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Carbohydrates & Lipids

IB Biology - Revision Notes

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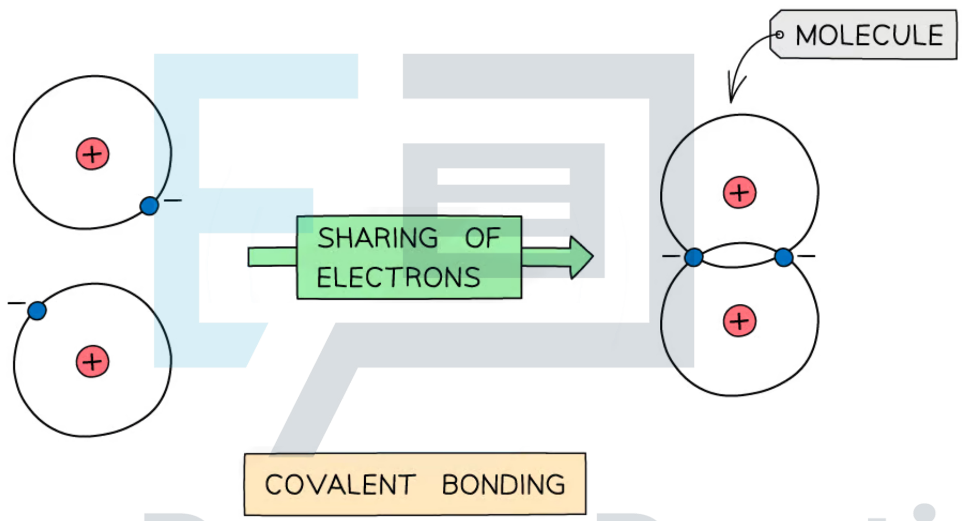
Properties of Carbon

Chemical Properties of Carbon

Carbon forms covalent bonds

- A covalent bond forms when a pair of **electrons are shared** between two atoms
- A single covalent bond is represented by a **short straight line** between the two atoms, e.g. H-H
- **Electrons are shared** between atoms to generate **strong bonds** within compounds



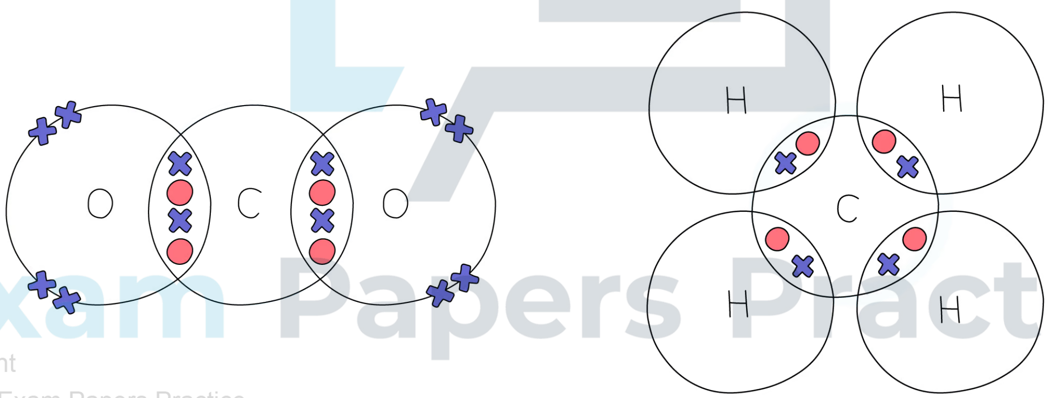
Electrons are shared in a covalent bond

Carbon in biological molecules

- Carbon is present in all of the four major categories of **biological molecules;** this is why life on Earth is often described as "**carbon based**"
- Carbon is present in:
  - Carbohydrates
  - Lipids
  - Proteins
  - Nucleic acids
- Carbon has **four electrons** in its outer shell, meaning that each atom can form **four covalent bonds**
  - Carbon can therefore be a component of **large, stable molecules**

- Carbon forms **millions of different covalently-bonded compounds**, mainly with hydrogen and oxygen
- Carbon atoms can arrange themselves to form a huge variety of chemical compounds; it can:
  - **Bond** to **other carbon atoms**, or **other atoms** such as hydrogen, nitrogen, oxygen and sulfur
  - Form molecules with long **branched chains** such as glycogen
  - Form long **straight chain** molecules such as cellulose
  - Form molecules containing **cyclic single rings** such as the pyrimidines (thymine, uracil and cytosine)
  - Form molecules with **multiple rings**, including starches and the purines (adenine and guanine)
  - Produce a **tetrahedral structure** which allows the formation of varied carbon compounds which have different 3-D shapes and hence, different biological properties
- Carbon atoms can form up to four **single covalent bonds** or a combination of **double** and single bonds, e.g.
  - Carbon dioxide contains two double bonds
  - Methane contains four single covalent bonds

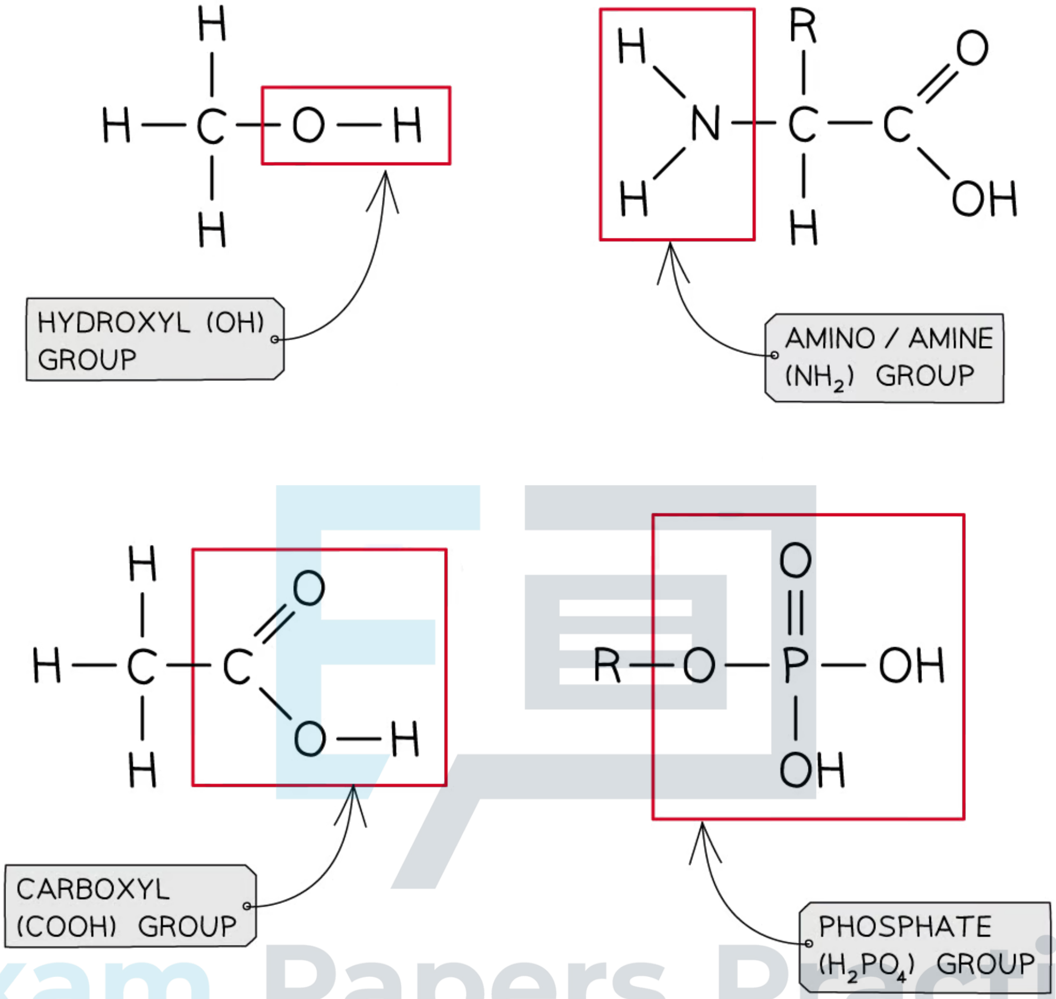
Covalent bonding in carbon-containing molecules diagram



Carbon atoms can form either single or double bonds in a variety of molecules. Carbon dioxide (left) contains double bonds, while methane (right) contains single bonds.

- **Double** and **triple bonds** can form with an adjacent carbon atom, allowing unsaturated compounds to form
- Carbon atoms can also form part of many different **functional groups** that give organic compounds their individual properties, e.g.
  - Hydroxyl groups
  - Carboxyl groups
  - Amino groups
  - Phosphate groups

Functional groups diagram



Functional groups include hydroxyl (OH), amino (NH_2), carboxyl (COOH), and phosphate (H_2PO_4) groups

NOS: Scientific conventions are based on international agreement

- The professional scientific community is **global**, meaning that scientists from all over the world may work on the same research, and need to be able to **communicate clearly** with each other
- Scientific conventions are thereby **agreed upon** and **used internationally**
  - **SI** (which stands for système international) **unit prefixes** is one example
    - kilo = 10^3
    - centi = 10^{-2}
    - milli = 10^{-3}
    - micro = 10^{-6}
    - nano = 10^{-9}

Macromolecules

Formation of Macromolecules

- Carbon compounds can be **large molecules** made from many **small, repeating subunits**
  - **Monomers** are the smaller units from which larger molecules are made
  - **Polymers** are molecules made from a large number of monomers joined together in a chain
  - The process by which monomers join to form polymers is **polymerisation**
- **Macromolecules** are very large molecules
  - They contain 1000 or more atoms and so have a **high molecular mass**
  - Polymers can be macromolecules, however, **not all macromolecules are polymers**; polymers must consist of many repeating subunits
    - E.g. lipids are not polymers, as they do not consist of repeating monomers

Key biological macromolecules table

Macromolecule	Monomer
Carbohydrates (polysaccharides)	Monosaccharides
Lipids	Fatty acids, glycerol, phosphate groups
Proteins (polypeptides)	Amino acids
Nucleic acids	Nucleotides

