Dr James Napier

CCEA AS

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Rewarding Learning

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**Colourpoint Educational**
*An imprint of Colourpoint Creative Ltd*
Colourpoint House
Jubilee Business Park
21 Jubilee Road
Newtownards
County Down
Northern Ireland
BT23 4YH

Tel: 028 9182 0505
E-mail: sales@colourpoint.co.uk
Web site: www.colourpoint.co.uk

***The Author***

**James Napier** is a former Vice-Principal in a large Northern Ireland grammar school. Dr Napier has written and co-written, a number of GCSE Biology and Science textbooks supporting the work of teachers and students in Northern Ireland. He has also published a range of popular science books throughout the areas of genetics and evolution.

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*Rewarding Learning*

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# Unit AS 1: Molecules and Cells

# Chapter 1 – Molecules

**Students should be able to:**

**1.1.1** Demonstrate knowledge and understanding of the importance of water as a solvent.

**1.1.2** Outline the role of inorganic ions – potassium, calcium, magnesium, iron, hydrogencarbonate, nitrate and phosphate.

**1.1.3** Demonstrate knowledge and understanding of the occurrence, structure and function of carbohydrates.

**1.1.4** Demonstrate knowledge and understanding of the occurrence, structure and function of lipids.

**1.1.5** Demonstrate knowledge and understanding of the occurrence, structure and function of proteins.

**1.1.6** Demonstrate knowledge and understanding of the occurrence, structure and function of nucleic acids.

**1.1.7** Demonstrate knowledge and understanding of the replication of DNA.

**1.1.8/9** Practical work to include biochemical tests to detect the presence of carbohydrates and proteins, and paper chromatography to identify amino acids.

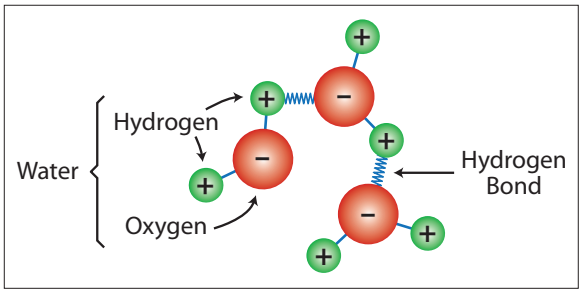
## Molecules and living organisms

Although there are many naturally occurring elements, only a small proportion are found in living organisms. The elements present in the largest proportions in living organisms are carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur, with the first three being by far the most abundant. Atoms of the elements found in living organisms combine to form biologically important molecules linked by strong covalent bonds.

### Water

Most of the oxygen and hydrogen in living organisms exists as water. In a water molecule ($H_2O$) each hydrogen atom shares a pair of electrons with the oxygen atom, forming a covalent bond. In a water molecule the hydrogen has a slight positive charge and the oxygen a slight negative charge. Therefore the molecule is described as being **polar**, a term used to describe molecules with an uneven distribution of charge.

The polar nature of water results in the formation of hydrogen bonds between adjacent water molecules. The hydrogen bonds extend between the oxygen on one water molecule and a hydrogen atom on another. Hydrogen bonds are important in many biological molecules, but although common they are not strong and are relatively easily broken.




*Hydrogen bonds in water*

Water is an excellent **solvent**, capable of dissolving a wide range of inorganic and organic substances. Molecules with charged groups, such as glucose and amino acids, and ions dissolve in water with the polar water molecules readily forming clusters around them.

Water forms between 50% to over 90% of the cells in living organisms. Its value as a solvent includes:

- the fact that most of a cell's reactions take place in an aqueous solution.
- its ability to act as a transport medium in living organisms.
- the different effects it has on hydrophilic ('water loving') and hydrophobic ('water hating') molecules. For example, lipids are hydrophobic and do not dissolve in water. The importance of lipids being insoluble in water is discussed later (on pages 63–64) in terms of its role in the cell surface membrane.

### Buffers and pH

Proteins are crucially important biological molecules, largely due to their ability to be formed in very specific three-dimensional (3-D) shapes. However, protein shape, and consequently function, is affected by changes in pH. While most proteins operate most effectively in the normal cellular pH of around 7 (neutral), some have a very different optimum pH. For example, the stomach enzyme pepsin has an optimum pH of around 2.

