds**.



Nucleotides

Nucleotides consist of **three** components:

- A **phosphate group**
- A **pentose sugar**: Deoxyribose (in DNA) or ribose (in RNA)
- A **nitrogenous base**: Adenine, cytosine, guanine, thymine, uracil (in RNA)



The image on the right shows the 4 DNA nucleotides:

There are two types of nitrogenous bases: **purines** and **pyrimidines**.

| | Purines | Pyrimidines |
|-----------|--------------------------|--|
| Bases | Adenine (A), Guanine (G) | Cytosine (C), Thymine (T), Uracil (U)* |
| Structure | Double-ring | Single-ring |

***Uracil** is only found in **RNA**, replacing the use of Thymine.





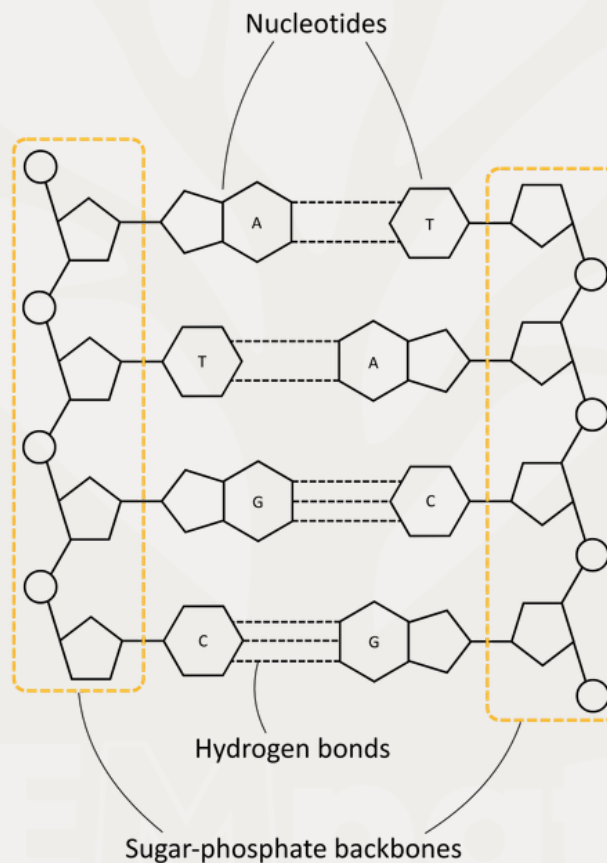
Phosphodiester Bonds

Phosphodiester bonds form in **condensation reactions**, where a molecule of water is lost, joining nucleotide monomers together to form nucleic acid polymers.

Phosphodiester bonds are **broken** in **hydrolysis reactions** (e.g., during digestion or replication) by using water, breaking nucleic acids back down into their nucleotide monomers.

Nucleotides and DNA Structure

Nucleotides form the **sugar-phosphate backbone** of the DNA double helix and in RNA. The **DNA double helix** is formed when **two** DNA strands are joined together by **hydrogen bonds** between their **nitrogenous bases**.



Module 2: Nucleotides and Nucleic Acids

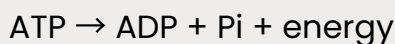


The table below compares and outlines **DNA** and **RNA**:

| | DNA | RNA |
|--------------|--|--|
| Full name | Deoxyribonucleic acid | Ribonucleic acid |
| Strands | Double-stranded | Single-stranded |
| Sugar | Deoxyribose | Ribose |
| Bases | A, T, C, G | A, U, C, G |
| Function | Stores genetic information | Transfers and translates genetic information |
| Structure | Long, double helix | Shorter, varies in shape |
| Base pairing | A-T (2 H bonds) C-G (3 H bonds) | A-U (2 H bonds) C-G (3 H bonds) |
| Location | Nucleus (some in mitochondria and chloroplast) | Made in nucleus, functions in cytoplasm |
| Polymer | Yes | Yes |

ATP (Adenosine Triphosphate)

Nucleotides also form **ADP** and **ATP** when they are **phosphorylated**.



This **releases energy**, which is used for active transport, muscle contraction, metabolic reactions, and more.

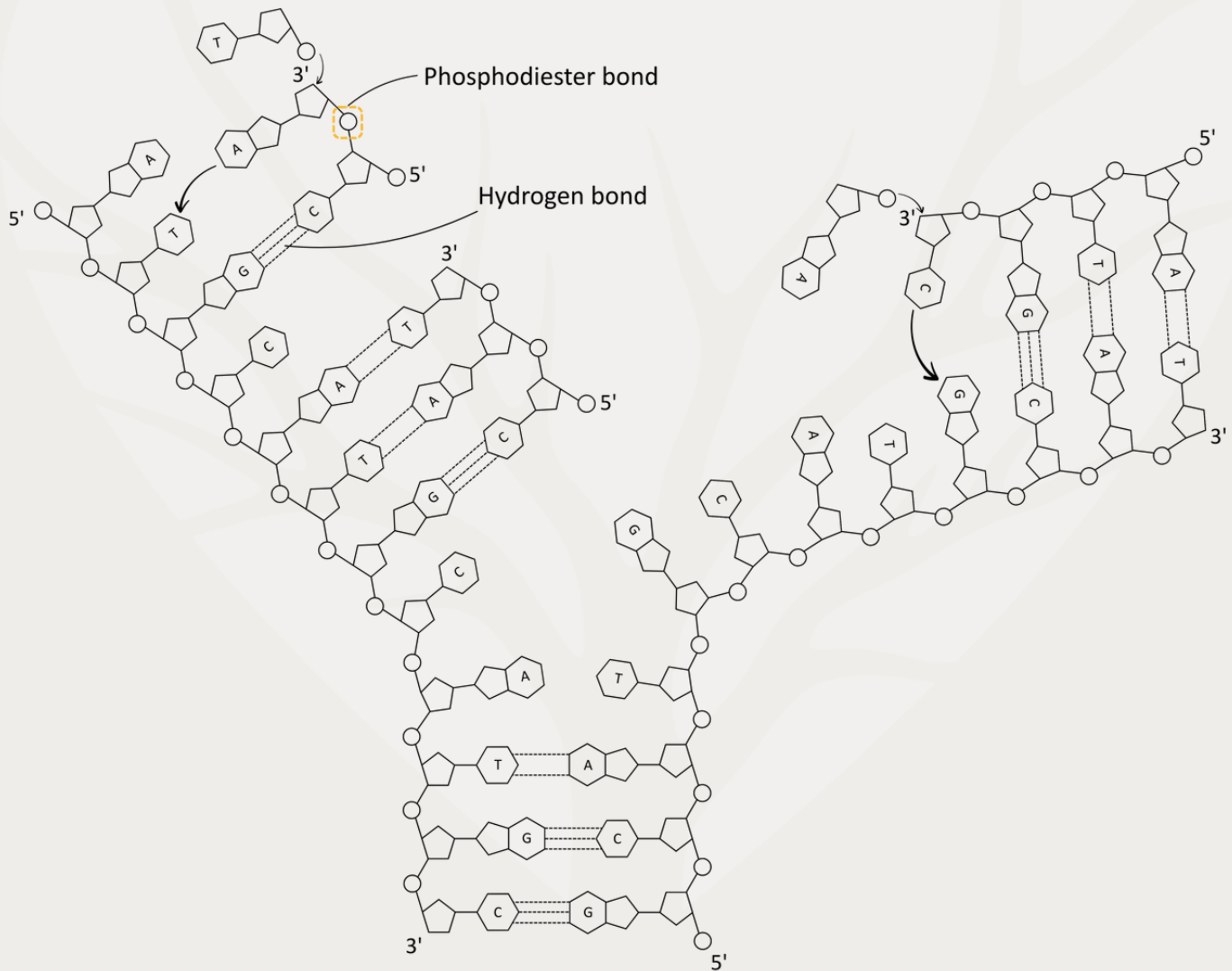
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DNA Replication

DNA synthesis refers to the assembly of a **new DNA polymer** from nucleotides.

Nucleotides are joined together by **DNA polymerase**, which catalyses condensation reactions between the phosphate groups of adjacent nucleotides in the **5' → 3' direction**.



This forms a **phosphodiester bond**, building the sugar-phosphate backbone of the DNA strand.

“5' → 3'” refers to the orientation of a nucleic acid strand in DNA. The phosphate group on the 5' carbon of one nucleotide is bonded to the hydroxyl group of the 3' carbon of the next nucleotide, so the strand is built up from the 5' end towards the 3' end.

DNA replication is the process by which an accurate **copy of the DNA** molecule is made during the **S phase** of the cell cycle.





Step-By-Step: DNA Synthesis

1. Nucleotide Formation

Each DNA nucleotide is formed by a condensation reaction between a deoxyribose sugar, a phosphate group, and a nitrogenous base (A, T, C, or G).

2. DNA Unwinding

DNA helicase breaks hydrogen bonds between bases, separating the two strands of the helix.

3. Primer Binding

RNA primers are added to both strands by primase, providing a starting point for DNA polymerase to begin synthesis.

4. Complementary Base Pairing

Free activated nucleotides pair with exposed bases on each template strand:

- A pairs with T
- C pairs with G

5. DNA Polymerase Activity

DNA polymerase adds nucleotides to the 3' end of the new strand, synthesising in the 5' → 3' direction.

It forms phosphodiester bonds between adjacent nucleotides using energy from hydrolysing the extra phosphate groups.

6. Leading Strand Synthesis

On the leading strand (template runs 3' → 5'), DNA polymerase works continuously in the same direction as the replication fork.

7. Lagging Strand Synthesis

On the lagging strand (template runs 5' → 3'), DNA polymerase works discontinuously away from the fork, producing short sections called Okazaki fragments.

Each fragment requires a new primer.

8. Joining of Fragments

DNA ligase joins Okazaki fragments by forming phosphodiester bonds, creating a complete and continuous strand.

9. Semi-Conservative Replication

Each resulting DNA molecule contains one original strand and one newly synthesised strand – this is semi-conservative replication.



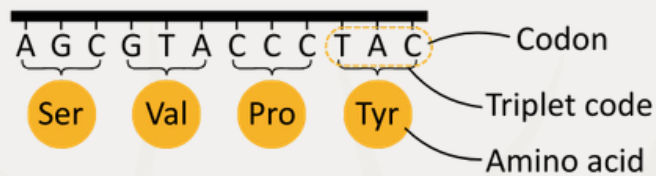


The Nature of the Genetic Code

Genes are **sections** of DNA that **code** for **proteins** (and some code for RNA).

The **order of bases** in a gene **determines** the **sequence of amino acids** in a polypeptide.

These bases are read in **groups of three**; this is known as the **triplet code**, and each group of three bases forms a **codon**.



The key features of the triplet genetic code are that it is **degenerate**, **non-overlapping**, and **universal**.

| Property | Description | Biological Importance |
|-----------------|---|---|
| Degenerate | 64 codons but only 20 amino acids. | Most amino acids have multiple codons. Reduces the impact of point mutations. |
| Non-overlapping | Bases are read in triplets (codons), each base used once. | Each base affects only one amino acid. |
| Universal | The same codons specify the same amino acids in almost all organisms. | Evidence for a common evolutionary ancestor. |

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Protein synthesis

Protein synthesis is when a **ribosome** uses genetic code (from transcription) to **make** a **polypeptide** chain **from amino acids** (during translation).

The table below outlines **transcription** and **translation**:

| Process | Location | Purpose |
|---------------|---|---|
| Transcription | Nucleus (in eukaryotes) Cytoplasm (in prokaryotes) | Synthesise a complementary mRNA copy of a gene |
| Translation | Cytoplasm (on ribosomes) | Read mRNA and assemble amino acids into a polypeptide chain |

Transcription

1. The DNA double helix unwinds and the hydrogen bonds between bases break.
2. RNA polymerase binds to the DNA and adds free complementary RNA nucleotides to the DNA bases (A–U, C–G); these are held in place by temporary hydrogen bonds.
3. Phosphodiester bonds form between RNA nucleotides, producing a strand of pre-mRNA that is a copy of the coding strand.

In eukaryotes, this **pre-mRNA** undergoes **splicing**:

- **Introns** (non-coding regions) are **removed**.
- **Exons** (coding regions) are **joined** to form mature mRNA.

In eukaryotes, mRNA must leave the nucleus via a nuclear pore and travel to the **cytoplasm** for **translation**.

Translation

1. mRNA binds to the ribosome.
2. tRNA brings specific amino acids.
3. The anticodon on tRNA pairs with codon on mRNA via temporary hydrogen bonds.
4. Ribosomes hold tRNA in place (with temporary hydrogen bonds).
5. Ribosome catalyses the formation of peptide bonds between amino acids using energy from ATP.
6. The ribosome moves along mRNA until a stop codon is reached (and then detaches from the polypeptide).

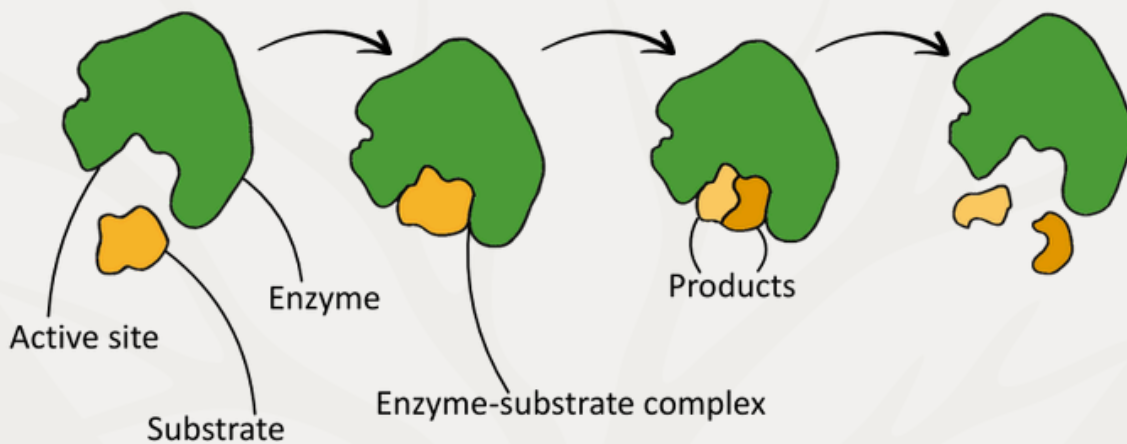




Enzymes

Enzymes are **globular proteins** with a **specific active site** (determined by their tertiary structure) that **catalyse** biochemical reactions by **lowering the activation energy** required.

This **active site** is **complementary** (specific) to a **substrate** with a specific **shape** (or at least substrates similar enough to fit into the active site). This is known as '**enzyme specificity**'.



Enzymes can break apart molecules (catabolism) or join them together (anabolism).

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Module 2: Enzymes



The two examples you need to know about are **amylase** (extracellular) and **catalase** (intracellular):

| | Amylase (humans) | Catalase (humans) |
|---------------------|--|--|
| Location | Extracellular | Intracellular |
| Function | Breaks down starch into maltose during digestion | Breaks down hydrogen peroxide (H_2O_2) into water and oxygen; protects cells from oxidative damage |
| Location (of work) | Mouth and small intestine | Found inside most cells |
| Produced By | Salivary glands and pancreatic cells | Most aerobic cells High levels in liver and white blood cells |
| Substrate | Starch | Hydrogen peroxide (H_2O_2) |
| Products | Maltose | Water and oxygen |
| Biological Role | Digestive enzyme | Protects against oxidative damage, used to kill pathogens (with oxidative damage) |
| Optimal pH | ~7 (salivary)~6.7–7.0 (pancreatic) | ~7 |
| Optimal Temperature | ~37°C | ~45°C |

Enzyme Action: Lock and Key, and Induced Fit

The table below summarises the two models of enzyme action:

| Model | Description |
|--------------|--|
| Lock and Key | The active site is a perfect fit for the substrate (they are complementary); like a key fitting into a lock. |
| Induced Fit | The active site undergoes a conformational change (changes shape slightly) to better fit the substrate when it binds. This improves binding and catalysis. |

These two models are typically discussed separately and compared, but the induced-fit hypothesis **builds upon** the lock-and-key hypothesis to **improve it**.



Module 2: Enzymes



The table below summarises the process of enzyme action:

| Stage | Description |
|-----------------------------------|--|
| 1. Enzyme + Substrate (E+S) | Substrate collides with the enzyme's active site. |
| 2. Enzyme-Substrate Complex (ESC) | Substrate binds to the enzyme's active site with temporary hydrogen bonds, ionic attractions, hydrophobic interactions and van der Waals forces. |
| 3. Enzyme-Product Complex (EPC) | The enzyme catalyses (anabolism or catabolism) the conversion of substrate into product. |
| 4. Enzyme + Product (E+P) | The product is released from the active site. |

Significance of Enzymes

The table below outlines some examples of the **structural** and **functional importance** of enzymes:

| Level | Structure | Function |
|--------------|--|--|
| Molecular | Build proteins, nucleic acids, and membranes | Catalyses essential chemical reactions |
| Cellular | Affects cell wall, cytoskeleton, and organelle shape | Controls respiration, division, and signalling |
| Tissue/Organ | Shapes connective tissue, cartilage, etc. | Supports digestion, immunity, and nerve function |
| Organism | Developmental patterning | Growth, anatomical development, and repair |

Cofactors

Cofactors are **non-protein** substances that help or enable an enzyme's function by making it **easier** for a substrate to **bind** to the **active site**.

They do this by:

- **Stabilising** charge distribution
- **Helping** substrates bind
- Directly **participating** in the reaction

Module 2: Enzymes



Cofactors typically bind to the enzyme's active site, or near it, either **temporarily** or **permanently**.

The table below outlines each type:

| Type | Description |
|------------------|---|
| Cofactor | Inorganic ions that temporarily bind to the enzyme to aid its function. |
| Cosubstrate | Organic molecules that act like substrates to complete the complementary shape. |
| Coenzyme | Organic, non-protein molecules derived from vitamins that temporarily bind to the enzyme's active site. |
| Prosthetic Group | Non-protein group permanently bound to the enzyme (covalently). Essential for enzyme function. |

Coenzymes and Vitamins

Organic **coenzymes** are usually derived from **vitamins**, and a **deficiency** in one or more of these impacts **metabolic function** due to the effects of **poor enzyme activity**.

The table below outlines these different vitamins:

| Vitamin | Vitamin Name | Coenzyme Derived | Human Deficiency Disease |
|-----------------|-----------------------|------------------------------|---|
| B ₁₂ | Cobalamin | Cobalamin coenzymes | Pernicious anaemia (progressive, fatal anaemia) |
| B ₉ | Folic acid (Folate) | Tetrahydrofolate | Megaloblastic anaemia (large irregularly shaped erythrocytes) |
| B ₃ | Niacin (Nicotinamide) | NAD, NADP | Pellagra (dementia, dermatitis, diarrhoea) |
| B ₅ | Pantothenic acid | Coenzyme A | Elevated blood-plasma triglyceride levels |
| B ₁ | Thiamine | Thiamine pyrophosphate (TPP) | Beriberi (heart failure, irregular heartbeat, mental confusion, muscular weakness, paralysis) |

Pearson's 2015 edition textbook for OCR A-level Biology incorrectly labels pantothenate as vitamin B₆, when it should be vitamin B₅ (pantothenic acid), and also (inconsistently) omits specifying that folic acid is vitamin B₉.





Inhibitors

Inhibitors are substances that **reduce** the **rate** of enzyme-controlled reactions.

Inhibitors work by **interfering** with the enzyme's ability to **form enzyme-substrate complexes**.

Inhibition is defined by:

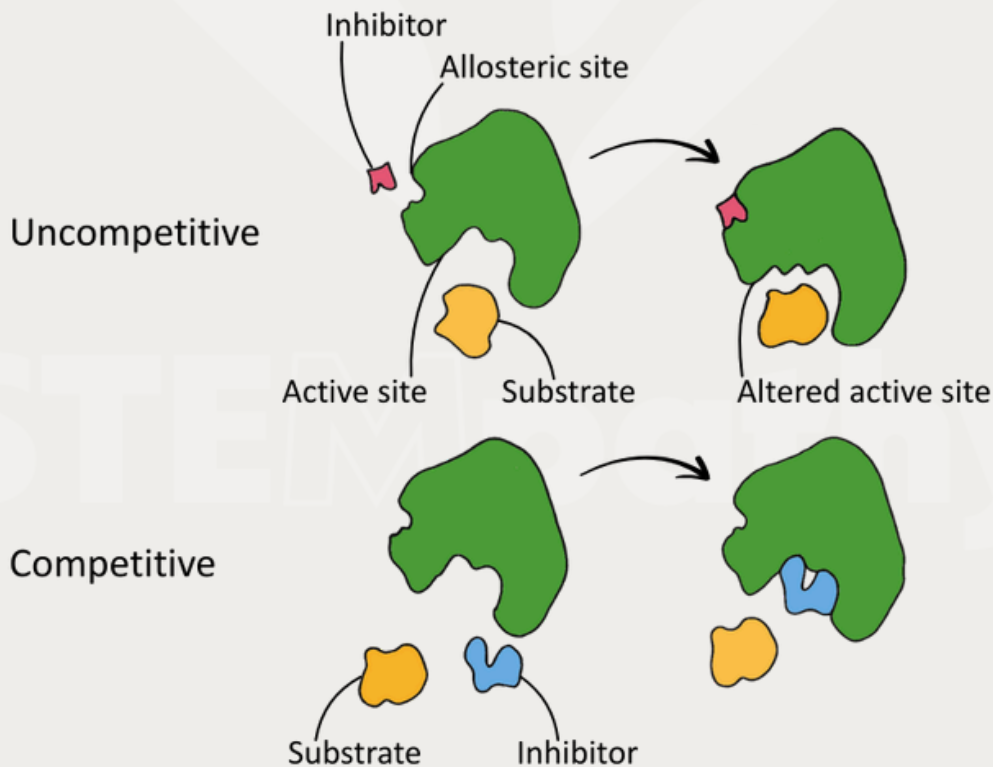
- **Reversibility** - Can the enzyme function normally 'if' the inhibitor unbinds?
- **Competition** - Does the inhibitor compete with the substrate for the active site?
- **Binding site** - Does the inhibitor bind to the active site, or the allosteric site (an external region on the enzyme)?

The two types of inhibitor are competitive and non-competitive:

| Type | Binding Site | Substrate Competition | Reversible? |
|-----------------|-----------------|-----------------------|-------------|
| Competitive | Active site | Yes | Yes* |
| Non-Competitive | Allosteric site | No | Varies |

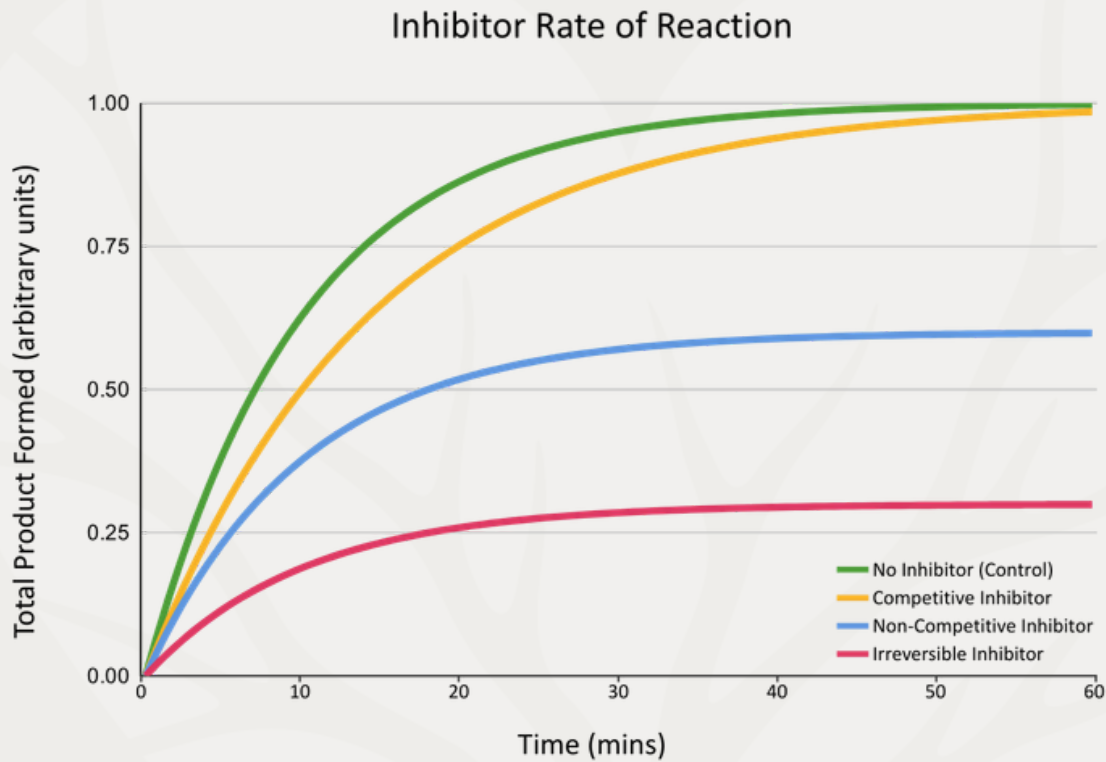
*Usually

The diagram below shows the binding action of competitive and non-competitive inhibitors.





The graph below shows the rates of reaction observed when different types of inhibitors are added to a reaction catalysed by enzymes:



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Biological Membranes

Biological membranes are **selectively** (partially) **permeable** lipid barriers that enable the **separation** of a cell's contents from its **external environment**.