Formation of macromolecules

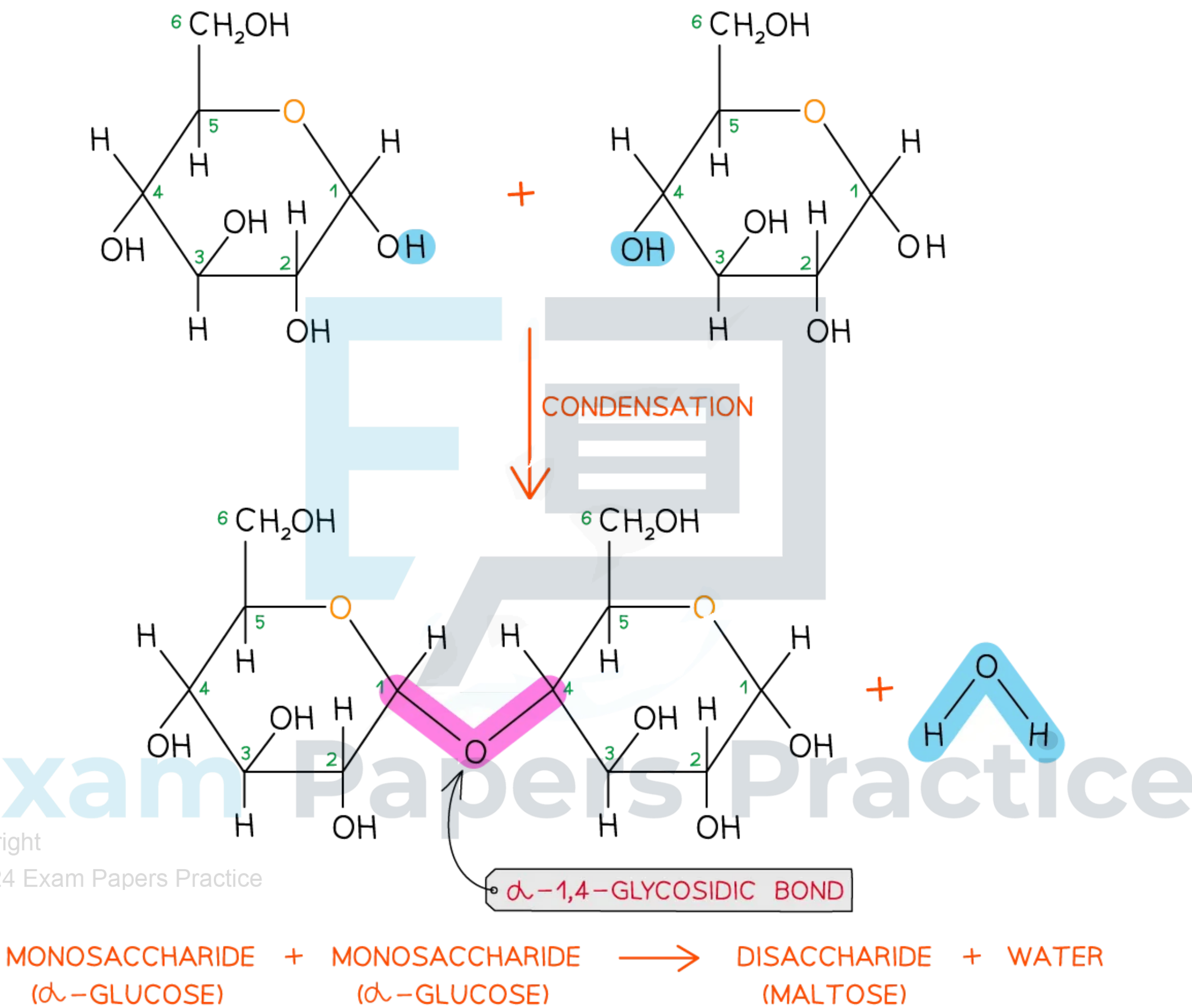
- Macromolecules are formed during **condensation reactions**
  - A **condensation reaction** occurs when molecules combine together, forming **covalent bonds** and resulting in **polymers** (polymerisation) or macromolecules
  - **Water** is **removed** as part of the reaction

Examples of condensation reactions

- **Polysaccharides**

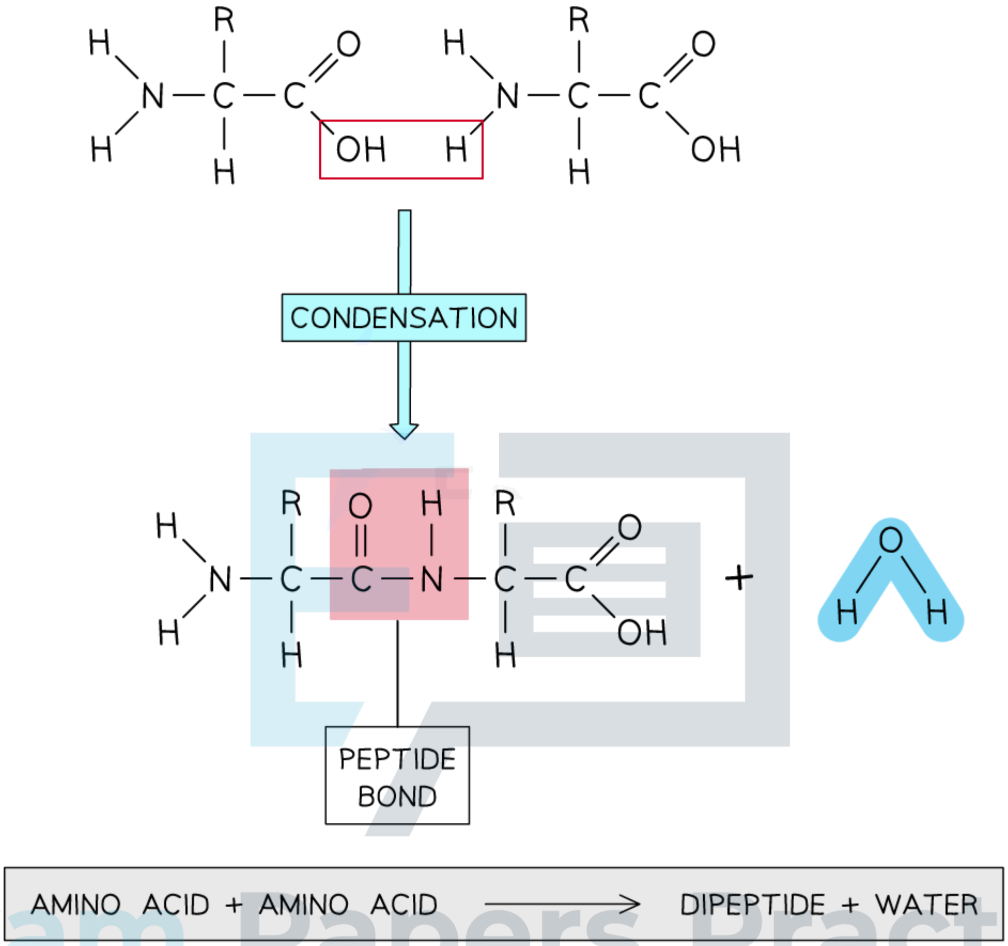
- Polysaccharides are formed when **two hydroxyl (OH) groups** on different monosaccharides interact to form a **strong covalent bond** called a **glycosidic bond**

Glycosidic bond formation diagram



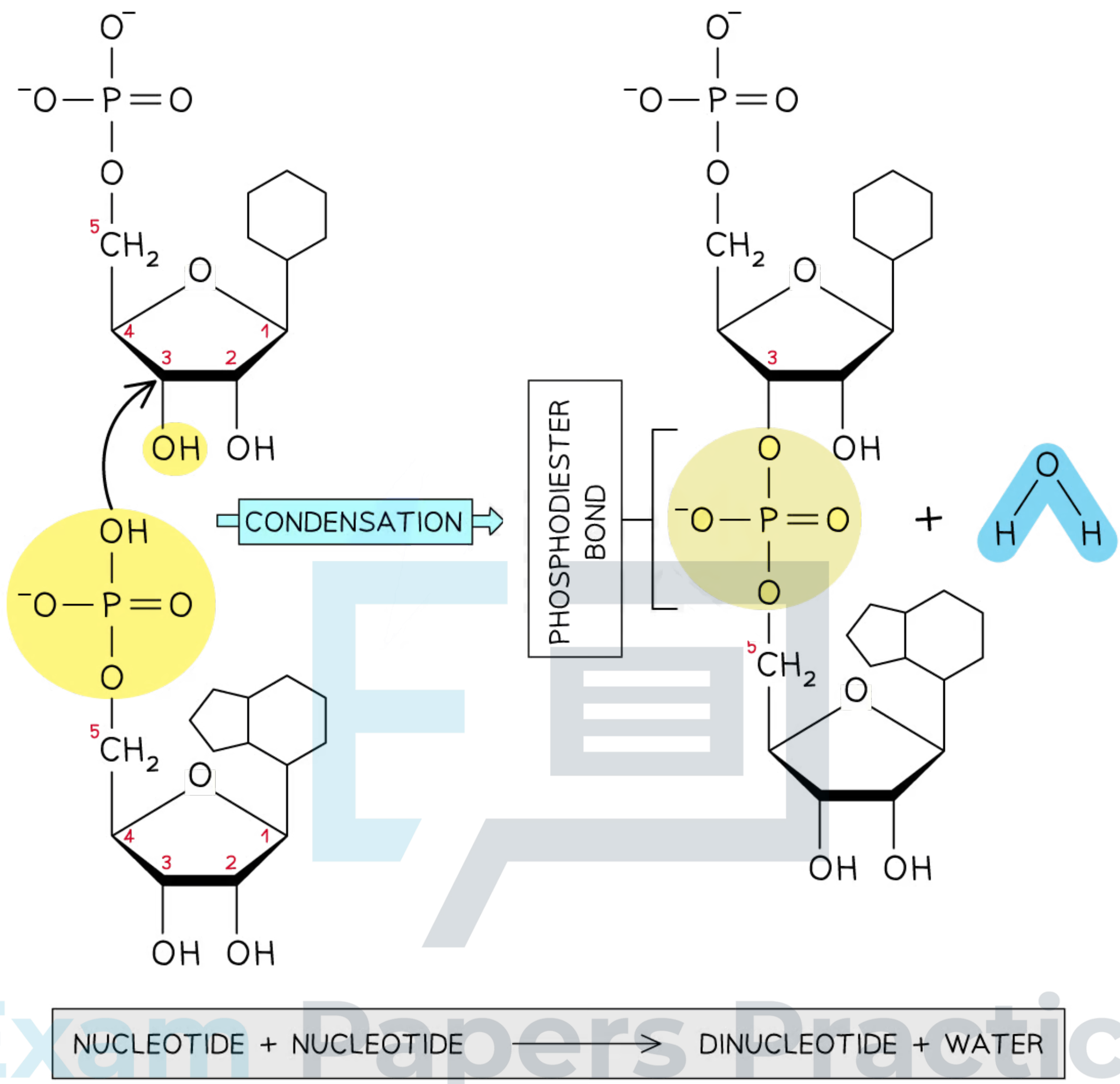
- **Polypeptides**
  - Polypeptides are formed by **condensation reactions**
  - **Two amino acid** monomers interact to form a **strong covalent bond** called a **peptide bond**

Peptide bond formation diagram



- **Nucleic acids**
  - Separate **nucleotides are joined together** via **condensation reactions** to form a **phosphodiester bond**
    - These condensation reactions occur between the **phosphate group** of one nucleotide and the **pentose sugar** of the next nucleotide
    - It is called a phospho**di**ester bond because it consists of a phosphate group and **two** ester bonds