Buffers are chemicals or substances that resist changes to pH and ensure that a particular environment maintains a particular pH. Examples include hydrogencarbonate ions and blood proteins such as albumin. Buffers are often used in practical investigations involving enzymes. The buffers help regulate the pH of solutions to ensure that the enzymes involved are operating at their optimum pH.

### Ions

Ions are atoms or a group of atoms that have an electrical charge due to the number of protons and electrons not balancing. Atoms of metals tend to lose electrons and therefore become positively charged ions. Atoms of non-metals tend to be able to gain electrons, thus becoming negatively charged.

Biologically important ions include:

- **calcium** ($Ca^{2+}$) – in plants calcium pectate is an essential component of the middle lamella of plant cell walls. Calcium is an essential component of bones and teeth in animals, and is essential in blood clotting and muscle contraction.
- **iron** ($Fe^{2+}$) – is part of the haem group in haemoglobin and an important constituent of electron carriers in respiration.
- **magnesium** ($Mg^{2+}$) – is essential in giving chlorophyll its light-absorbing properties.
- **potassium** ($K^{+}$) – is important in maintaining electrical gradients across neurones.
- **nitrate** ($NO_3^-$) – is a component of amino acids, nucleic acids and chlorophyll.
- **phosphate** ($PO_4^{3-}$) – as phospholipids, phosphate is an important component of cell membranes. It is also a major component of other important biological molecules including adenosine triphosphate (ATP) and nucleic acids.
- **hydrogencarbonate** ($HCO_3^-$) – is important as a natural buffer.

### Organic molecules

Organic molecules are complex carbon-containing molecules. **Carbohydrates**, **proteins** and **lipids** are all examples of organic molecules. Organic molecules form the basis of all life on Earth and it is essential that you have a good understanding of the key organic molecules in 'A' level Biology. Many organic molecules are formed of sub-units called **monomers**, which join together to form larger **polymers** through the process of **polymerisation**.

## Carbohydrates

Carbohydrates contain carbon, hydrogen and oxygen only. The ratio of hydrogen atoms to oxygen atoms is 2:1.

Carbohydrates are divided into three main types:

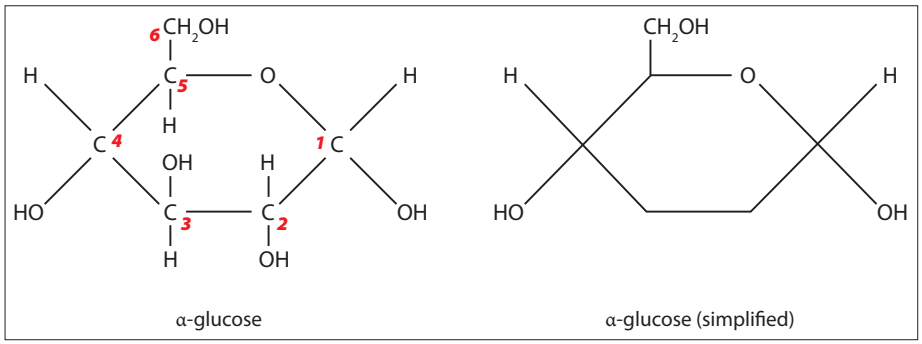
- **Monosaccharides** – are the basic carbohydrate monomers, ie single sugars. There are different categories of monosaccharide depending on the number of carbon atoms present. Biologically important monosaccharides contain three (**trioses**), five (**pentoses**) or six (**hexoses**) carbon atoms.
- **Disaccharides** – are double sugars formed from two monosaccharide monomers.
- **Polysaccharides –** are complex molecules usually consisting of many monosaccharide monomers.

### Monosaccharides

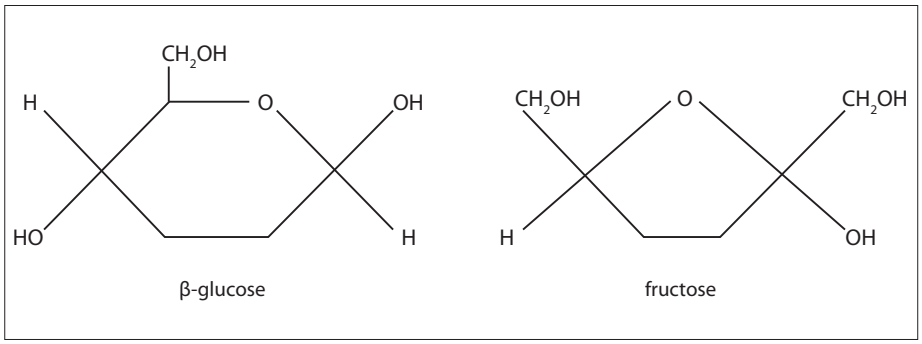
**Glucose** is a hexose monosaccharide with the formula $C_6H_{12}O_6$. The diagram immediately below shows how the atoms of α-glucose are arranged. **α-glucose** is the basic sub-unit of complex polysaccharides such as starch and glycogen.

