1

Introducing the chemistry of life

Prior knowledge

In this chapter you will need to recall that:

- carbohydrates contain the chemical elements carbon, hydrogen and oxygen in the ratio $C_x(H_2O)_y$
- carbohydrates include simple sugars, such as glucose, and complex carbohydrates, such as cellulose and starch
- simple sugars are used in respiration; complex carbohydrates might be glucose stores (starch) or structural components of cells (cellulose)
- lipids also contain the chemical elements carbon, hydrogen and oxygen, but there is much less oxygen in lipids than in carbohydrates
- lipids can be useful storage compounds and can also be structural components of cells
- inorganic ions are present in the cytoplasm of cells and in body fluids; each type of ion has a specific function
- water is essential for life and most of the mass of an organism comprises water
- water is a reactant in many cell reactions; these reactions also occur in solution in water.

Test yourself on prior knowledge

1 Give **one** way in which the composition of a carbohydrate molecule is similar to that of a lipid and **one** way in which it is different from that of a lipid.

2 Name **one** type of carbohydrate used for energy storage in an animal and **one** used for energy storage in a plant.

3 How do animal lipids differ from plant lipids at room temperature?

4 Give **two** functions of lipids.

5 Calcium ions are essential for healthy growth in animals and plants. Give **one** function of calcium ions in humans and **one** function of calcium ions in plants.

6 In cells, water is a reactant in hydrolysis reactions and in condensation reactions. Describe the difference between these two types of reaction.

Some basic concepts

Chemical elements are the units of pure substance that make up our world. The Earth is composed of about 92 stable elements; living things are built from some of them. Table 1.1 shows a comparison between the most common elements in the Earth's crust and in us. You can see that the bulk of the Earth is composed of the elements oxygen, silicon, aluminium and iron. Of these, only oxygen is a major component of our cells.

Table 1.1 Most common elements

Earth's crust		Human body	
Element	**% of atoms**	**Element**	**% of atoms**
Oxygen	47.0	Hydrogen	63.0
Silicon	28.0	Oxygen	25.5
Aluminium	7.9	Carbon	9.5
Iron	4.5	Nitrogen	1.4
Calcium	3.5	Calcium	0.3
Sodium	2.5	Phosphorus	0.2

In fact, about 16 elements are required to build up all the molecules of the cell, and are therefore essential for life. Consequently, the full list of essential elements is a relatively short one. Furthermore, about 99 per cent of living matter consists of just four elements: carbon, hydrogen, oxygen and nitrogen.

The elements carbon, hydrogen and oxygen predominate because living things contain large quantities of water, and also because most other molecules present in cells and organisms are compounds of carbon combined with hydrogen and oxygen, including the carbohydrates and lipids. We will examine the structures and roles of carbohydrates and lipids shortly.

The element nitrogen is combined with carbon, hydrogen and oxygen in compounds called amino acids, from which proteins are constructed (Chapter 2). First, we will introduce some inorganic ions essential for organisms, and then discuss water.

Atoms, molecules and ions

The fundamental unit of chemical structure is the **atom**. Atoms group together to form molecules and molecules are the smallest part of most elements or compounds that can exist alone under normal conditions. For example, both oxygen and nitrogen naturally combine with another atom of the same type to form a molecule (O_2 and N_2, respectively).

If an atom gains or loses an electron, an **ion** is formed. Depending on their charge, ions migrate to the poles of an electric field. Positively charged ions migrate to the negative pole (cathode) and so are called **cations**. In contrast, negatively charged ions migrate to the positive pole (anode) and so are called **anions**.

Key terms

Atom The smallest part of an element that can take part in a chemical change.

Ions Charged particles formed when atoms gain or lose electrons. **Cations** are positively charged, whereas **anions** are negatively charged.

Acid A compound that releases hydrogen ions in solution. Acidic solutions have a pH value below 7.

Acids and bases

An **acid** is a compound that releases hydrogen ions in solution. We are familiar with the sharp taste that acids such as lemon juice or vinegar give to the tongue. These are relatively weak acids, weak enough to use on foods. The stronger the acid the more dangerous and corrosive it is, and the more hydrogen ions it releases. An example of a strong acid is hydrochloric acid. In water, this acid dissociates completely. The word dissociate means 'separates into its constituent ions':

$$\underset{\text{hydrochloric acid}}{HCl} \rightarrow \underset{\text{hydrogen ion (proton)}}{H^+} + \underset{\text{chloride ion}}{Cl^-}$$

With organic acids such as citric acid (present in lemon juice) and ethanoic acid (found in vinegar), which we recognise as weak acids, relatively few molecules dissociate, and few hydrogen ions are present:

$$\underset{\text{ethanoic acid}}{C_3H_3COOH} \rightarrow \underset{\text{ethanoate ion}}{C_2H_5COO^-} + \underset{\text{hydrogen ion (proton)}}{H^+}$$

A **base** is a compound that can take up hydrogen ions in solution. In doing so it can neutralise an acid, forming a salt and water in the process. Many bases are insoluble in water. Those that are soluble in water are called alkalis. Examples of strong bases (that are also alkalis) are sodium hydroxide and potassium hydroxide. Strong alkalis, like strong acids, are completely dissociated in water:

$$\underset{\text{sodium hydroxide}}{NaOH} \rightarrow \underset{\text{sodium ion}}{Na^+} + \underset{\text{hydroxide ion}}{OH^-}$$

Key term

Base A compound that can take up hydrogen ions in solution. Basic solutions have a pH value above 7.

Tip

Remember when dealing with logarithmic values that a value of 2 ($\log_{10} 100$) is ten times greater than a value of 1 ($\log_{10} 10$), not two times greater.

pH and buffers

pH is a measure of the acidity or alkalinity of a solution. Strictly, pH is a measure of the hydrogen ion concentration. Since these concentrations involve a very large range of numbers, the pH scale uses logarithms:

$$\text{pH} = -\log_{10} \text{H}^+ \text{ concentration}$$

The pH value of pure water is 7. A solution with a pH value less than 7 is acidic; strong acids have a pH value of 0 to 2. A solution with a pH value more than 7 is alkaline; strong alkalis have a pH value of 12 to 14.

pH can be measured experimentally, either using an indicator solution or a pH meter. For example, universal pH indicator is a mixture of several different indicators, and changes colour with the pH, as shown in Figure 1.1.

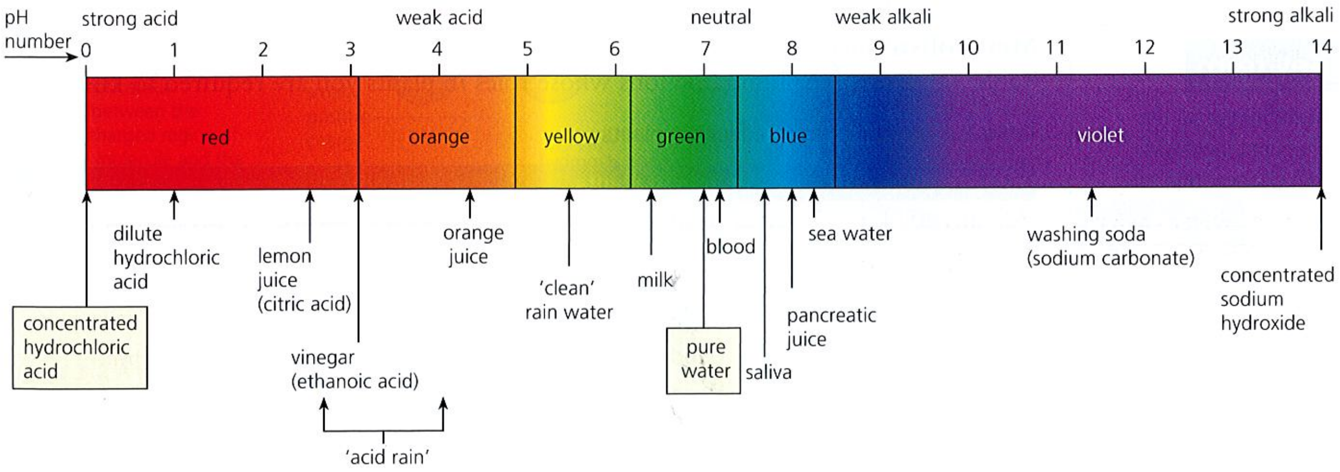


Figure 1.1 The pH scale of universal pH indicator solution

pH is very important in living organisms, largely because pH affects the shape of enzymes, almost all of which are proteins (page 34). In a mammal's body there are mechanisms that stabilise pH at a value just slightly above pH 7.0. If the pH varies much from this value this lack of stabilisation is quickly fatal. For plants that obtain essential mineral ions from the soil solution, the pH of the soil affects the availability of the ions for absorption.