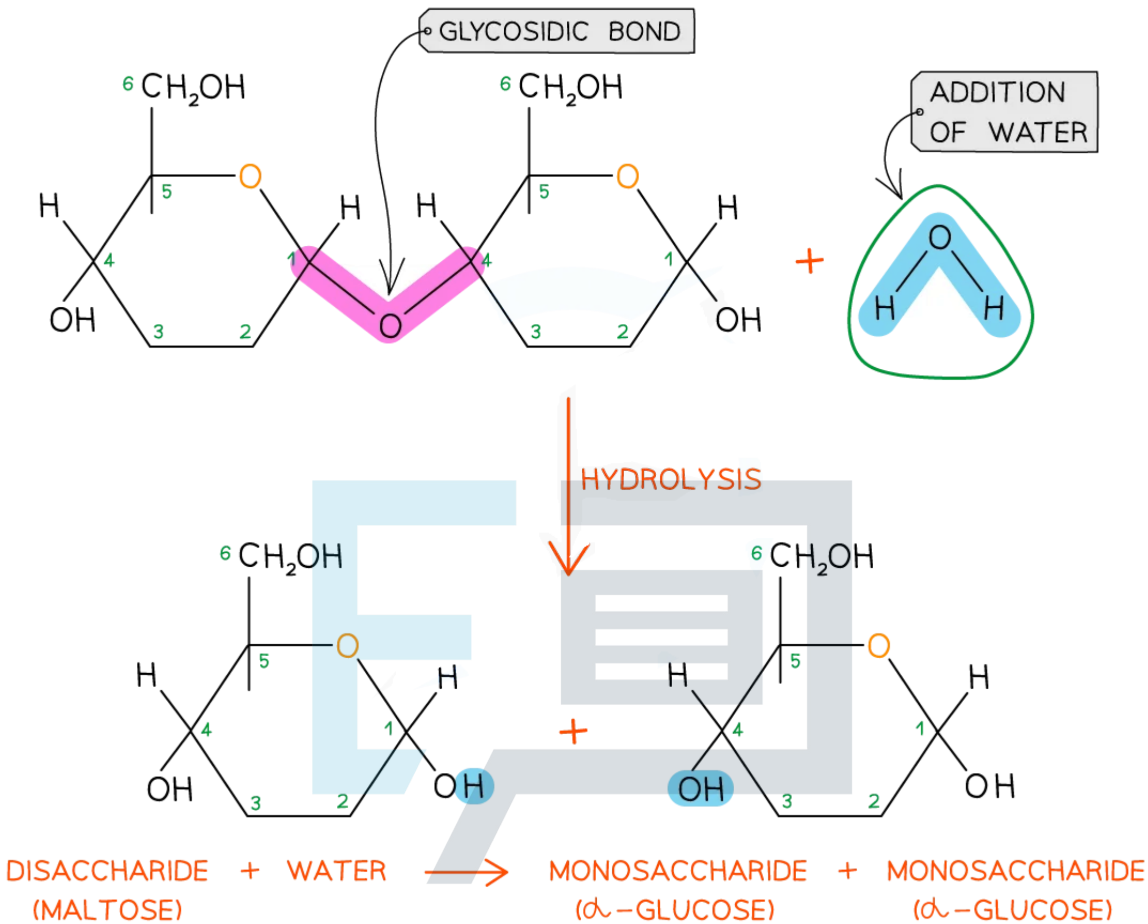
Phosphodiester bond formation diagram



Digestion of Polymers

- Macromolecules often need to be **broken down into their monomers**, e.g. this happens in digestion
- The reaction that allows this to occur is a **hydrolysis reaction**
  - Hydrolysis means '*lyse*' (to break) and '*hydro*' (with water)
- In the hydrolysis of macromolecules, **covalent bonds** are **broken** when **water** is **added**
  - The **-O** and **-OH** from the water molecule are used to form the functional groups of the products
- Examples of hydrolysis reactions include:
  - The hydrolysis of glycosidic bonds in poly- or disaccharides to produce monosaccharides
  - The hydrolysis of peptide bonds in polypeptides to produce amino acids
  - Hydrolysis of ester bonds in triglycerides to produce three fatty acids and glycerol

Hydrolysis of a disaccharide diagram

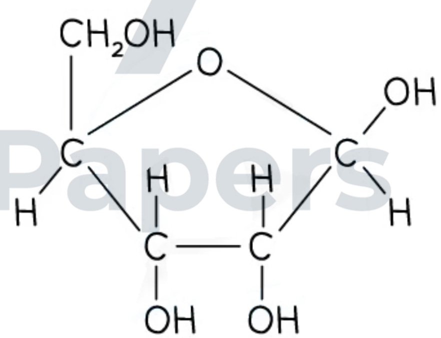

GLYCOSIDIC BOND
ADDITION OF WATER
HYDROLYSIS
DISACCHARIDE (MALTOSE) + WATER → MONOSACCHARIDE (α-GLUCOSE) + MONOSACCHARIDE (α-GLUCOSE)

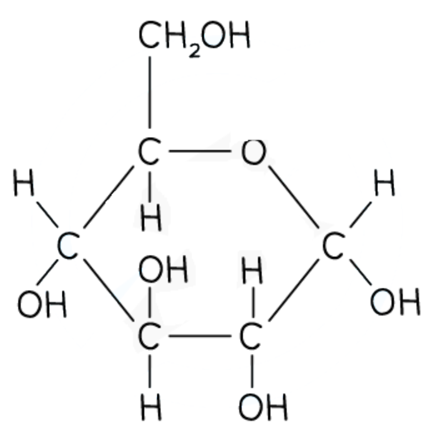
Carbohydrates: Definition, Functions & Examples

Monosaccharides

- The monomers of carbohydrates are **monosaccharides**
  - Two monosaccharides can join to form a **disaccharide**
  - Many monosaccharides join to form a **polysaccharide**
- Monosaccharides can join together via condensation reactions
  - The new chemical bond that forms between two monosaccharides is known as a **glycosidic bond**
- Monosaccharides have the **general formula $C_nH_{2n}O_n$**
  - Where 'n' is the number of carbon atoms in the molecule
  - Note that this formula only applies to monosaccharides
- Monosaccharide **properties** include:
  - Colourless crystalline molecules
  - Soluble in water
- There are different types of monosaccharide formed from molecules with varying numbers of carbon atoms, for example:
  - **Triose** molecules contain 3 carbon atoms, e.g. glyceraldehyde
  - **Pentose** molecules contain 5 carbon atoms, e.g. ribose
  - **Hexose** molecules contain 6 carbon atoms, e.g. glucose

Ribose and glucose structure diagrams



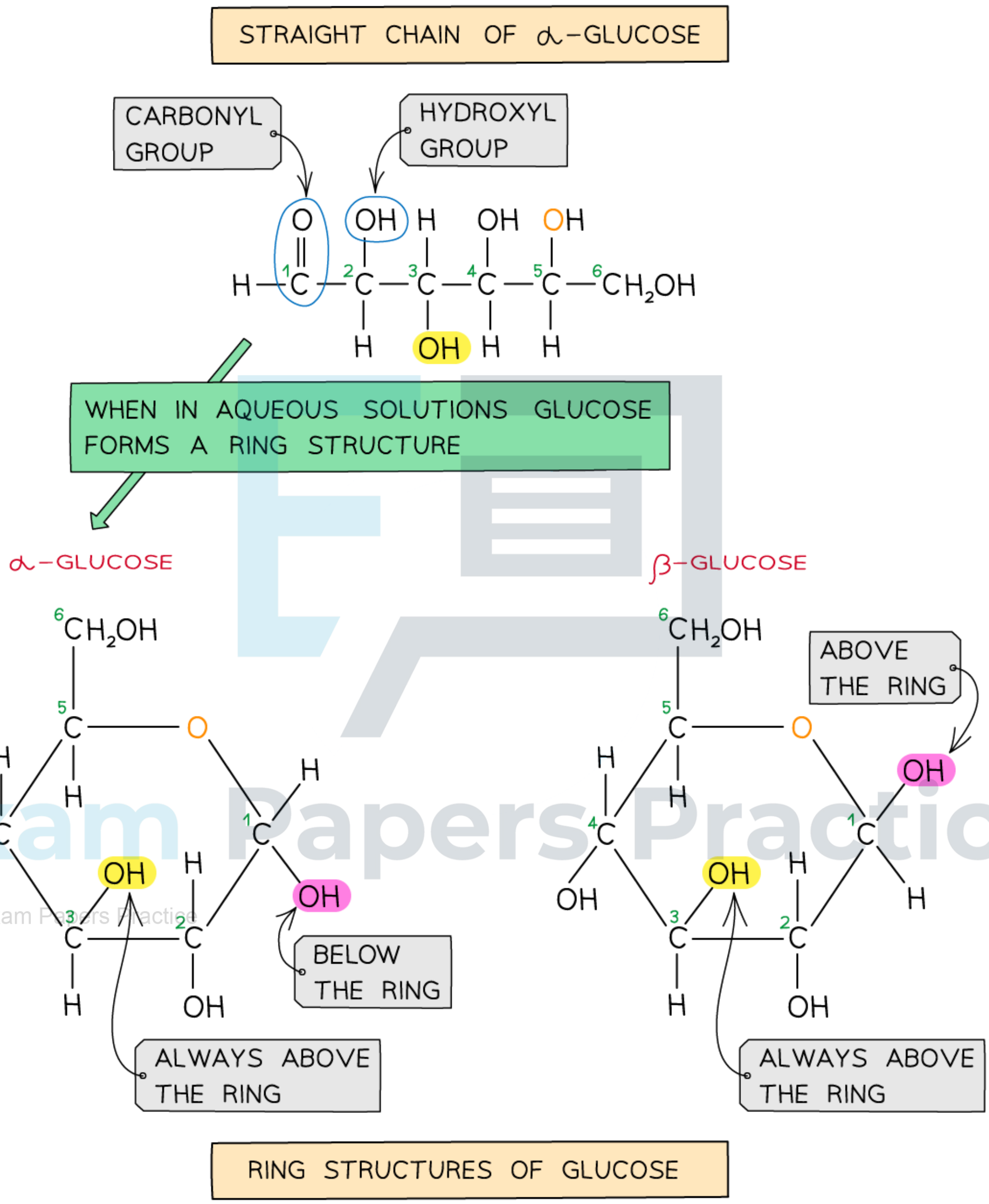


Pentose sugars, such as ribose (top), can be recognised by their five-point carbon rings and hexose sugars, such as glucose (bottom) by their six-point carbon rings

Glucose

- The most well-known carbohydrate monomer is **glucose**
- Glucose has the molecular formula **$C_6H_{12}O_6$**
  - Glucose is the most common monosaccharide and is of central importance to most forms of life
  - Glucose is the main substrate used in respiration, releasing energy for the production of ATP
  - Glucose is produced during photosynthesis
- Glucose exists in two structurally different forms, **alpha (α) glucose** and **beta (β) glucose,** these structures are known as the **isomers** of glucose
  - This structural variety results in different functions between carbohydrates
  - This **seemingly minor example of isomerism** has **far-reaching consequences** on the functions of the polymers

Glucose structure diagrams



The straight chain structure of glucose can form rings of alpha glucose. Glucose also forms rings of beta glucose.

- Different polysaccharides are formed from the **two isomers of glucose**
  - **Starch** and **glycogen** are made from molecules of **alpha glucose**
  - **Cellulose** is made from molecules of **beta glucose**

Properties of glucose

- Glucose has several properties that are essential to its function in living organisms
  - **Stable structure** due to the presence of **covalent bonds** which are strong and hard to break
  - **Soluble in water** due to its polar nature
  - Easily **transportable** due to its water solubility
  - A **source of chemical energy** when its covalent bonds are broken

Exam Tip

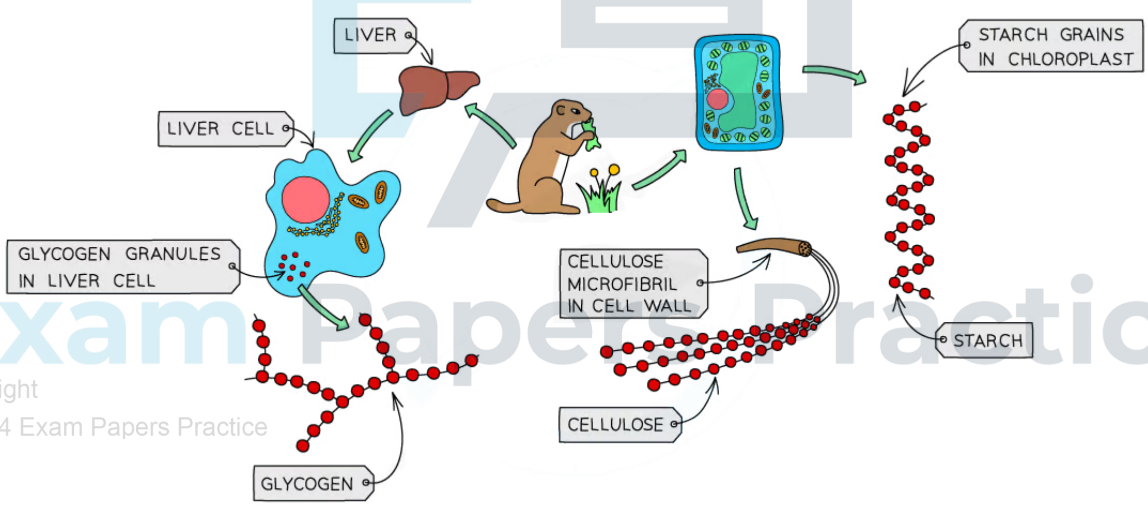
You should be able to recognise ring structures of hexose and pentose monosaccharides, and use glucose as an example of a hexose monosaccharide