*α-glucose*

The simplified diagram is often used. Although simplified, it still shows detail at carbon positions 1, 4 and 6 – the positions important in bonding different monosaccharide molecules together.




A slight change in the arrangement of the atoms gives **β-glucose**.
In β-glucose the hydrogen and hydroxyl (-OH) groups at carbon (position) 1 are reversed. β-glucose has different properties to α-glucose and it is the constituent monomer of cellulose. Further small changes give the hexose sugar **fructose**.




*β-glucose and fructose*

Hexose monosaccharides, such as glucose, are very important as energy sources in living organisms.

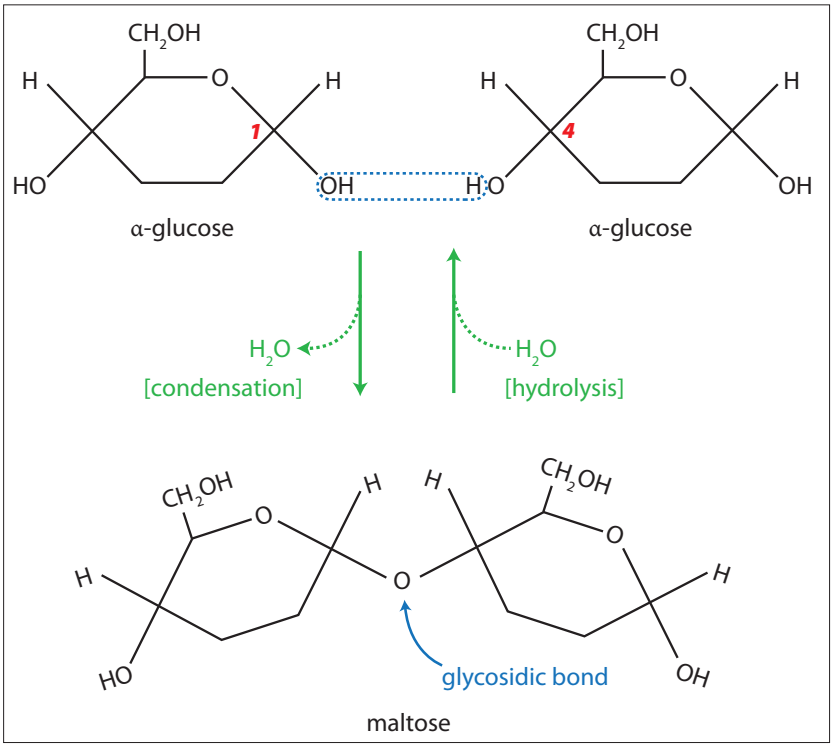
Substances such as the monosaccharides just discussed, which have the same **molecular formula**, but different **structural formulae**, are described as being **isomers** of each other.

## Disaccharides

**Disaccharides** are formed when two monosaccharides, usually hexoses, react together in a chemical reaction known as a **condensation** reaction. This is a reversible reaction, as a disaccharide molecule can be broken down into its constituent monosaccharide monomers in a **hydrolysis** reaction. Hydrolysis reactions are important in the digestion of food.

**Note:** during condensation one molecule of water is lost – during hydrolysis one molecule of water is gained.

The bond that is formed between two hexose sugars in the formation of a disaccharide is called a **glycosidic bond**. If you study the diagram below closely, you will see that the bond is between the carbons 1 and 4 on the respective monomers (α-glucose); therefore the bond is described as being an **α-1,4 glycosidic bond**. Note in the diagram that the orientation of the bond means that the two glucose residues lie at an angle when the disaccharide is formed.




*The formation and breakdown of the disaccharide maltose*

**Note:** in examination questions many candidates mix up the type of **reaction** with the name of the **bond**!

All disaccharides have the general formula $C_{12}H_{22}O_{11}$. They dissolve in water to produce sweet tasting solutions, as they are all 'sugars'.