Key term

Buffer solution
A solution that resists changes in pH; usually a mixture of a weak acid and one of its soluble salts.

A **buffer solution** is one that will resist pH change when diluted, or if a little acid or alkali is added. Many buffers used in laboratory experiments contain a weak acid (such as ethanoic acid and one of its soluble salts, for example sodium ethanoate). In this case, if acid is added, the excess hydrogen ions are immediately removed by being combined with ethanoate ions to form undissociated ethanoic acid. Alternatively, if alkali is added, the excess hydroxyl ions immediately combine with hydrogen ions, forming water. At the same time, more of the ethanoic acid dissociates, adding more hydrogen ions to the solution. The pH does not change in either case.

In the body of a mammal, the blood is very powerfully buffered by the presence of a mixture of phosphate ions, hydrogencarbonate ions and blood proteins (page 226). The blood is held between pH 7.35 and 7.45.

Test yourself

1 Distinguish between a sodium atom and a sodium ion.

2 A pH value is calculated as $-\log_{10}$ hydrogen ion concentration. By how many times is the concentration of hydrogen ions in a solution with a pH value of 2 greater than one with a pH value of 8?

3 Explain the importance of using buffer solutions during investigations into the rate of enzyme-controlled reactions.

4 Explain the meaning of the term *dissociation*.

5 Explain why a positively charged ion is called a cation.

Inorganic ions used by plants

Key term

Metabolism All the chemical reactions that occur within an organism.

Metabolism involves a range of inorganic ions, in addition to those mentioned above. Table 1.2 shows four inorganic ions whose roles in plants you are required to know.

Table 1.2 The role of selected ions in plants

Inorganic ion	Role in plants
Nitrate (NO_3^-)	Used to synthesise the nitrogenous bases in DNA and RNA nucleotides and to synthesise the amino groups of amino acids.
Calcium (Ca^{2+})	Used to synthesise calcium pectate, which exists as a layer, called the middle lamella, between the walls of adjacent plant cells.
Magnesium (Mg^{2+})	Used to synthesise the photosynthetic pigment, chlorophyll.
Phosphate (PO_4^{3-})	Used to synthesise adenosine triphosphate (ATP) from adenosine diphosphate (ADP) and to synthesise DNA and RNA

Water

Living things are typically solid, substantial objects, yet water forms the bulk of their structures – between 65 and 95 per cent by mass of most multicellular plants and animals (about 80 per cent of a human cell consists of water). Despite this, and the fact that water has some unusual properties, it is a substance that is often taken for granted.

Water is composed of atoms of the elements hydrogen and oxygen. One atom of oxygen and two atoms of hydrogen combine by sharing of electrons in an arrangement known as a **covalent bond** (see Figure 1.2). The large nucleus of the oxygen atom draws electrons (negatively charged) away from the smaller hydrogen nuclei (positively charged) with an interesting consequence. Although overall the water molecule is electrically neutral, there is a weak negative charge (represented by δ^-) on the oxygen atom and a weak positive charge (represented by δ^+) on each hydrogen atom. In other words, the water molecule carries an unequal distribution of electrical charge within it. This arrangement is known as a **polar molecule**.

Key terms

Covalent bond
A relatively strong chemical link between two atoms in which electrons are shared between them.

Polar molecule
A molecule that contains weak positive charges (represented by δ^+) and weak negative charges (represented by δ^-)

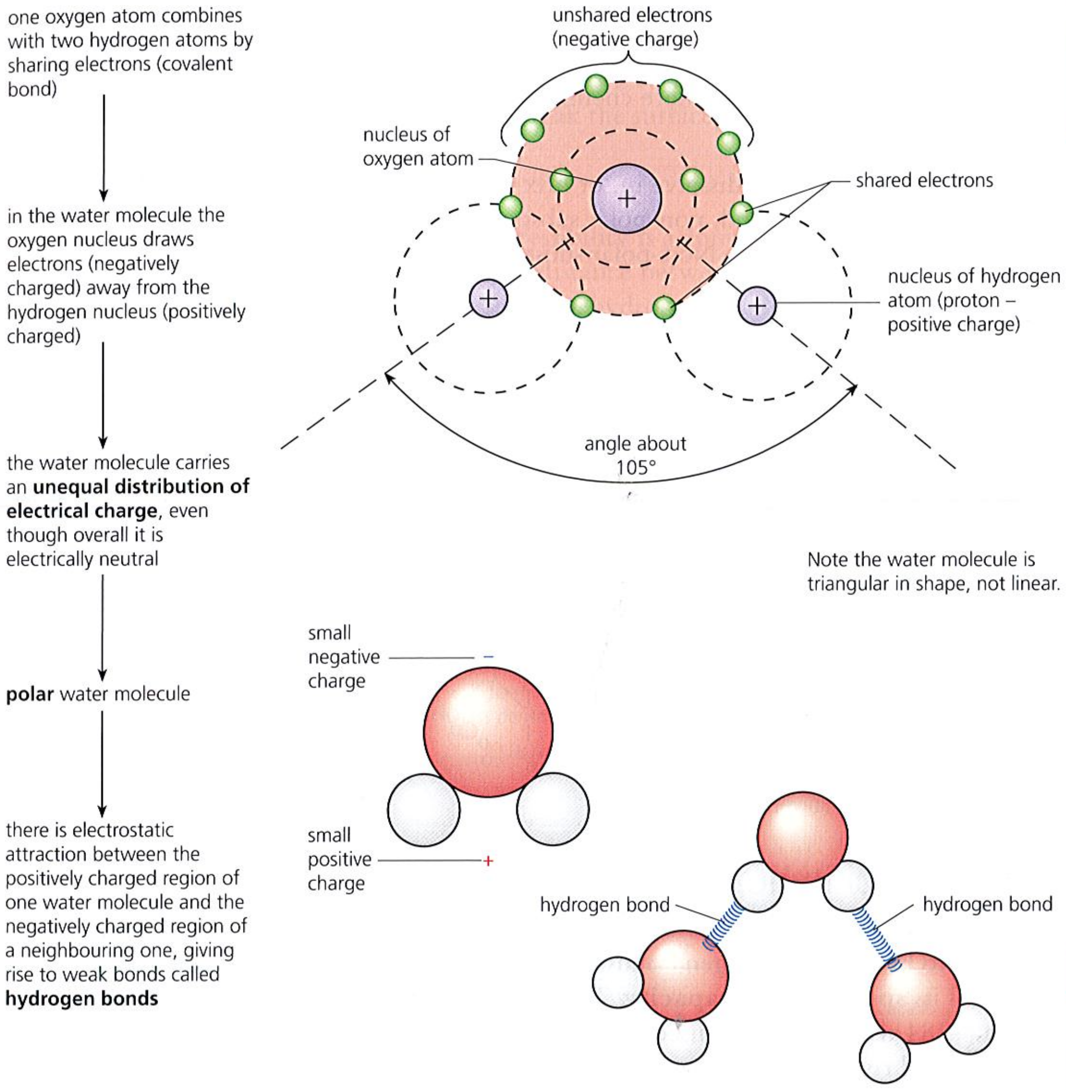


Figure 1.2 A water molecule and the hydrogen bonds it forms

Hydrogen bonds

The positively charged hydrogen atoms of one molecule are attracted to negatively charged oxygen atoms of nearby water molecules by forces called **hydrogen bonds**. These are weak bonds compared with covalent bonds, yet they are strong enough to hold water molecules together. This is called **cohesion**; it not only attracts water molecules to each other but also to another charged particle or charged surface. In fact, hydrogen bonds largely account for the unique properties of water, which are examined next.

Key terms

Hydrogen bond A relatively weak link between two atoms in which a weakly negative atom attracts another weakly positive atom.

Cohesion The force by which hydrogen bonds hold polar molecules together, or to a charged surface.

Solvent properties of water

Because water molecules are polar, water is a powerful solvent for other polar substances (Figure 1.3). These include:

- ionic substances like sodium chloride (Na^+ and Cl^-). All ions become surrounded by a shell of orientated water molecules (Figure 1.3)
- carbon-containing (organic) molecules with ionised groups, such as the carboxyl group ($-COO^-$) and amino group ($-NH_3^+$). Soluble organic molecules like sugars dissolve in water due to the formation of hydrogen bonds with their slightly charged hydroxyl groups ($-OH^-$).

Once they have dissolved, the **solute** molecules are free to move around in water (the **solvent**) and, as a result, are more chemically reactive than when in the undissolved solid state.