Polysaccharides: Energy Storage

The function of carbohydrates

- Carbohydrates function as essential **energy storage** molecules and as **structural molecules**
- **Starch** and **glycogen** are effective storage polysaccharides because they are:
  - **Compact**
    - Large quantities can be stored in a small space
  - **Insoluble**
    - This is essential because soluble molecules will dissolve in cell cytoplasm, lowering the water potential and causing water to move into cells
    - If too much water enters an animal cell it will burst
- **Cellulose** is a structural polysaccharide because it is:
  - **Strong** and **durable**
  - **Insoluble** and slightly **elastic**
  - Chemically **inert**; few organisms possess enzymes that can hydrolyse it

Polysaccharide function diagram



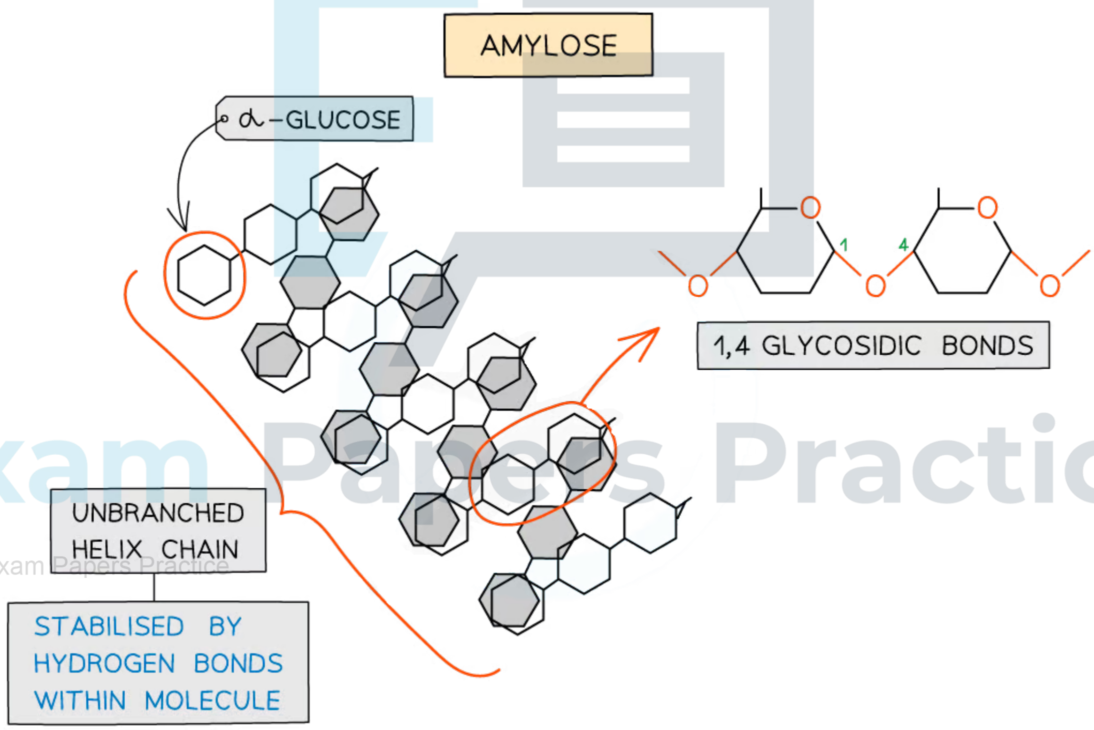
The different structures of starch, glycogen and cellulose allow each polysaccharide to perform different functions

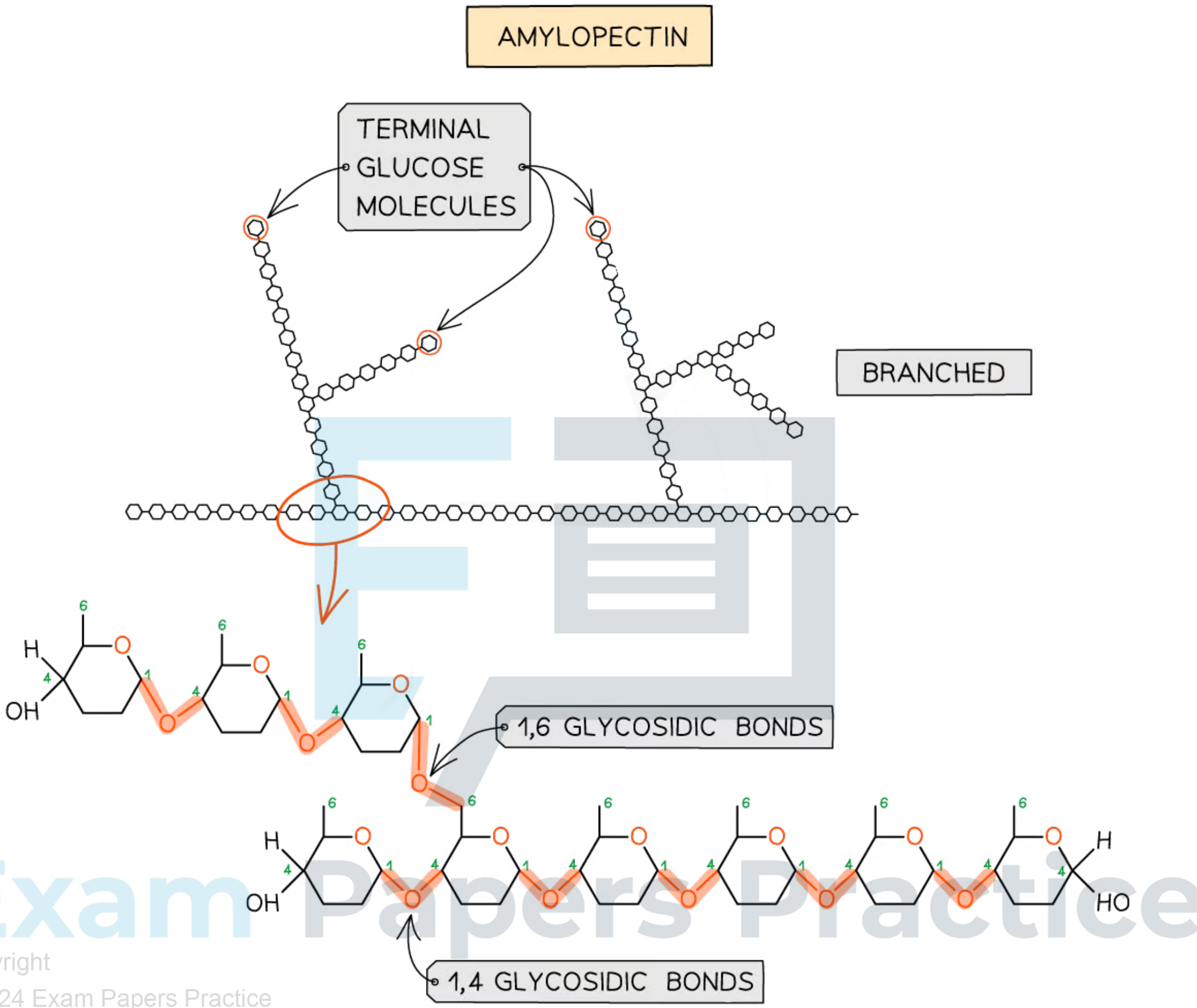
Starch

- Starch is the **storage** polysaccharide of **plants**
  - Starch is stored as granules in chloroplasts

- It is made of **alpha glucose monomers**
- Starch is constructed from **two different** polysaccharides:
  - **Amylose** (10 - 30 % of starch)
    - **Unbranched** helix-shaped chain with 1,4 glycosidic bonds between **α-glucose molecules**
    - The helix shape enables it to be more **compact** and thus it is more resistant to digestion
  - **Amylopectin** (70 - 90 % of starch)
    - Contains 1,4 glycosidic bonds between **α-glucose** molecules as well as 1, 6 glycosidic bonds, creating a **branched** molecule
    - The branches result in **many terminal glucose molecules** that can be **easily hydrolysed** for use during cellular respiration, or added to for storage

Amylose and amylopectin structure diagrams





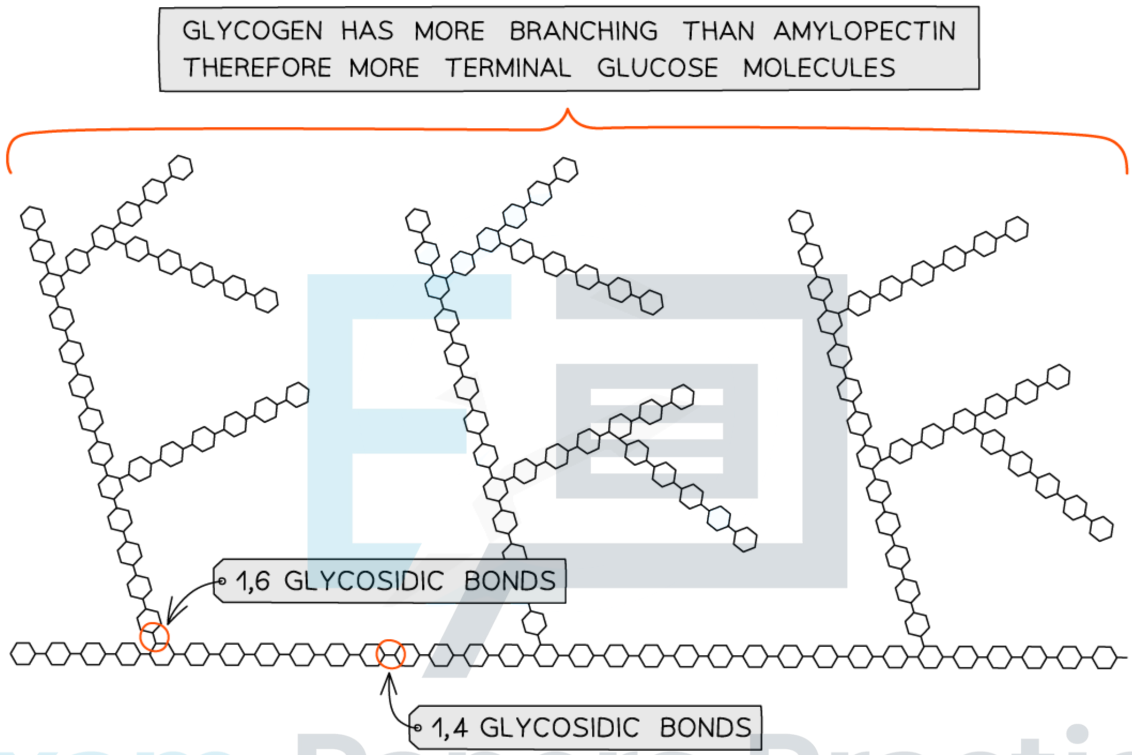
Amylose (top) and amylopectin (bottom); the two polysaccharides that form starch in plant cells

Glycogen

- Glycogen is the **storage** polysaccharide of **animals** and **fungi**
- The **monomer** of glycogen is **alpha glucose**, joined by **1,4 –** and **1,6 glycosidic bonds**
- Glycogen is **more branched** than amylopectin, providing **more free ends** where glucose molecules can be removed by **hydrolysis**
  - This means that glycogen can be **broken down quickly**, supplying the **higher metabolic needs** of animal cells

- **Liver** and **muscles** cells contain glycogen as visible granules, enabling high rates of cellular respiration