Important disaccharides include:

- **maltose** – formed when two α-glucose molecules are linked through a condensation reaction.
- **sucrose** – formed when an α-glucose molecule condenses with a fructose molecule.

Maltose is formed when starch is digested – the maltose requires further digestion to form the monomer glucose. Sucrose is the form in which carbohydrate is transported through phloem in plants.

## Polysaccharides

These are complex carbohydrates which often form very long chains. They are formed through condensation reactions joining a large number of monomers together to make complex polymers.

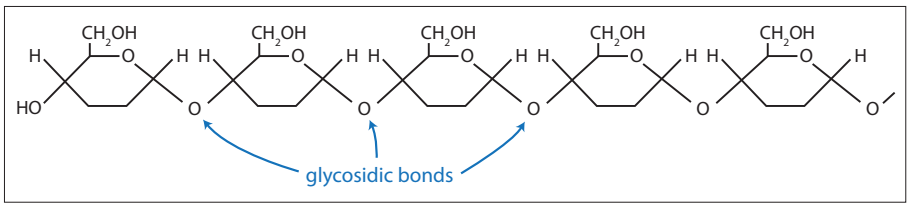
The general formula for a polysaccharide is $(C_6H_{10}O_5)_n$ where $n$ is a large number that can vary. Polysaccharides are not 'sugar'; they are not sweet and they are insoluble in water. Very important polysaccharides are **starch**, **glycogen** and **cellulose**.

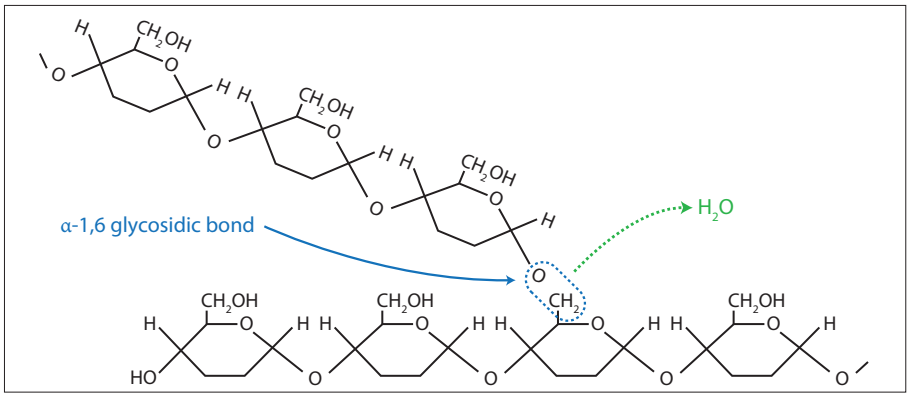
## Starch

Starch is a polymer of α-glucose. However, starch consists of a mixture of two types of chains. Although each type of chain consists of only α-glucose, the α-glucose has different bonding arrangements in each type of chain.

1. **Amylose** – In amylose, α-glucose molecules are linked by **α-1,4 glycosidic bonds**. These chains are coiled to form a spiral, with the spirals held in place by hydrogen bonds. As only 1,4 bonds are involved, amylose forms long **unbranched chains**. Approximately 20% of starch is formed from amylose. Due to the presence of the bulky side groups that cause the α-glucose molecules to lie at different angles, amylose chains form a coiled configuration.

*Amylose*




*Amylopectin*

2. **Amylopectin** – Amylopectin also links its constituent α-glucose monomers together by **α-1,4 glycosidic bonds**. In addition, **α-1,6 glycosidic bonds** form side branches to produce a **branched** molecule. The branches may occur as often as one branch every ten α-glucose monomers. About 80% of starch is normally in amylopectin form.

## Why is starch such a good storage molecule?

Starch is an excellent storage carbohydrate and is the storage compound of many plants. It is commonly stored as solid grains and can often be seen in electron micrographs of plant chloroplasts. Its benefits include:

- the molecules of both amylose and amylopectin are very **compact** (aided by the coiled configuration), therefore they contain a rich store of glucose in a small space.

- as it is **insoluble** it will not affect the water relations of the cell – if significant quantities of carbohydrate were stored as glucose this would cause a lot of water to enter by osmosis.
- being a **large molecule** it can be retained in the cell and will not easily pass through the cell membrane.
- the **branching** nature of amylopectin creates **many terminal ends** that are **easily hydrolysed**. This aids in the rapid enzymatic breakdown of starch into its constituent glucose molecules at times of high respiratory demand.