In addition to **controlling** the **movement of substances**, membranes have many more functions important to both prokaryotic and eukaryotic cells, detailed in the table below:

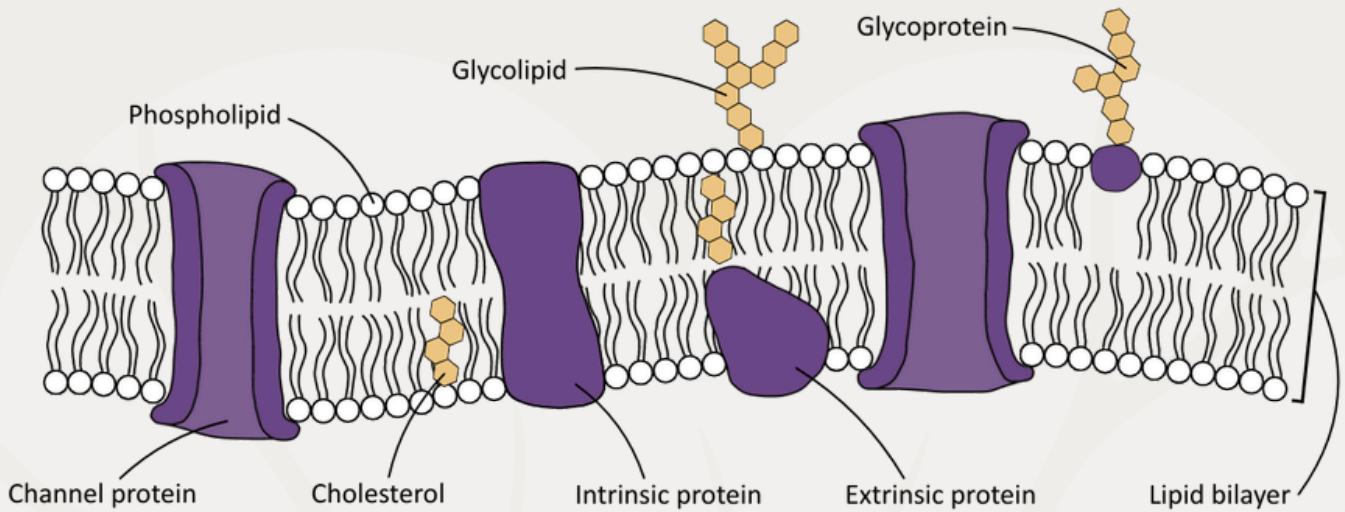
| Role of Membrane | Structure(s) Involved | Main example |
|--|--|---|
| Control the entry and exit of substances | <ul style="list-style-type: none">- Phospholipid bilayer*- Proteins | <ul style="list-style-type: none">- Cell surface membrane- Organelle membranes (e.g. mitochondria, nucleus) |
| Cell communication | <ul style="list-style-type: none">- Glycoproteins- Receptor proteins- Vesicles | <ul style="list-style-type: none">- Cell surface membrane |
| Cell recognition | <ul style="list-style-type: none">- Glycoproteins- Glycolipids | <ul style="list-style-type: none">- Cell surface membrane |
| Chemical reactions | <ul style="list-style-type: none">- Embedded enzymes | <ul style="list-style-type: none">- Inner mitochondrial membrane (aerobic respiration)- Thylakoid membranes (photosynthesis) |
| Maintains electrochemical gradients | <ul style="list-style-type: none">- Proton pumps- Ion channels | <ul style="list-style-type: none">- Inner mitochondrial membrane- Thylakoid membranes- Cell surface membrane |
| Transport and secretion | <ul style="list-style-type: none">- Vesicles | <ul style="list-style-type: none">- Golgi apparatus- Endoplasmic reticulum- Cell surface membrane |

The Fluid Mosaic Model

The **cell surface membrane** consists of a **phospholipid bilayer** with proteins (and some other molecules) embedded in it.

At GCSE it was enough to call it 'the cell membrane', but at A level this is too vague to score any marks.





The **protein components** (e.g. glycoprotein, carrier protein) can be classified as either

- **Integral proteins:** Go from one side of the lipid bilayer to another
- **Peripheral proteins:** Are located only on one side of the lipid bilayer

Because the components are **free to move** around each other (it's fluid) and the components are **interspersed** with each other (like a mosaic), this **model** of how the plasma membrane works is called the **fluid mosaic model**.

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Module 2: Biological Membranes



The table below outlines the components of the plasma membrane:

| Component | Structure | Function |
|----------------------|--|--|
| Phospholipid bilayer | Two layers of phospholipids with hydrophobic fatty acid tails facing inwards and hydrophilic phosphate heads facing outwards | <ul style="list-style-type: none"> - Provides a barrier to most water-soluble substances - Allows lipid-soluble molecules to pass - Allows small uncharged molecules to pass through |
| Cholesterol | Found between phospholipids | <ul style="list-style-type: none"> - Gives mechanical stability and flexibility - Stabilises the membranes' fluidity by reducing fluidity at high temperatures and preventing rigidity at low temperatures |
| Glycolipids | Phospholipids with a carbohydrate chain attached | <ul style="list-style-type: none"> - Used in cell signalling and recognition - Stabilises the plasma membrane, as carbohydrate chains interact with the aqueous environment |
| Glycoproteins | Proteins with carbohydrate chains | <ul style="list-style-type: none"> - Antigens - Receptors - Important in signalling and immune response - Stabilises the plasma membrane, as carbohydrate chains interact with the aqueous environment |
| Channel proteins | Globular proteins with a pore (integral) | Passive movement (diffusion) of ions and small polar molecules. |
| Carrier proteins | Globular proteins with a pore (integral) | Used in facilitated diffusion and active transport. |
| Embedded proteins | Globular proteins (peripheral) | <ul style="list-style-type: none"> - Enzymes - Antigens - Receptors |

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Membrane Permeability

The relative abundance of each component in a plasma membrane affects its permeability to different substances, for example:

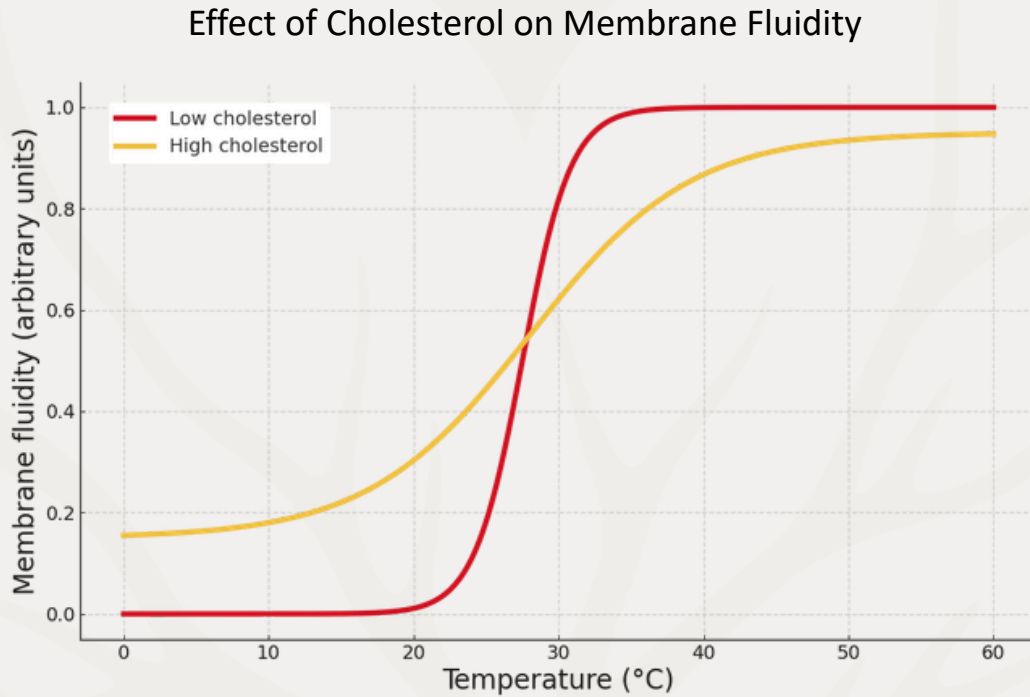
| An Increase In... | Effect on Permeability |
|-------------------|---|
| Phospholipids | ↑ permeability to small, non-polar molecules (e.g. O ₂ , CO ₂) |
| Cholesterol | ↓ permeability to water and small polar molecules |
| Channel proteins | ↑ permeability to ions (e.g. Na ⁺ , K ⁺ , Cl ⁻) |
| Carrier proteins | ↑ permeability to larger polar molecules (e.g. glucose) |
| Aquaporins | ↑ permeability to water |

The structure of a membrane can be affected by environmental conditions listed in the table below:

| Factor | Effect | Mechanism |
|-------------------------|--|---|
| Low temperature | <ul style="list-style-type: none"> - Membrane becomes less fluid and more rigid (brittle) - Permeability decreases | Saturated fatty acid tails on the phospholipids pack together more closely |
| High temperature | <ul style="list-style-type: none"> - The membrane becomes more fluid - Permeability increases - Proteins may denature | <ul style="list-style-type: none"> - Phospholipids move more, so there are more gaps in the membrane - Tertiary structure bonding (hydrogen and ionic) disrupted or denatured |
| Solvents (e.g. ethanol) | <ul style="list-style-type: none"> - Disrupt membrane structure - Increase permeability | Organic solvents dissolve lipids, disrupting the bilayer and allowing substances to leak through |
| pH changes | <ul style="list-style-type: none"> - Denatures membrane proteins | Alters ionic and hydrogen bonding in the tertiary structure |
| Detergents | <ul style="list-style-type: none"> - Break apart the membrane completely | Detergents emulsify phospholipids, disrupting the plasma bilayer |



The diagram below shows the combined effects of temperature and cholesterol on the fluidity of a plasma membrane.



Transport Across Membranes

Cellular transport processes are divided into **two types**:

- **Active**: Uses ATP
- **Passive**: Does not use ATP

The movement of substances in **passive transport** processes is driven by **concentration gradients**, from a high concentration to a low concentration.

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The table below outlines the different transport processes:

| Process | Definition | Needs ATP? | Suitable molecules |
|-----------------------|--|-----------------|--|
| Simple diffusion | Net movement from high to low concentration through the bilayer. | ✗ | Small Non-polar Lipid soluble |
| Facilitated diffusion | Movement down conc. gradient via channel or carrier proteins. | ✗ | Small Polar Lipid insoluble |
| Osmosis | Net movement of water from high to low water potential across a plasma membrane. | ✗ | Water (only) |
| Active transport | Movement against a concentration gradient using ATP and carrier proteins. | ✓ | Charged ions Polar molecules Lipid insoluble |
| Co-transport | Movement of one substance down its gradient pulls another against its gradient (ATP indirectly). | ✓ (indirect) | Small Polar Lipid insoluble |
| Endocytosis | Bulk transport into the cell via vesicle. | ✓ | Too large |
| Exocytosis | Bulk transport out of the cell via vesicle. | ✓ | Too large |

Effect of distance

Diffusion distance (mostly) applies to simple diffusion. It is just the idea that the **further a substance** has to move to get from 'A to B', the **lower its rate of diffusion**.

This is minimised in **exchange surfaces** to decrease the **distance** between 'A and B' as much as possible.

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Module 2: Biological Membranes



The table below gives the specialised exchange surfaces that **minimise diffusion distance** encountered in A level Biology:

| Exchange Surface | Adaptation | Substances |
|----------------------|--|---|
| Alveoli | <ul style="list-style-type: none">- One-cell-thick alveolar wall- One-cell-thick capillary wall- Squamous epithelium | O ₂ , CO ₂ |
| Capillaries | <ul style="list-style-type: none">- One cell-thick endothelium | O ₂ , CO ₂ , glucose, amino acids |
| Villi and microvilli | <ul style="list-style-type: none">- Single-layer epithelial cells | Glucose, amino acids, fatty acids |
| Root hair cells | <ul style="list-style-type: none">- Thin cell wall | Water, mineral ions (e.g. nitrates) |
| Leaf mesophyll | <ul style="list-style-type: none">- Thin, flat cells- Air spaces between cells | CO ₂ , O ₂ |
| Placenta | <ul style="list-style-type: none">- A thin membrane between maternal and fetal blood | O ₂ , glucose, urea, CO ₂ |

Effect of size (of molecule)

Smaller molecules diffuse at a **faster rate** than larger ones, which (mostly) applies to simple diffusion.

For processes using transport proteins, size mainly relates to whether or not the molecule can fit into the transport protein shaped specifically for it, and is irrelevant for bulk transport.

Effect of surface area (of the cell)

The **greater the surface area**, the **more** of a substance can **cross the plasma membrane**, at the same time, through its transport process.

In cells using transport proteins, the surface area may directly affect how many they have to use.

Specialised cells will have **adaptations** to increase their surface area.

Module 2: Biological Membranes



The table below gives an overview of two specialised exchange surfaces that minimise diffusion distance:

| Exchange Surface | Adaptation to Increase Surface Area | Substances Exchanged |
|------------------|---|-------------------------------------|
| Alveoli | <ul style="list-style-type: none">- Millions of small alveoli- Folded internal structure | O ₂ , CO ₂ |
| Root hair cells | <ul style="list-style-type: none">- Long, thin root hair extensions- Numerous root hairs | Water, mineral ions (e.g. nitrates) |

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Osmosis and Water Potential

Osmosis is the **net movement of water** across a **partially permeable** membrane, from an area of **higher** water potential to an area of **lower** water potential.

Water potential (Ψ) measures how **likely** water is to move from one area to another. It's measured in **kilopascals** (kPa) because water molecules exert **pressure**.

Water potential is determined by:

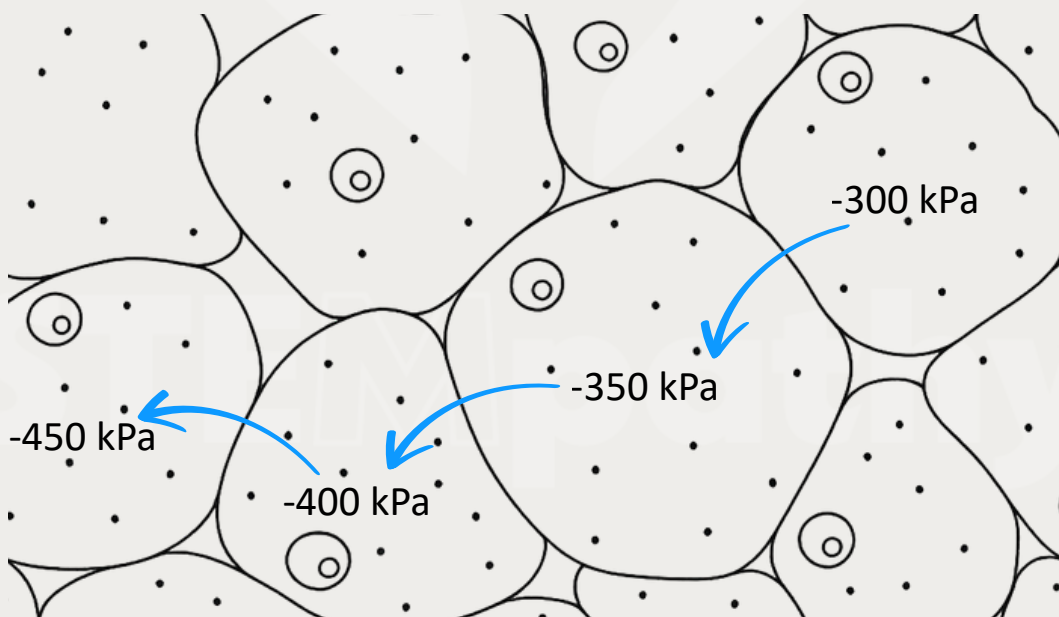
- **Solute potential** (Ψ_s): Solute molecules attract water, reducing **how freely** water can move.
- **Pressure potential** (Ψ_p): The **pressure** from the cell's contents **pressing** on the membrane or wall.

Giving us: $\Psi = \Psi_s + \Psi_p$

- **Pure water** has the highest water potential: **0 kPa**.
- **Adding solutes** lowers water potential, making the **value more negative**.
- In animal cells, Ψ_p is usually very small.

When **comparing** two places with different water potentials, the difference is called the **water potential gradient**.

The diagram below shows water potential gradient between cells in animal tissue:





Osmotic Effects on Cells

Osmosis can affect the physical structure and metabolic function of a cell. Cells can shrink, swell, and even burst if the pressure exerted by the solution contained within the cell surface membrane is too high.

Effects of Osmosis on Animal Cells

| External Solution | Direction of Water Movement | Effect on Cell |
|---------------------------|-----------------------------|----------------------------------|
| Higher Ψ (hypotonic) | Into cell | Swells and may burst (cytolysis) |
| Equal Ψ (isotonic) | No net movement | No change |
| Lower Ψ (hypertonic) | Out of cell | Shrinks (crenation) |

Effect of Osmosis on Plant Cells

| External Solution | Direction of Water Movement | Effect on Cell |
|---------------------------|-----------------------------|---|
| Higher Ψ (hypotonic) | Into cell | Becomes turgid |
| Equal Ψ (isotonic) | No net movement | No change |
| Lower Ψ (hypertonic) | Out of cell | Plasmolysed (the plant tissue as a whole becomes flaccid) |

Water transport pathways in plants

Water potential and **osmosis** are important in plants as they drive the **movement** of many other substances (dissolved in water-based solutions).



Module 2: Water Potential and Osmosis



The table below outlines the different pathways that water can take through plant tissue:

| Pathway | Route | How it works | Features |
|----------|---|--|--|
| Apoplast | Through cell walls and intercellular spaces | Water moves by mass flow, no membranes involved | Fastest route; blocked by Casparian strip in endodermis |
| Symplast | Through the cytoplasm, via plasmodesmata | Water moves by osmosis from cell to cell through the cytoplasm | Slower than apoplast; allows selective control of substances |
| Vacuolar | Through the cytoplasm and vacuoles | Water crosses the tonoplasts and cell membranes between cells | Even slower, less common than the other two |

The diagram below shows the pathways that water can take through plant tissue from a root hair cell to the xylem:



Module 2: Eukaryotic Cell Cycle



The Eukaryotic Cell Cycle

The **cell cycle** is the distinct **phases** a cell goes through in preparation for **cell division**.

The cell cycle in **eukaryotes** is outlined in the table below:

| Stage | Description |
|-------------|---|
| Interphase | Cellular growth and DNA replication; broken into G_1 , S and G_2 and (sometimes) G_0 phase. |
| Mitosis (M) | Division of the nucleus to produce two genetically identical nuclei. |
| Cytokinesis | Division of the cytoplasm, producing two genetically identical cells. |

The three phases (G_1 , S and G_2) are separated by **restriction points**; checkpoints that reduce the risk of a cell failing to divide and **mutating**.

The table below gives an overview of the **phases of the cell cycle**, and some of the mechanisms in place to reduce the risk of mutation:

| Phase | Events | Anti-mutation mechanisms |
|-------------|---|---|
| G_1 | <ul style="list-style-type: none">- The cell grows in size- Protein synthesis (transcription and translation)- Organelles duplicate | <ul style="list-style-type: none">- p53 (a tumour suppression gene), CDKs (cyclin-dependent kinases) and cyclins (proteins) regulate this phase.- G_1/S restriction point prevents uncontrolled division and repairs damaged DNA. |
| S | <ul style="list-style-type: none">- DNA is replicated, producing sister chromatids | <ul style="list-style-type: none">- CDKs and cyclins regulate this phase. |
| G_2 | <ul style="list-style-type: none">- Proteins responsible for forming the spindle and condensing chromosomes are made | <ul style="list-style-type: none">- CDKs and cyclins regulate this phase.- G_2/M restriction point prevents uncontrolled division and repairs damaged DNA |
| M | <ul style="list-style-type: none">- Mitosis occurs, the nucleus' contents divide | <ul style="list-style-type: none">- Spindle restriction point (in metaphase) ensures that the right number of chromosomes end up in each daughter cell |
| Cytokinesis | <ul style="list-style-type: none">- Cytoplasmic division | n/a |
| G_0 | <ul style="list-style-type: none">- The cell cycle pauses- Differentiation- Senescence (ageing)- Apoptosis | n/a: p53 can cause cells to enter G_0 as a result of mutation and undergo apoptosis. |



Module 2: Eukaryotic Cell Cycle



Cancer cells typically arise from mutations in the genes responsible for regulating the cell cycle directly (p53) or indirectly (cyclins and CDKs that control the restriction points).

If a restriction point is unable to repair damaged DNA, or fix a nutrient deficiency or lack of organelles, then the cell may undergo apoptosis (programmed cell death); this eliminates a potentially cancerous cell to protect the entire organism.

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Mitosis

Mitosis is the process of **nuclear division** in **eukaryotic** cells and consists of four stages:

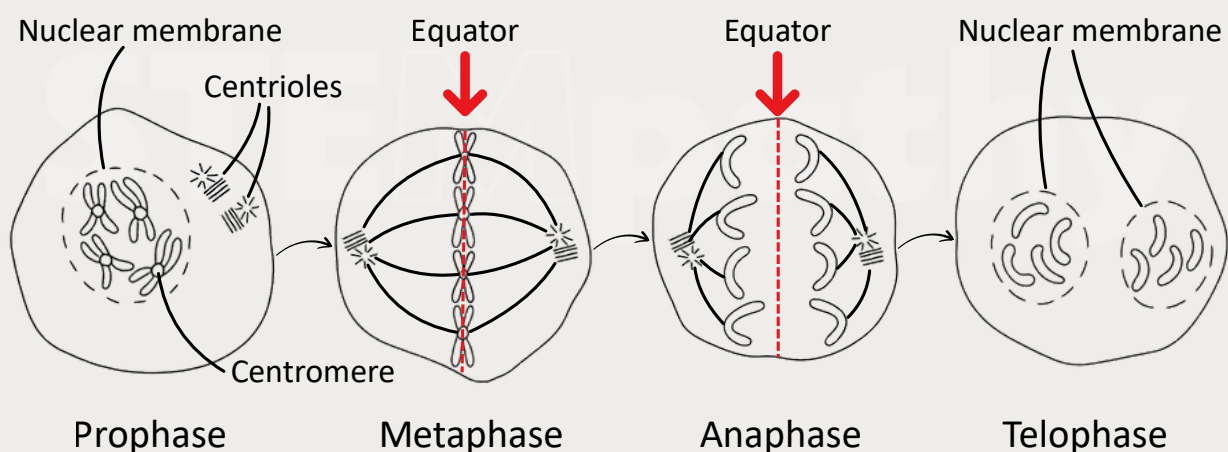
- Prophase
- Metaphase
- Anaphase
- Telophase

Mitosis produces **two genetically identical** daughter cells; they each have the same (and number of) chromosomes.

The table below outlines the stages of mitosis, and the key events of each:

| Stage | Key Events |
|-----------|--|
| Prophase | <ul style="list-style-type: none"> - DNA supercoils and condense into chromosomes - Nuclear envelope breaks down - Centriole divides, and the daughter centrioles migrate to opposite poles - Spindle begins to form from centrioles (in animals) - Spindle begins to form from cytoplasm (in plants) |
| Metaphase | <ul style="list-style-type: none"> - Chromosomes line up along the equator (also called the metaphase plate) - Spindle fibres attach to the chromosomes' centromeres - Restriction point (M phase) ensures all chromosomes are correctly attached |
| Anaphase | <ul style="list-style-type: none"> - Chromosome centromeres divide, separating sister chromatids - Spindle fibres shorten, pulling chromatids to opposite sides of the cell - Motor proteins pull sister chromatids towards opposite poles |
| Telophase | <ul style="list-style-type: none"> - Chromatids reach the poles - Chromosomes uncoil and uncondense (back into chromatin) - Nuclear envelopes reform around each set of chromosomes - Spindle fibres disassemble |

The diagram below shows the changes which occur in each phase of mitosis:





Cytokinesis

Cytokinesis is the **division** of the cellular **cytoplasm** (to produce two genetically identical cells).

In **animal cells** the plasma membrane '**pinches inwards**' around the **equator**, contracting further until the two halves separate.

In **plant cells**, the cell elongates and then **divides itself** into two by forming a **new cellulose cell wall** along the metaphase plate and depositing a **new plasma membrane** on either side of it.

Importance of Mitosis

Mitosis ensures that DNA is **replicated exactly** to ensure it remains the **same** within all cells of an organism, and in any asexually produced offspring.

It is essential in the life cycles of multicellular eukaryotes:

- **Growth:** Of either the whole organism, or tissues and organs.
- **Tissue repair:** By replacing damaged or dead cells
- **Asexual reproduction:** For some animals, plants and fungi.

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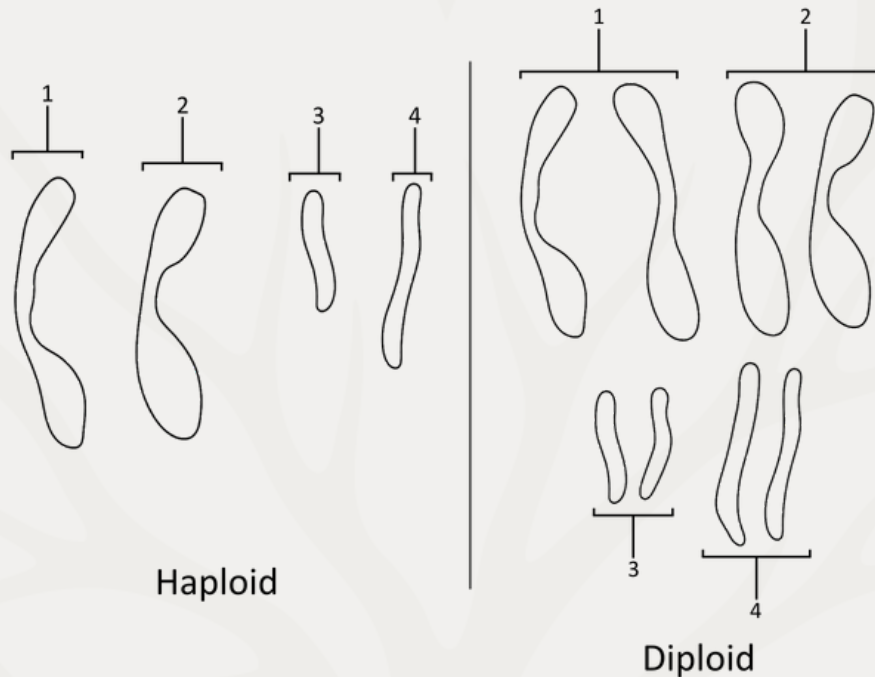




Meiosis

Meiosis is a type of **nuclear division** that produces **haploid gametes**.

Haploid means they only have one of each type of **chromosome**, whilst **diploid** means they have **2** of each.



Humans have **46** chromosomes (their **diploid** number) in their **body cells**, whilst their **gametes** (sperm and ova) have 23 (their **haploid** number).

Gametes are sex cells, and will typically be **haploid** so that when fertilisation occurs, the newly formed organism will have a 'full' genome with the **correct number of chromosomes**. This is true of most animals and plants, whilst some fungi can have more complex reproductive lifecycles.

Sexual Reproduction: Genetic Variation

Meiosis enables **sexual reproduction** to occur, and is important because it:

- Maintains chromosome numbers across generations.
- Introduces genetic variation (crossing over, independent assortment, and random fertilisation).
- Enables natural selection (and long-term species survival).



The table below outlines the mechanisms that generate genetic variation:

| Source of Variation | Explanation |
|-------------------------|--|
| Crossing over | Non-sister chromatids swap DNA sections during prophase I → shuffling alleles → creating new allele combinations → more potential genotypes |
| Independent assortment* | The side of the cell that homologous chromosomes (in metaphase I) and sister chromatids (in metaphase II) line up on the equator is random → random segregation → more potential genotypes |
| Random fertilisation | Haploid gametes containing a random set of chromosomes can fuse with another gamete in numerous genetic possibilities. |

*It is important to note that independent assortment occurs during metaphase (I or II), whilst random segregation occurs during anaphase (I or II).