Polar substances that can dissolve in, or mix in, water are termed **hydrophilic** (water-loving). On the other hand, non-polar substances are repelled by water, as in the case of oil on the surface of water. Non-polar substances are **hydrophobic** (water-hating).

Key terms

Hydrophilic Refers to substances that will mix with water.

Hydrophobic Refers to substances that will not mix with water.

Ionic compounds like NaCl dissolve in water:

$NaCl \rightleftharpoons Na^+ + Cl^-$

with a group of orientated water molecules around each ion.

Sugars and alcohols dissolve due to hydrogen bonding between polar groups in their molecules (e.g. –OH) and the polar water molecules.

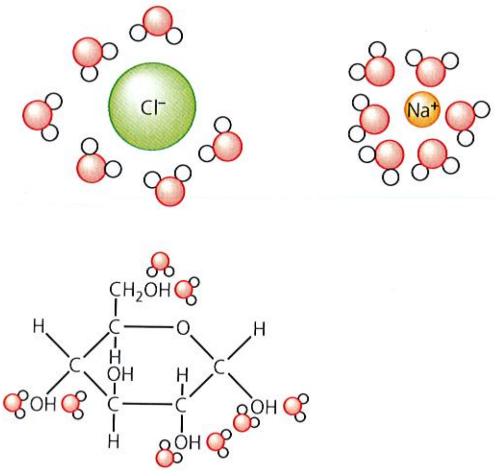


Figure 1.3 Water as universal solvent

High specific heat capacity of water

A lot of heat is required to raise the temperature of water. This is because heat is needed to break the hydrogen bonds between water molecules. This property of water is its **specific heat capacity**. The specific heat capacity of water is extremely high ($4.184\,kJ\,kg^{-1}\,°C^{-1}$). Consequently, the temperature of aquatic environments like streams and rivers, ponds, lakes and seas is very slow to change when the surrounding air temperature changes. Aquatic environments have much more stable temperatures than do terrestrial (land) environments.

Another consequence is that the temperature of cells and the bodies of organisms does not change readily. Bulky organisms, particularly, tend to have a stable temperature in the face of a fluctuating surrounding temperature, whether in extremes of heat or cold.

Tip

The specific heat capacity of water given in the text is $4.184\,kJ\,kg^{-1}\,°C^{-1}$. You need to be confident in using compound units. In this case, the unit means that it takes 4.184 kJ of heat to increase the temperature of 1 kg of water by 1 degree Celsius.

Surface tension of water

Compared with other liquids, water has extremely strong adhesive and cohesive properties.

As we saw earlier, cohesion is the force by which charged molecules stick together. Water molecules are held together by hydrogen bonding. In practice, these bonds continually break and reform with other surrounding water molecules but, at any one moment, a large number are held together by their hydrogen bonds.

At an air–water interface, cohesion between water molecules results in **surface tension**. The outermost molecules of water form hydrogen bonds with water molecules below them. This gives a very high surface tension to water, which you can see being exploited by the pond skater in Figure 1.4. This insect has a waxy cuticle that prevents wetting of its body and its mass is not great enough to break the surface tension of the water.

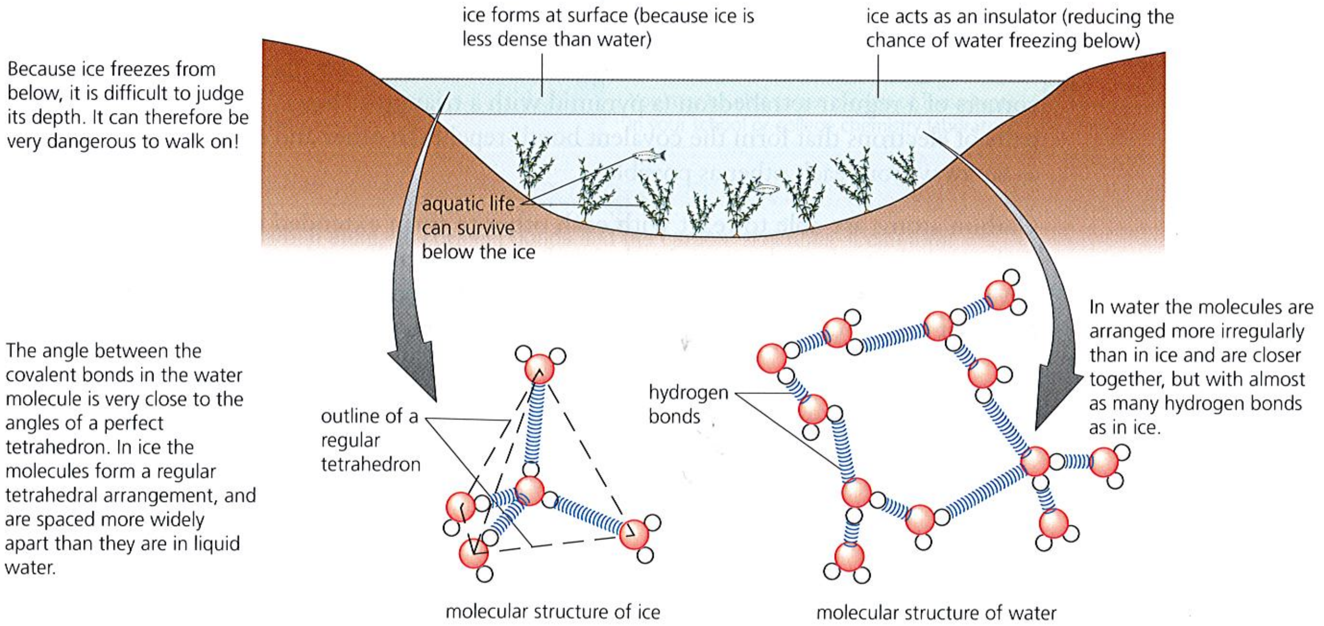
Figure 1.4 A pond skater moving over the water surface

Incompressibility of water

Water is essentially incompressible. Incompressibility is a common property of liquids but water is especially so. There is much less distance between the molecules in a liquid than in a gas, and the intermolecular force of the hydrogen bonds aids this property. Because of this incompressibility, a water-filled cavity within an organism can act as a hydrostatic skeleton.

Maximum density of water at 4 °C

Most liquids contract on cooling, reaching maximum density at their freezing point. Water is unusual in reaching its maximum density at 4 °C (Figure 1.5). So as water freezes, the ice formed is less dense than the cold water around it. As a consequence, ice floats on top of very cold water. The floating layer of ice insulates the water below. The consequence is that lakes rarely freeze solid; aquatic life can generally survive freezing temperatures.



Because ice freezes from below, it is difficult to judge its depth. It can therefore be very dangerous to walk on!

The angle between the covalent bonds in the water molecule is very close to the angles of a perfect tetrahedron. In ice the molecules form a regular tetrahedral arrangement, and are spaced more widely apart than they are in liquid water.

In water the molecules are arranged more irregularly than in ice and are closer together, but with almost as many hydrogen bonds as in ice.

Figure 1.5 Ice forms on the surface of water

Test yourself

6 Suggest what symptoms would be shown by a plant growing in magnesium-deficient soil. Explain your answer.

7 What is meant by the term *metabolism*?

8 The text includes five properties of water that make it essential in biology. Use your knowledge of metabolism to suggest a sixth property.

9 Water that evaporates from the leaves of a flowering plant is replaced when a water column is pulled up the plant in xylem tissue. This water column is under negative pressure (tension). Explain why this does *not* cause the water column to break.

10 Explain why the pond skater shown in Figure 1.4 can walk on water but you cannot.

Introducing the carbon of organic compounds

Key term

Organic compound
A compound in which carbon atoms are linked by covalent bonds to each other and to hydrogen molecules. The molecules of organic compounds can be very large and can exist as chains or rings of carbon atoms.

Carbon is a relatively uncommon element of the Earth's crust but, as Table 1.1 showed, in cells and organisms it is the third most abundant element. The majority of the carbon compounds found in living organisms are relatively large molecules in which many carbon atoms are linked together and to hydrogen and oxygen atoms by covalent bonds. They are known as **organic compounds**.