Glycogen structure diagram

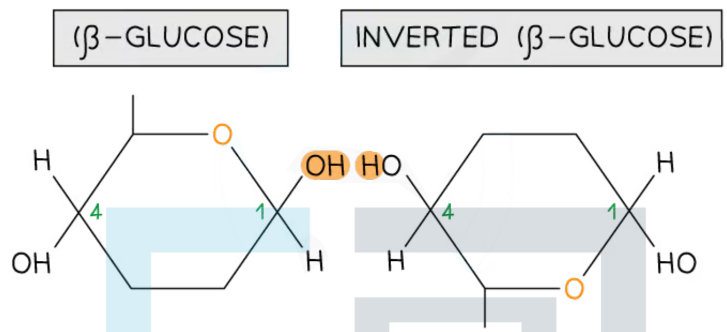


Glycogen is a highly branched storage molecule present in animals and fungi

The Structure of Cellulose

- Cellulose is a structural carbohydrate found in the cell walls of plants
- Molecules of cellulose are **straight** and **unbranched**
- Cellulose is a polymer of **β-glucose** monomers
  - β-glucose differs very slightly in structure to α-glucose; the hydroxyl group on carbon 1 **sits above the carbon ring in β-glucose**, whereas it sits **below the ring in α-glucose**
  - It means that in order to form a glycosidic bond with a molecule of β-glucose, every alternate molecule of β-glucose in the chain must **invert itself**, or flip upside down

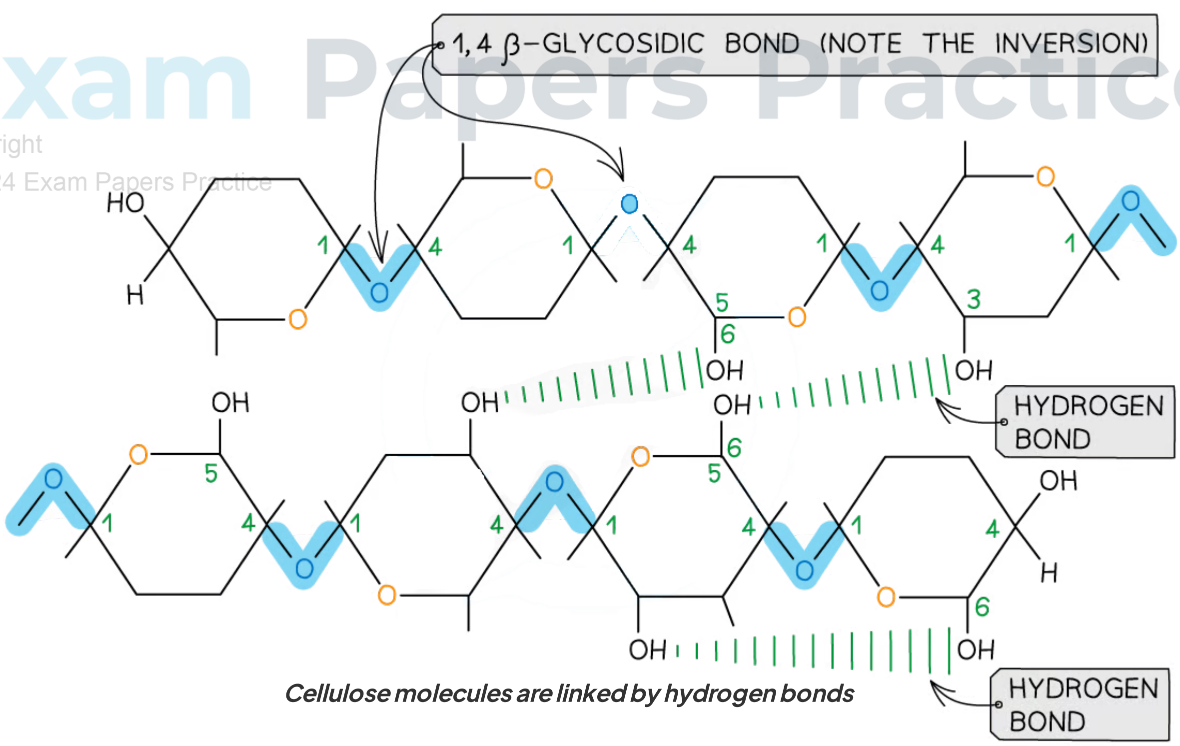
Beta glucose in cellulose diagram



Every other molecule of beta glucose needs to flip upside down in order for glycosidic bonds to form in cellulose

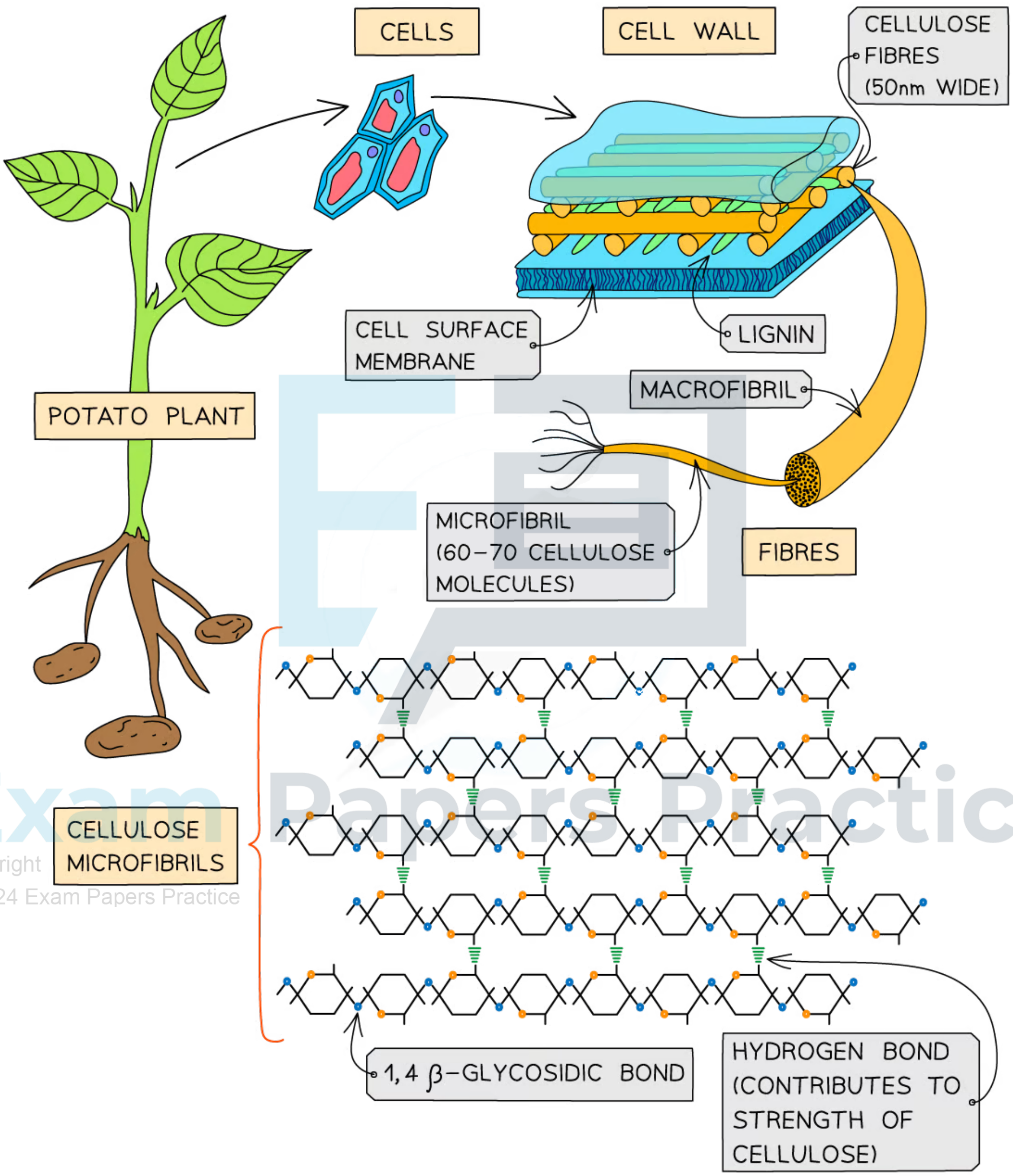
- The alternating pattern of the monomers in cellulose allows **hydrogen bonding** to occur between strands of β-glucose monomers, **adding strength** to the polymer
  - Hydrogen bonds link several molecules of cellulose to form **microfibrils**

Hydrogen bonding in cellulose diagram



Cellulose molecules are linked by hydrogen bonds

Cellulose function diagram



Cellulose molecules are joined by hydrogen bonds to form microfibrils; this gives cellulose its structural strength

Polysaccharide structure summary table

Feature	Starch		Glycogen	Cellulose
	Amylose	Amylopectin		
Monomer	α-glucose	α-glucose	α-glucose	β-glucose
Branches	No	Yes (approximately every 20 monomers)	Yes (approximately every 10 monomers)	No
Helix shape	Yes	No	No	No
Glycosidic bonds	1, 4	1, 4 and 1, 6	1, 4 and 1, 6	1, 4
Present in cell type	Plant	Plant	Animal	Plant

Role of Glycoproteins

Role of Glycoproteins

- **Carbohydrates** and **polypeptides** can combine, via covalent bonds, to make structures called **glycoproteins**
  - These are classed as proteins
- Glycoproteins, along with another group of molecules called glycolipids, form part of the structure of cell surface membranes
- They act as **receptor molecules** in processes such as
  - **Cell recognition** and **identification**
  - **Receptors for cell signalling** molecules such as hormones and neurotransmitters
  - Endocytosis
  - Cell adhesion and **stabilisation**

Glycoproteins and ABO blood types

- Glycoproteins can act as **antigens** which can identify cells as either "self" or "non-self"
  - Cells that are recognised as non-self will trigger an immune response within the organism
- A person's **blood type** is determined by the glycoprotein antigens on the surface of their red blood cells
  - Blood type A individuals have type A glycoprotein antigens
  - Blood type B individuals have type B glycoprotein antigens
  - Blood type AB individuals have both types of glycoprotein antigens
  - Blood type O individuals have neither
- The presence of antibodies within an individual can create an interaction with the glycoproteins if blood of the wrong type enters their body
  - E.g. a person with Type A antigens on their red blood cells will have antibodies in their blood against type B antigens
- This can cause fatal issues during blood transfusions if the incorrect blood type is given, as the antibodies cause the incorrect antigens (from the transfused blood) to clump together, blocking blood vessels

Blood Types and their Antigens and Antibodies Table

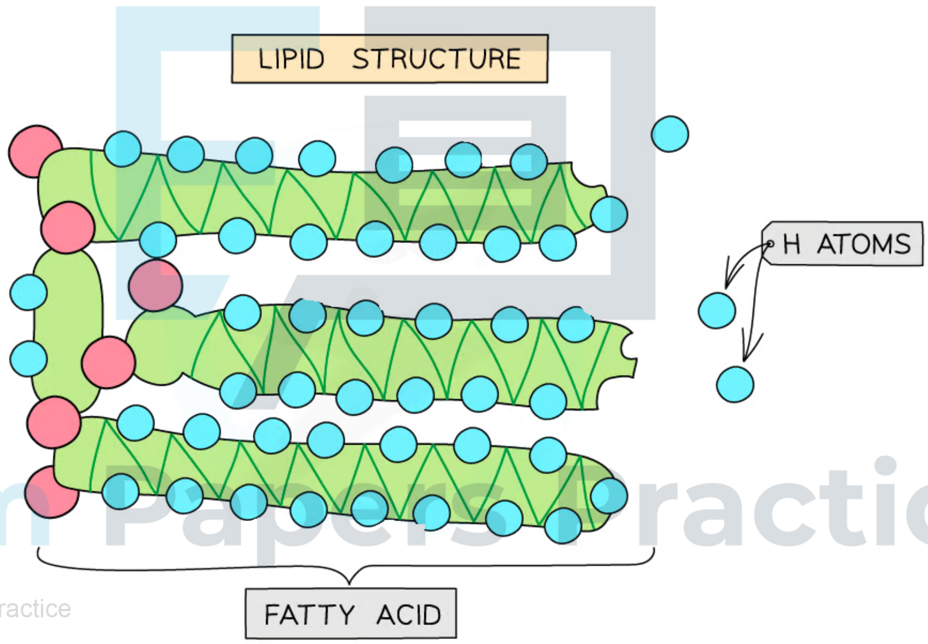
	Blood type A	Blood type B	Blood type AB	Blood type O
Red blood cell surface antigens	Type A	Type B	Type A & B	None
Antibodies present in plasma	Anti-B	Anti-A	None	Anti-B & anti-A
Blood groups that may be used for transfusion	A & O	B & O	A, B, AB, O	O