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Stages of Meiosis

The table below outlines the events which occur during each stage of **meiosis I and II**, the differences between each stage's I and II are indicated in bold:

| Stage | Events and Notes |
|----------------------------|---|
| Prophase I | <ul style="list-style-type: none"> - DNA supercoils and chromosomes condense - Nuclear envelope breaks down - Homologous chromosomes pair up and form a bivalent: non-sister chromatids cross arms at the chiasmata - Crossing over occurs: alleles are shuffled - Spindle begins to form (from centrioles in animals; from cytoplasm in plants) |
| Metaphase I | <ul style="list-style-type: none"> - Bivalents (homologous pairs of crossed-over chromosomes) line up at the equator - Spindle fibres attach to centromeres - Chromosome arrangement is random: independent assortment occurs |
| Anaphase I | <ul style="list-style-type: none"> - Homologous chromosomes are pulled to opposite poles - Bivalents separate: Allele shuffling has occurred - Independent segregation: Homologous chromosomes are pulled to opposite sides |
| Telophase I (animals only) | <ul style="list-style-type: none"> - Nuclear envelope (may) reform around each set of chromosomes (in animals) - Most plant cells skip telophase I and go to prophase II |
| Cytokinesis (animals only) | 1 cell splits into 2 haploid cells, but the chromosomes consist of two sister chromatids |
| Interphase (animals only) | Short interphase: chromosomes uncoil |
| Prophase II | <ul style="list-style-type: none"> - Reformed nuclear envelopes break down (if they reformed) - DNA supercoils and chromosomes condense |
| Metaphase II | <ul style="list-style-type: none"> - Chromosomes line up on the equator - Spindle fibres attach to centromeres - Chromatid arrangement is random: independent assortment occurs |
| Anaphase II | <ul style="list-style-type: none"> - Sister chromatids are pulled to opposite poles - Centromeres are pulled apart (as sister chromatids separate) - Independent segregation: sister chromatids are pulled to opposite sides |
| Telophase II | Nuclear envelopes form around each set of chromosomes |
| Cytokinesis | Each cell divides, producing 4 haploid gametes. |





Stem Cells

Stem cells are **unspecialised** cells that can **divide** and **differentiate** by expressing different genes when needed.

Stem cells are important because they give rise to **new cells**, allowing an organism to **grow, replace** dead or damaged cells (repair tissues) and (in some organisms) enable **asexual reproduction**.

Mitosis is done by **stem cells**, which is why they share those three important roles.

Potency

Potency is the **number** of types of cells a stem cell can **give rise to** (differentiate into).

The main types of stem cell potency are outlined in the table below:

| Potency | What it can become | Example |
|-------------|-------------------------------|------------------------|
| Totipotent | All body + placental cells | Zygote |
| Pluripotent | All body cells | Embryonic stem cells |
| Multipotent | A range of related cell types | Bone marrow stem cells |
| Unipotent | One specific type only | Skin stem cells |

A **zygote** (fertilised egg cell) is **totipotent** and can become **all types** of cells, because it can express all of its genes.

Other types of (animal) stem cells cannot differentiate into as many types of cells because some of their **genes** will be **permanently** turned off (or on).





Uses of Stem Cells

Stem cells have enormous potential in the field of medicine; a select few are described in the table below:

| Application | Description |
|-----------------------|--|
| Tissue Repair | Treat damaged cartilage, skin and cardiac tissue |
| Neurological Therapy | For replacing damaged neurones/nerve tissue: <ul style="list-style-type: none">- Spinal injuries- Parkinson's- Alzheimer's |
| Developmental Biology | Helps understand differentiation, signalling and regeneration |

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Differentiated and Specialised Animal Cells

In **multicellular** animals, cells become **specialised** to perform **specific roles** more effectively.

These **differentiated** cells **work together** to form **tissues, organs, and organ systems**.

Specialised Cells

Specialised cells are metabolically and structurally **adapted** for their role.

These are the specialised cells you need to know about for OCR A level Biology:

| Cell Type | Function | Adaptations |
|---------------------|----------------------------------|---|
| Erythrocytes | Transport oxygen | <ul style="list-style-type: none">- Biconcave shape- No nucleus- No mitochondria- Flexible cytoskeleton- Lots of haemoglobin |
| Neutrophils | Phagocytosis | <ul style="list-style-type: none">- Flexible multi-lobed nucleus- Lysosomes- Move by chemotaxis |
| Squamous Epithelium | Lining cells that exchange gases | Flat thin cells, to reduce the diffusion distance |
| Ciliated Epithelium | Lining cells that move mucus | Has cilia that move in waves |
| Sperm Cells | Fertilise ovum | <ul style="list-style-type: none">- Haploid nucleus- Acrosome with enzymes to digest the outer layer of the ovum- Many mitochondria for making ATP for the undulipodium- Undulipodium for swimming |

Erythrocytes and **neutrophils** are examples of two different specialised cells which both arise from the same multipotent stem cells in the **bone marrow**.

Module 2: Organisation in Animals



The table below gives an overview of how they compare:

| Feature | Erythrocyte | Neutrophil |
|--------------------|---|---|
| Function | Transports oxygen from the lungs to the tissues | Engulfs and digests pathogens via phagocytosis |
| Origin | Derived from stem cells in the bone marrow | Derived from stem cells in the bone marrow |
| Nucleus | ✗ - nucleus is ejected to increase space for haemoglobin | ✓ - multi-lobed nucleus aids movement through narrow capillaries and tissue |
| Mitochondria | ✗ - relies on anaerobic respiration | ✓ - Lots of ATP needed for chemotaxis and phagocytosis |
| Cell Division | ✗ - cannot divide - enucleated | ✗ - cannot divide - short-lived |
| Cytoplasm contents | Contains a high concentration of haemoglobin | Contains lysosomes for hydrolytic digestion |
| Motile? | ✗ - Transported by blood flow | ✓ - Moves by chemotaxis to infection sites |
| Shape | Biconcave shape increases the surface area:volume ratio for gas exchange, and is flexible to pass through capillaries | Flexible cytoskeleton and surface receptors for pathogen recognition |

Animal Tissues

A **tissue** is a **group** of the **same type** of **specialised cell**, all working together to fulfil a function.

These are the animal tissues you need to know about for OCR A level Biology:

| Tissue | Description | Function |
|---------------------|---|---|
| Squamous Epithelium | Flat, smooth lining cells | Allows rapid diffusion (e.g. lungs) |
| Ciliated Epithelium | Lining cells with cilia and goblet cells | Moves mucus and traps pathogens |
| Cartilage | Connective tissue with matrix | Structural support; flexible but strong |
| Muscle | Long fibres with myofilaments made up of actin and myosin | Enables movement through contraction |





Animal Organs

An **organ** is where **two or more tissues** come together to fulfil a **function**.

Here are some of the most common animal organs encountered in OCR A level Biology:

| Organ | Function |
|---------|---|
| Heart | Pumps blood around the body |
| Lungs | Carry out gas exchange |
| Kidneys | Filter blood and regulate water balance |
| Liver | Metabolises toxins, produces bile |

Animal Organs

An **organ** is where **two or more tissues** come together to fulfil a **function**.

Here are some of the most common animal organs encountered in OCR A level Biology:

| System | Main Organs/Structures | Function |
|-------------|-------------------------------|---|
| Circulatory | Heart, blood vessels | Transport of gases, nutrients, and hormones |
| Respiratory | Lungs, trachea, diaphragm | Gas exchange, excretion |
| Urinary | Kidneys, ureters, and bladder | Osmoregulation, excretion |
| Nervous | Brain, spinal cord, nerves | Communication, control and coordination |





Differentiated and Specialised Plant Cells

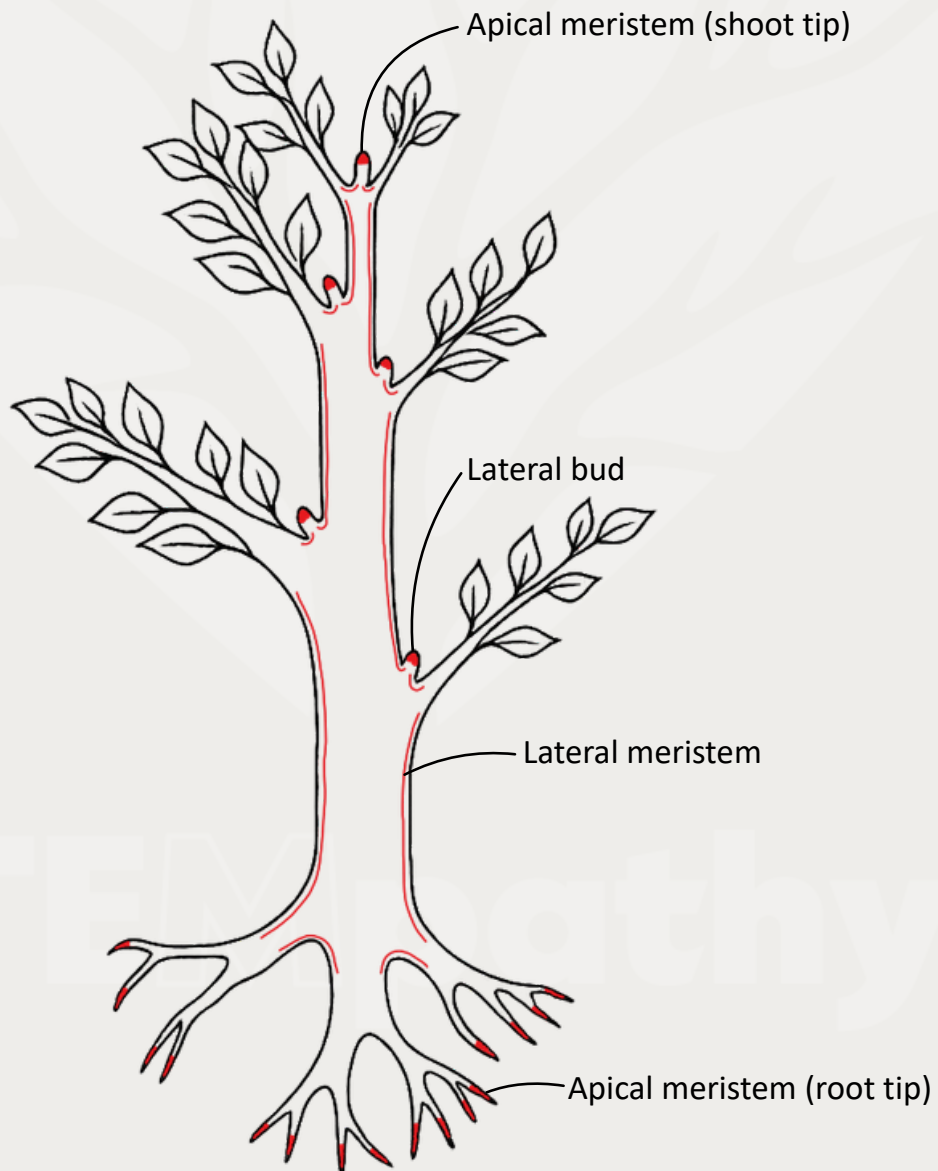
In plants, cells become **specialised** to perform specific roles more effectively.

These **differentiated** cells work together to **form tissues, organs, and organ systems**.

Specialised Cells

Meristem cells (plant stem cells) **differentiate** into specialised cells.

They are found in the tips of plant shoots, roots and in a ring in the cambium; this allows the plant to grow longer and wider.



Module 2: Organisation in Plants



Specialised cells are metabolically and structurally **adapted** for their role, with unneeded genes switched off.

The table below provides an overview of the examples you need to know for OCR A level Biology:

| Cell Type | Function | Adaptations |
|-----------------|---|---|
| Palisade Cells | Photosynthesis | <ul style="list-style-type: none">- Many chloroplasts- Large vacuole pushes chloroplasts to the edge for light maximisation- Cylinder shape allows for close packing in palisade mesophyll with space for CO₂ diffusion |
| Root Hair Cells | Water and mineral ion absorption | <ul style="list-style-type: none">- Long projections increase the surface area- Mitochondria make ATP for active transport- Many carrier proteins for active transport- No chloroplasts (as there is no light) |
| Guard Cells | Control stomatal opening for gas exchange | <ul style="list-style-type: none">- Chloroplasts make ATP for the active transport of K⁺ (cannot do photosynthesis)- Can inflate and deflate vacuole- Uneven cellulose cell wall thickness causes the pore to open/close |

Plant Tissues

The table below outlines the most common **plant tissues** encountered in A level OCR biology:

| Tissue | Structure | Function |
|--------------|---|--|
| Xylem | Dead vessels with lignin | Transport of water and minerals |
| Phloem | Living sieve tubes with companion cells | Transport of sugars via mass flow |
| Meristematic | Small, undifferentiated stem cells | Divide to form other tissue types, enabling growth |

Xylem and phloem are examples of two different specialised cells which both arise from the **same meristematic tissue** in the cambium, forming vascular bundles.



Module 2: Organisation in Plants



The table below gives an overview of how they compare:

| Feature | Xylem | Phloem |
|-------------------------|---------------------------------------|---|
| Cell Type | Dead hollow tubes | Living sieve tubes (supported by companion cells) |
| Transported Substance | Water and mineral ions | Sucrose (and other solutes) |
| Differentiation Changes | Cell death, lignification | Sieve plates form, organelles are lost in sieve tubes |
| Mechanism | Capillary action: cohesion & adhesion | Mass flow: sucrose loading/unloading changes water potential/pressure |

Plant Organs

Plant **tissues** come together to **form organs** in plants.

Here are some of the most common **plant organs** encountered in OCR A level Biology:

| Organ | Function |
|-------|---|
| Leaf | <ul style="list-style-type: none">- Photosynthesis- Gas exchange |
| Root | <ul style="list-style-type: none">- Water/mineral ion uptake- Anchorage- Starch storage |
| Stem | <ul style="list-style-type: none">- Supports leaves- Transport- Stores photosynthesis products (starch and/or sugars) |

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Specialised Exchange Surfaces

Exchange surfaces are adaptations to overcome the limits of surface area.

Surface area to volume ratio

Surface area to volume ratio (SA:V) compares the surface area of an object to its internal volume.

It is calculated using the formula:

$$\text{Surface area to volume ratio} = \text{Surface area} \div \text{Volume}$$

The table below gives some examples:

| Cube Length (cm) | Surface Area (cm ²) | Volume (cm ³) | SA:V Ratio |
|------------------|---------------------------------|---------------------------|-----------------|
| 1 | $6 \times 1^2 = 6$ | $1^3 = 1$ | 6:1 |
| 2 | $6 \times 2^2 = 24$ | $2^3 = 8$ | $24:8 = 3:1$ |
| 3 | $6 \times 3^2 = 54$ | $3^3 = 27$ | $54:27 = 2:1$ |
| 4 | $6 \times 4^2 = 96$ | $4^3 = 64$ | $96:64 = 1.5:1$ |

As **size increases**, the **SA:V ratio decreases**, so larger organisms (or cells) have less surface area per unit volume.

The illustration below demonstrates how the **surface area to volume ratio** (in micrometres) of organisms **decreases with their size**.



Note: Not to scale



Exchange Surfaces

To **maximise the rate** of diffusion, osmosis or active transport, exchange surfaces are adapted to their function with a variety of different features.

In OCR A level Biology, the **lungs**, **gills** and **root hair cells** are the relevant exchange surfaces for transport systems that are studied.

The table below breaks down their specialised exchange surfaces by their features:

| Feature | Alveoli (Lungs) | Gills (Fish) | Root Hair Cells (Plants) |
|--------------------|--|--|---|
| Large surface area | ~300 million alveoli provide ~70 m ² surface area. | Gill filaments and lamellae create a large folded surface. | Long, thin extensions of root hair cells provide a vast surface area. |
| Thin barrier | Alveolar and capillary walls are one cell thick (~0.5 μm) and in close contact for a short diffusion distance. | Lamellae have thin epithelial layers for a short diffusion distance. | The cell membrane is thin to allow easy diffusion. |
| Good transport | An extensive capillary network for continuous blood flow to bring/remove substances. | Counter-current blood flow system maintains a steep gradient. | Active transport of ions maintains a steep water potential gradient. |
| Bulk movement | Ventilation by breathing refreshes air in the alveoli, maintaining concentration gradients. | Mouth and operculum create pressure that pushes water over the gills, maintaining concentration gradients. | Continuous uptake of minerals and water maintains flow into the root. |

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Module 3: Mammalian Gaseous Exchange System

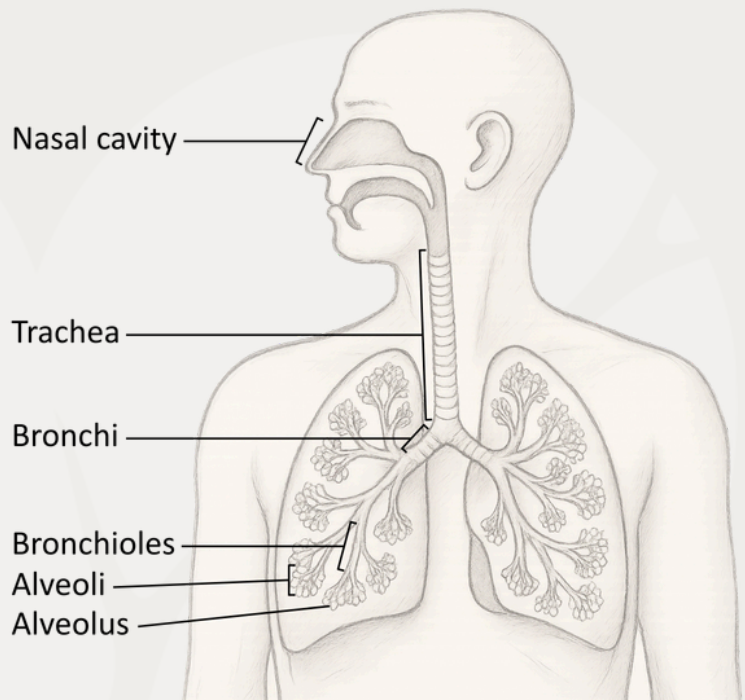


Gaseous Exchange

For the effective exchange of oxygen and carbon dioxide, mammals have a **highly specialised gaseous exchange system** consisting of a series of airways that filter, warm, and moisten air before it reaches the alveoli.

The pathway that air follows during inhalation is:

Nasal cavity → Trachea → Bronchi → Bronchioles → Alveoli



The table below provides an overview of some functions and features of these structures:

| Part | Structure | Function(s) |
|-------------|--|---|
| Trachea | <ul style="list-style-type: none"> - Single-wide tube supported by C-shaped cartilage rings. - Lined with ciliated epithelium and goblet cells. - Contains smooth muscle and elastic fibres. | <ul style="list-style-type: none"> - Cartilage prevents the collapse of the airway. - Cilia and mucus trap and remove debris. - Smooth muscle regulates airway diameter. - Elastic fibres recoil after stretching. |
| Bronchi | <ul style="list-style-type: none"> - Two tubes branching from the trachea into each lung. - Supported by cartilage plates. - Lined with ciliated epithelium and goblet cells. - Contains smooth muscle and elastic fibres. | <ul style="list-style-type: none"> - Cartilage prevents airway collapse. - Cilia and mucus trap and remove debris and microorganisms. - Smooth muscle controls airway diameter. - Elastic fibres provide recoil after stretching. |
| Bronchioles | <ul style="list-style-type: none"> - Narrower tubes containing smooth muscle and elastic fibres. - Ciliated epithelium and goblet cells are present in larger bronchioles. | <ul style="list-style-type: none"> - Elastic fibres help keep airways open and allow recoil after stretching. - Cilia and mucus trap and remove debris and microorganisms. |
| Alveoli | <ul style="list-style-type: none"> - Large surface area with an extensive capillary network. - Short diffusion distance (~0.5 μm). - Microscopic air sacs with squamous epithelium and many elastic fibres. | <ul style="list-style-type: none"> - Main site of gas exchange. - Elastic fibres allow recoil to expel air during exhalation. |



Module 3: Mammalian Ventilation



Ventilation (Breathing) In Mammals

Ventilation enables the effective exchange of oxygen and carbon dioxide in the alveoli by taking in oxygen and removing waste carbon dioxide; this **maintains a concentration gradient to maximise diffusion**.

The table below compares the events of **inhalation** and **exhalation**:

| Step | Inhalation | Exhalation |
|---------------|--|---|
| 1 | The diaphragm contracts and flattens | Diaphragm relaxes: returns to a dome shape |
| 2 | External intercostal muscles contract, pulling the ribs up and out | External intercostal muscles relax, allowing ribs to move down and in |
| 3 | The thoracic cavity volume increases | The thoracic cavity volume decreases |
| 4 | Pulmonary lung pressure decreases below atmospheric pressure (negative pressure) | Pulmonary lung pressure increases above atmospheric pressure (positive pressure) |
| 5 | Air flows into the lungs down the pressure gradient | Air flows out of the lungs down the pressure gradient |
| (Forced only) | Internal intercostal muscles relax (inactive during normal inhalation) | Internal intercostal muscles contract (during forced exhalation), pulling ribs down and in further, decreasing thoracic volume more rapidly |

Forced inhalation and **forced exhalation** are active breathing processes involving **additional muscle groups** beyond those used in normal, quiet breathing, such as during exercise, singing or coughing.

The table below outlines the key changes which occur during **inhalation** and **exhalation**:

| Change | Inhalation | Exhalation |
|-----------------------|-------------------------------|-------------------------------|
| Diaphragm | Contracts | Relaxes |
| External intercostals | Contract | Relax |
| Internal intercostals | Relax (inactive) | Contract (when forced) |
| Thoracic volume | Increases | Decreases |
| Pulmonary pressure | Decreases (below atmospheric) | Increases (above atmospheric) |
| Air movement | Into lungs | Out of lungs |





Oxygen Uptake

Oxygen uptake is the rate at which oxygen moves into the bloodstream (in mammals) per minute.

The **rate of oxygen uptake** is affected by the effectiveness of **pulmonary ventilation**. It can be measured as the volume of air breathed per minute, calculated as:

Tidal Volume × Breathing Rate

Where:

- **Tidal volume** is the volume of air inhaled or exhaled in a breath at rest
- **Breathing rate** is the number of breaths per minute

Tidal volume is affected by the lung's vital capacity, a key indicator of respiratory health.

Vital capacity is the maximum volume of air that can be inhaled and exhaled during a forced breath.

So, **oxygen uptake** can increase if:

- Tidal volume increases (deeper breaths)
- Breathing rate increases (more breaths per minute)

Vital capacity is a fixed **maximum** and only changes with lung health and fitness.

Residual volume is the volume of air that **remains** in the lungs after forced exhalation.

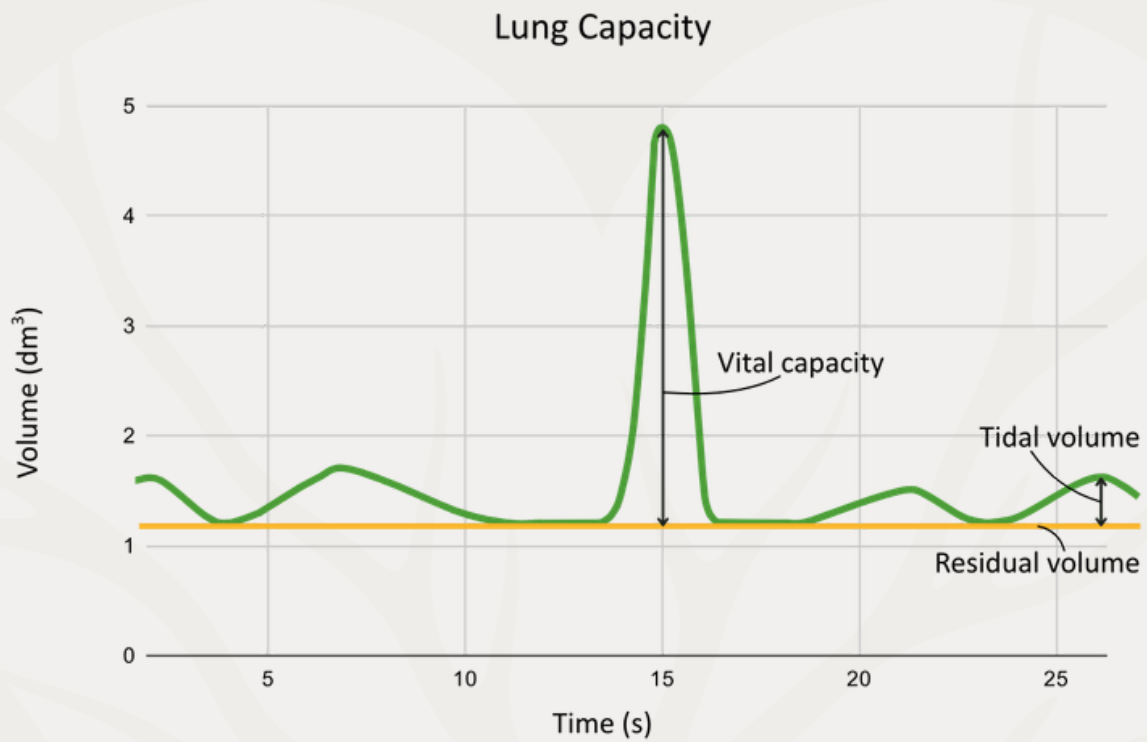
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Module 3: Oxygen Uptake in Mammals



The diagram below shows how these factors affect each other:



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Module 3: Measuring Oxygen Uptake in Mammals

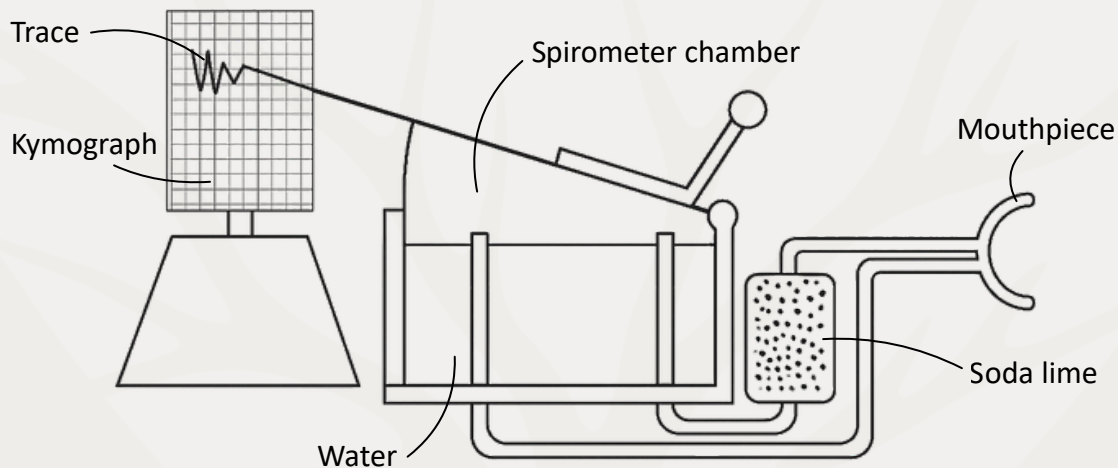


Measuring oxygen uptake: Respirometer vs Spirometer

A **respirometer** is a device that can be used to measure **oxygen uptake**.

A **spirometer** measures **breathing patterns**, and produces a **trace** on **graph paper** as the test subject breathes; the graph produced is a reflection of the subject's **tidal volume** and **breathing rate**.

The diagram below presents a typical spirometer set-up and accompanying spirometer trace.