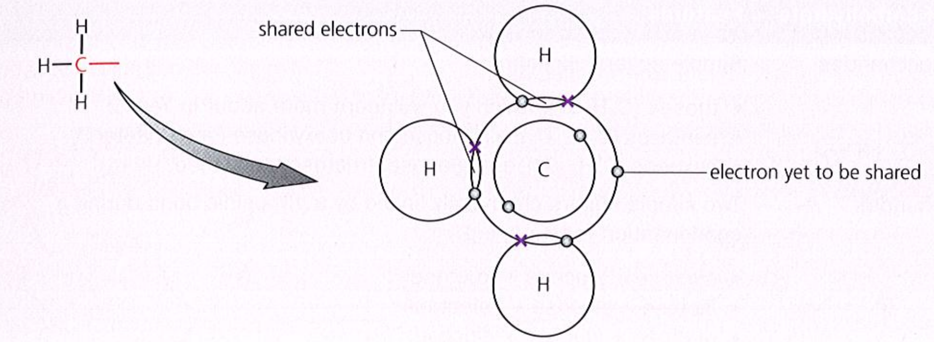
Some carbon-containing compounds are not like this – for example, the gas carbon dioxide (CO_2) and hydrogencarbonate ions (HCO_3^-) are not organic forms of carbon.

The properties of carbon

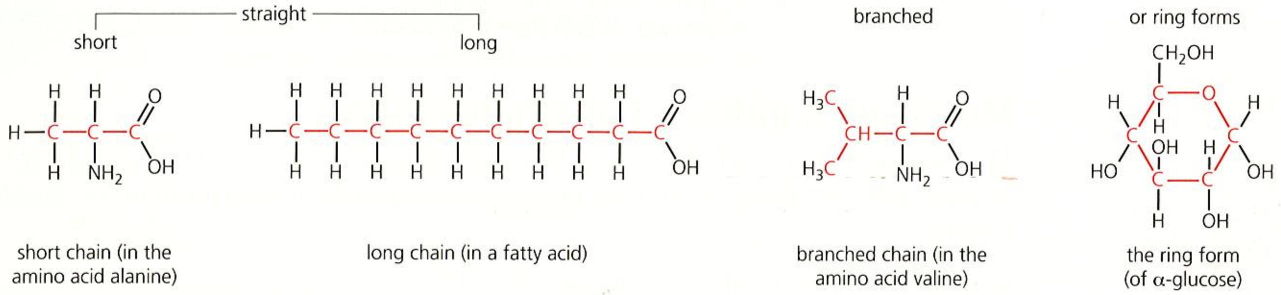
Carbon has remarkable properties. It has a relatively small atom, but it is able to form four strong, stable, covalent bonds. As you can see in Figure 1.6, these bonds point to the corners of a regular tetrahedron (a pyramid with a triangular base). This is because the four pairs of electrons that form the covalent bonds repel each other and so position themselves as far away from each other as possible.

Carbon atoms are able to react with each other to form extended chains. The resulting carbon 'skeletons' can be straight chains, branched chains or rings. Carbon also bonds covalently with other atoms, such as oxygen, hydrogen, nitrogen and sulfur, forming different groups of organic molecules with distinctive properties.

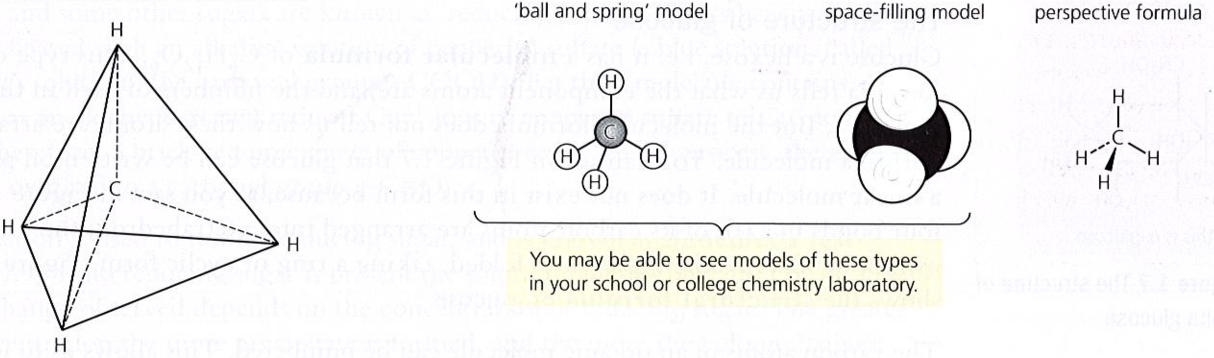
Covalent bonds are formed by sharing of electrons, one from the carbon atom and one from the neighbouring atom it reacts with:



Carbon atoms bond with other carbon atoms to form carbon 'skeletons':



The carbon atom is at the centre of the tetrahedron, a three-dimensional structure, e.g. methane:



You may be able to see models of these types in your school or college chemistry laboratory.

Figure 1.6 A tetrahedral carbon atom, its covalent bonds and the carbon 'skeletons' it can form

One inevitable outcome of these features is that there are vast numbers of organic compounds – more than the total of known compounds made from other elements, in fact. Biologists think the diversity of organic compounds has made possible the diversity of life. Fortunately, very many of the organic chemicals of living things fall into one of four discrete groups or 'families' of chemicals with many common properties, one of which is the carbohydrates. We will consider this family of molecules first before looking at a second family, the lipids.

Carbohydrates

Carbohydrates include sugars, starch, glycogen and cellulose. They contain only three elements: carbon, hydrogen and oxygen, in the ratio $C_x(H_2O)_y$. Table 1.3 summarises features of the three types of carbohydrates you should recognise.

Table 1.3 Carbohydrates of cells and organisms.

Type of carbohydrate	Features
Monosaccharides	Simple sugars, including: • trioses ($C_3H_6O_3$), which you will learn more about in Year 2 • pentoses ($C_5H_{10}O_5$), e.g. ribose and deoxyribose (see Chapter 3) • hexoses ($C_6H_{12}O_6$), e.g. glucose, fructose, galactose.
Disaccharides	Two simple sugars chemically linked by a glycosidic bond during a condensation reaction, e.g. • sucrose = glucose + fructose • lactose = glucose + galactose • maltose = glucose + glucose.
Polysaccharides	Very many simple sugars chemically linked by glycosidic bonds, e.g. • starch (a fuel store in plants) • glycogen (a fuel store in animals) • cellulose (a major component of plant cell walls).

Monosaccharides – the simple sugars

Monosaccharides are carbohydrates with relatively small molecules. They are soluble in water and taste sweet. In biology, glucose is an especially important monosaccharide because:

- all green leaves manufacture glucose using light
- all cells use glucose in respiration – we call it one of the respiratory substrates.

The structure of glucose

Glucose is a hexose, i.e. it has a **molecular formula** of $C_6H_{12}O_6$. This type of formula tells us what the component atoms are, and the numbers of each in the molecule. But the molecular formula does not tell us how these atoms are arranged within a molecule. You can see in Figure 1.7 that glucose can be written on paper as a linear molecule. It does not exist in this form because, as you saw in Figure 1.6, the four bonds in each of its carbon atoms are arranged into a tetrahedron; the molecule cannot be 'flat'. Rather, glucose is folded, taking a ring or cyclic form. Figure 1.7 also shows the **structural formula** of glucose.

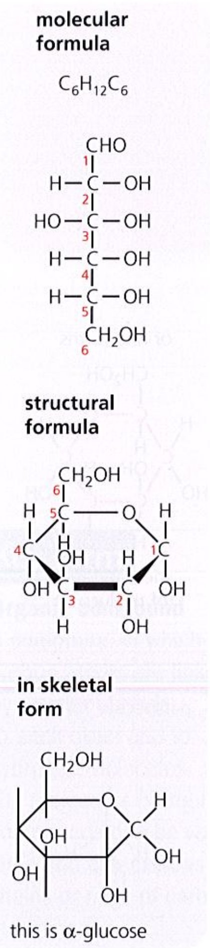


Figure 1.7 The structure of alpha glucose

The carbon atoms of an organic molecule can be numbered. This allows us to identify which atoms are affected when the molecule reacts and changes shape. For example, as the glucose ring forms, the oxygen on carbon atom 5 (carbon-5) becomes linked to that on carbon atom 1 (carbon-1). As a result, the glucose ring contains five carbon atoms and an oxygen atom; again, you can see this in Figure 1.7.

Isomers of glucose

Molecules with the same molecular formula but different structural formulae are known as **isomers**. Many organic compounds exist in isomeric forms, and so it is often important to know the structure of an organic compound as well as its composition.