Lipids

Lipids: Hydrophobic Properties

- Examples of lipids in living organisms are
  - Fats
  - Oils
  - Waxes
  - Steroids
- Lipid macromolecules contain **carbon, hydrogen** and **oxygen** atoms

Basic lipid structure diagram



Lipid molecules are composed of a glycerol molecule and fatty acid hydrocarbon chains

Lipid solubility

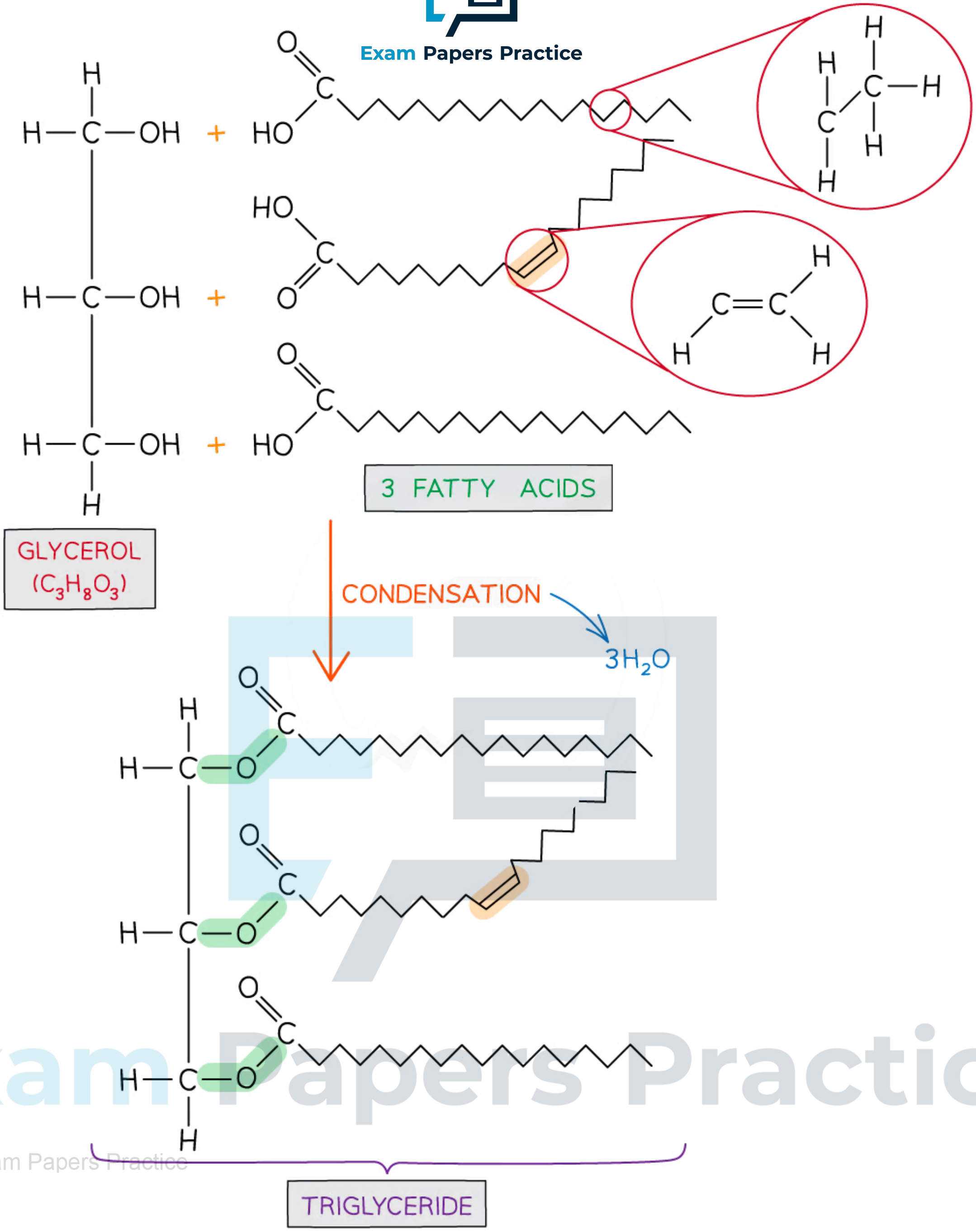
- The structure of lipids affects their solubility
- Lipids contain hydrocarbon molecules which contain many non-polar covalent bonds
- The non-polar nature of lipid molecules means that lipids are **insoluble** in **water** or other polar solvents
- In living organisms, lipid solubility can be improved by combining lipid molecules with other molecules, e.g.
  - Glycolipids
  - Lipoproteins

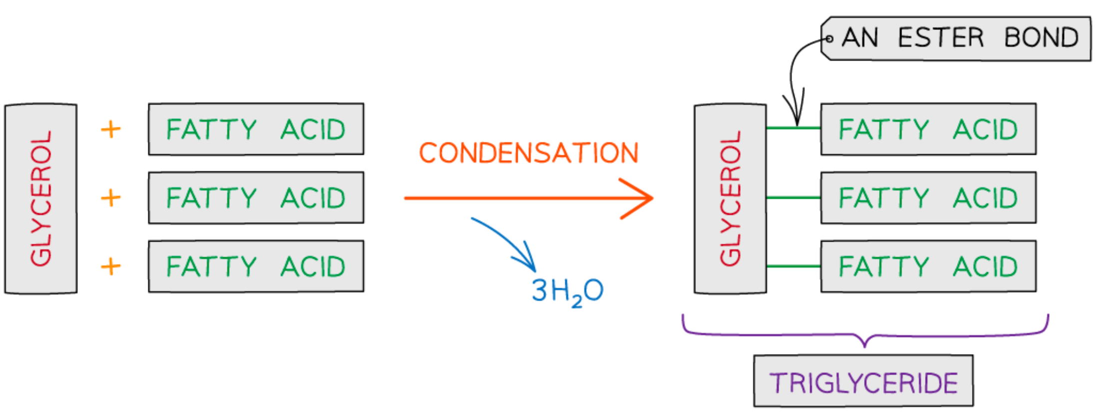
Formation of Triglycerides & Phospholipids

Formation of triglycerides

- Some lipids are categorised as **triglycerides**
- **Three fatty acids** join to **one glycerol** molecule to form a **triglyceride**
  - Fatty acids contain hydrocarbon chains that can be either saturated or unsaturated
    - Saturated fatty acids contain only single carbon-carbon bonds
    - Unsaturated fatty acids contain one or more double bonds
- Triglycerides are formed by a process known as **esterification**
  - An **ester bond** forms when the hydroxyl (-OH) group of a glycerol molecule bonds with the carboxyl group (-COOH) of a fatty acid
  - The formation of an ester bond is a **condensation reaction**
    - For each ester bond formed a water molecule is released
    - Therefore for one triglyceride to form, three water molecules are released

Formation of a triglyceride diagram



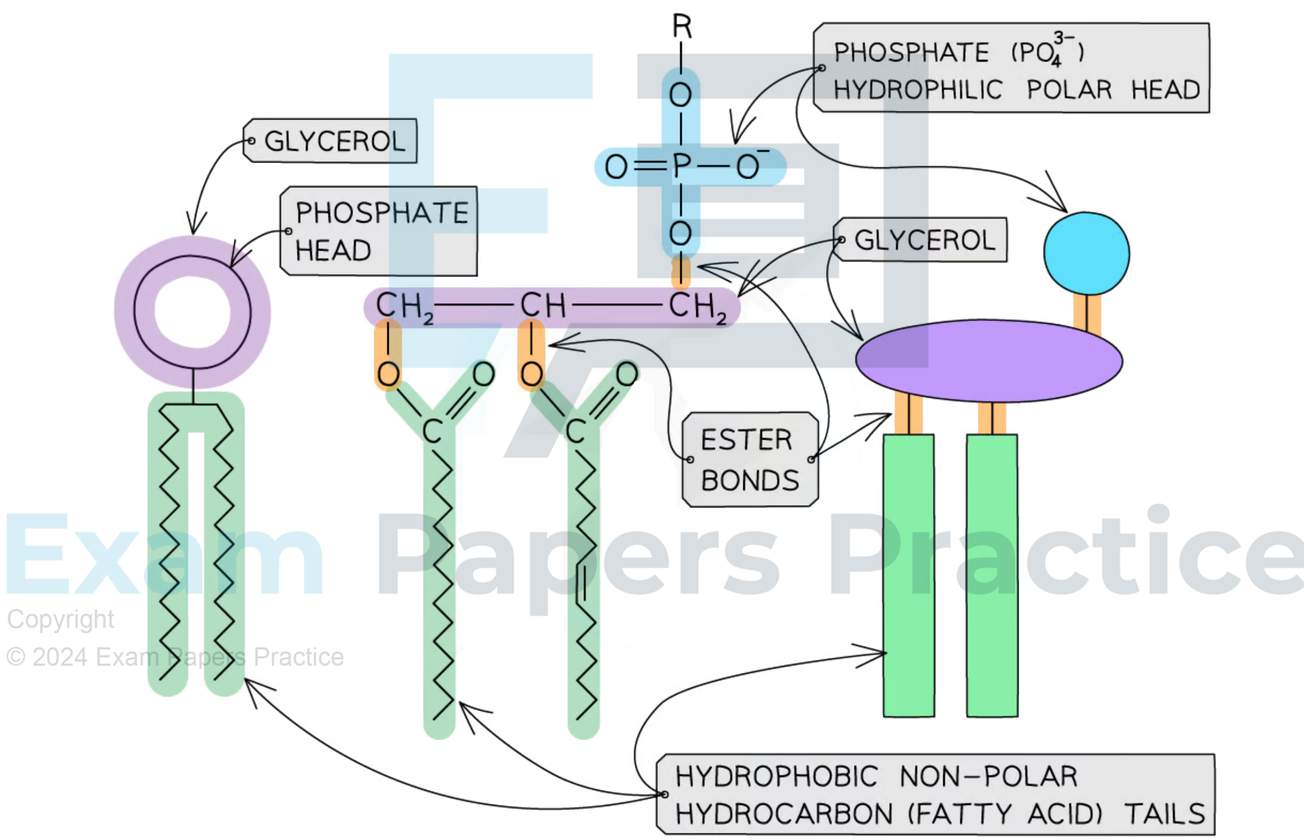


A triglyceride forms from a glycerol molecule and three fatty acid molecules by the process of esterification

Formation of phospholipids

- Phospholipids are also formed from glycerol and fatty acids
- Unlike triglycerides, phospholipids contain only **two fatty acids** bonded to a glycerol molecule, as the third has been replaced by a **phosphate ion (PO_4^{3-})**
- As the phosphate is **polar**, it is soluble in water, or **hydrophilic**
- The fatty acid 'tails' are **non-polar** and therefore insoluble in water, or **hydrophobic**
- Phospholipids are said to be **amphipathic**, meaning that they have both hydrophobic and hydrophilic regions
  - As a result of having hydrophobic and hydrophilic parts, phospholipid molecules can form monolayers or bilayers when placed in water

Structure of a phospholipid diagram



Phospholipids are the major components of cell surface membranes. They have fatty acid tails that are hydrophobic and a phosphate head that is hydrophilic, attached to a glycerol molecule.