The table below outlines the key components needed to set up a spirometer and their function:

| Component | Purpose |
|-----------------------|---|
| Soda lime (KOH) | Absorbs carbon dioxide, so that the volume changes reflect oxygen uptake only |
| Spirometer chamber | A sealed air tank that moves up and down with each breath |
| Kymograph/data logger | Records breathing patterns (tidal volume, breathing rate, etc.) |
| Water bath/heater | Maintains a constant temperature for the spirometer chamber, preventing volume changes due to thermal expansion |
| Nose clip | Ensures all air is breathed through the mouthpiece |



Module 3: Measuring Oxygen Uptake in Mammals



Spirometer interpretation

A spirometer trace allows you to calculate:

- **Tidal Volume:** Height of each wave
- **Breathing Rate:** Number of waves per minute
- **Oxygen Uptake:** Overall volume change over time

These measurements can be used to assess respiratory health, athletic performance, and how someone is affected by conditions like asthma or emphysema.

The table below outlines how you determine these values:

| Measurement | What to Measure | How to Calculate |
|---------------------------------|--|--|
| Tidal Volume (TV) | Height between the peak of inhalation and the trough of exhalation. | The value gives the volume of air per breath (usually in dm^3 or ml). |
| Breathing Rate (BR) | The number of complete breathing waves in a set time period. | Divide the number of breaths by the time interval (in minutes) to get breaths per minute. |
| Oxygen Uptake (VO_2) | The overall drop in baseline volume is due to oxygen absorption over time. | Measure volume change over time (e.g. per minute) to calculate oxygen uptake rate in $\text{dm}^3 \text{min}^{-1}$. |

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Module 3: Ventilation and Gas Exchange in Gills



Gills: Gaseous exchange in bony fish

Gas exchange systems in bony fish **maximise the rate of diffusion** of oxygen into the bloodstream and carbon dioxide out into the water.

A single **gill** (of which there are many on each side) consists of a **bony** or **cartilaginous gill arch**, from which extend many **gill filaments**: long, thin, (horizontal) tubular projections.

The table below outlines the structure and function of the gill's components:

| Component | Structural Description | Function |
|-------------------|--|--|
| Gill Arch | A bony or cartilaginous structure that supports a gill. | Provides rigid support for the gill filaments and lamellae, keeping them well-positioned for gas exchange. |
| Gill Filaments | Long, thin horizontal projections extending from the gill arches. | Increases the surface area available for gas exchange, maximising oxygen uptake and carbon dioxide removal. |
| Lamellae | Thin, plate-like structures lined up along each gill filament; they have a rich capillary network. | Provides a large surface area and thin diffusion distance, maximising oxygen uptake and carbon dioxide removal. |
| Capillary Network | A dense network of capillaries within each lamella. | <ul style="list-style-type: none"> - Blood flows opposite to the water flow (counter-current system). - The capillary network maintains a steep oxygen concentration gradient across the entire gill, maximising gas exchange. |
| Operculum | A bony flap covering and protecting the gills. | <ul style="list-style-type: none"> - Protects delicate gill structures. - Pumps water over the gill surfaces when the fish is stationary to ensure a constant oxygen supply. |

Ventilation in fish follows the three stages outlined in the table below:

| Stage | Action |
|---------------------|---|
| Inhalation | <ul style="list-style-type: none"> - Mouth opens - Floor of buccal cavity lowers → volume increases - Water enters |
| Buccal cavity rises | <ul style="list-style-type: none"> - Mouth closes - Buccal cavity contracts → pressure increases - Water forced over the gills |
| Exhalation | <ul style="list-style-type: none"> - Operculum (bony flap) opens - Water exits via the opercular cavity |



Module 3: Ventilation and Gas Exchange in Insects



Tracheae: Gaseous exchange in insects

Gas exchange systems in insects are adapted for the air.

The table below outlines the structure and function of each component:

| Component | Structure | Function |
|-----------------|---|--|
| Spiracles | Small external openings are located along the thorax and abdomen. | <ul style="list-style-type: none">- Allow air to enter and carbon dioxide to exit the body.- Open and close to regulate gas exchange and reduce water loss. |
| Tracheae | Large air-filled tubes are supported with chitin rings (taenidia) to prevent collapse. | A passage for air from the spiracles to travel deeper into the body. |
| Tracheoles | Fine, unreinforced tubes branching from tracheae, extending to individual cells with fluid-filled ends. | Provide a short diffusion distance between the air and the cell cytoplasm for gas exchange. |
| Tracheole Fluid | A thin layer of fluid at the ends of tracheoles. | Oxygen dissolves in this fluid before diffusing into cells, supporting gas exchange. |

Ventilation in Insects

Gas movement through the tracheal system can occur by **passive diffusion**, and may be sufficient when the insect is at rest, but is **actively ventilated** during periods of high activity.

These ventilation mechanisms are outlined below:

| Method | Description |
|------------------------|--|
| Diffusion at rest | Gases diffuse down concentration gradients: oxygen diffuses in, carbon dioxide diffuses out. |
| Abdominal contractions | In active insects, abdominal muscles contract and relax, compressing air sacs and the tracheae, pumping air in and out of the network. |
| Spiracle control | Spiracles open and close (done by muscular valves) to regulate gas exchange and minimise water loss. |

Carbon dioxide is expelled from the cells via **diffusion** through the **tracheoles** and out through the **spiracles**, ensuring the **removal** of metabolic waste.





The Need for Transport Systems

As an animal (and plant) **increases in size** and complexity, their **surface area to volume ratio (SA:V) decreases**; diffusion alone cannot meet its metabolic requirements.

The table below outlines the limitations on diffusion in multicellular animals:

| Limitation | Reason |
|-------------------------|---|
| Low SA:V ratio | A lower SA:V provides less space for substances to enter or leave the organism via the skin compared to their volume. |
| High metabolism | Metabolically active tissues (e.g. muscles, brain) need a high rate of oxygen and glucose delivery for making ATP. |
| Long diffusion distance | Internal cells are far from the external surface, and those that aren't may be covered by an impermeable barrier; it takes too long for substances to get to where they are needed. |

To overcome these limitations, animals have evolved **specialised transport systems** which:

- Deliver substances to cells (e.g. oxygen, glucose, amino acids, hormones)
- Remove toxic waste products (e.g. carbon dioxide, urea)
- Deliver hormones (hormonal signalling)

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Module 3: Transport Systems in Animals



Types of Circulatory Systems

There are different types of circulatory systems, **open** and **closed**.

The table below compares closed and open circulatory systems:

| Feature | Open Circulatory System | Closed Circulatory System |
|-------------------|---|---|
| Definition | Blood (or haemolymph) is not enclosed in vessels. | Blood is enclosed in vessels. |
| Examples | Insects (e.g. grasshoppers), molluscs (e.g., snails). | Vertebrates (e.g. mammals, fish), some invertebrates (e.g. annelid worms). |
| Transport Medium | Haemolymph: blood and tissue fluid (does not transport oxygen in insects). | Blood: remains separate from tissue fluid. |
| Pressure | Low-pressure. | High pressure (overall, varies). |
| Pumping Mechanism | Varies: <ul style="list-style-type: none">- Body movement- Peristalsis- Heart (simple and open) | The heart pumps blood through vessels; capillaries allow exchange with tissues. |

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Types of Closed Circulatory Systems: Single and double

In OCR A level Biology, you need to know about the structure of the double circulatory system in mammals and the single circulatory system in fish (as well as the open circulatory system in insects).

The table below outlines the features of these three types of circulatory systems for comparison:

| Feature | Double (Mammals) | Single (Fish) | Open (Insects) |
|------------------------|--------------------------------------|------------------------------|--|
| No. of circuits | 2 | 1 | 0 |
| Pathway | Heart → pulmonary → heart → systemic | Heart → gills → body | Heart → body |
| Heart passes per cycle | 2 | 1 | 1 |
| Blood pressure to body | High | Low | Low |
| Oxygen flow to body | High flow High pressure | Lower flow Lower pressure | None: No oxygen in haemolymph. Via tracheae. |
| Blood vessels | Closed | Closed | Mostly absent* |

*Some insects have open-ended tubular extensions on their heart that deliver blood to more metabolically active regions.

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Blood Vessels

The mammalian **circulatory system** uses a network of blood vessels to transport blood throughout the body.

The **structure** and **function** of these vessels vary depending on their **role** and **position** in the circulatory system.

The table below outlines the structure and function of these blood vessels:

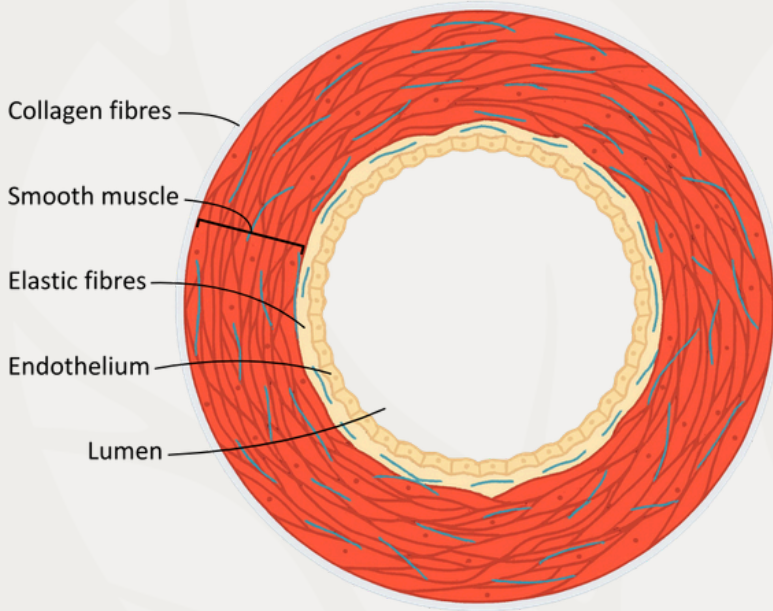
| Vessel Type | Function | Structure |
|-------------|--|---|
| Arteries | Carries blood away from the heart at high pressure. | <ul style="list-style-type: none"> - Thick muscular walls with elastic tissue to recoil and maintain blood flow. - Narrow lumen. - No valves |
| Arterioles | <ul style="list-style-type: none"> - Carries blood into the capillaries. - Controls blood flow into the capillaries by vasoconstriction or vasodilation. | <ul style="list-style-type: none"> - Smaller than arteries. - More smooth muscle, less elastic tissue. - Narrow lumen. |
| Capillaries | <ul style="list-style-type: none"> - Exchanges substances between blood and tissues. - Short diffusion distance and large surface area. | <ul style="list-style-type: none"> - One-cell-thick walls (endothelium only). - Very narrow lumen (one red blood cell wide, to reduce diffusion distance). |
| Venules | Carries blood from the capillaries and returns it to the veins. | <ul style="list-style-type: none"> - Small vessels with thin walls - Some smooth muscle, little elastic tissue. - Wider lumen than capillaries. |
| Veins | Returns blood to the heart. | <ul style="list-style-type: none"> - Thin walls, wide lumen. - Little smooth muscle and elastic tissue. - Skeletal muscles help blood flow. - Valves are present to prevent backflow. |

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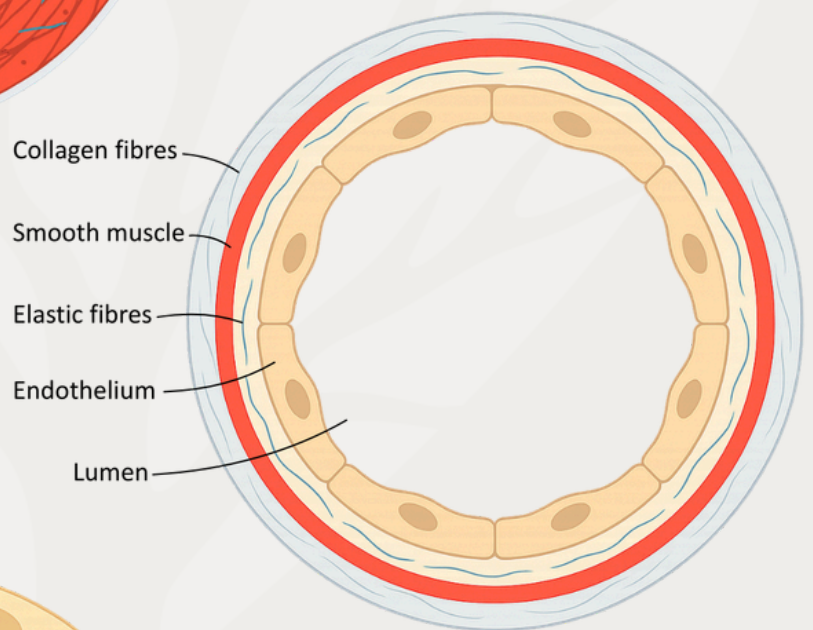


The diagram below shows the different structural compositions of blood vessel types:

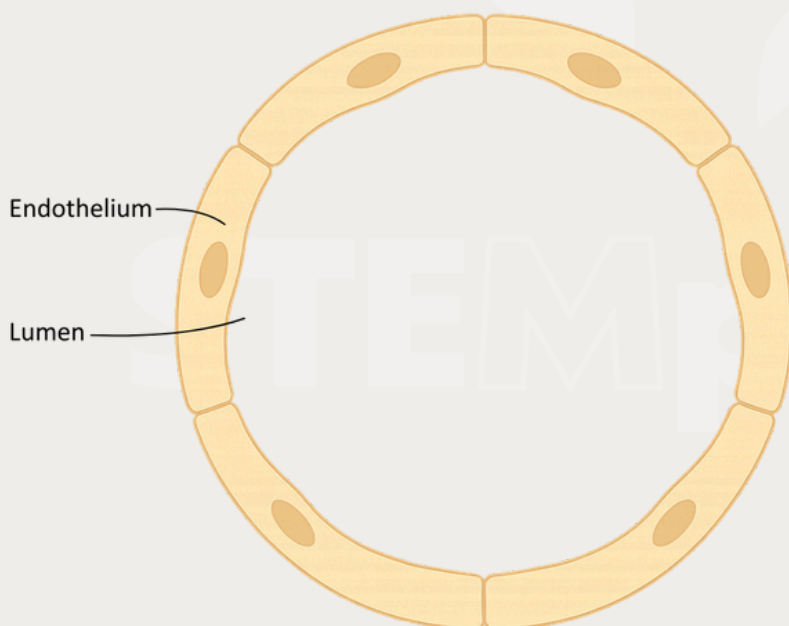
Artery



Vein



Capillary



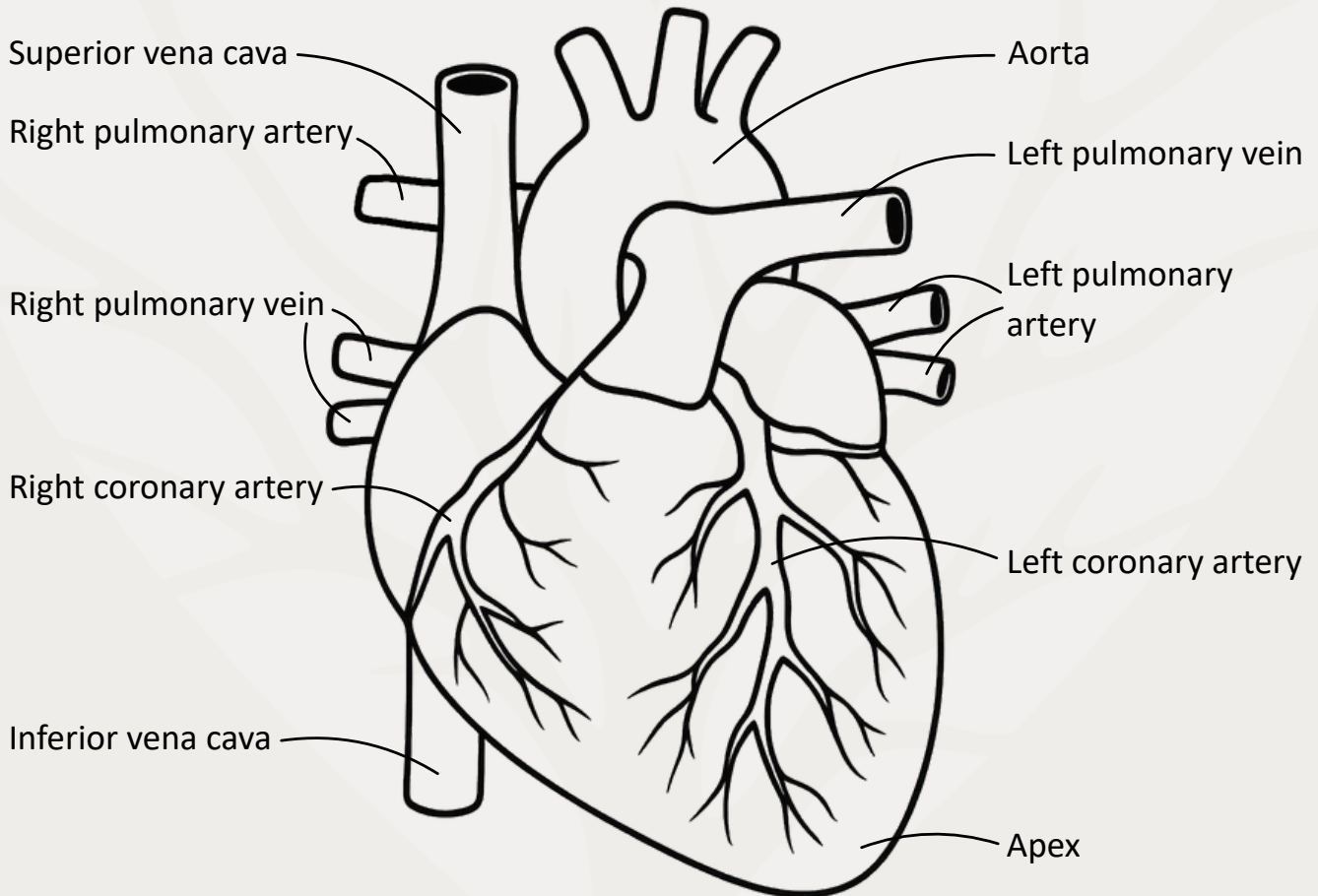
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External Structure Of The Heart

The heart is a muscular organ located in the **thoracic cavity** between the lungs. It is enclosed in a tough, fluid-filled sac called the **pericardium**, which **protects** the heart and **reduces friction** as it beats.



The table below outlines the heart's external anatomical features:

| Feature | Description | Function |
|-------------------|---|---|
| Cardiac muscle | The heart wall is made of myogenic striated muscle. | Contracts rhythmically and does not fatigue. |
| Coronary arteries | Blood vessels on the external surface that branch off from the aorta. | Supply oxygenated blood to the heart muscle. |
| Apex | The pointed lower end of the heart tilted towards the left. | Helps identify the left side of the heart in dissection or imaging. |



The following major blood vessels are visible on the outside of the heart:

| Blood Vessel | Description | Function |
|------------------|--|---|
| Vena cava | Large vein entering the right atrium from above (superior) and below (inferior). | Returns deoxygenated blood from the body. |
| Pulmonary artery | Emerges from the right ventricle; divides into two branches. | Carries deoxygenated blood to the lungs. |
| Pulmonary veins | Two veins from each lung enter the left atrium. | Return oxygenated blood from the lungs. |
| Aorta | Large artery leaving the left ventricle, arching over the heart. | Carries oxygenated blood to the rest of the body. |

Internal Structure of the Heart

The mammalian heart is a **double pump**, keeping **oxygenated** and **deoxygenated** blood **separated** to ensure efficient oxygen transport.

The path blood takes through the heart, when returning deoxygenated blood from the body, is as follows:

[Systemic circuit] → Vena cava → Right atrium → Atrioventricular valve → Right ventricle → Semilunar valve → Pulmonary artery → [Pulmonary circuit] → Pulmonary veins → Left atrium → Atrioventricular valve → Left ventricle → Semilunar valve → Aorta → [Systemic circuit]

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Module 3: The Heart



The table below outlines the structural components of the heart:

| Feature | Description | Function |
|------------------------------|--|---|
| Left atrium | Upper chamber on the left side. | Receives oxygenated blood from the lungs. |
| Right atrium | Upper chamber on the right side. | Receives deoxygenated blood from the body. |
| Left ventricle | Lower chamber on the left side; has a thicker muscular wall. | Pumps oxygenated blood to the body via the aorta. Must pump more strongly to transport blood further. |
| Right ventricle | Lower chamber on the right side; has a thinner muscular wall compared to the left chamber. | Pumps deoxygenated blood to the lungs via the pulmonary artery. |
| Septum | Muscular wall separating the left and right sides of the heart. | Prevents mixing of oxygenated and deoxygenated blood. |
| Atrioventricular (AV) valves | Membranes attached by elastic tissue found between the atria and ventricle. | Prevent backflow of blood from ventricles to the atria. |
| Semilunar valves | Membranes attached by elastic tissue found at the ventricle exits. | Prevent backflow of blood from arteries into the ventricles. |
| Coronary arteries | Branches from the aorta that return to the outside of the heart, supplying it with oxygenated blood. | Ensure the heart muscle gets oxygen and glucose for continuous aerobic respiration. |

The Cardiac Cycle

The cardiac cycle is the sequence of events that occurs during one complete heartbeat.

The table below outlines the 3 stages of the cardiac cycle:

| Stage | Key Events |
|---------------------|--|
| Atrial systole | Both atria contract, increasing the pressure in the atria. Blood is pushed through the AV valves into the ventricles. Ventricles remain relaxed. |
| Ventricular systole | Both atria relax. Both ventricles contract, increasing the pressure in the ventricles. AV valves close, preventing backflow. Semilunar valves open, forcing blood into the pulmonary artery and the aorta. |
| Diastole | Ventricles relax, and as the pressure drops, the semilunar valves close to prevent backflow from the arteries. Atrial pressure increases as blood flows passively into the atria. |



Module 3: The Heart



The table below compares the overall pressure and volume of blood in the heart across the different stages:

| Stage | Event | Pressure | Volume (of blood) | Notes |
|---------------------|---|----------|-------------------|----------------------------------|
| Diastole | Heart relaxes; chambers fill | ↓ | ↑ | AV valves open, SL valves closed |
| Atrial systole | Atria contract → ventricles fill | ↑ | Same | AV valves remain open |
| Ventricular systole | Ventricles contract → blood is forced out | ↑ ↑ | ↓ | AV valves shut, SL valves open |

Coordination of Heart Contraction

The heart is **myogenic**, meaning it **generates** its own electrical **impulses** to **control** the rhythm of atrial and ventricular **contraction** without stimulation from the nervous system.

Electrical stimulation **coordinates** the atria and ventricular **contractions**, ensuring they do so in the right order and at the right time, to effectively move blood throughout the heart and prevent backflow.

Myogenic control of the heart is carried out by the components outlined in the table below:

| Component | Location & Structure | Function |
|-----------------------------|--|--|
| Sinoatrial Node (SAN) | Right atrium wall. | Generates electrical impulses at regular intervals, acting as a natural pacemaker. |
| Atrioventricular Node (AVN) | In the upper septum between the atria and ventricles. | Delays the impulse slightly to allow the atria to finish contracting before the ventricles contract. |
| Bundle of His | Conductive fibres running down the septum wall to the apex of the heart. | Transmits impulses from the AVN to the Purkinje* fibres in the ventricles. |
| Purkinje fibres* | Spread through the ventricular walls up from the apex. | Distribute the impulse throughout the ventricular walls to ensure even ventricular contraction up from the apex. |

*Purkinje fibers are also known as Purkyne tissue.

The order of events is as follows:

SAN fires → atria contract → AVN delays the impulse → Bundle of His carries the impulse to Purkyne fibres → Purkyne fibres spread the impulse → ventricles contract from apex upwards



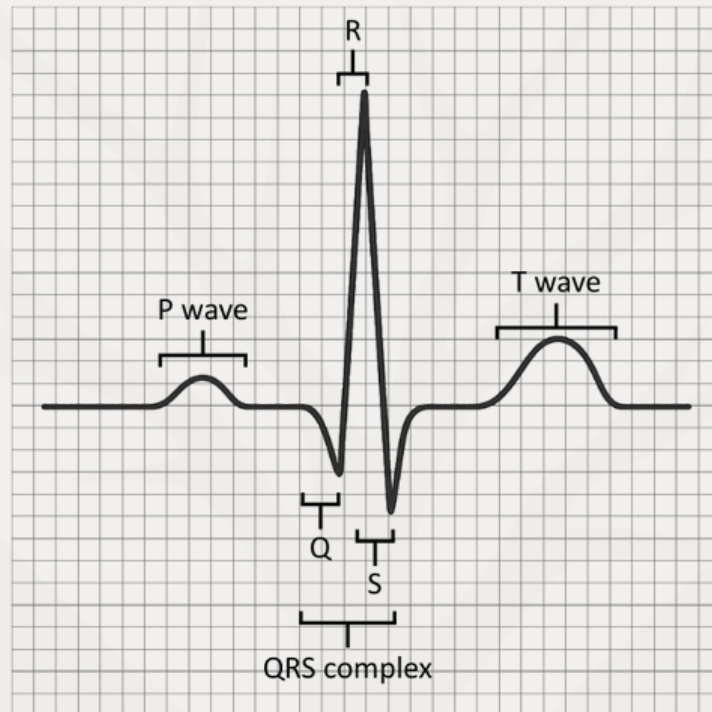


Electrocardiograms

The electrical activity of these events can be recorded, measured and observed with an **ECG**.

There are three distinct 'waves' of polarisation and depolarisation that can be observed:

- **P wave**: Depolarisation of the atria (they are electrically stimulated and contract).
- **QRS complex**: Depolarisation of the ventricles (they are electrically stimulated and contract).
- **T wave**: Repolarisation of the ventricles (the ventricles relax).







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Module 3: The Heart



Heart conditions can be identified and classified with the use of ECG:

| Condition | ECG Feature | Trace | Cause |
|--------------|--|--|--|
| Tachycardia | Rapid heart rate: >100 bpm |  | Stress Fever Exercise |
| Bradycardia | Slow heart rate: <60 bpm |  | Can be normal Disease |
| Ectopic beat | Early contraction of atria or ventricles. |  | Often harmless Can indicate arrhythmia. |
| Fibrillation | Uncoordinated contractions (an irregular trace). |  | Damage to myogenic structures |

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Module 3: Haemoglobin and Red Blood Cells



Red Blood Cells

Erythrocytes are specialised cells adapted for the **transport of oxygen** in the blood by using **haemoglobin**.

The table below outlines the structural adaptations of RBCs:

| Structure | Function |
|--------------------------|---|
| No nucleus or organelles | Maximises space for haemoglobin (Hb), allowing more oxygen to be carried. |
| Biconcave shape | Increases the surface area to volume ratio, speeding up the diffusion of oxygen and carbon dioxide. |
| Flexible membrane | Enables cells to squeeze through narrow capillaries without them rupturing. |
| Thin cell | Short diffusion distance between plasma and haemoglobin. |

Oxygen transport and haemoglobin

RBCs are packed with **haemoglobin**, and each one can bind **reversibly** with up to four oxygen molecules, forming **oxyhaemoglobin** (HbO₂).

Haemoglobin + O → Oxyhaemoglobin

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Module 3: Haemoglobin and Red Blood Cells



Oxygen Affinity

Whether or not oxygen will bind to haemoglobin depends on the haemoglobin's **affinity** for oxygen.