## Glycogen

This is the storage carbohydrate found in animal and fungal cells. It is stored in the form of small granules. Structurally, glycogen is very similar to amylopectin, being formed of chains of α-glucose monomers. Glycogen also has α-1,4 glycosidic and α-1,6 glycosidic bonds but the chains are **more branched** and shorter than the amylopectin chains.

Glycogen is stored in **liver** and **muscle** cells in mammals. Its properties are very similar to starch. It is compact and insoluble, therefore not affecting cell water relations. However, as it has no unbranched chains and shorter chains than in amylopectin, it has proportionally **more terminal ends**, enabling **faster hydrolysis** when conditions demand.

## Cellulose

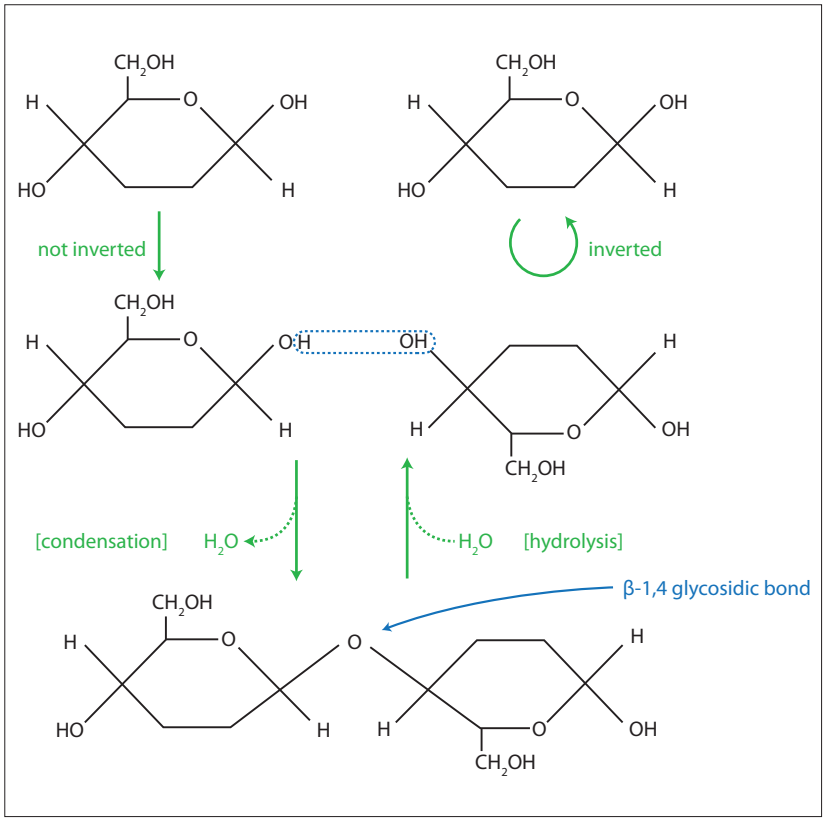
Cellulose is not a storage polysaccharide – its role is **structural**. Consequently, it has a very different structure to the relatively similar starch and glycogen.

Cellulose is made of monomers of **β-glucose**. In cellulose, when the two β-glucose molecules join together and form β-1,4 glycosidic bonds, alternate molecules are rotated through 180°. This rotation is a necessary consequence due to the different structure of β-glucose compared to α-glucose.

This 'flipping' of adjacent glucose monomers has two effects:

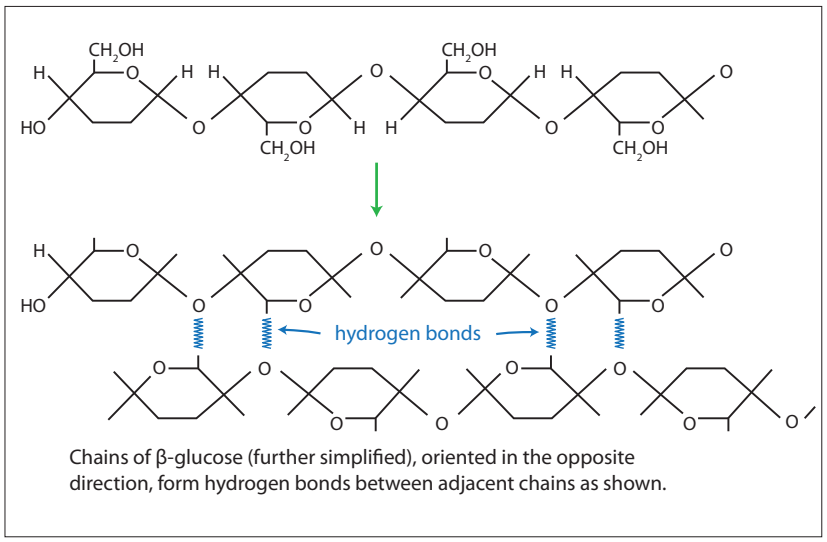
- the unbranched chains are **straighter**, as the bulky -$CH_2OH$ side groups alternate between being above and below the chain.
- **hydrogen bonds** can form cross-linkages between adjacent chains (due to the oxygen and the side groups being available on both sides

*The formation of cellulose*



of the chain following the inversion of alternate β-glucose molecules).

The cellulose chains (molecules) are grouped together in microfibrils, with each microfibril consisting of many cellulose molecules. Plant cell walls are formed of the cellulose microfibrils orientated into many planes in a lattice structure to further increase its tensile strength.




Chains of β-glucose (further simplified), oriented in the opposite direction, form hydrogen bonds between adjacent chains as shown.

*Cellulose*

## Lipids

Lipids contain carbon, hydrogen and oxygen but the proportion of hydrogen relative to oxygen is much greater than the 2:1 ratio associated with carbohydrates.

Although lipids form large molecules (macromolecules), they are not polymers. They are not soluble in water (**hydrophobic**) but they are soluble in organic solvents such as ether or ethanol.

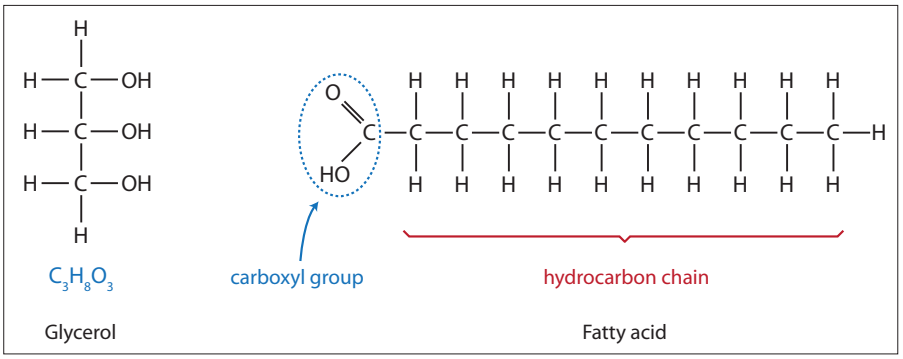
The main types of lipids are **triglycerides** (fats and oils), **phospholipids** (a major component of membranes), waxes and steroids.

### Triglycerides

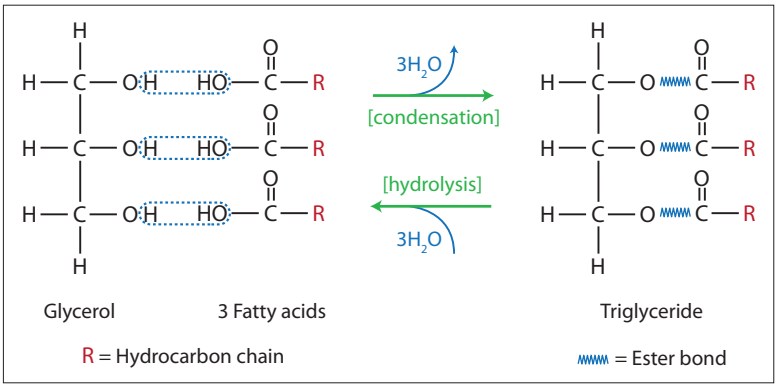
Triglycerides are formed through the combination of **glycerol** and **fatty acid** molecules.

Fatty acids are organic acids that form long hydrocarbon tails linked to a carboxyl group (-COOH) at one end of the chain. Different fatty acids have different lengths of hydrocarbon tail.