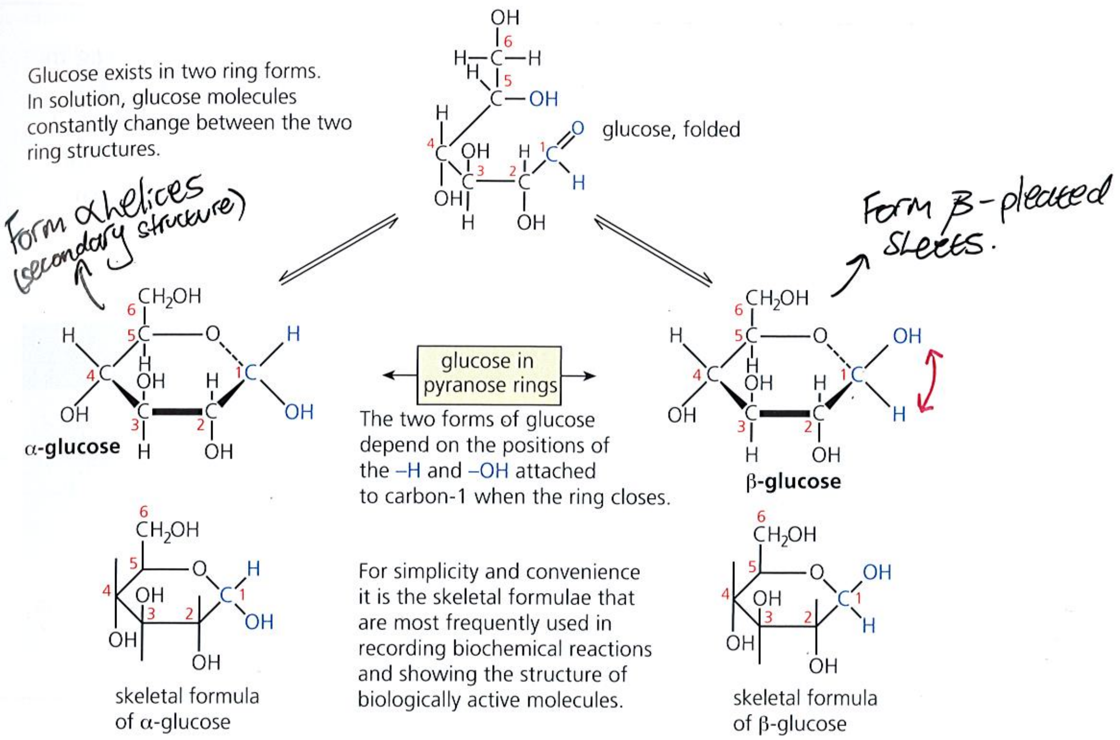
In the ring structure of glucose the positions of –H and –OH that are attached to carbon-1 can lie in one of two directions, giving rise to two isomers, known as **alpha-glucose** (α-glucose) and **beta-glucose** (β-glucose). You can see these isomers in Figure 1.8. The significance of the differences between them will become apparent when we compare the structures of starch, glycogen and cellulose (pages 13–16).

Key terms

Molecular formula Shows the nature and number of atoms in a molecule, for example $C_5H_{10}O_5$.

Structural formula Shows the way in which the atoms within a molecule are arranged in space.

Isomers Two or more different structural formulae of the same molecular formula.



Glucose exists in two ring forms. In solution, glucose molecules constantly change between the two ring structures.

Form α helices (secondary structure)

Form β-pleated sheets.

The two forms of glucose depend on the positions of the –H and –OH attached to carbon-1 when the ring closes.

For simplicity and convenience it is the skeletal formulae that are most frequently used in recording biochemical reactions and showing the structure of biologically active molecules.

Figure 1.8 Alpha and beta glucose

A test for the presence of glucose, a 'reducing sugar'

Glucose and some other sugars are known as 'reducing sugars'. This is because, when they are heated with an alkaline solution of copper(II) sulfate (a blue solution, called Benedict's solution), the carboxyl group (–COOH) that their molecule contains (known as an aldehyde group) reduces Cu^{2+} ions of copper(II) sulfate to Cu^+ ions, which then form a brick-red precipitate of copper(I) oxide. In the process, the aldehyde group is oxidised to a carbonyl group (–C=O).

This reaction is used to test for reducing sugar, and is known as **Benedict's test** (Figure 1.9). If no reducing sugar is present the solution remains blue after heating. The colour change observed depends on the concentration of reducing sugar. The greater the concentration the more precipitate is formed, and the more the colour changes:

blue → green → yellow → brown → red

5 cm^3 of Benedict's solution (blue) was added to 10 cm^3 of solution to be tested → test tubes were placed in a boiling water bath for 5 minutes → tubes were transferred to a rack and the colours compared

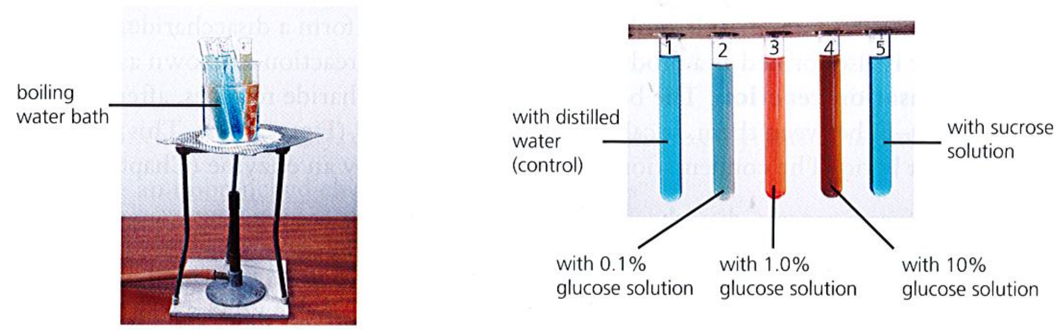
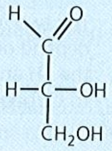
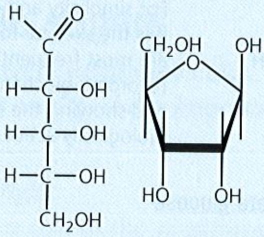
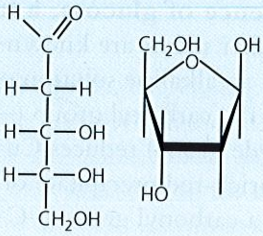


Figure 1.9 The test for reducing sugar. Wear eye protection when performing this test

Other monosaccharides of importance in living cells

Glucose, fructose and galactose are examples of hexose sugars commonly occurring in cells and organisms, but it is only the structure of α- and β-glucose that you need to know. Other monosaccharide sugars produced by cells and used in metabolism include a 3-carbon sugar (Table 1.4), and two 5-carbon sugars (**pentoses**), namely ribose and deoxyribose. These pentoses are components of the nucleic acids and you will learn about their structure in Chapter 3.

Table 1.4 Other monosaccharides important in cell chemistry

Length of carbon chain	Name of sugar	Molecular formula	Formula	Roles
3C = triose	glyceraldehyde	$C_2H_6O_2$		intermediate in respiration and photosynthesis
5C = pentoses	ribose	$C_5H_{10}O_5$		in RNA, ATP and hydrogen acceptors NAD and NADP
	deoxyribose	$C_5H_{10}O_4$		in DNA

Disaccharides

A disaccharide is a carbohydrate made of two monosaccharides linked together. For example, sucrose is formed from a molecule of glucose and a molecule of fructose chemically linked together.

Condensation and hydrolysis reactions

When two monosaccharide molecules are combined to form a disaccharide, a molecule of water is also formed as a product, and so this type of reaction is known as a **condensation reaction**. The bond between monosaccharide residues, after the removal of H–O–H between them, is called a **glycosidic bond** (Figure 1.10). This is a strong, covalent bond. The condensation reaction is catalysed by an enzyme (Chapter 2).

In the reverse process, disaccharides are 'digested' to their component monosaccharides in a **hydrolysis reaction**. Of course this reaction involves adding a molecule of water ('*hydro-*') as splitting ('*-lysis*') of the glycosidic bond occurs. It is catalysed by an enzyme, too, but it is a different enzyme from the one that brings about the condensation reaction.

Key terms

Condensation reaction
A reaction in which two molecules are chemically linked together with the elimination of a molecule of water.

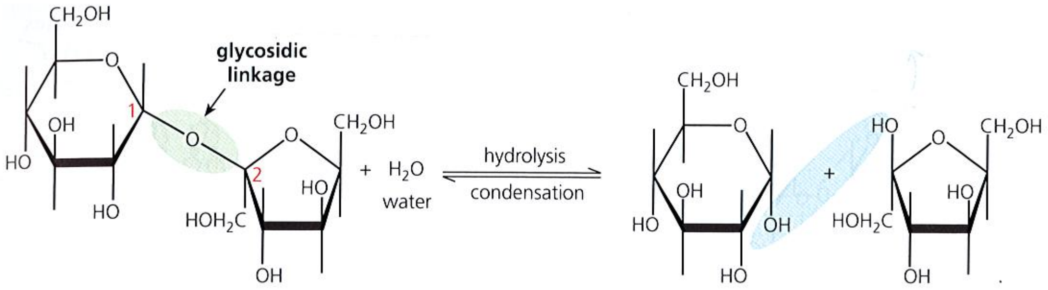
Glycosidic bond
A covalent bond between two monosaccharides.