Properties of Triglycerides

Lipids as an energy store

- The hydrolysis of triglycerides releases glycerol and fatty acids, which can form useful respiratory substrates
- Lipids are **energy-dense** in comparison to carbohydrates due to their high number of C-H bonds
  - They contain **2× more energy per gram** than most carbohydrates
- Lipids are **insoluble** so are not transported around the body easily and remain in their storage cells
- When lipids are respired **a lot of water is produced** compared to the respiration of carbohydrates
  - This is called **metabolic water** and can be used as a **dietary water source** when drinking water is unavailable
    - A **camel's hump** is not filled with water, but is a lipid-rich storage organ that yields metabolic water for the camel in its dry desert habitat
    - A **bird's egg** also makes use of lipid-rich yolk to provide energy and metabolic water to the growing chick
- All these features make lipids **ideal for long term energy storage**

Storage of lipids

- In **animals**, lipids are stored in **adipose tissue**
  - **Subcutaneous** fats are stored below the skin
  - **Visceral** fats are stored around the major internal organs
- Fat is stored in **adipose cells**, which are specialised to contain large globules of fat
  - **Adipose cells shrink** when the fat is respired to generate metabolic energy
- Adipose tissue can be used as a **thermal insulator** in animals that live in particularly cold environments
  - Seals and walruses are endotherms and have thick adipose tissue called blubber which helps trap heat generated by respiration
- In many plants, **seeds** have evolved to store fats to provide energy for a growing seedling plant
  - **Olives**, **sunflowers**, **nuts**, **coconuts** and **oilseed rape** are good examples of crops whose oils are harvested for edible oil production by humans

Fatty Acids

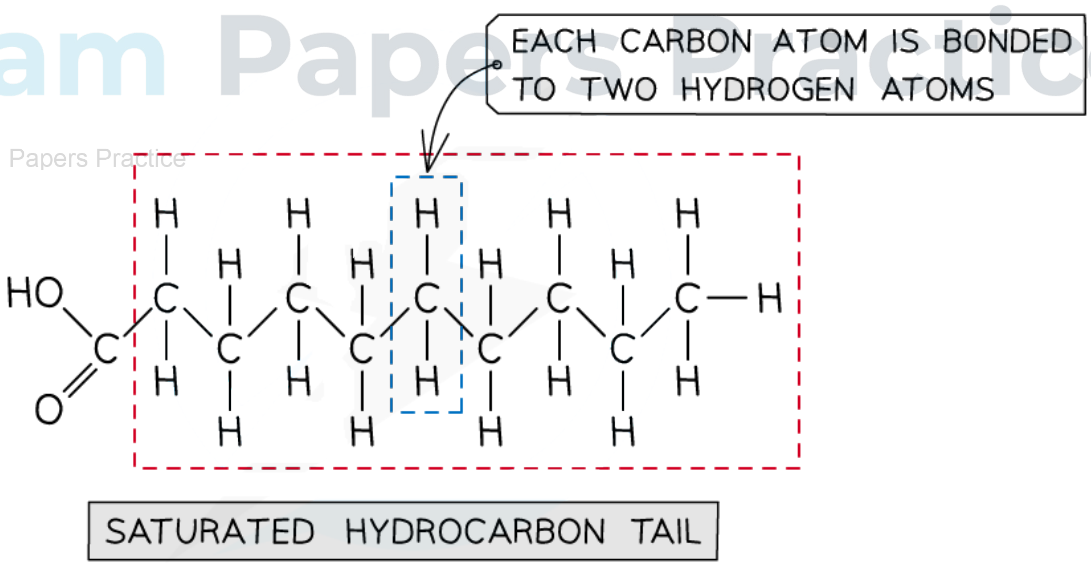
Fatty Acids

- Both triglycerides and phospholipids contain **glycerol** with molecules known as **fatty acids** attached
- These fatty acids have **long hydrocarbon 'tails'**
  - Hydrocarbons are molecules that contain hydrogen and carbon
- Fatty acids occur in **two** forms:
  - **Saturated** fatty acids
  - **Unsaturated** fatty acids
    - Unsaturated fatty acids can be **monounsaturated** or **polyunsaturated**

Saturated fatty acids

- In saturated fatty acids the bonds between the carbon atoms in the hydrocarbon tail are **all single bonds**
- The fatty acid is said to be **'saturated' with hydrogen**
  - This means that each carbon atom in the hydrocarbon tail (except for the final carbon atom) is bonded to **two hydrogen atoms**
- Saturated fatty acids are **straight molecules**, meaning that lipid molecules containing them are able to pack tightly together
  - This **increases their melting point** and causes them to be solid at room temperature
  - Saturated fatty acids are often used as **storage molecules in animals** for this reason, e.g. the fats in meat and butter

Saturated fatty acid diagram

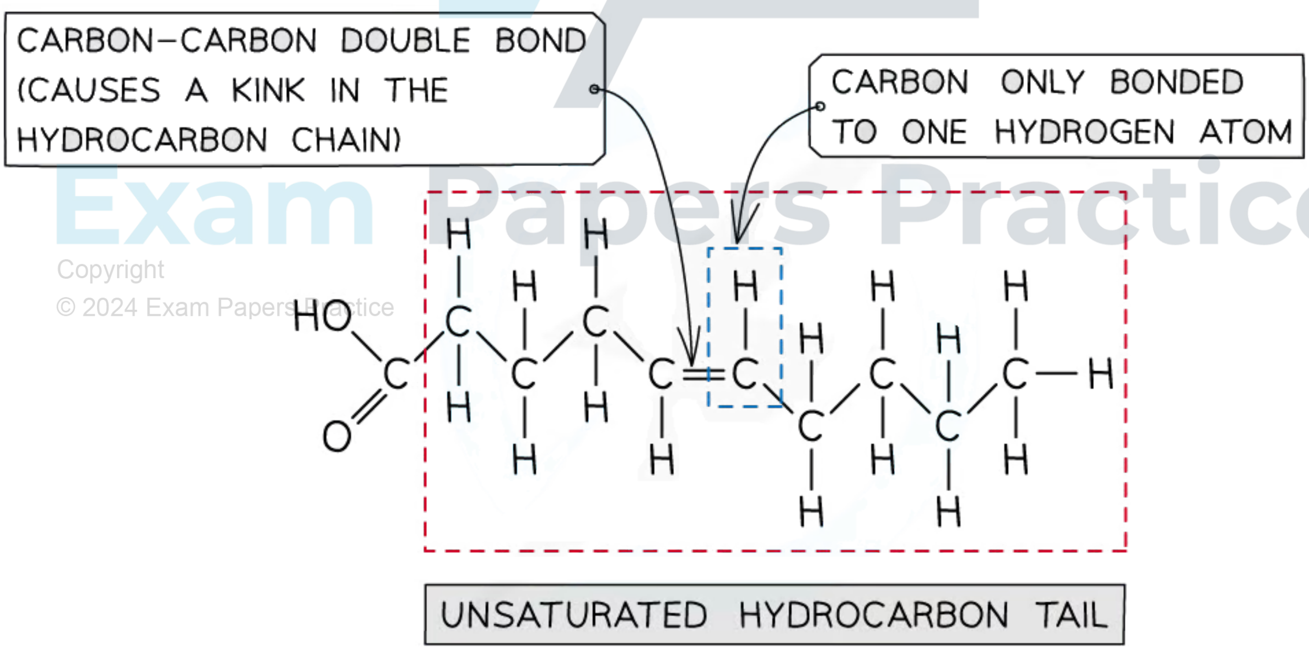


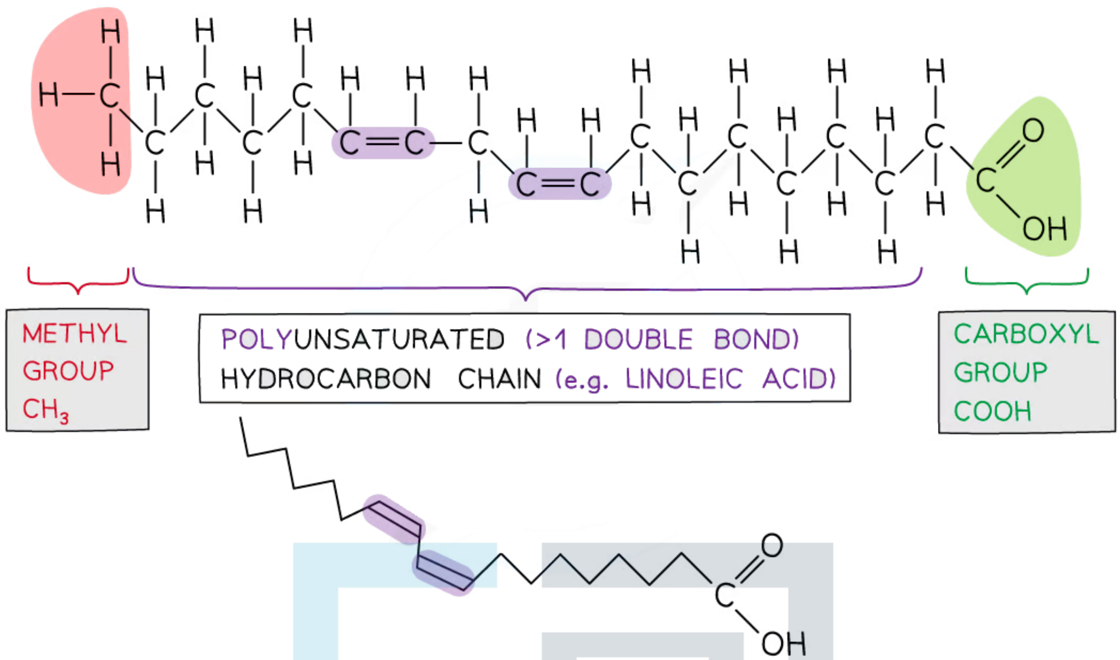
Saturated fatty acids contain only single carbon-carbon bonds

Unsaturated fatty acids

- In unsaturated fatty acids the bonds between the carbon atoms in the hydrocarbon tail are **not all single bonds**
  - The fatty acid is said to be **'unsaturated'** because the hydrocarbon tail **does not contain the maximum number of hydrogen atoms** possible; each carbon atom in a carbon-carbon double bond **can only bond to one hydrogen atom** instead of two
- These double bonds can cause the hydrocarbon tail of unsaturated fatty acids to **kink**, or **bend**, meaning they are **not as straight as saturated fatty acids**
  - Unsaturated fatty acids cannot pack as tightly together as saturated fatty acids, so fats containing unsaturated fatty acids are often liquids at room temperature
- Unsaturated fatty acids contain **at least one carbon-carbon double bond**
  - A fatty acid with **one C=C double bond** is known as **monounsaturated** fatty acid
    - Lipids that contain monounsaturated fatty acids have a **lower melting point** than saturated fatty acids, meaning that they form liquid oils; some animals and plants store energy in the form of oils
  - In some unsaturated fatty acids, there are **many** carbon-carbon double bonds; these are known as **polyunsaturated** fatty acids
    - Lipids containing polyunsaturated fats also have a **low melting point**, so form oils that are used for energy storage in plants

Mono- & polyunsaturated fatty acid diagrams





Monounsaturated fatty acids (top) contain only one carbon-carbon double bond, while polyunsaturated fatty acids (bottom) contain more than one