*Glycerol and fatty acid*




*The formation and hydrolysis of a triglyceride*




In each triglyceride, one glycerol molecule is joined with three fatty acid molecules by (three) **condensation reactions**. There are over 70 types of fatty acid and in each triglyceride the three fatty acids can be the same or a range of different types. The condensation reactions occur between the -OH groups of the glycerol and the

carboxyl group of each fatty acid. For each condensation reaction, an **ester bond** is formed.

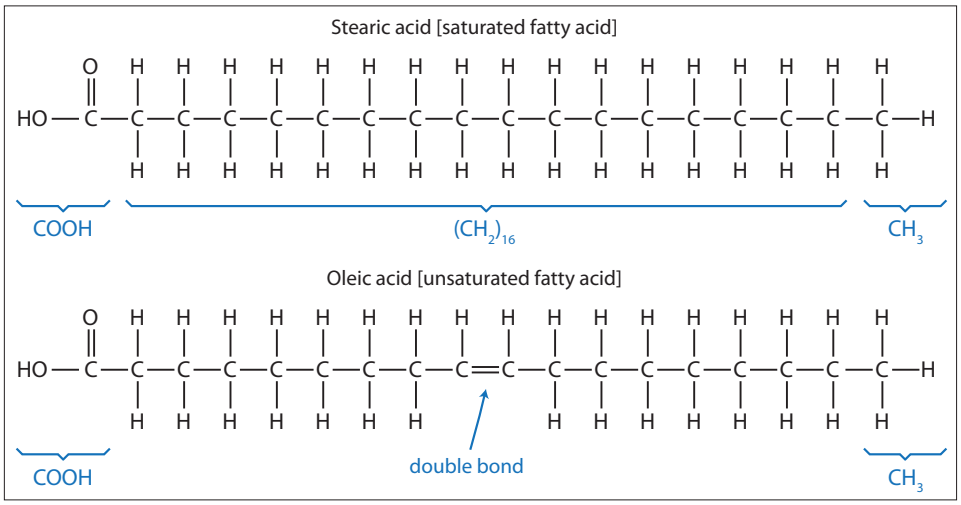
The reverse reaction can also occur. Hydrolysis of a triglyceride (as happens during lipid digestion) uses three molecules of water and produces three fatty acids and one molecule of glycerol.

## Unsaturated and saturated fatty acids

**Saturated** fatty acids contain the maximum number of hydrogen atoms, ie along the length of the hydrocarbon chain each carbon atom is linked with two hydrogen atoms (the carbons are saturated!). Also, the carbon atoms are linked by C-C single bonds.

Unsaturated fatty acids have at least one C=C double bond in the chain. If there is one double bond it is **monounsaturated** and if there is more than one double bond, it is **polyunsaturated**.

Oleic acid, the lower fatty acid in the diagram opposite, has only one double bond within the chain and is therefore a monounsaturated fatty acid. Other fatty acids, such as linoleic acid, have more than one double bond and are polyunsaturated fatty acids.




*Saturated and unsaturated fatty acids*

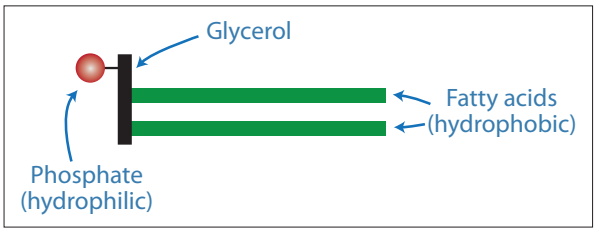
**Fats** and **oils** are both triglycerides and chemically very similar. Fats are solid at room temperature and oils are liquid at room temperature. In general, though not exclusively, fats are animal products and oils are made by plants, for example, energy stores in seeds.

Fats tend to be formed from saturated fatty acids, whereas oils are usually formed from triglycerides with unsaturated hydrocarbon chains (or shorter chains).

Triglycerides are an excellent **energy store** as they release more energy per unit mass than carbohydrate. Fats are also important for **insulation** and are stored in a layer below the body surface in many animals. Many body organs are **protected** by a layer of fat.

## Phospholipids

Phospholipids are similar to triglycerides, except that one of the fatty acid molecules is replaced by a phosphate group.

The fatty acid molecules repel water and are insoluble in water, forming **hydrophobic** 'tails', whereas the phosphate gives the glycerol part ('head') of the

*Phospholipid*