Hydrolysis reaction
A reaction in which a molecule of water is used in breaking a chemical bond (the reverse of a condensation reaction).

Apart from sucrose, other disaccharide sugars produced by cells and used in metabolism include:

- maltose, formed by a condensation reaction of two molecules of glucose
- lactose, formed by a condensation reaction of galactose and glucose.

$$\text{sucrose} + \text{water} \underset{\text{condensation}}{\overset{\text{hydrolysis}}{\rightleftharpoons}} \text{glucose} + \text{fructose}$$



This structural formula shows us how the glycosidic linkage forms/breaks.

$$\text{maltose} + \text{water} \underset{\text{condensation}}{\overset{\text{hydrolysis}}{\rightleftharpoons}} \text{glucose} + \text{glucose}$$

$$\text{lactose} + \text{water} \underset{\text{condensation}}{\overset{\text{hydrolysis}}{\rightleftharpoons}} \text{galactose} + \text{glucose}$$

Figure 1.10 Sucrose, a disaccharide, and the monosaccharides that form it

Polysaccharides

A polysaccharide is built from many monosaccharides linked by glycosidic bonds formed during condensation reactions. '*Poly*' means many, and in fact thousands of saccharide (sugar) units make up a polysaccharide. So a polysaccharide is a giant molecule, a macromolecule. Normally each polysaccharide contains only one type of **monomer**. A chemist calls this a **polymer** because it is constructed from a huge number of *identical* monomers.

Some polysaccharides function as fuel stores. Both glycogen and starch are examples, as we shall shortly see. On the other hand, some polysaccharides, such as cellulose, have a structural role. Cellulose has huge molecules that are not so easily hydrolysed by enzyme action.

Key terms

Polymer A large molecule comprising repeated, identical smaller molecules (**monomers**) linked together by chemical bonds.

Residues When monomers are linked together in a polymer, we can no longer refer to them as molecules. Instead, we can call them residues.

Starch

Starch is a mixture of two polysaccharides, both of which are polymers of α-glucose:

- **amylose** – an unbranched chain of α-glucose residues
- **amylopectin** – branched chains of α-glucose residues.

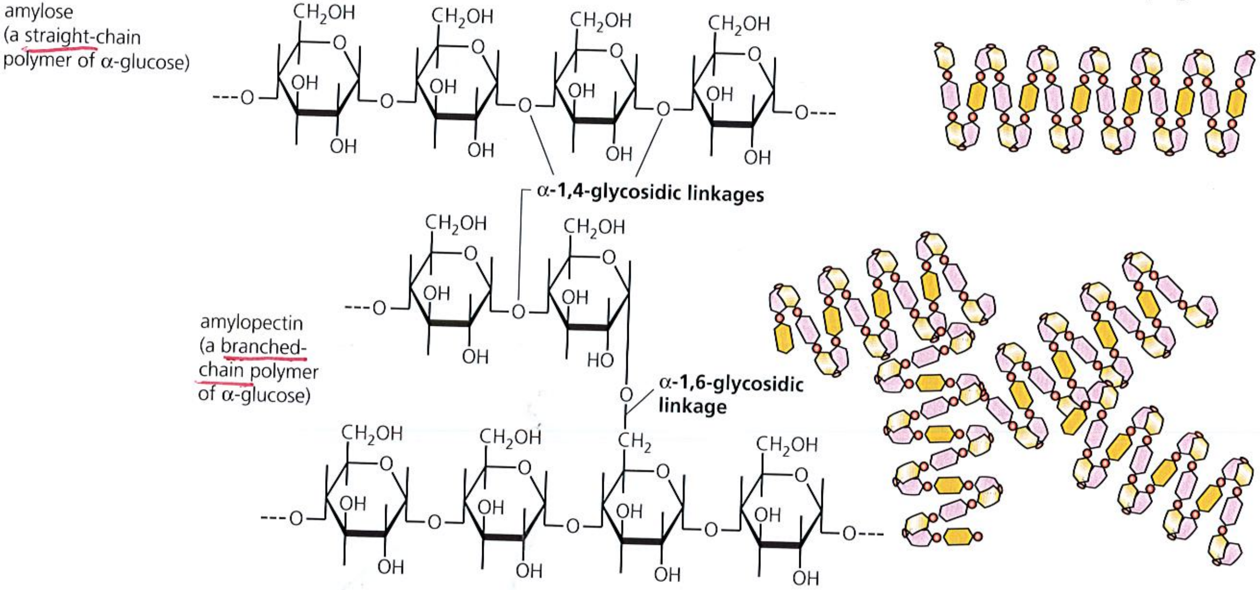
The glycosidic bonds between α-glucose residues in starch bring the molecules together in such a way that a helix forms. The whole starch molecule is then stabilised by countless hydrogen bonds between parts of the component glucose **residues**.

Starch is the major storage carbohydrate of most plants. It is laid down as compact grains. It is useful because its molecules are both compact and insoluble, but are readily hydrolysed to form sugar when required. Of course, enzymes are involved in this reaction, too.

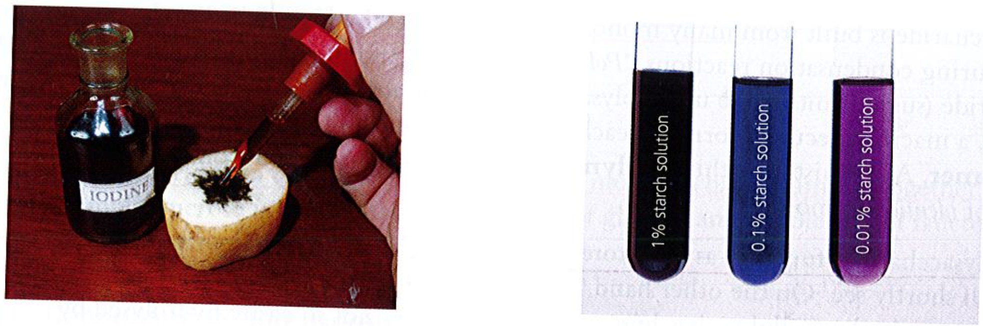
We sometimes see 'soluble starch' as an ingredient of manufactured foods. Here the starch molecules have been broken down into short lengths, making them dissolve more easily.

A test for the presence of starch

We test for starch by adding a solution of iodine in potassium iodide. Iodine molecules fit neatly into the centre of a starch helix, creating a blue-black colour (Figure 1.11).



In the test for starch with iodine in potassium iodide solution, the blue-black colour comes from a starch/iodine complex:



a) on a potato tuber cut surface

b) on starch solutions of a range of concentrations

c)

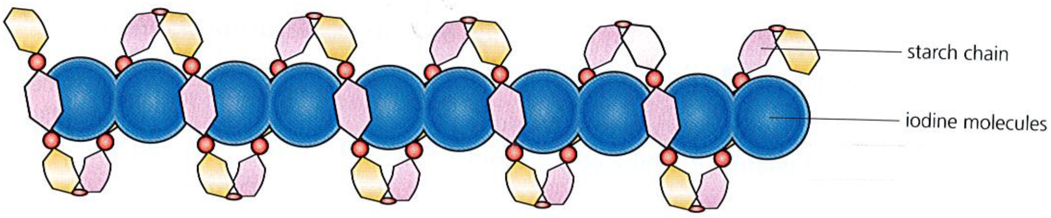
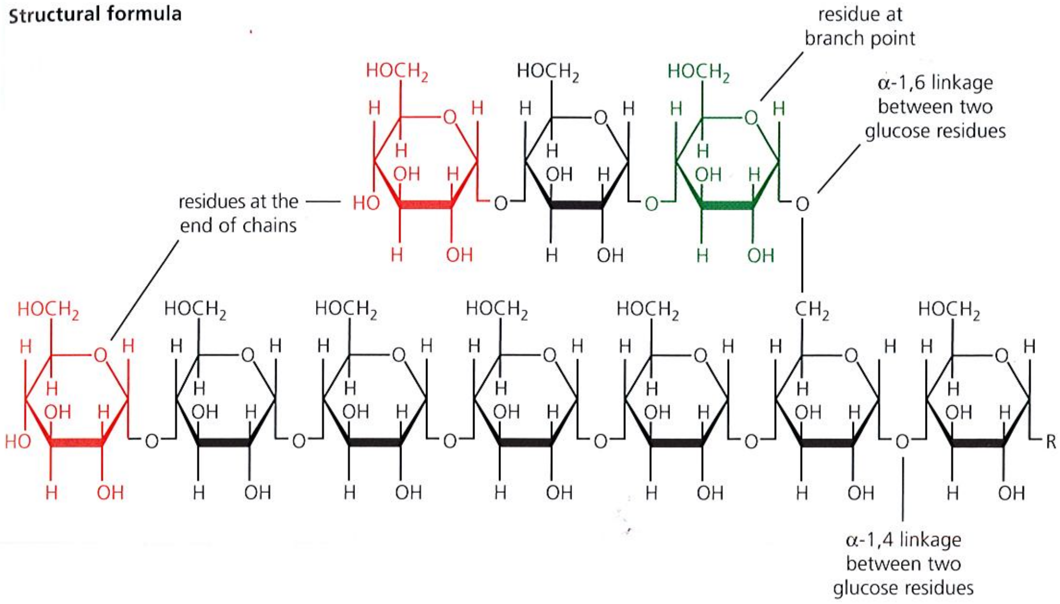