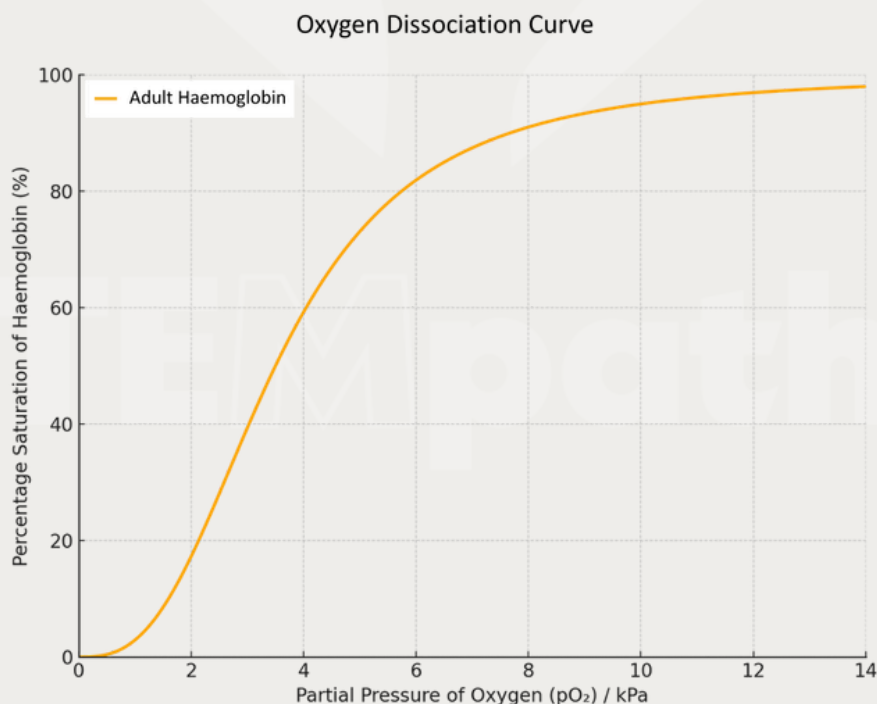
The table below outlines the different factors that can affect haemoglobin's affinity for oxygen:

| Factor | Effect on Affinity | Explanation |
|---|---|--|
| Cooperative binding | Varies | The number of pre-existing oxygen atoms bound to haemoglobin can make it easier or harder for subsequent oxygen atoms to bind. |
| Partial pressure of CO ₂ (pCO ₂) | Decreases with higher pCO ₂ (Bohr shift) | CO ₂ lowers pH, causing haemoglobin to release oxygen more readily. |
| pH (H ⁺ concentration) | Decreases with lower pH | H ⁺ ions bind to haemoglobin, changing its shape and reducing oxygen affinity. |

Cooperative Binding

Cooperative binding is the phenomenon by which the **first** oxygen atom **binding** to haemoglobin makes it easier for **subsequent** oxygen atoms to also bind.

This is reflected in the **sigmoid curve** of an **oxygen dissociation curve** showing **haemoglobin's saturation**.

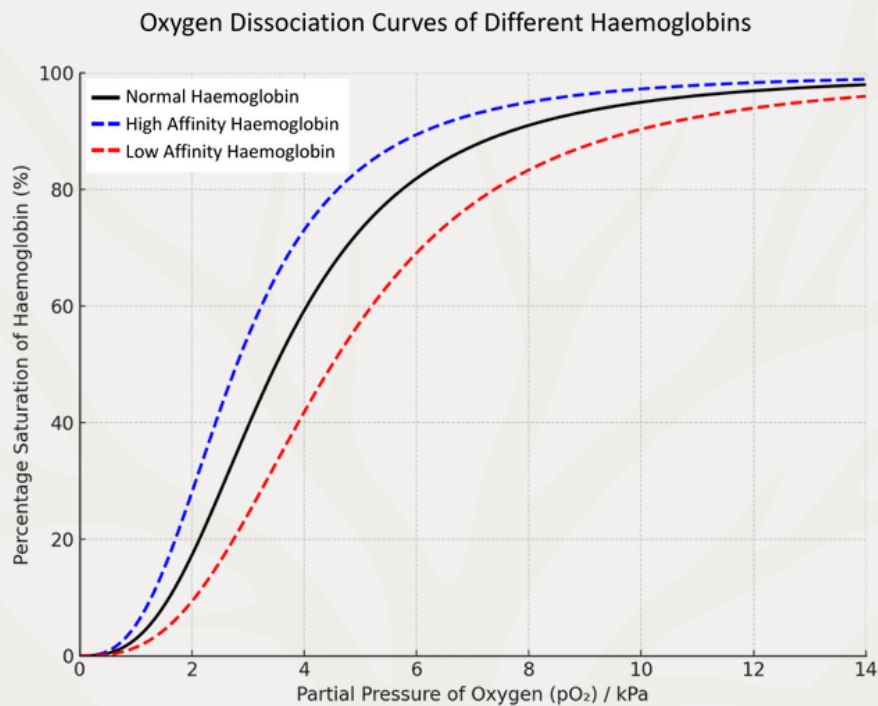


Module 3: Haemoglobin and Red Blood Cells



Haemoglobin's hold on oxygen **varies at different pO_2 levels** because its shape changes due to carbon dioxide dissolved in the surrounding tissue fluid – the acidity affects its **tertiary structure**.

The graph below compares how easily different haemoglobins bind to oxygen, including normal human haemoglobin, a higher-affinity form (like fetal haemoglobin), and a lower-affinity form (such as in active tissues):



The **black** line is typical **human** haemoglobin, the **blue** line is haemoglobin which **more readily binds** with oxygen (it has a higher affinity), and the **red** line is haemoglobin which **less readily binds** with oxygen (it has a lower affinity).

Interpreting a standard (Adult) Oxygen Dissociation Curve:

- The curve is **sigmoidal** (S-shaped) due to **cooperative binding**: as one molecule of oxygen binds to haemoglobin, the molecule's affinity for oxygen increases.
- At **high pO_2** (e.g. in the lungs), haemoglobin becomes **highly saturated** with oxygen.
- At **low pO_2** (e.g. in respiring tissues), haemoglobin releases oxygen, aiding diffusion into cells.



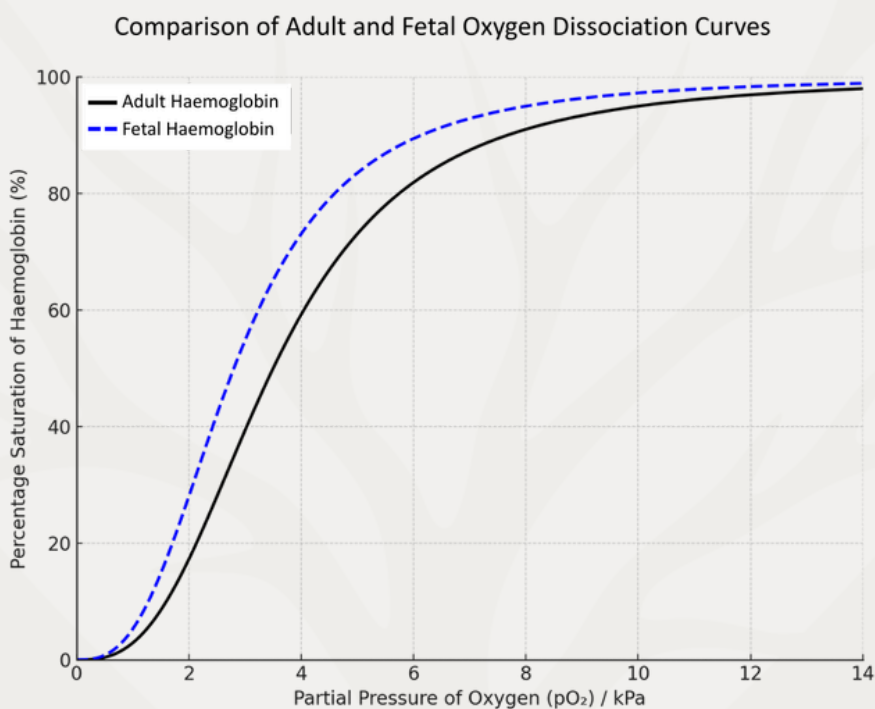
Module 3: Haemoglobin and Red Blood Cells



Comparing Adult and Fetal Haemoglobin

The **placenta** has a relatively **low pO_2** , causing maternal haemoglobin to release oxygen, which can then be taken up by fetal haemoglobin (which has a higher affinity for oxygen at the same pO_2).

The **fetal haemoglobin curve** is **shifted to the left** of the adult haemoglobin curve at the same pO_2 :



Fetal haemoglobin is more saturated at the same pO_2 compared to **adult haemoglobin**, meaning it will **load** oxygen in conditions where **adult Hb** would **release** it; facilitating the **transfer** of oxygen from maternal blood to fetal blood at the placenta.

Bohr shift

Bohr shift (also known as the Bohr effect) is where **increasing CO_2** concentrations in the blood plasma **lower** haemoglobin's **affinity** for oxygen.

This is because **CO_2** dissolves in blood plasma to form **carbonic acid**, lowering its pH and changing haemoglobin's **conformational shape**.

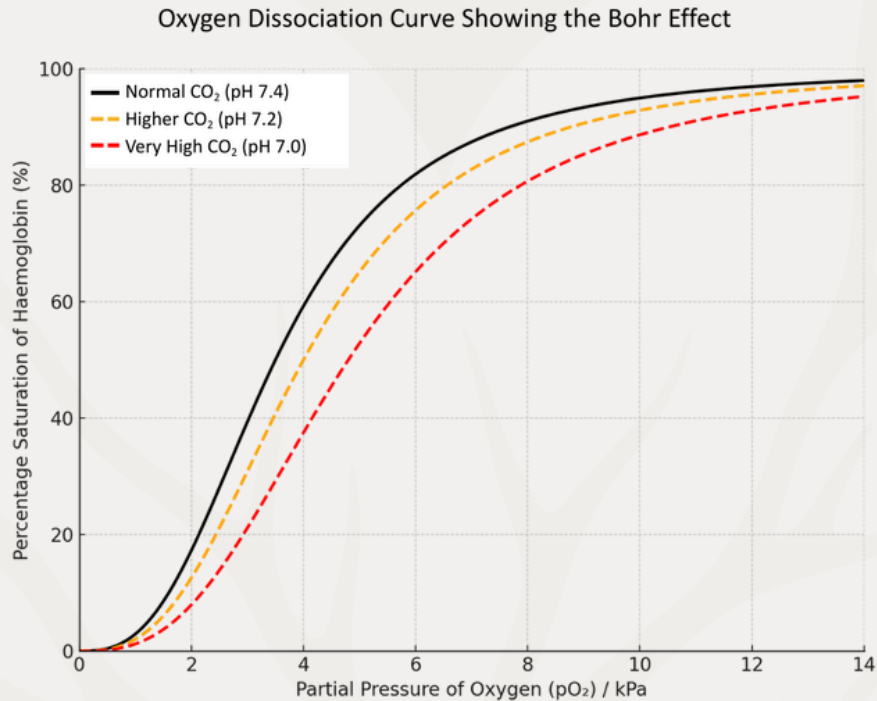
The result of a Bohr shift is to **promote** oxygen unloading in actively **respiring tissues**.



Module 3: Haemoglobin and Red Blood Cells



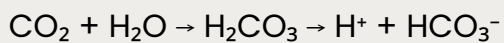
The graph below shows the effect of different concentrations of CO₂ on a standard dissociation curve:



If there is **more carbon dioxide**, then the **pH drops**, so haemoglobin is (on average) **less saturated** (as it is releasing oxygen more readily due to a lower affinity). The **curve shifts to the right**. This is the **Bohr effect**.

Carbon Dioxide Transport

CO₂ **diffuses** into red blood cells (RBCs) and reacts with water, **catalysed** by **carbonic anhydrase**:



The **hydrogencarbonate ions** (HCO₃⁻) **diffuse** out of the RBC into the **plasma**.

Chloride ions (Cl⁻) move into the RBC from the plasma, balancing out the **electronegativity** of the departing HCO₃⁻; this is called the **chloride shift**.



Tissue Fluid

Tissue fluid is the liquid that **surrounds** body cells, and enables the **exchange of substances** (e.g. oxygen, glucose, carbon dioxide, urea).

Tissue fluid **forms at the arteriole end** (where there is a higher pressure) of the capillary bed, and then is **'reabsorbed' at the venous ends** (where the osmotic pull of water pulls it back in).

The table below compares the composition of blood plasma, tissue fluid and lymph:

| Component | Plasma | Tissue Fluid |
|--|-------------------------------------|---|
| Water | ✓ | ✓ |
| Ions (e.g. Na ⁺ , Cl ⁻) | ✓ | ✓ |
| Glucose | ✓ | ✓ |
| Amino acids | ✓ | ✓ |
| Plasma proteins | ✓ | ✗* |
| RBCs | ✓ | ✗ |
| WBCs | ✓ | ✗ |
| Function | Transports substances in the blood. | Surrounds cells for substance exchange. |

*Some proteins may be present, such as antibodies from lymphocytes.

Tissue Fluid Formation

The **formation** and **return** of tissue fluid is **determined** by two **opposing pressures**:

- **Hydrostatic pressure:** The **outward force** exerted by the blood on capillary walls caused by heart contractions (blood pressure).
- **Oncotic pressure:** The **inward osmotic pull** caused by **plasma proteins** (mainly albumin) that cannot leave the capillaries, causing a low potential.

Module 3: Tissue Fluid Formation



The table below outlines the formation and return of tissue fluid:

| Location | Key Events |
|------------------|---|
| Arterial end | <ul style="list-style-type: none">- Hydrostatic pressure (from heart contraction) is higher than oncotic pressure.- Water and small solutes are forced out of the capillaries into tissue spaces.- Large plasma proteins and red blood cells remain inside. |
| Venous end | <ul style="list-style-type: none">- Hydrostatic pressure is lower than oncotic pressure.- Oncotic pressure draws water (and dissolved solutes) back in by osmosis down a water potential gradient.- Around 90% of the fluid is reabsorbed. |
| Lymphatic system | <ul style="list-style-type: none">- About 10% of fluid is left over and it enters the lymphatic system, becoming lymph, which eventually returns to the blood. |

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The Need for Transport Systems

Multicellular plants cannot fulfil their metabolic needs or excrete all waste by diffusion alone.

The table below outlines the limitations which make diffusion insufficient:

| Limitation | Explanation |
|----------------------------------|--|
| Low surface area to volume ratio | As plants increase in size, diffusion of substances via the outer surface cannot keep up with internal demands. |
| Metabolic activity | Regions of high growth (e.g. meristems, leaves and storage organs) need a constant supply of substrates and to remove excess products. |
| Diffusion distance | Many specialised cells are too far away from the source of a metabolic input (e.g. leaves from water, or roots from sucrose). |

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Vascular Systems in Plants

The **vascular bundle** is a collection of **xylem** and **phloem** tissue:

- **Xylem** transports **water** and dissolved **mineral ions** from the roots to the leaves (only up) using **mass flow**.
- **Phloem** transports organic solutes such as **sucrose**, amino acids, and hormones (dissolved as phloem sap) throughout the plant (**up and down**) using **translocation**.

Xylem Tissue

The table below outlines the structural features of **xylem tissue** and its benefits:

| Structural Feature | Benefit |
|------------------------------------|---|
| Dead hollow cells | Allow an uninterrupted flow of water from the root to the leaf through a continuous column |
| Vessels with no end walls | Create a continuous tube for mass flow |
| Lignin rings/spirals in cell walls | Lignification strengthens cell walls to provide mechanical support to the xylem (resisting collapse under tension) and to support the plant |
| Bordered pits | Gaps in the lignified xylem vessels that allow water to move from one xylem to another, or into surrounding tissue |
| Narrow lumen | Enables capillary action to support water cohesion, stopping the water column from breaking |

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Phloem Tissue

The table below outlines the structural features of **phloem tissues** and its benefits:

| Structural Feature | Benefit |
|--------------------------|--|
| Sieve tube elements | Long, thin (living) cells with sieve plates at their ends for the passage of phloem sap from tubes end to end |
| Sieve plates | <ul style="list-style-type: none">- Specialised cellulose cell walls with perforations to allow phloem sap from one sieve tube element to another- In the event of injury or infection, the perforations (sieve pores) are blocked with callose |
| No nucleus or organelles | Maximises space for phloem sap |
| Companion cells | <ul style="list-style-type: none">- Contain many mitochondria to provide ATP for the active loading of sucrose into sieve tubes for translocation- Carry out metabolic functions for the sieve tube elements |
| Plasmodesmata | Connects sieve tube elements and companion cells, enables hormonal communication and the transport of substances |

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Vascular Tissue Arrangement

Vascular tissue is arranged differently in different plant organs, which can be used to identify them.

The table below describes the arrangement of vascular tissue in different plant organs:

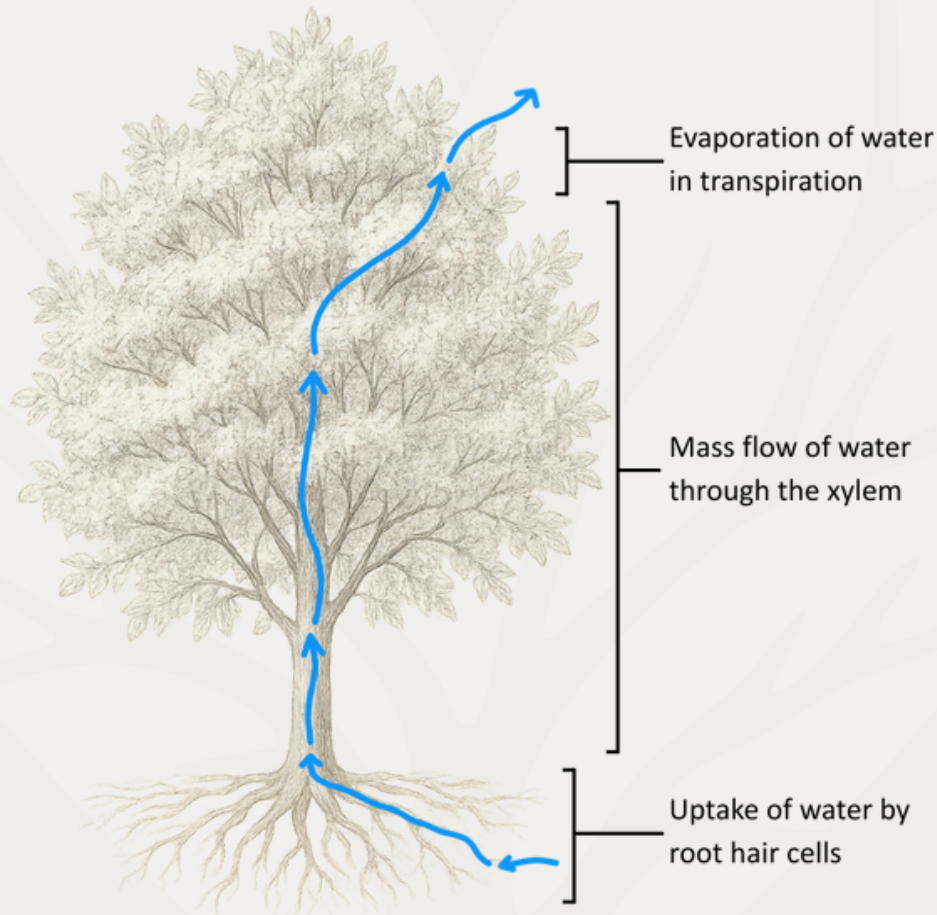
| Organ | Vascular Tissue Arrangement | Diagram |
|-------|---|---------|
| Root | Xylem is in an X-shape at the centre with phloem between the arms. | |
| Stem | Vascular bundles are arranged in a ring near the outer edge, with xylem on the inner side and phloem on the outer side. | |
| Leaf | Vascular tissue in the midrib and veins, with xylem above and phloem below in the bundle sheath. | |





Plant Transport of Water

The **transpiration stream** is a continuous column of water that moves **upwards** through the plant from the roots to the leaves:



The Transpiration Stream

The table below provides an overview of the transpiration stream:

| Location | Process | Driving Force |
|---------------------|--|--|
| Soil → root hairs | Osmosis | Water potential gradient |
| Root cortex → xylem | Apoplast (diffusion) Symplast (osmosis) Vacuolar (osmosis) | Water potential gradient Hydrostatic pressure |
| Xylem | Cohesion-tension mechanism | Transpiration pull from the leaf |
| Leaf → atmosphere | Evaporation and diffusion via stomata | Water potential gradient and stomatal opening |





Processes

The table below provides an overview of the key processes involved in the transpiration stream:

| Process | Description |
|------------------|--|
| Evaporation | Water evaporates from the cellulose cell walls of mesophyll cells into leaf air spaces. |
| Diffusion | Water vapour diffuses out through open stomata, down a water vapour potential gradient. |
| Cohesion-Tension | A decrease in pressure caused by the loss of water molecules creates tension between hydrogen-bonded water molecules that pull more water into the mesophyll from, and up, the xylem (transpiration pull). |
| Adhesion | Hydrogen bonding between the water column and the xylem walls helps water move upwards against gravity. |
| Root pressure | The active transport of mineral ions into the medulla and xylem draws in water by osmosis, increasing water pressure that pushes the water column up the xylem. |

Transpiration

Transpiration is the **evaporation** of water from the **stomata**.

1. Water moves by osmosis into the spongy mesophyll from the xylem (through cellulose cell walls) or via the apoplast pathway.
2. Some may be used for photosynthesis or maintaining cell turgidity.
3. Unused water evaporates into the air spaces.
4. Water vapour builds up in the air spaces, creating a high water vapour potential.
5. Water vapour diffuses towards the stomata, where there is a lower water vapour potential.
6. Water vapour moves out of the air spaces via the stomata, lowering the water vapour potential just inside the leaf.

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Factors Affecting Transpiration Rate

The following environmental factors affect the rate of transpiration:

| Factor | Factor change that increases transpiration | Mechanism |
|-------------------|--|--|
| Light intensity | Increase | Opens stomata, increasing diffusion. |
| Temperature | Increase | Faster evaporation and diffusion. |
| Humidity | Decrease | Increases the water vapour potential gradient. |
| Air movement | Increase | Increases the water vapour potential gradient. |
| Leaf surface area | Increase | More surface area for more stomata. |

The Importance of Transpiration

Some key examples of why transpiration is important are that it:

- Maintains water movement through the xylem (it enables the transpiration stream).
- Transports mineral ions to growing tissues.
- Enables leaf turgor for mechanical support.
- Cools the plant via the latent heat of evaporation.

Mass Flow

Mass flow is the **upward** movement of **water** and dissolved **mineral ions** through the **xylem**.

Whilst the **water column** is pulled **upwards** by **transpiration pull**, which is assisted by adhesion, upwards pressure from the root also contributes to this movement.

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Root Pressure

Water enters the root through **root hair cells**, which have a **low water potential** due to dissolved mineral ions, so water enters down a water potential gradient from the soil by osmosis.

Water travels through the **cortex** to the **endodermis** via three possible pathways:

- **Apoplast:** Through the cell wall.
- **Symplast:** Through cytoplasm via plasmodesmata.
- **Vacuolar:** Through vacuoles.



At the **endodermis**, the **Casparian strip blocks** the apoplast route, so water is forced into the symplast pathway. This ensures that it enters the xylem.

Mineral ions are **actively transported** into the medulla and xylem, **lowering** the water potential there. Water moves down its water potential gradient by **osmosis** into the xylem, **increasing** the root pressure, which pushes water up into the xylem.

This pressure helps move water up the plant.



Plant Adaptations to Water

Plant species are **adapted** to the environments in which they evolved, and will have adaptations that **maximise** their chances of **survival**.

Regarding water, plants can be categorised as:

- **Xerophytes:** Adapted to **dry** environments by minimising water loss and maximising water retention
- **Hydrophytes:** Adapted to aquatic or very **wet** environments by increasing access to oxygen as well as mineral ions by maximising the transpiration stream

Adaptations to Dry Environments

The table below outlines some adaptations found (in some) **xerophytes**:

| Adaptation | Function |
|--------------------------|---|
| Thick waxy cuticle | Reduces evaporation (water loss) through the cellulose cell wall |
| Sunken stomata | Traps moist air to decrease the water vapour potential gradient by reducing the wind |
| Rolled leaves | Traps moist air to decrease the water vapour potential gradient by reducing the wind |
| Hairy surfaces | Traps moist air to decrease the water vapour potential gradient |
| Reduced leaf surface | - Spines or needle-like leaves reduce the surface area available for transpiration - Photosynthesis occurs on the fleshy plant stems instead (like a cactus) |
| Fleshy stems | Provides storage space for water, and can swell to accommodate more |
| Deep or widespread roots | Maximise water uptake by accessing deep or widespread soil moisture |



Module 3: Plant Adaptations to Water



Adaptations to Wet Environments

The table below outlines some adaptations found (in some) **hydrophytes**:

| Adaptation | Function |
|--------------------------------------|---|
| Air spaces in the tissue | Enable floating on/in water to access the air (for oxygen) and light, and to promote gas exchange |
| Stomata on the upper surface | So that gas exchange can occur with the atmosphere (in floating leaves) |
| Reduced vascular tissue | <ul style="list-style-type: none">- Xylem is not required for water transport, saving resources and energy- Less mechanical support is needed |
| Thin, flexible stems with airtissues | <ul style="list-style-type: none">- Allows flexibility with water movement to reduce breakage, so less lignin is made (saving energy and resources)- Helps the plant float, and provides a shorter diffusion pathway for oxygen to the roots |

Required Examples: Marram Grass, Cactus and Water Lilies

These are the three plants whose adaptations you are expected to know for the OCR A level Biology course.

The adaptations they each have are listed in the table below:

| Marram Grass(Xerophyte) | Cactus(Xerophyte) | Water Lily(Hydrophyte) |
|------------------------------|---------------------------------|------------------------------|
| Rolled leaves | Spines instead of leaves | Stomata on the upper surface |
| Hairy leaf surfaces | Photosynthetic stem | Large air spaces in tissues |
| Sunken stomata | Fleshy stem for water storage | No waxy cuticle |
| Thick waxy cuticle | Thick waxy cuticle | Reduced vascular tissue |
| Extensive root system (deep) | Shallow, widespread root system | Thin, flexible stems |
| | Sunken stomata | Minimal root system |





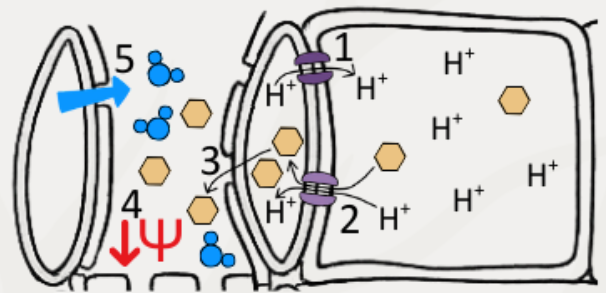
Translocation

Translocation is the movement of dissolved substances (called assimilates) in the phloem sap **from a source** (e.g. leaves, tubers) **to sinks** (e.g. roots, fruits, tubers).