Exam Tip

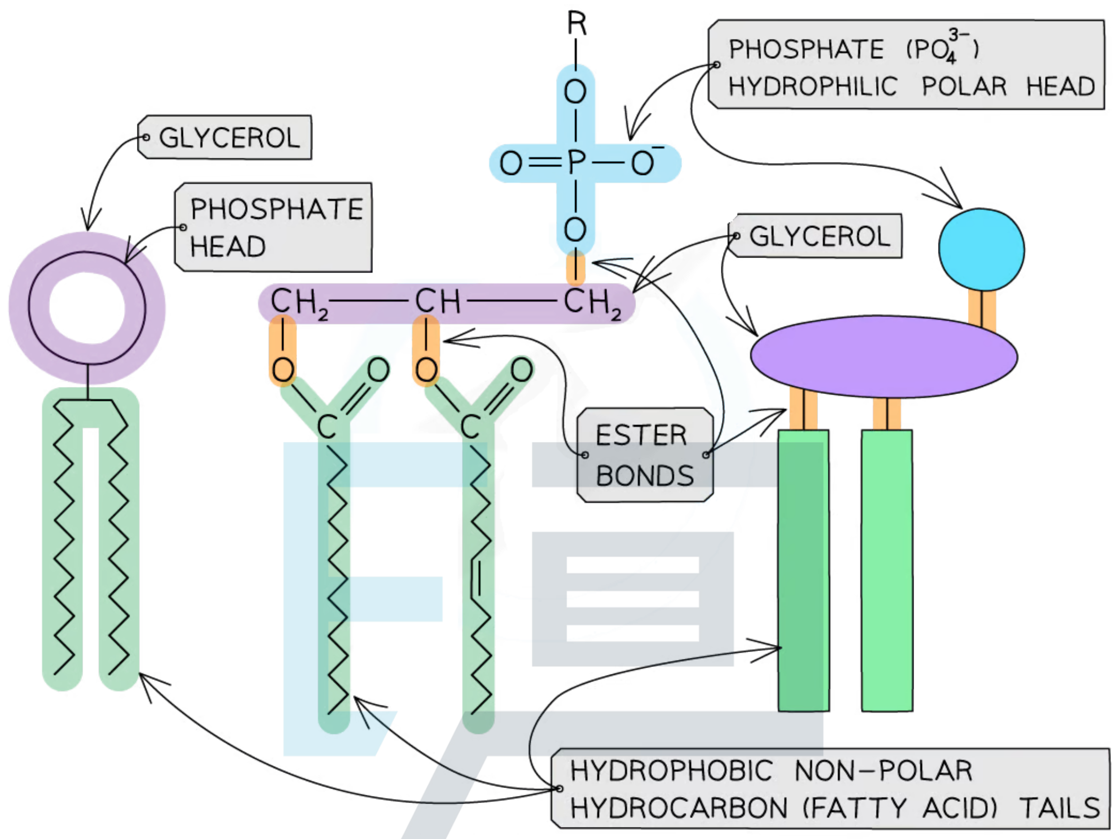
You should be able to recognise from a diagram whether a fatty acid is **saturated**, **monounsaturated** or **polyunsaturated** (look for any carbon-carbon double bonds)!

Phospholipids

Formation of Phospholipid Bilayers

- Phospholipids form the basic structure of the cell membrane
  - Cell membranes are phospholipid bilayers
- Membranes are formed when a hydrophilic **phosphate head** bonding with two hydrophobic **hydrocarbon (fatty acid) tails**
- Phospholipids have a hydrophobic and a hydrophilic region
  - The **phosphate head** of a phospholipid is **polar**, so is hydrophilic and therefore **soluble** in water
  - The **fatty acid tail** of a phospholipid is **nonpolar**, so is hydrophobic and therefore **insoluble** in water
- Molecules with both polar/hydrophilic and non-polar/hydrophobic regions are said to be **amphipathic**

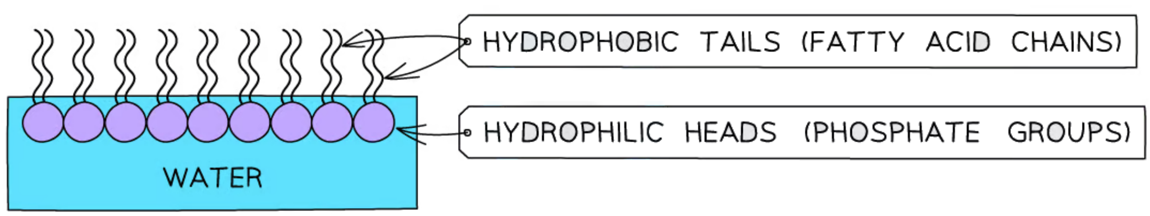
Phospholipid structure diagram



Phospholipids contain polar heads and non-polar tails, so are said to be amphipathic

- When placed in water, the **hydrophilic** phosphate heads of phospholipids orient themselves towards the water and the **hydrophobic** hydrocarbon tails orient themselves away from the water, causing them to form a **phospholipid monolayer**

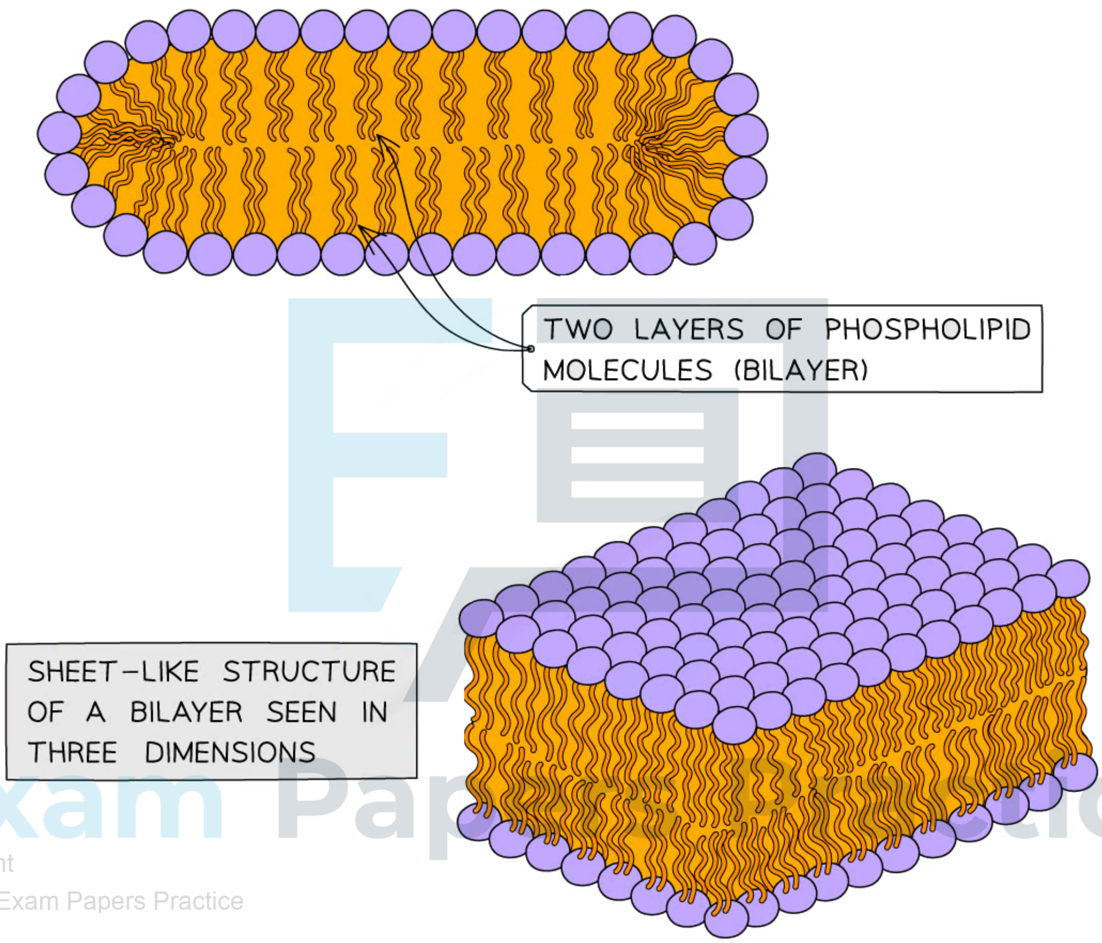
Phospholipid monolayer diagram



Phospholipids can form monolayers on the surface of water

- When phospholipids are mixed with water, two-layered structures known as **phospholipid bilayers** can form; this is the basic structure of the **cell membrane**

Phospholipid bilayer diagram



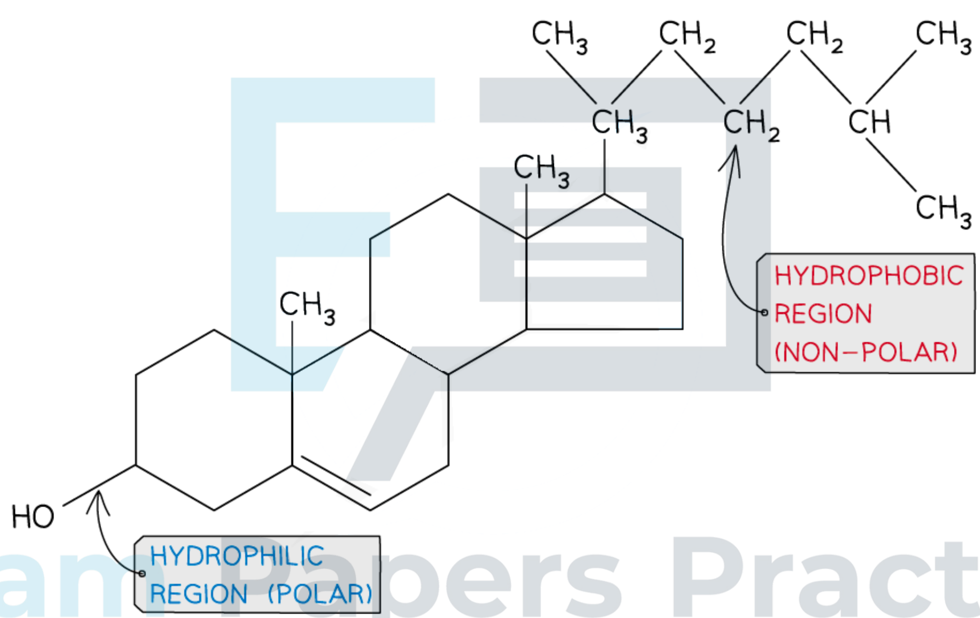
A phospholipid bilayer is composed of two layers of phospholipids; their hydrophobic tails face inwards and hydrophilic heads face outwards

- The **amphipathic nature** of phospholipids means that the phospholipid bilayer acts as a **barrier to most water-soluble substances**
  - The non-polar fatty acid tails prevent polar molecules or ions from passing between them across the membrane
- This **means that water-soluble molecules such as sugars, amino acids and proteins cannot leak out of the cell** and unwanted water-soluble molecules cannot get in

Passage Through Phospholipid Bilayers

- **Small, nonpolar molecules**, such as O_2 and CO_2, are **soluble** in the lipid bilayer and can therefore easily cross cell membranes to be utilised by the cell
  - They do not need proteins for transport and can diffuse across quickly
- Other **larger, non-polar molecules** can also enter the cell across the lipid bilayer, e.g. **steroid** hormones
  - Steroid hormones contain **cholesterol**, a type of lipid
- The **hydrocarbon** region of cholesterol is **non-polar,** allowing it to cross lipid bilyars

Cholesterol structure diagram



Cholesterol has hydrophobic and hydrophilic regions

- **Oestradiol** and **testosterone** are two examples of **steroid hormones** formed from cholesterol
  - They are produced by gonadal tissues in the reproductive organs
- Due to their lipid structure they **can cross the lipid bilayer** and can readily travel into and out of cells and nuclei
  - Inside the nucleus these hormones alter and direct the process of transcription