Figure 1.11 Starch

Glycogen

Glycogen is also a polymer of α-glucose. It is chemically very similar to amylopectin, although larger and more highly branched. Granules of glycogen are seen in liver cells and muscle fibres when observed by the electron microscope, but they occur throughout the human body, except in the brain cells (where there are virtually no carbohydrate reserves). During prolonged and vigorous exercise we draw on our glycogen reserves first. Only when these are exhausted does the body start to metabolise stored fat.

Structural formula



TEM of a liver cell (x7000)

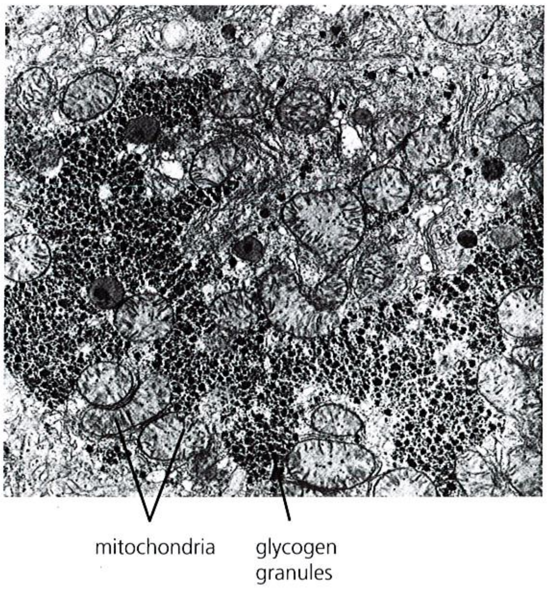
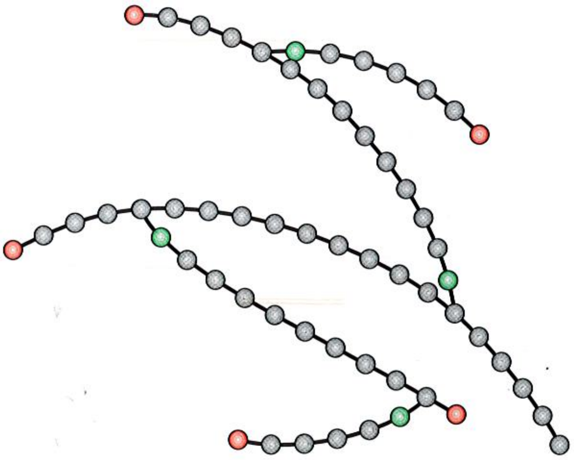


Diagram to show the branching pattern of a glycogen molecule



Glycogen and amylopectin compared

glycogen	amylopectin
branch point every 10 glucose residues	branch point every 30 glucose residues

Figure 1.12 Glycogen

Cellulose

Cellulose is a polymer of around 2000 to 3000 units of beta-glucose (β-glucose). Look back to Figure 1.8, which shows the difference in structure between α-glucose and β-glucose.

Can you spot what it is?

The only difference between the two molecules is the way in which the –H and –OH groups are bonded to carbon-1. In α-glucose the –H group is uppermost whereas in β-glucose the –OH group is uppermost. Although this might seem trivial, it has a big effect when molecules of β-glucose become linked together. As Figure 1.13 shows, the way glycosidic bonds form causes adjacent β-glucose units to be upside down with respect to each other. These glycosidic bonds are referred to as β-1,4 glycosidic bonds. This arrangement leads to cellulose molecules being long, straight-chains.

About 200 of these chains naturally become packed into fibres, held together by hydrogen bonds (Figure 1.13). The strength of plant cell walls results from the combined effect of the bonds between β-glucose monomers, the hydrogen bonds within and between these chains of β-glucose and the way in which the fibres are arranged in different directions.

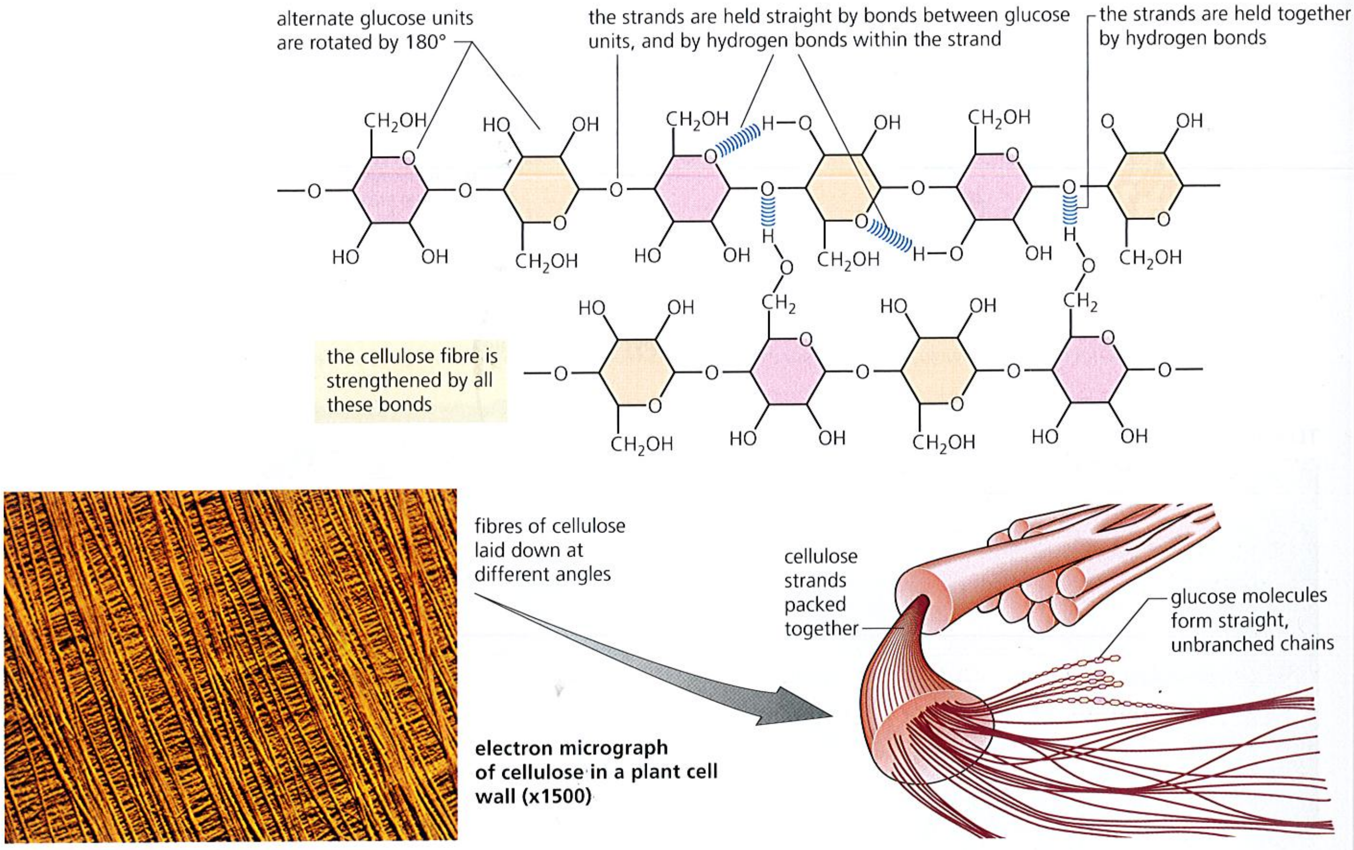


Figure 1.13 The chemistry and structure of cellulose

Test yourself

11 Explain the difference between a molecular formula and a structural formula.

12 α-glucose and β-glucose are isomers. Explain what this means.