Translocation: The Pressure Flow Hypothesis

Loading (at the source):

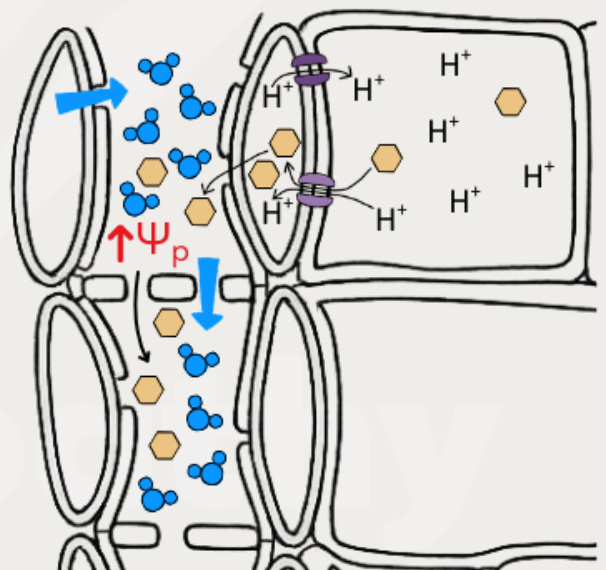
1. Companion cells use ATP to transport H^+ into the surrounding source tissues.
2. H^+ diffuse back into the companion cells through cotransporter proteins alongside sucrose.
3. Sucrose diffuses down its concentration gradient into the sieve tube elements via the plasmodesmata from the companion cells.
4. This lowers the water potential inside sieve tubes.



Water enters from adjacent xylem into this area down its water potential gradient by osmosis, increasing the hydrostatic pressure.

Mass flow (through phloem):

- Higher hydrostatic pressure at the source pushes the phloem sap toward the sink, where the pressure is lower.
- This is a bulk flow mechanism.

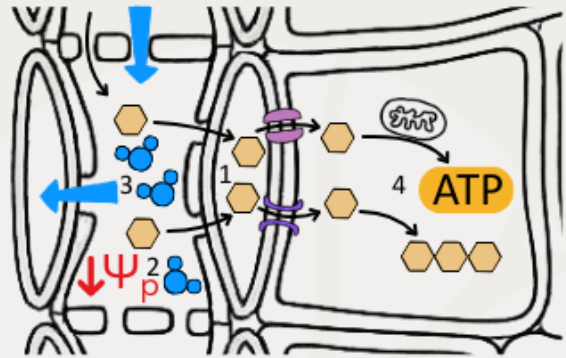


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Unloading (at the sink):

1. Sucrose is removed from the phloem by companion cells using active transport, or through the plasmodesmata by diffusion.
2. The removal of sucrose from the phloem increases the water potential in the phloem at the sink.
3. Water moves to a lower water potential back into the xylem by osmosis, lowering the hydrostatic pressure at the sink.
4. Sucrose is used in respiration or stored.



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Module 4: Communicable Diseases



Communicable Diseases

Communicable diseases are caused by **pathogens** which invade a host and cause **harm**; they are **infectious**.

Pathogens are **disease-causing microorganisms** that damage the host's cells and disrupt normal biological functioning.

Microorganisms can infect both animals and plants.

There are four main types of pathogenic microorganisms: **bacteria, fungi, protoctists** and **viruses**.

The table below summarises the key pathogens you need to know in OCR A level Biology, along with the diseases they cause and how they are transmitted; candidates have not been expected to recall the effects and symptoms of these different pathogens.

The table below gives two **bacterial** pathogens:

| Disease | Host | Transmission |
|-------------------|--------------------|---|
| Tuberculosis (TB) | Humans | Airborne droplets |
| Ring Rot | Potatoes, Tomatoes | Contact with contaminated tools, soil, or infected tubers |

The table below gives three **viral** pathogens:

| Disease | Host | Pathogen | Transmission Method |
|--|----------------------------|-----------------------------------|---|
| AIDS (Acquired Immune Deficiency Syndrome) | Humans | HIV: Human Immunodeficiency Virus | <ul style="list-style-type: none">- Bodily fluids (e.g. blood, semen).- Unprotected sex.- Needle sharing. |
| Influenza | Humans | Influenza virus | <ul style="list-style-type: none">- Airborne droplets.- Contaminated surfaces. |
| Tobacco Mosaic Virus | Plants (Tobacco, tomatoes) | TMV: Tobacco mosaic virus | <ul style="list-style-type: none">- Contact with contaminated tools, hands or other plants.- Insect vectors.- Soil. |



Module 4: Communicable Diseases



The table below gives two **protocista** pathogens:

| Disease | Host | Transmission Method |
|---------|--------------------|--|
| Malaria | Humans | Vector transmission by female Anopheles mosquitoes. |
| Blight | Potatoes, Tomatoes | Spores: Spread by the wind, rain and contaminated soil. |

The table below gives two **fungal** pathogens:

| Disease | Host | Transmission Method |
|----------------|---------|--|
| Athlete's Foot | Humans | Direct contact with contaminated floors, towels or communal showers. |
| Black Sigatoka | Bananas | Airborne spores that spread in warm and humid environments. |

Transmission

Transmission is how pathogens spread, and can be **direct** or **indirect**:

- **Direct:** The pathogen is transmitted from one organism to another; there is **no intermediate** organism.
- **Indirect:** The pathogen is transmitted from one organism to another via a vector; an intermediate organism **carries the pathogen** from an infected organism to an uninfected one.

Transmission in Animals

The table below outlines some of the ways animals can be infected by direct transmission:

| Method of Transmission | Description |
|------------------------|--|
| Direct Contact | Physical contact between an infected and a healthy individual, or with contaminated surfaces. |
| Ingestion | Consuming food or drink contaminated by infected urine or faeces. |
| Droplet Infection | Pathogens are carried in droplets of mucus/saliva through the air when an infected person coughs or sneezes. |
| Spore Transmission | Spores in the air, soil, or on surfaces enter through cuts, inhalation, or wounds. |



Module 4: Communicable Diseases



The table below outlines some of the ways animals can be infected by indirect transmission:

| Method of Transmission | Description |
|------------------------|--|
| Vector | Another organism (the vector) carries the pathogen between hosts. |
| Fomites* | Inanimate objects contaminated by pathogens which are passed between individuals (e.g. bedding, clothing, hospital equipment). |

*You do not need to know this term.

Transmission in plants

The table below outlines some of the ways plants can be infected by **direct transmission**:

| Method of Transmission | Description |
|------------------------|--|
| Direct Contact | Contact between a healthy plant and an infected plant. |
| Soil Contamination | Pathogens in the soil infect healthy plants, and some remain viable for years. |

The table below outlines some of the ways plants can be infected by **indirect transmission**:

| Method of Transmission | Description |
|------------------------|--|
| Vectors | Insects transfer pathogens between plants. |
| Water and Wind | Spores, bacteria, or viruses spread by the wind or movement of water (e.g. rain splashing, irrigation) |
| Human Activity | Pathogens spread by contaminated hands, tools, machinery, or transport of infected plant material. |

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Social Factors in Transmission

Social factors influence how easily pathogens spread through a population. These factors generally **increase transmission** by:

- **Increasing contact** between individuals, such as in crowded or shared environments.
- **Reducing sanitation and hygiene**, allowing pathogens to persist on surfaces or in water.
- **Enabling direct transmission** routes, especially through behaviours or shared equipment.
- **Delaying diagnosis and treatment** allows infections to spread unchecked.

Prevention strategies target these risk points by reducing exposure, promoting hygiene, limiting shared contamination routes, and improving access to healthcare.

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Module 4: Plant Defences Against Pathogens



Plant Defences Against Pathogens

Plants have **two types** of defence against pathogens:

- **Chemical defences** are antibiotics, antifungals, hydrolytic enzymes, antimicrobial proteins or other metabolic products that can inhibit or kill microorganisms.
- **Physical defences** are structures that keep out microorganisms or contain their spread within the organism.

Different types of chemical and physical defences are categorised as:

- **Active Defences:** Produced in response to infection, helping to contain or destroy pathogens.
- **Passive Defences:** Always present, designed to prevent the entry of pathogens.

Active Defences

The table below outlines some of the **active chemical defences** plants have:

| Examples | Description |
|-----------------------------|--|
| Alkaloids, Phenols | Inhibit key metabolic processes (e.g. enzymes for digestion or protein synthesis). |
| Defensins, Oxidative bursts | Disrupt pathogen plasma membranes or ion transport. |
| Hydrolytic enzymes | Break down microbial cell walls (e.g. chitinases for fungi, lysozymes for bacteria). |
| Terpenoids, Phenols | Act as general antimicrobials (antibacterial and antifungal). |

The table below outlines some of the **active physical defences** plants have:

| Examples | Description |
|--|---|
| Cell wall thickening, Callose deposition | Strengthen cell walls and block plasmodesmata to prevent pathogen spread between cells. |
| Necrosis | Localised cell death to isolate infection. |



Module 4: Plant Defences Against Pathogens



Passive Defences

The table below outlines some of the **passive chemical defences** plants have:

| Examples | Description |
|-----------------------|--|
| Phenols, Tannins | Stored in bark and tissues, they have broad antimicrobial and antifungal properties. |
| Terpenoids, Alkaloids | Bitter or aromatic compounds that deter herbivores and inhibit pathogens. |
| Defensins | Protein-based inhibitors present in tissues act against microbial growth. |
| Hydrolytic enzymes | Pre-formed enzymes (e.g. chitinases, lysozymes) that degrade invading pathogen cell walls. |

The table below outlines some of the **passive physical defences** plants have:

| Examples | Description |
|------------------------------------|--|
| Bark, Cellulose cell walls, Lignin | Physical barriers that are tough, waterproof, and contain antimicrobial compounds. |
| Callose, Tylose | Internal blockages that restrict pathogen movement in phloem or xylem. |
| Waxy cuticle, Stomatal closure | Surface defences that prevent pathogen entry. |

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Module 4: Non-Specific Defences in Animals



Primary Non-Specific Defences Against Pathogens

Primary nonspecific defences keep microorganisms from entering the body.

Primary defences are non-specific because they will **target** and respond to a **wide range** of pathogens.

Examples of primary defences include:

| Type | Examples |
|-------------------------|--|
| Physical Barriers | Skin, mucous membranes, ear wax, and mucus plug in the cervix. |
| Chemical Barriers | Sebum, stomach acid, and lysozymes in tears and saliva. |
| Mechanical Reflexes | Coughing, sneezing, vomiting, diarrhoea. |
| Physiological Responses | Blood clotting, inflammation. |

Physical Barriers

The Skin

The **outer layer** of the skin is the **epidermis**, a tough, waterproof layer.

The **epidermis** is mostly made up of **keratinocytes**, which specialise into **dead cells** containing **keratin**, which makes them tough and waterproof; this is known as **keratinisation**.

Because the keratinocytes are dead (and flake off), they must be continuously **replaced**.

Skin Damage

When the skin is damaged, it provides an entry point for pathogens. The body **prevents infection** by sealing the wound temporarily (**blood clotting**) and permanently (**wound repair**).

Blood clotting

Blood clotting involves **platelets** releasing substances that trigger a reaction chain that produces **fibrin**, an insoluble protein. **Fibrin** forms a mesh-like network that captures extra platelets and forms a **stable clot**.



Module 4: Non-Specific Defences in Animals



Wound repair

A clot hardens into a **scab**, creating a **temporary seal** and drawing the wound edges together. Underneath, **collagen** is laid down while **skin stem cells divide** to repair the tissue, and new blood vessels grow. Once healing is complete, the scab is shed.

Inflammation

Inflammation is **swelling** and **redness**. It occurs to help contain pathogens and encourage the action of white blood cells.

Mast cells in the skin detect microorganisms if they have entered the area, and release the cell-signalling molecule **histamine**.

Histamine mainly causes **vasodilation**, so that the capillary **dilates** and becomes more permeable to **white blood cells** and plasma proteins.

More white blood cells and blood plasma can now enter the infected area from the capillaries, forming more **tissue fluid** and causing **oedema** (swelling).

Inflammation also occurs during **allergic reactions** when mast cells mistake substances for pathogens.

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Module 4: White Blood Cells and Secondary Defences



White Blood Cells

Different roles in the immune response are performed by different types of **white blood cells**, each specialised for their role.

The table below lists the different types of white blood cells named in the OCR A level Biology course, and what type they are:

| White Blood Cell | Phagocyte | Antigen-Presenting Cell (APC) | Lymphocyte | Non-specific Response | Specific Immune Response |
|-------------------------------|-----------|-------------------------------|------------|-----------------------|--------------------------|
| Neutrophil | ✓ | | | ✓ | |
| Monocyte / Macrophage | ✓ | ✓ | | ✓ | ✓ |
| Plasma Cell / B effector cell | | | ✓ | | ✓ |
| B Memory | | | ✓ | | ✓ |
| T Helper | | | ✓ | | ✓ |
| T Killer | | | ✓ | | ✓ |
| T Memory | | | ✓ | | ✓ |
| T Regulatory | | | ✓ | | ✓ |

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Module 4: White Blood Cells and Secondary Defences



Identifying white blood cells

The main types of white blood cells you need to know can be identified from a **blood smear** under a microscope:

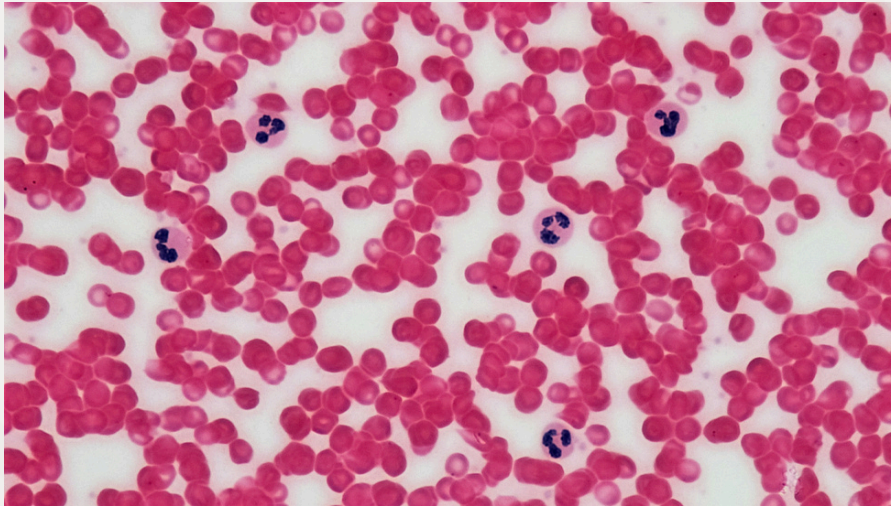


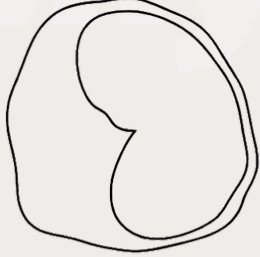


Photo by Fayette Reynolds, 2024

The table below outlines the main distinguishing features you would be expected to recognise in an exam:

| Lymphocyte | Distinguishing Feature | Image |
|-----------------------|--|---|
| Neutrophils | Multi-lobed nucleus |  |
| Lymphocytes | Large round nucleus |  |
| Monocytes/Macrophages | Kidney-shaped nucleus Larger than other lymphocytes |  |



Module 4: White Blood Cells and Secondary Defences



Secondary Defences: Non-Specific and the Specific Immune Response

Secondary defences are for when pathogens get past primary defences and **enter the body**.

The **secondary defences** of the immune system are either:

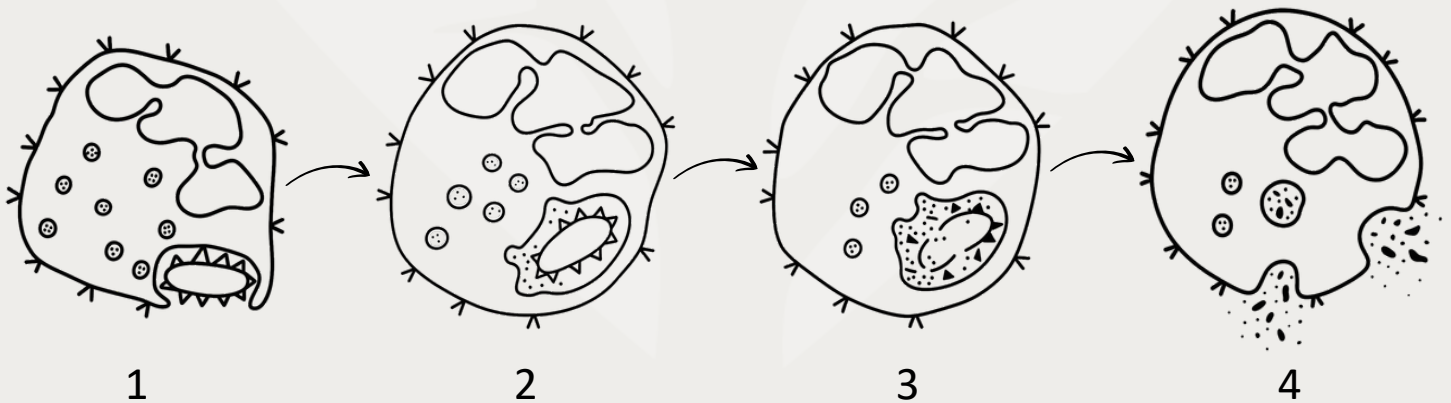
- **Non-specific:** The response of white blood cells is **indiscriminate**, targeting any 'foreign' antigens.
- **Specific:** The response of white blood cells is controlled by the presence of **particular antigens** which they **target**.

Macrophages are **non-specific** in how they approach **phagocytosis**, but their **display of antigens** involves them in the start of the specific immune response.

Only **phagocytes** are involved in the **secondary non-specific** immune response.

Phagocytes

Phagocytes are cells that **do phagocytosis**: the engulfing of a pathogen and destroying it with hydrolytic enzymes.



The process of phagocytosis is:

1. **Recognition:** The phagocyte binds to the antigen on the pathogen's surface.
2. **Engulfment:** The pathogen is engulfed by endocytosis and enclosed in a phagosome.
3. **Digestion:** Lysosomes fuse with the phagosome and release hydrolytic enzymes.
4. **Absorption or Release:** Harmless products are absorbed or expelled to be used as nutrients.

The two types of phagocyte taught in OCR A level Biology are **neutrophils** and **macrophages**.

Module 4: White Blood Cells and Secondary Defences



The table below compares the main features of neutrophils and macrophages that you need to know:

| Feature | Neutrophils | Macrophages |
|-----------------|--|---|
| Origin | Bone marrow | Bone marrow (as monocytes) |
| Maturation site | Bone marrow | Lymph nodes (and other tissues) (differentiating from monocytes) |
| Lifespan | Short-lived (hours to days) | Long-lived (can persist for months) |
| Role | Phagocytosis of pathogens | - Phagocytosis - Antigen presentation |
| Structure | - Multi-lobed nucleus - Many lysosomes - Many mitochondria - Many ribosomes - Chemotaxis | - Kidney-shaped nucleus* - Many lysosomes - Many mitochondria - Many ribosomes - Chemotaxis |

*Monocytes have the kidney shaped nucleus, which becomes irregular as they mature into macrophages.

Non-specific immune response

In the **non-specific immune response** neutrophils and macrophages carry out **phagocytosis** on **any foreign** microorganisms they find.

Microorganisms are **recognised** as being foreign due to the **antigens** they have.

Neutrophils and macrophages are '**non-specific**' because they will respond to **any antigen**, not just certain ones (as happens in the specific immune response).

The specific immune response

The **specific immune response** identifies certain pathogens by **recognising** their **antigen marker molecules** and **targeting** them (mostly) exclusively.

This allows pathogens, or infected cells, to be destroyed more effectively. The immune system can then **make powerful antibodies** that inhibit the pathogen's function. It also **provides immunity** by recognising the same pathogen upon reinfection.

The main types of white blood cells involved are:

- **B cells:** Responsible for **making antibodies** that target specific antigens.
- **T cells:** Responsible for **attacking infected host cells** and stimulating B cells.



Module 4: White Blood Cells and Secondary Defences



Both B and T lymphocytes are involved in immunity by **making memory cells**.

The actions of B and T lymphocytes in the specific immune response are driven by 4 processes:

- **Antigen presentation:** Where a cell **displays an antigen** on its cell surface membrane to **activate** specific B and T cells with a **complementary** receptor.
- **Clonal selection:** Where specific T and B lymphocytes are **activated** after binding with a complementary antigen on an antigen-presenting cell (APC).
- **Clonal expansion:** Where activated B and T lymphocytes **divide by mitosis**; each new cell is able to produce **complementary receptors** or **antibodies** to the **same antigen**.
- **Differentiation:** Where some B and T cells are produced by **clonal selection** and turn into specialised lymphocytes.

The activity of the immune system is controlled by **cell signalling**, including:

- **Antigen-presentation:** Some lymphocytes have **complementary** protein receptors to specific antigens, and binding to these, either directly on pathogens or on APCs, will activate them.
- **Cell signalling molecules:** Chemical messengers between B and T cells stimulate the immune system (e.g. cytokines and interleukins*), whilst other body cells can release substances to alert lymphocytes that they are infected (e.g. interferon for viral infections).

*Technically, interleukins are just a type of cytokine, but this is misrepresented in many educational materials.

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Module 4: White Blood Cells and Secondary Defences



B and T Cells

The table below outlines the roles of the lymphocytes involved in specific immunity:

| Cell Type | Function |
|-------------------------------|--|
| Undifferentiated lymphocyte | <ul style="list-style-type: none">- Detects antigens using complementary receptors on its surface.- Activated via antigen presentation and clonal selection, then undergoes clonal expansion. |
| B Memory cell | <ul style="list-style-type: none">- Provides long-term immunity.- Responds rapidly to known antigens by undergoing clonal expansion. |
| Plasma Cell / B Effector Cell | <ul style="list-style-type: none">- Produces and secretes antibodies specific to one antigen. |
| T Memory Cell | <ul style="list-style-type: none">- Provides long-term immunity.- Responds rapidly to known antigens by undergoing clonal expansion. |
| T Killer Cell | <ul style="list-style-type: none">- Destroys infected cells that activate it with antigen presentation and interleukins.- Releases perforins and hydrolytic enzymes. |
| T Helper Cell | <ul style="list-style-type: none">- Coordinates the immune response.- Releases interleukins to stimulate clonal selection and clonal expansion of B and T cells. |

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Module 4: The Primary and Secondary Immune Response



The Primary and Secondary Immune Response

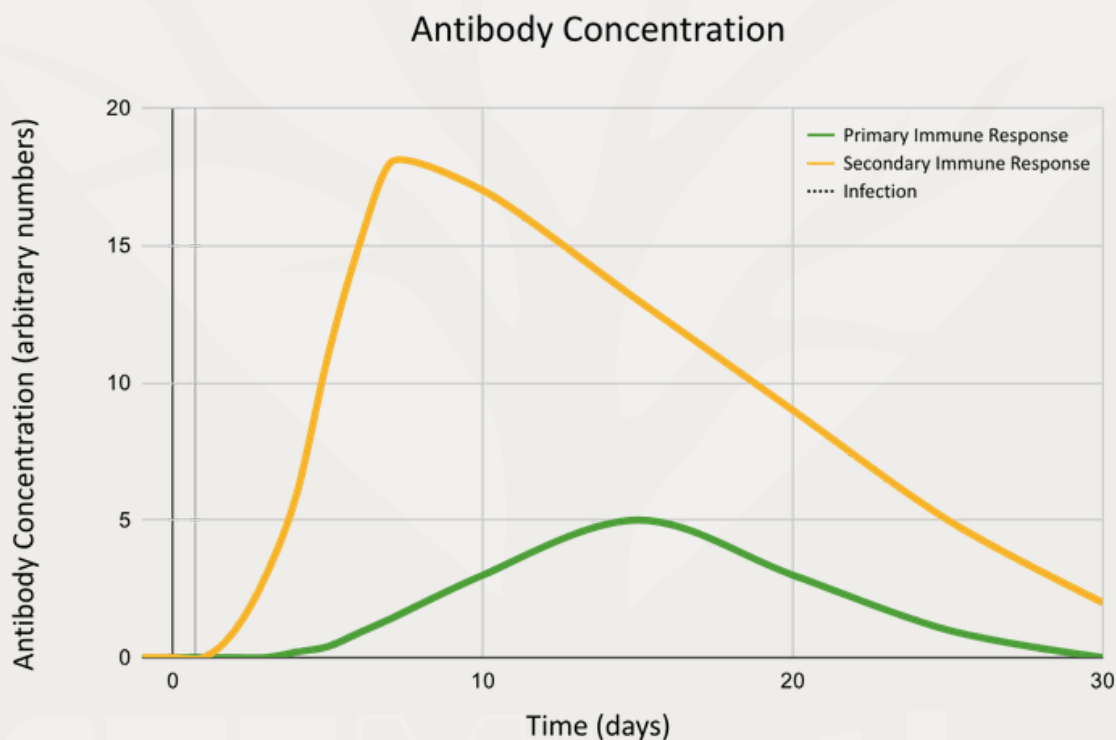
The **first exposure** to a pathogen is called the **primary response**, and **subsequent exposures** are known as a **secondary response**:

- **Primary response**: Characterised by a **delay** in, **slower rate** of, and **lower** overall total concentration of **antibody production**.
- **Secondary response**: Characterised by a **rapid, high rate** of, and **higher** overall total concentration of **antibody production**.

Exposure to a pathogen, or its antigens, could be from **infection** or **vaccination**.

Memory cells are produced by **T killer cells** and **plasma cells**, allowing new T killer and plasma cells to be produced **faster upon reexposure**.

The graph below visualises the difference between the primary and secondary response:



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Types of Immunity

Immunity is the ability to resist infection by pathogens by **having complementary antibodies** or **memory cells** that can rapidly make them.

Immunity can be either **active** or **passive**:

- **Active:** The host's immune system **makes its own antibodies** after being exposed to a pathogen.
- **Passive:** The host receives **antibodies** from an **external source**.

Immunity can be **acquired** either **naturally** or **artificially**:

- **Natural:** A normal **biological process** confers immunity.
- **Artificial:** **Medical intervention** confers immunity.

The table below summarises these types of immunity with examples:

| | Natural | Artificial |
|---------|---|---|
| Active | The immune system produces antibodies after infection (e.g. chickenpox) | Antigen introduced via vaccine (e.g. MMR, TB) |
| Passive | Antibodies from the mother via the placenta or breast milk | Antibodies injected (e.g. antivenom, hepatitis treatment) |

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Antibodies

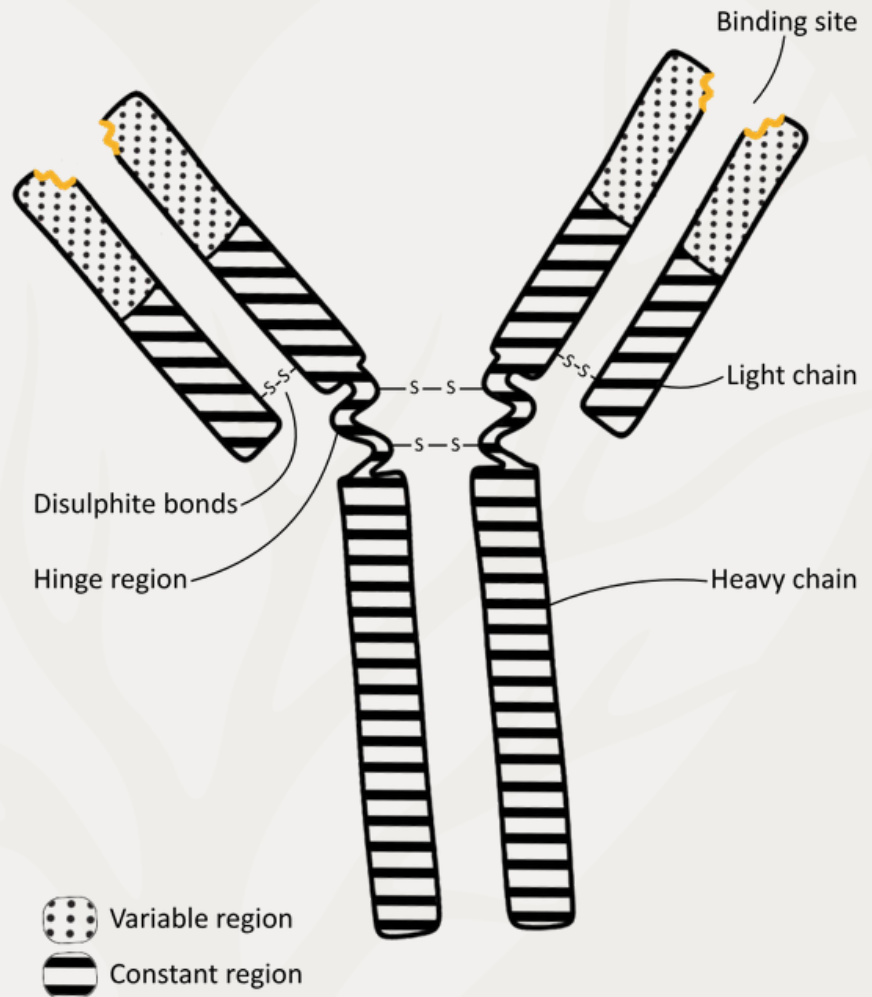
Antibodies are glycoproteins involved in the function of the immune system.

They have a quaternary structure made up of four polypeptide chains; there are **two heavy chains** and **two light chains**.

The **structure** of an antibody is **Y-shaped**, as illustrated in the diagram below:

The components labelled are:

- **Arms:** The two **branches** of an antibody.
- **Variable region:** An area at the end of the antibody arm that differs between types of antibody; the **binding site** is found here.
- **Binding site:** A **3D area** on the variable region that is **complementary** to one type of antigen.
- **Constant region:** A structure that is the **same across all antibodies**; it may have a **receptor** to help **phagocytes bind to it**.
- **Hinge region:** A **flexible** part of the antibody which allows more than one pathogen to be attached to (by each arm).
- **Disulfide bonds:** These hold the polypeptide chains together.



There are **three types** of antibodies, each with a different role:

- **Opsonins:** Bind to antigens on pathogens to make it easier for phagocytes to engulf them by **providing a binding site for phagocytosis**.
- **Agglutinins:** Bind to antigens on different pathogens so that they are **clumped together** (agglutinated), allowing **more to be engulfed by phagocytes**.
- **Anti-toxins:** Bind to the **toxins** made by pathogens, making them inactive and **neutralising their harmful effects**.





Autoimmune Diseases

Autoimmune diseases occur when the immune system **attacks** the body's **own tissues**, mistaking **self-antigens as foreign antigens**.

The causes of this are not always known, but may include **genetic** and **environmental triggers**.

Immunosuppressants are the most common **treatment**, but have side effects (e.g. vulnerability to pathogens).

Rheumatoid arthritis is the named example you are expected to know, characterised by membranes around joints being targeted, leading to **pain, swelling** and **inflammation**.

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Vaccination

Vaccination stimulates the production of **memory cells** without causing illness.

It **exposes** the immune system to a harmless* **antigen**, stimulating the **production of complementary antibodies and memory cells**.

*Although it should be noted that side effects (such as allergic reactions) are possible, and in rare cases, the vaccine does not work.

Forms of antigenic material in (some) vaccines:

- **Antigens:** A selection of **antigens** from the **pathogen**, such as hepatitis B.
- **Attenuated microorganisms:** A **weakened** and **harmless pathogen**, such as the measles and TB vaccines.
- **Dead microorganisms:** **Killed** so that they are **harmless**, such as cholera.

Vaccination Programmes

Vaccination protects individuals from pathogens, but the **immunisation** of large groups of people can strategically protect **nonimmune** and **immunocompromised** people.

Two key elements are:

- **Herd Immunity:** When enough of the **population is immune**, the pathogen's spread is **highly reduced**.
- **Ring Vaccination:** All individuals who have or may be **in contact** with someone who is infected are **vaccinated** to prevent the pathogen from spreading.

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Controlling epidemics

The **occurrence** of disease is monitored at both a national and an international level in both animals and humans to prepare for and prevent the possibility of an **epidemic** or a **pandemic**.

Outbreaks in animals are monitored due to their **economic importance** in the food supply (e.g. cattle), as well as their ability to spread diseases across borders (e.g. wild birds).

The table below outlines some of the key considerations when managing epidemics with vaccines:

| Aspect | Consideration |
|--------------------|--|
| Cooperation | Is a disease widespread, or transmissible enough, to require international cooperation. |
| Disease Traits | <ul style="list-style-type: none">- Can the disease infect animals and humans.- What is its lethality.- How long does immunity last for. |
| Cost-effectiveness | <ul style="list-style-type: none">- How cheap is the vaccine to produce.- How costly are the economic or health impacts. |

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Developing New Medicines

The discovery and development of new medicines are of major importance in healthcare.

New medicines can come from nature, observation, or scientific innovation, and all require **extensive testing before use**.

The need for new medicines

New drugs are constantly required because:

- **New diseases** continue to emerge (e.g. SARS, Ebola, COVID-19)
- Existing diseases still **lack effective cures** (e.g. Alzheimer's, cancer)
- Antimicrobial **resistance** makes current **treatments less effective** (e.g. MRSA)

New drugs can be discovered through different approaches:

| Approach | Description |
|-----------------------|--|
| Traditional remedies | Traditionally used plants may have active ingredients. |
| Wildlife observation | Animals and insects utilise plants to treat and prevent infectious disease, which can be investigated for new biomolecules. |
| Disease mechanisms | Researching the exact mechanisms of infection and disease creates insights that can be exploited with the development of new biomolecules. |
| Synthetic biology | Organisms can be genetically engineered to produce medicines, or entirely new biomolecules can be designed and created. |
| Personalised medicine | Existing medicines can be tailored using information on an individual's genetics and metabolism, reducing side effects and increasing effectiveness. |

Drug discovery is a strong argument for the conservation of biodiversity, as unexplored ecosystems may contain **undiscovered compounds with medicinal value**.





Antibiotics: Importance and Use

Antibiotics are **medicines** that either **kill** bacteria or **inhibit** their growth.

Penicillin, the first antibiotic, was discovered by Alexander Fleming in 1928 from the fungus *Penicillium notatum*.

Antibiotic Resistance

Antibiotic resistance occurs when bacteria **evolve** mechanisms to **survive** exposure to **antibiotics**. This poses a serious risk to public health, as it can make infections:

- Harder to treat
- More likely to spread
- More likely to cause complications or death

MRSA (methicillin-resistant *Staphylococcus aureus*) is a major example of a resistant “superbug” that has become prevalent in hospitals, making routine surgery more dangerous.

The factors which accelerate the evolution of antibiotic resistance include:

| Factor | Explanation |
|---------------------------------|---|
| Overuse of antibiotics | Increases selection pressure for resistance |
| Incomplete courses of treatment | Leaves behind resistant bacteria |
| Use in agriculture | Antibiotics given to livestock may spread resistance genes to human pathogens |

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Biodiversity

Biodiversity is the measurable **differences between organisms**, both as individuals and as species.

Biodiversity can be considered at **different levels**, such as:

- **Habitat biodiversity:** The number of different ecosystems or habitat types in a defined area (e.g. woodland, grassland, sand dune and streams).
- **Species biodiversity:** The number of different species in a defined area (species richness) and their relative abundance (species evenness).
- **Genetic biodiversity:** The genetic variation between individuals of the same species.

Declining Biodiversity

Biodiversity can be **reduced** by both natural and human-driven (anthropogenic) factors. Human activity is currently the largest cause of biodiversity loss worldwide.

Human Population Growth

As the **global population increases**, demand for space, food, water, and energy also rises. This leads to:

- **Habitat loss** (e.g. deforestation, urbanisation)
- **Pollution** (e.g. air, water, and soil contamination)
- **Overexploitation** of natural resources (e.g. hunting, fishing, agriculture)

Agriculture

Modern farming practices often reduce biodiversity:

- **Monoculture:** Growing a **single crop** (a monoculture) across large areas eliminates habitat variety, reduces species diversity and reduces nutrients in the soil.
- **Selective breeding:** **Reducing the genetic diversity** within a domesticated species to ensure only desired characteristics are expressed (genetic erosion).
- **Pesticides and herbicides:** **Non-target species are killed** directly, or killed indirectly through contaminated food chains (e.g. bioaccumulation).

Climate Change

Changing temperature and rainfall patterns **alter ecosystems**, such as:

- Some **species migrate** to more suitable areas (if they can), and others may go extinct.
- Coral bleaching and desertification are examples of **habitat loss** caused by climate change.





Conserving Biodiversity

Biodiversity provides essential **resources, services, and benefits** to ecosystems and human society. There are **ecological, economic, and aesthetic** reasons for protecting it.

Ecological Reasons

- **Interdependence of species** means that the loss of one species can affect **many** others.
- **Keystone species** have a **disproportionately large effect** on their ecosystem by supporting many species as a side effect of their behaviour.
- **Genetic diversity** provides **natural variation** that can be used to identify new medicines or produce new crops more resistant to drought or disease.

Economic Reasons

- **Soil depletion** caused by monoculture can lead to **lower crop yields**, requiring fertiliser and reducing long-term sustainability.
- **Biodiversity** supports **ecotourism** and recreation industries.

Aesthetic Reasons

- **Natural environments** have **cultural, spiritual, and recreational value**.
- **Landscapes** with high biodiversity are more attractive and can **improve human well-being**.

Conservation Methods: In Situ and Ex Situ

Conservation can be carried out **in situ** or **ex situ**. Each approach has **advantages** and **limitations**.

In Situ Conservation

This involves protecting species **in their natural environment**.

In situ conservation typically revolves around designating areas as a type of **wildlife reserve** to **protect habitats** and the species that live there.



Module 4: Conserving Biodiversity



The table below outlines the types of wildlife reserves:

| Method | Actions |
|---------------------------------|---|
| In General | |
| Wildlife reserves | <ul style="list-style-type: none">- Designated to protect habitats and species from human interference and activity.- Preserves existing traditional use of the land (e.g. spiritual and hunting purposes).- Cooperate with local people to manage issues such as animal-human conflict over agriculture, logging and poaching. |
| Specific (UK) Types | |
| SSSI | Sites of Special Scientific Interest protect rare, vulnerable or highly biodiverse areas with an emphasis on conservation and research. |
| LNR | Local Nature Reserves are designated by local authorities as important areas for conservation work. |
| Marine conservation zone | Protect marine biodiversity by restricting fishing, oil drilling, and tourism. |
| National Park | Emphasise the aesthetic protection of UK landscapes for the access, enjoyment and use of everyone. |
| NNR | National Nature Reserves protect vulnerable environments for research and public education. |

Ex Situ Conservation

This involves protecting species by **removing** part of the **population from a threatened habitat** and placing it in a controlled environment.

The table below outlines the main approaches to ex situ conservation:

| Method | Actions |
|--------------------------|--|
| Zoo/Wildlife Park | <ul style="list-style-type: none">- Breed endangered animals in captivity, using artificial insemination, IVF and embryo transfer.- Educate the public.- Research into endangered species. |
| Botanic gardens | <ul style="list-style-type: none">- Grow rare or endangered plants.- Research plants and educate the public about them.- Collect and store seeds for easy long-term conservation at scale. |
| Seed banks | <ul style="list-style-type: none">- Long-term storage and distribution of seeds for agricultural, conservation, research and humanitarian work. |



Module 4: Conserving Biodiversity



Conservation Agreements

Conservation agreements help coordinate efforts to **protect endangered species and ecosystems** through shared objectives, legislation, and funding.

International agreements address conservation issues which are global and cross international borders; CITES (1973) and the CBD (1992) are two examples.

| Agreement | Purpose |
|--------------|--|
| CITES | The Convention on International Trade in Endangered Species of Wild Fauna and Flora is an international agreement that regulates and monitors the trade of over 25,000 species. |
| CBD | The Rio Convention on Biological Diversity promotes the conservation of biodiversity for the sustainable use of resources and sharing of research to the benefit of the communities from which organisms originate. |

*Examination materials typically provide the full name and abbreviation, and (so far) have tested candidates' knowledge and understanding of the named agreement, instead of testing their ability to identify and name it.

National and local agreements address conservation issues in an entire country, particular regions, or types of habitat. The CSS (1991), and later the ESS (2005) in the UK are two examples.

| Agreement | Purpose |
|-------------|--|
| CSS* | The Countryside Stewardship Scheme funds and supports farmers and landowners to promote biodiversity and heritage conservation. |
| ESS* | The Environmental Stewardship Scheme funds and supports farmers to conserve, enhance and promote the countryside. |

*Examination materials typically provide the full name and abbreviation, and (so far) have tested candidates' knowledge and understanding of the named agreement, instead of testing their ability to identify and name it.

The endorsed OCR A level textbook indicates that the CSS was replaced by the ESS, whilst in reality both programs are still running.



Module 4: Measuring Biodiversity



Measuring Biodiversity

Sampling techniques allow for a reliable **estimation of biodiversity** to be made by collecting data on which species are **present** in an area and their **abundance**.

The table below outlines the different sampling methods:

| Sampling Method | Description | Advantage | Disadvantage |
|-----------------|---|--|---|
| Random | Sites are chosen randomly. | Removes bias. | Species may be missed. |
| Opportunistic | Locations are chosen based on availability, accessibility or knowledge. | Produces data quickly. | Inherently biased, making the data highly unreliable |
| Stratified | The habitat is divided into areas (strata) based on their differences, and each is sampled. | All different areas of a habitat are sampled. | Some areas may be smaller, overrepresenting some species. |
| Systematic | Samples are taken at regular intervals along a measurable abiotic gradient. | Provides paired data: The location and abundance of species sampled is linked with measured abiotic factors. | Species outside of the transect are missed. |

Field equipment

Several standard techniques are used to collect data on different organisms:

- **Pitfall traps:** Containers sunk into the ground to catch small ground-dwelling animals.
- **Pooters:** Suck up small invertebrates into a container without harm.
- **Quadrats:** Square frames (e.g. 0.5 m × 0.5 m or 1 m × 1 m) used to estimate plant abundance. Quadrats are laid randomly or at intervals along a transect. Species may be counted directly or estimated by percentage cover.
- **Sweep nets:** Used for catching insects in tall vegetation.
- **Transects:** Lines across the habitat. A line transect records species touching the line; a belt transect involves placing quadrats along the line.

Measuring Species Richness and Species Evenness

Biodiversity within a habitat depends not only on the number of different species present, but also on how **evenly** the individuals are **distributed** among those species.

Module 4: Measuring Biodiversity



For example, the table below compares the abundance of 20 species in two habitats:

| Habitat | Species Present | Richness | Evenness | Interpretation |
|-------------------|--|----------|----------|--|
| Wildflower meadow | 20 species, each with similar abundance. | High | High | High biodiversity: many species with balanced populations. |
| Managed lawn | 20 species, dominated by 2 species. | High | Low | Lower biodiversity: same richness but reduced evenness. |

Simpson's Index of Diversity

Simpson's Index of Diversity (D) provides a quantitative measure of biodiversity that takes both species richness and evenness into account.

It can be used for **comparing different habitats** or monitoring changes over time.

The Formula

$$D = 1 - \sum (n / N)^2$$

Where:

- **n** = number of individuals of a particular species
- **N** = total number of individuals of all species
- Σ = the sum of
- **D** = a value between 0 and 1.

Interpreting D

A **high D** (closer to 1) means high biodiversity; many species and/or even populations.
A **low D** (closer to 0) means low biodiversity; few species and/or dominated by one.

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Module 4: Measuring Biodiversity



Example Calculation

Suppose a habitat has the following species counts:

| Species | Number of Individuals (n) |
|-----------|---------------------------|
| Buttercup | 25 |
| Dandelion | 25 |
| Daisy | 25 |
| Dock | 25 |
| Total (N) | 100 |

Using the formula:

$$D = 1 - \sum (n/N)^2$$

For convenience, data is typically processed in the following format:

| Species | n | n/N | (n/N) ² |
|-----------|----|------------------|--------------------|
| Dandelion | 85 | 0.85 | 0.7225 |
| Buttercup | 5 | 0.05 | 0.0025 |
| Daisy | 5 | 0.05 | 0.0025 |
| Dock | 5 | 0.05 | 0.0025 |
| | | sum (Σ) | 0.73 |
| | | D = 1 - Σ | 0.27 |

This low Simpsons Index of Diversity value (D) indicates low species evenness and biodiversity.



Assessing Genetic Biodiversity

Measuring genetic diversity allows scientists to monitor population health, detect signs of inbreeding or bottlenecks, and **guide conservation** or breeding decisions.

Examples include:

- **Endangered wild species**, such as cheetahs or Ethiopian wolves, which may have experienced genetic bottlenecks.
- **Captive breeding programmes** in zoos, where maintaining variation is vital to avoid inbreeding.
- **Rare domestic breeds** and pedigree animals, where selective breeding can reduce genetic diversity.

Measuring Genetic Biodiversity

Genetic diversity calculations are especially useful when assessing populations at risk of low genetic variation.

The **proportion of genotypes** for an allele in a population can be **calculated** using the **Hardy–Weinberg equation**.

There are three common ways to **measure** or **estimate** genetic biodiversity:

- **Hardy–Weinberg equation***: Predicts expected genotype frequencies in a population, assuming no migration, mutation, random mating, a large population size, and no selection pressure.
- **Polymorphic gene loci**: Estimates the proportion of gene loci in a population that have more than one allele.
- **Heterozygous gene loci**: Estimates the proportion of gene loci in an individual that are heterozygous.

*A2 content only, but presented here for relevance.

The Hardy–Weinberg Equation

The **Hardy–Weinberg** principle **predicts** expected **genotype frequencies** within a **non-evolving population** (allele frequencies do not change across generations).

Module 4: Measuring Genetic Biodiversity

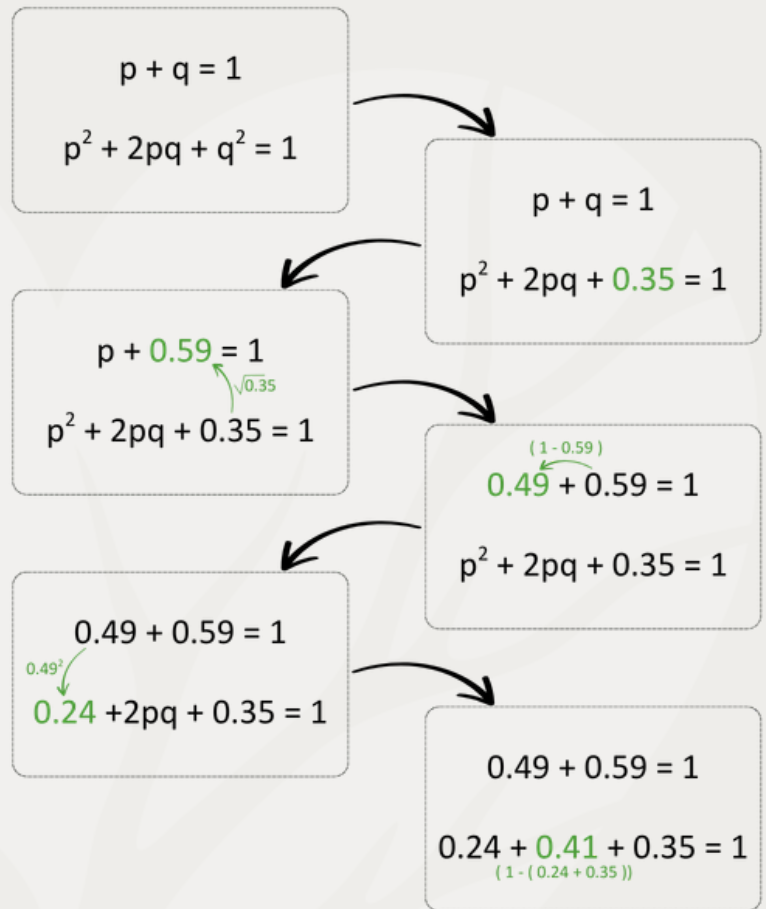


$$p^2 + 2pq + q^2 = 1$$

Where:

- **p** = frequency of the dominant allele (A)
- **q** = frequency of the recessive allele (a)
- **p²** = homozygous dominant (AA)
- **2pq** = heterozygous (Aa)
- **q²** = homozygous recessive (aa)

Because $p + q = 1$, knowing one allele, or genotype, frequency allows the rest to be calculated.



Determine The Percentage Polymorphic Gene Loci

You can **calculate** the **proportion** of **gene loci** in a population that are **polymorphic**.

$$\text{Proportion of polymorphic loci} = (\text{Number of polymorphic loci}) \div (\text{Total number of loci})$$

To express this as a percentage:

$$\text{Genetic diversity (\%)} = (\text{Polymorphic loci} \div \text{Total loci}) \times 100$$

Determine The Number of Heterozygous Gene Loci in an Individual

An **individual's** genetic diversity can be estimated by calculating the **proportion of loci** for which it is **heterozygous**:

$$\text{Heterozygosity (\%)} = (\text{Number of heterozygous loci} \div \text{Total loci in genome}) \times 100$$





Variation

Variation is the **differences** between individual organisms.

These differences may occur and be measured within a species (**intraspecific variation**) or between species (**interspecific variation**).

| Type of variation | Description | Example |
|-------------------|---|------------------------------------|
| Intraspecific | Variation between individuals of the same species | Eye colour in humans |
| Interspecific | Variation between different species | Cats and dogs have different teeth |

Continuous and Discontinuous Variation

Variation is either **continuous** or **discontinuous**, which affects its distribution in a population.

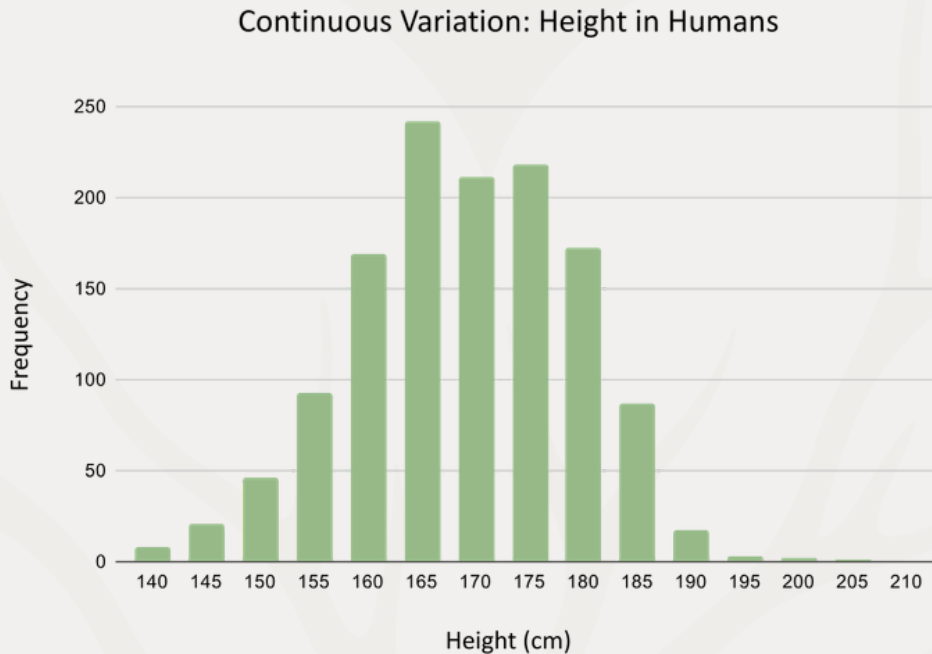
- **Continuous variation** is usually caused by **multiple genes** (are polygenic) and may be influenced by the environment. It shows a range of intermediate values.
- **Discontinuous variation** is usually caused by **one gene** (monogenic) and is not affected by the environment. It shows distinct categories.

Continuous data should typically be plotted onto a **histogram**, but line graphs are commonly used.

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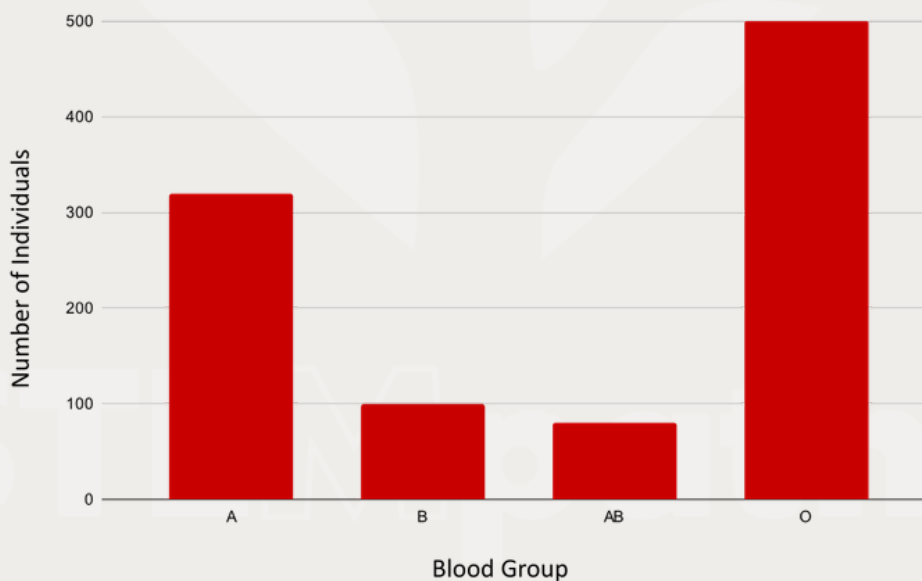


The graph below gives an example data set of a random sample of 1000 people, presented as a histogram, showing a typical **bell-shaped curve**.



Discontinuous data is typically plotted onto a **bar chart**.

The graph below gives an example data set of a random sample of 1000 people's blood type, presented as a bar chart, showing **distinct categories** of traits.





Quantitative vs Qualitative

Measuring variation produces data that can be **quantitative** or **qualitative**.

Quantitative data involves numerical measurements and is typically associated with **continuous variation** (e.g. height, mass).

Qualitative data describes categories or characteristics and relates to **discontinuous variation** (e.g. blood group, flower colour).

Examples of Continuous and Discontinuous Variation

The table below outlines some common examples of **continuous traits**:

| Trait | Description | Genetic Control |
|----------------------|---|-------------------------------------|
| Height in humans | Varies gradually; influenced by the environment | Polygenic and environmental factors |
| Body mass in animals | Influenced by diet, activity, and genetics | Polygenic and environmental factors |

The table below outlines some common examples of **discontinuous traits**:

| Trait | Description | Genetic Control |
|-----------------------|--|-----------------------------------|
| Human blood group | A, B, AB, or O | Single gene with multiple alleles |
| Flower colour in peas | Distinct categories (e.g. purple or white) | Single gene |

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Module 4: Causes of Variation



Causes of Variation

Variation in organisms is caused by differences in their **genetic information** and **environmental conditions**.

- **Environmental:** Caused by **differences** in **external conditions** or **experiences** that affect an organism's characteristics.
- **Genetic:** Caused by **differences** or **changes** in an organism's **DNA**, including the expression of genes in its genome.
- **Combined:** Caused by the interaction between genetic factors and environmental influences.

Environmental Causes of Variation

Environmental variation is caused by the conditions in an organism's surroundings influencing **how genes are expressed**.

The table below outlines some environmental factors and their effect on an organism:

| Environmental Factor | Effect on Organism |
|-------------------------------|--|
| Diet | Affects nutrient availability; a poor childhood diet can limit growth (e.g. human height). |
| Predators or Disease Exposure | Triggers stress and immune responses. |
| Human Activity | Introduces pollutants that can disrupt normal gene function. |
| Light | Influences hormones that control development; causes tanning in human skin. |
| Temperature | Alters enzyme activity; e.g. hawthorn trees grow tall in the wild but stay bushy when trimmed. |

Mutation

A **mutation** is a permanent **change in the base sequence of DNA**.

Mutations can be neutral, harmful, or (rarely) beneficial.

A mutation may:

- Change the amino acid sequence of a protein, and its structure or function.
- Affect gene regulation and expression.
- Have no effect at all.



Causes of Mutation

Mutations may occur due to cellular mishap or be induced by environmental factors (mutagens).

Genetic Causes of Mutation

Genetic mutations occur due to random errors by enzymes (e.g. DNA polymerase) or structural instability (e.g. spindle fibres failing to separate chromosomes).

Environmental Causes of Mutation

Mutations can occur due to environmental factors known as mutagens.

Mutagens increase the rate of mutation by damaging DNA or interfering with replication.

The table below outlines some mutagenic factors and the damage they cause:

| Cause | Type of Damage | Examples |
|--------------------|--|------------------------------------|
| Ionising radiation | Breaks DNA strands | X-rays, gamma rays |
| UV light | Causes thymine dimers | Sunlight |
| Chemicals | Modify bases or interfere with DNA replication | Cigarette smoke, asbestos, benzene |
| Viruses | Insert viral DNA into the host genome | HPV, retroviruses |





Adaptations

Adaptations are **characteristics** that improve an organism's ability to **survive** and **reproduce**, such as:

- Gain food, light, or water
- Avoid predators or disease
- Tolerate environmental stress (e.g. drought, salinity, cold)
- Reproduce successfully
- Respond to environmental changes

There are **three** main categories of **adaptation**:

- Anatomical
- Behavioural
- Physiological

Anatomical Adaptations

Anatomical adaptations are the **structural features** of an organism's body.

Plant examples include:

| Organism | Adaptation | Function |
|--------------|------------------------------|---|
| Marram grass | Long and/or deep roots | Stabilise dunes and absorb more water |
| Marram grass | Curled leaves | Reduce wind exposure |
| Marram grass | Hairy lower epidermis | Reduce airflow → trap moist air |
| Marram grass | Sunken and sunken stomata | Reduce air flow and water loss → reduce transpiration |
| Marram grass | Thick waxy cuticle | Prevent evaporation from leaf surfaces |
| Water lily | Stomata on the upper surface | Allow gas exchange while floating on water |
| Water lily | Air spaces in leaf tissues | Aid buoyancy and flotation |
| Water lily | Flexible leaf stalks | Allow movement with water currents |



Module 4: Adaptations



Animal examples include:

| Organism | Adaptation | Function |
|------------|-----------------------|---|
| Arctic fox | Small ears, thick fur | Reduce heat loss in cold climates |
| Camel | Wide calloused feet | Distribute surface area for walking on hot sand |

Behavioural Adaptations

Behavioural adaptations are actions or **responses** that improve survival or reproduction.

Plant examples include:

| Organism | Behaviour | Purpose |
|--------------|---------------------------------|--|
| Marram grass | Leaves roll up tighter when dry | Reduces surface area and conserves water |
| Marram grass | Close stomata when water is low | Limit water loss through transpiration |
| Marram grass | Grows upwards when buried | Reaches sunlight after sand deposition |

Animal examples include:

| Organism | Behaviour | Purpose |
|--------------|--|--------------------------------|
| Earthworm | Retreats into a burrow when touched | Avoids predation |
| Swallow | Migrates in winter | Avoids cold and food shortages |
| Sea cucumber | Ejects guts and fluids when threatened | Startles predators/aids escape |

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Physiological Adaptations

Physiological adaptations involve **internal processes** or chemical changes.

Plant examples include:

| Organism | Adaptation | Function |
|--------------|---------------------------------|---|
| Marram grass | Low water potential in cells | Allows water uptake in salty or dry soils |
| Marram grass | Turgor changes roll/unroll leaf | Minimises water loss from transpiration |

Animal examples include:

| Organism | Adaptation | Function |
|----------------|---------------------------------|-----------------------------|
| Desert animals | Produce very concentrated urine | Conserve water |
| Antarctic fish | Produce antifreeze proteins | Prevent blood from freezing |
| Humans | Sweating | Thermoregulation |

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Natural selection is a process by which those individuals who are **best adapted** to their environment **survive and reproduce more successfully** than those who are not, passing on their **alleles** to the next generation.

Over many generations, these **alleles**, and the characteristics they code for, **increase in frequency** in the population.

Evolution is when the **characteristics** in a species **change** due to significant **changes in allele frequencies**.

Speciation is when a **new species evolves**; the population becomes distinct enough from the ancestral precursor species that they can **no longer interbreed** to produce fertile offspring.

Natural Selection

The process of natural selection can be simplified into the following stages:

1. There is variation within a population caused by alleles which arise from mutation.
2. Some individuals will be better adapted (fitter) than others.
3. Selection pressures allow only the fitter individuals to survive and reproduce.
4. These individuals pass on their alleles for their traits to their offspring.
5. These characteristics, and their alleles, become more common in the next generation.
6. If enough time passes, as this process repeats over time genetic differences will accumulate within the population that it may be considered a new species from its ancestral one.

Natural Selection Example: Peppered Moths

Peppered moths are a historical example that occurred in England during the Industrial Revolution, as the burning of coal created soot that **darkened** the surfaces of **trees**. The **white and speckled** peppered moth, camouflaged to blend in with tree bark, now **stood out** and was easily **hunted** and eaten by predators. However, some individuals carried a **mutated allele that caused melanism** (black pigment). This trait was previously selected against and remained uncommon in the population, but now conferred a distinct **survival advantage** in the new environment, over time becoming the dominant characteristic in the population.

Module 4: Natural Selection



Once England's air pollution was resolved, a reversal occurred in the population's occurrence of phenotypes, and now the white speckled peppered moth is the most common form.

The natural selection process at work is:

1. There is variation within a population of peppered moths.
2. Some individuals have preexisting alleles, or a new mutation, that confers darker colouring (melanism).
3. The population is exposed to the selection pressure of industrial soot pollution, which darkens tree bark and makes pale moths more visible to predators, whilst darker moths are better camouflaged and less likely to be seen and eaten.
4. Those with the beneficial allele for melanism survive and reproduce, passing on the allele to their offspring.
5. The allele for dark colouring increases in frequency in the next generation, and so this new population is more likely to survive in polluted environments.
6. This process repeats over many generations, leading to the evolution of a population adapted to urban, soot-covered habitats.



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Speciation

Speciation is when an **isolated population** of a species **evolves** to become different enough that it can **no longer reproduce** with the original species' population to produce fertile offspring.

Populations become isolated – either **geographically** or **reproductively** – and stop interbreeding. Once isolated, the populations experience **different selection pressures** and, over time, **accumulate genetic differences**.

Types of Speciation

There are two main types of **speciation**:

Allopatric: Occurs when populations are **geographically separated**.

Sympatric: Occurs when populations are **reproductively isolated**.

Allopatric and sympatric speciation do have their own technical terms, which are not required for OCR A level Biology, and are not explored here.

Examples of Allopatric Speciation

The table below outlines some situations that result in geographical isolation:

| Description | Example |
|---|---|
| Continental or sea-level changes separate populations | Ostriches and emus are evolving separately |
| Ice sheets isolate species during glaciation | Sticklebacks in isolated post-glacial lakes |
| Separated populations adapt to contrasting local conditions | Lizards on either side of a canyon |

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Examples of Sympatric Speciation

The table below outlines some processes that result in reproductive isolation:

| Process | Description | Example |
|-------------------------|--|--------------------------------|
| Habitat Differentiation | Populations evolve to be adapted to different resources in the same area | Apple vs hawthorn maggot flies |
| Sexual Selection | Preferences for certain traits isolate groups (mate choice divergence) | African cichlid fish |
| Temporal Isolation | Groups reproduce at different times of year or day | 13-year vs 17-year cicadas |

Convergent Evolution

Convergent evolution is when **unrelated** species independently evolve **similar traits** or adaptations in response to **similar selection pressures**, even though they are **not closely related**.

The **key features** of convergent evolution is that it:

- Occurs in **unrelated species** living in similar environments
- Driven by **similar selection pressures**, not shared ancestry
- Results in **analogous structures** (same function, different origin)

The table below outlines some common examples of convergent evolution:

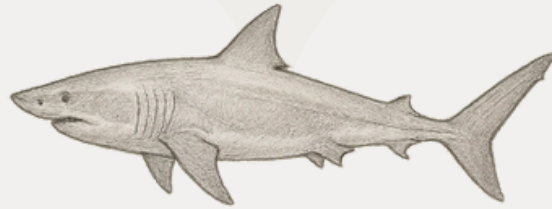
| Species 1 | Species 2 | Shared Adaptation(s) | Reason for Convergence |
|----------------|----------------|--|---|
| Marsupial mole | Placental mole | - Streamlined body - Strong forelimbs - Reduced eyes | Adaptation for life underground (burrowing) |
| Shark | Dolphin | - Fins - Streamlined body - Powerful tail | Fast swimming in aquatic environments |
| Cactus | Euphorbia | - Thick - Fleshy stems - Spines | Water storage and herbivore protection in desert environments |



Module 4: Evolution and Speciation



The image below compares the typical anatomical profile of sharks (fish), ichthyosaurs (reptiles) and dolphins (mammals), which became similar through convergent evolution:



Shark



Ichthyosaur



Dolphin

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Evidence for Natural Selection and Evolution

Anatomy, DNA, fossils, biomolecules and real-time observations provide **evidence** and **examples** for species **evolving by natural selection**.

Fossil Evidence

Fossils are the **preserved remains or traces** of organisms from the past.

The fossil record provides direct evidence of:

- Extinct species that once existed
- New species which resemble older ones
- Transitional fossils which show intermediate changes

Anatomical Evidence

Similarities and differences in the anatomical structures of different species offer insight into **evolutionary relationships**.

Homologous structures are anatomical features which are present in different species, but have adapted over time to **serve different functions**, such as the bones found in a human hand vs the same bones found in a bat's wing.

Genetic Evidence for Evolution

The discovery of DNA and the development of techniques to sequence and compare different genes and genomes allow for evolutionary changes and relationships to be accurately explored.

The table below outlines some of the different types of genetic material that can be investigated:

| Evidence | What It Shows |
|-----------------------------------|--|
| DNA sequence similarity | Closely related species have more similar base sequences. |
| % of shared genes/conserved genes | Homologous (matching) genes appear in many species, indicating descent from a common ancestor and the genes' importance in being selected for. |
| Genetic markers/mutations | Shared mutations or marker sequences indicate common ancestry. |





Biomolecular Evidence

The **biomolecules** synthesised in organisms are **determined** by their underlying **genetic code**. In some situations it may be easier, or more informative, to examine and compare these, particularly proteins, to determine evolutionary relationships.

The table below outlines the different biomolecules which can be investigated:

| Evidence | What It Shows |
|--|---|
| Shared amino acid sequences in proteins | Closely related species have similar or identical amino acid sequences. |
| Differences in protein primary structure | Distantly related species have more differences. |
| Shared non-coding DNA | Identical sequence insertions passed down from a common ancestor. |
| Mutated DNA repeat regions | Some mutations have harmful effects, but may still be passed on. |

Observing Evolution Today

While most **evolutionary changes** take place over **long periods**, some examples of natural selection can be seen happening within just a few generations. These examples often arise in response to strong selection pressures such as drugs, pollution, or pesticides.

They demonstrate how beneficial traits can become more common over time.

The table below outlines some important examples of modern evolution in action:

| Example | What It Shows |
|-----------------------|--|
| Antibiotic resistance | Random mutations made some bacteria resistant, and these resistant strains became more common. |
| Peppered moths | Changes in pollution affected camouflage success, so darker or lighter morphs were selected. |
| Mosquitoes and DDT | Insecticide use favoured resistant mosquitoes, so the population became resistant over time. |



Module 4: Charles Darwin and Alfred Russel Wallace



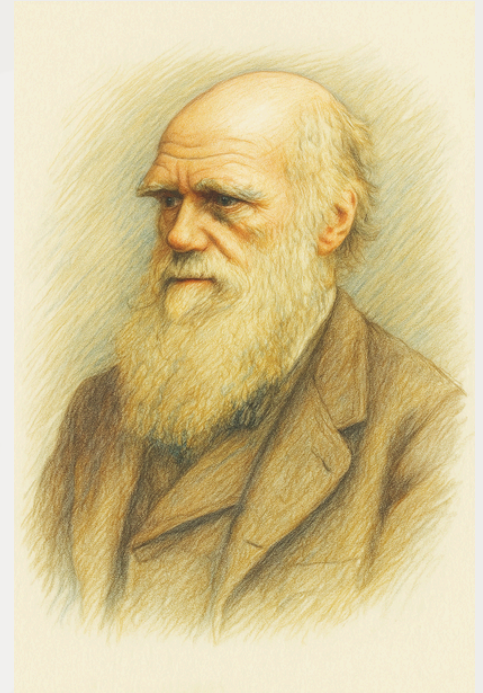
Charles Darwin's Evidence for Natural Selection

Charles Darwin travelled around the world on HMS Beagle between 1831 and 1836.

The observations Darwin made during this time gave him the idea that all **species** were **descended from other**, earlier species, and that all species **may be related**.

This became the basis of Darwin's theory of **evolution by natural selection**, a scientifically supported explanation for **how species change over time**.

The table below outlines **Darwin's** key observations and the subsequent hypotheses and theories:



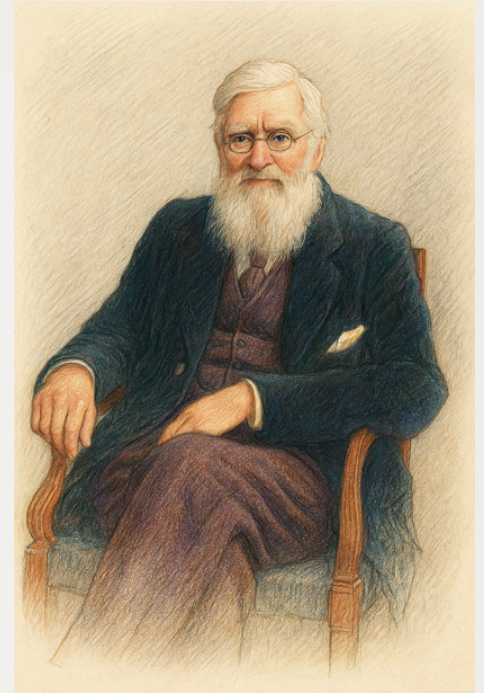
| Observation | Hypothesis | Theory |
|---|---|---|
| Fossils of extinct animals resembled living species in the same region | Extinct and extant species may be related | Species change over time and may evolve from earlier forms |
| Variation existed between individuals of the same species | Some individuals are better adapted to survive and reproduce | Variation means some individuals will pass on their traits more successfully than others: natural selection |
| Offspring resembled their parents more than others, yet still varied | Advantageous traits are often inherited and passed to offspring | Traits that increase survival and reproduction become more common over time |
| Different species lived in similar habitats but shared similar features | The environment determines which traits are useful | Different species can evolve similar traits under the same selection pressures |
| Different finches and tortoises on each Galápagos island | Populations adapt to local environments over time | Isolation and natural selection can lead to new species evolving |

Module 4: Charles Darwin and Alfred Russel Wallace



Alfred Russel Wallace's Evidence for Natural Selection

Alfred Russel Wallace was a British naturalist, collector, and explorer who **independently** developed a **theory of evolution by natural selection** at the same time as Charles Darwin.



The table below outlines **Russel Wallace's** key observations and the subsequent hypotheses and theories:

| Observation | Hypothesis | Theory |
|--|--|--|
| Species on either side of a geographical divide were completely different. | Long-term geographical separation prevents populations from mixing. | Isolation leads to gradual divergence and the formation of distinct species. |
| Animal species had traits suited to where they lived. | Species evolve over time in response to selection pressures caused by their environment. | Natural selection causes populations to become adapted to their environment. |
| Variation existed between individuals of the same species. | Some individuals are better adapted to survive and reproduce. | Variation means some individuals will pass on their traits more successfully than others. |
| Tropical islands had high numbers of unique species. | Isolated, or diverse habitats accelerate the development of new species | Evolution occurs rapidly where populations are both separated and ecologically varied, driving speciation. |

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Classification

Classification is the process of placing organisms into **groups**.

Classification helps scientists to:

- Identify and name organisms
- Predict shared characteristics
- Organise biological knowledge
- Understand evolutionary relationships

Organisms can be classified by:

- **Observable characteristics** such as limbs or flower colour.
- **Cellular features** such as the presence of a nucleus.
- **Molecular traits** such as DNA and RNA sequences.
- **Physiological processes** (e.g. respiration type)

Artificial vs Natural Classification

The table below outlines the characteristics of artificial and natural selection:

| Feature | Artificial Classification | Natural Classification |
|--------------------------------|----------------------------------|--|
| Based on | A selection of observable traits | A wide range of characteristics with a focus on genetic evidence |
| Reflects evolutionary history? | ✘ No | ✔ Yes |
| Stability | Relatively constant | Changes with new molecular data |
| Example | Grouping plants by leaf shape | Grouping by DNA sequence similarity |

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Natural Classification: Molecular Evidence

Natural classification emphasises the classification of organisms based on their evolutionary relationships and common ancestry using the following molecules:

| Molecule | Use in Classification | Example Use |
|----------|---|--|
| DNA | Compares gene sequences to reveal evolutionary relationships | Comparing conserved genes like Hox or 16S rRNA |
| RNA | - rRNA used for ancient divergence - mRNA to study gene expression | - 18S rRNA for eukaryotes, 16S for prokaryotes - mRNA profiles in related species |
| Protein | Compares amino acid sequences for functional similarity | Cytochrome c (respiratory protein) sequence comparison in animals |

The Taxonomic Hierarchy

Taxonomic ranks (also known as taxonomic levels) are **hierarchical groups** into which organisms are **sorted** (hierarchical classification) to reflect their relative '**closeness**' to each other.

Binomial nomenclature (also known as the binomial system) is a **two-part naming** system that uses the **genus** and **species names** from the taxonomic hierarchy to produce a unique two-part name for **identifying** a species.

Each organism is given a two-part Latin name:

Genus (capitalised) + species (lowercase)
e.g. *Homo sapiens*

The **binomial name** is traditionally written in **italics**, but is commonly underlined when handwritten.

The **advantages** of the binomial naming system included:

- **Universality:** Latin was the common language (of the time), avoiding confusion **across different languages**, and even within different regions of the same country.
- **Precision:** Identifies a single species **without ambiguity**.
- **Relationships:** Including the genus shows the **evolutionary relationships** between species.



Module 4: Classification and Phylogenetics



The table below outlines the groups you need to recall at each taxonomic level:

| Rank | Groups |
|---------|--|
| Domain | <ul style="list-style-type: none"> - Bacteria (Kingdom: Eubacteria) - Archaea (Kingdom: Archaeobacteria) - Eukarya (Kingdoms: animals, plants, fungi, protists) |
| Kingdom | <ul style="list-style-type: none"> - Animalia (animals) - Plantae (plants) - Fungi (mushrooms, yeasts) - Protocista (also known as Protista or protists) (unicellular eukaryotes) - Eubacteria ('true' bacteria) - Archaeobacteria ('ancient' bacteria)* |
| Phylum | <p>Not expected to recall, but hopefully familiar with:</p> <ul style="list-style-type: none"> - Chordata (vertebrates) - Arthropoda (insects, spiders, crustaceans) |
| Class | <p>Not expected to recall, but hopefully familiar with:</p> <ul style="list-style-type: none"> - Mammalia (mammals) - Insecta (insects) - Reptilia (reptiles) - Aves (birds) - Amphibia (amphibians) |
| Order | <p>Not expected to recall, but hopefully familiar with:</p> <ul style="list-style-type: none"> - Primates (apes, humans) - Carnivora (dogs, cats, bears) |
| Family | <p>Not expected to recall, but hopefully familiar with:</p> <ul style="list-style-type: none"> - Hominidae (great apes) - Felidae (cats) - Canidae (dogs) - Muridae (mice) |
| Genus | <p>Not expected to recall, but hopefully familiar with:</p> <ul style="list-style-type: none"> - Homo (humans) - Canis (dogs, wolves) - Felis (cats) |
| Species | <p>Not expected to recall, but hopefully familiar with:</p> <ul style="list-style-type: none"> - Homo sapiens (humans) - Canis lupus (grey wolf) - Felis catus (domestic cat) |

*Archaeobacteria is a misleading name, as Eubacteria appear to be the older evolutionary lineage.

You are expected to know and place organisms in the correct **Domain** and **Kingdom** with some provided information, but you do not need to recall the groups of the lower ranks beyond expected general knowledge (which has been included in the table for convenience).





A commonly used **mnemonic** to recall the order of these ranks is:

Dear King Philip Came Over For Good Soup

The Five Kingdoms System

The **5 Kingdoms system** was the 1960s taxonomic system that arose from centuries of research:

| Kingdom | Features |
|--------------|--|
| Animalia | No cell wall, heterotrophic, motile, multicellular |
| Fungi | Chitin cell wall, saprophytic, extracellular digestion |
| Plantae | Cellulose cell wall, autotrophic, multicellular |
| Protocista | Mostly unicellular, some plant-like or animal-like |
| Prokaryotae* | No nucleus, unicellular, peptidoglycan cell wall |

*Not to be confused with the term prokaryote/prokaryotic, which describes a cell without membrane-bound organelles, not what kingdom it belongs to.

At this point in time, archaea had not been discovered/recognised yet, and the domain level of classification had not been invented.

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Module 4: Classification and Phylogenetics



The features used to classify organisms into the 'correct' Kingdom are outlined in the table below:

| Feature | Animalia | Plantae | Fungi | Protocista | Prokaryotae* |
|------------------------------|----------------------------------|-----------------|--|---|-------------------|
| Cell type | Eukaryotic | | | | Prokaryotic |
| Nucleus | Present | | | | Absent |
| DNA | Linear chromosomes with histones | | | | Loop of naked DNA |
| Membrane-bound organelles | Present | | | | Absent |
| Ribosomes | 80s | | | | 75s |
| Reproduction | Sexual and/or asexual | | | | Asexual |
| Unicellular or multicellular | Multicellular | | Unicellular (e.g. yeasts) or multicellular (e.g. mycelium) | Mostly unicellular (some multicellular algae) | Unicellular |
| Cell wall | None | Yes (cellulose) | Yes (chitin) | Some (peptidoglycan) | |
| Nutrition | Heterotrophic | Autotrophic | Heterotrophic | Autotrophic or heterotrophic | |
| Mobility | Most can | Can't | | Some can | |

*These features do not apply to the archaea, whose discovery ended the 5 Kingdoms system.

The Three-Domain System

By 1990 **Carl Woese's** research had revealed significant differences between organisms within the 5 Kingdom's prokaryotae group.

Structural **differences** between the **bacteria** and **archaea** can be found in their:

- Cell membrane
- Cell wall
- DNA replication
- Flagella
- Genetic material (bacteria lack histone-like proteins)
- RNA synthesis (they have different enzymes)



Module 4: Classification and Phylogenetics



The structural **similarities** between the archaea and eukarya include:

- DNA replication (similar mechanisms and enzymes)
- Genetic material (both have histone-like proteins)
- RNA synthesis (similar enzymes/RNA polymerase)

The differences observed between bacterial and archaea cells, and the similarities shared between the archaea and eukaryotes, provided substantial evidence that the archaea were more **closely related** to the eukaryotes than bacteria are. This insight led Woese to propose the **3 domain system** above the traditional kingdom ranks which, after initial opposition, was widely accepted.

Phylogeny

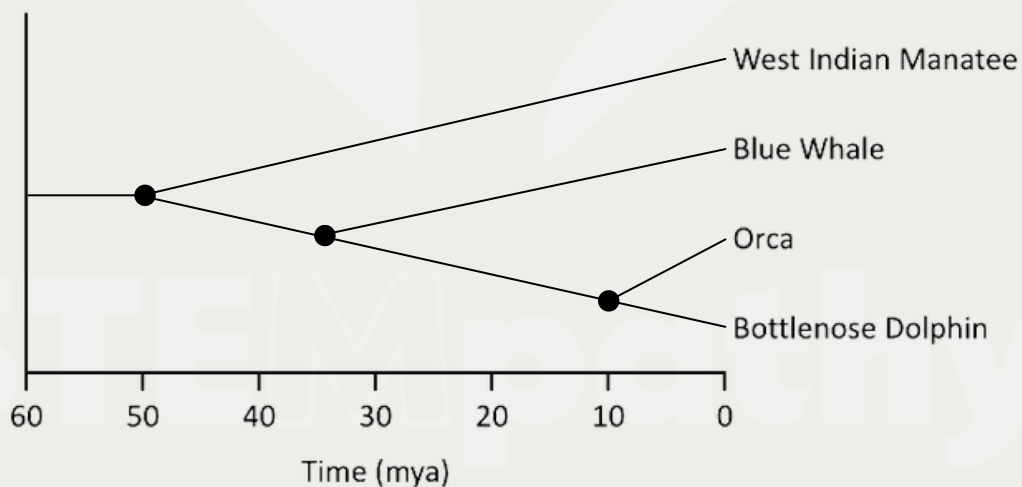
Phylogeny is the study of **evolutionary relationships** between organisms.

Phylogeny defines a species as a group of organisms that are very similar genetically (and subsequently), metabolically, physiologically and anatomically.

This definition avoids many of the problems with the traditional definition of a species, which does not apply to asexually reproducing organisms.

Phylogenetics is a scientific field of research that determines and reconstructs the evolutionary relationships between organisms.

These relationships are often shown as phylogenetic trees:



- Tips: present-day species
- Nodes: common ancestors
- Closer branches: more recent common ancestor



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