13 What is the difference between a pentose and a hexose sugar?

14 Lactose is a disaccharide found in milk. Into which monosaccharides is it broken down in your intestines?

15 Starch is a polymer. What is meant by a *polymer*?

16 Both starch and glycogen can be broken down to provide glucose, used in respiration. Name the type of reaction by which both are broken down.

17 The reaction by which amylose and amylopectin are hydrolysed produces disaccharides.
- **a)** Name the disaccharide formed.
- **b)** Which compound, amylase or amylopectin, would you expect to be hydrolysed faster? Explain your answer.

Lipids

The second 'family' of organic molecules to consider here is the lipids. These occur in mammals as fats and in plants as oils. Fats and oils appear to be rather different substances, but the basic difference between them is that, at about 20 °C (room temperature), oils are liquid and fats are solid. Like the carbohydrates, lipids also contain the elements carbon, hydrogen and oxygen, but in lipids the proportion of oxygen is much less.

Lipids are insoluble in water, i.e. are hydrophobic. However, lipids can be dissolved in organic solvents such as alcohol (for example ethanol).

Key term

Ester bond The bond formed during a condensation reaction between a fatty acid and glycerol.

Here we will consider only two types of lipid: triglycerides and phospholipids.

Triglycerides

Triglycerides are formed during condensation reactions between glycerol (an alcohol) and three fatty acids. The bonds formed are known as **ester bonds**.

Fatty acids are long hydrocarbon chains, anything between 14 and 22 carbon atoms long.

The structures of a fatty acid commonly found in cells and that of glycerol are shown in Figure 1.14 and the steps to triglyceride formation in Figure 1.15. Enzymes catalyse the condensation reactions by which triglycerides are formed.

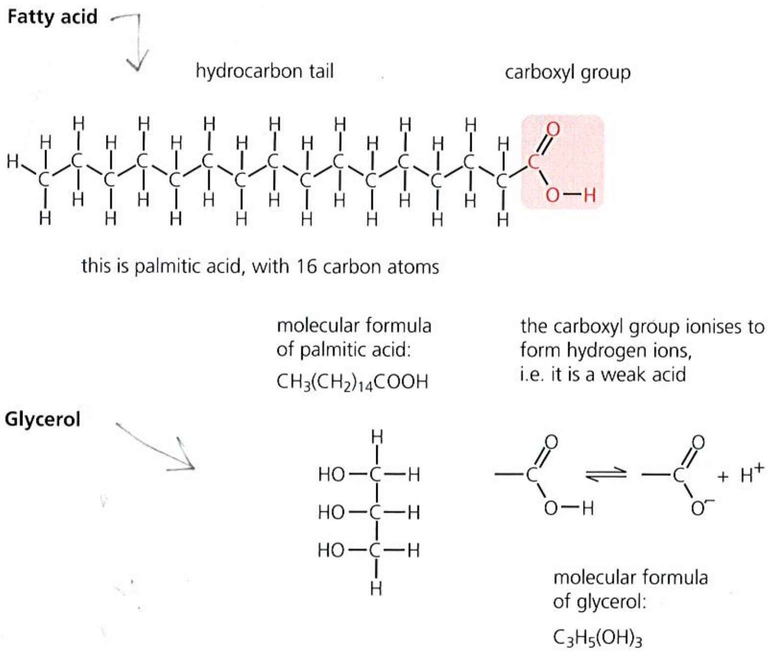
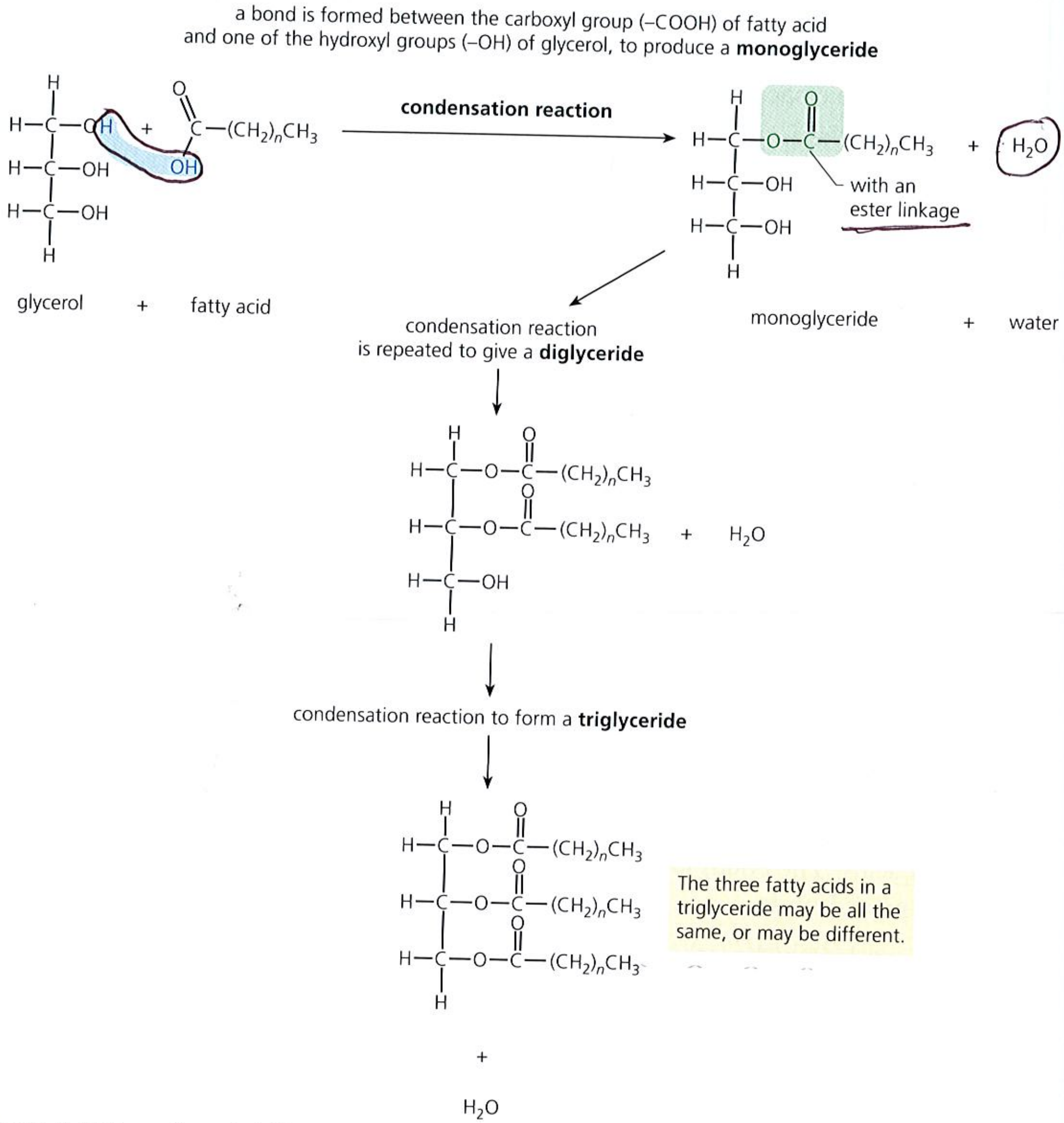


Figure 1.14 Fatty acids and glycerol, the building blocks of lipids

The hydrophobic properties of triglycerides are caused by the hydrocarbon chains of the component fatty acids. A molecule of triglyceride is quite large, but relatively small when compared with macromolecules such as starch. However, because of their hydrophobic properties, triglyceride molecules clump together (aggregate) into huge globules in the presence of water, making them appear to be macromolecules.



a bond is formed between the carboxyl group (–COOH) of fatty acid and one of the hydroxyl groups (–OH) of glycerol, to produce a **monoglyceride**

The three fatty acids in a triglyceride may be all the same, or may be different.

Figure 1.15 Formation of triglyceride

Saturated and unsaturated lipids

We have seen that the length of the hydrocarbon chains is different from fatty acid to fatty acid. These chains can differ in another way, too. To understand this latter difference, we need to note another property of carbon atoms and the ways they can combine together in chains. This concerns the existence of double covalent bonds (Figure 1.16).

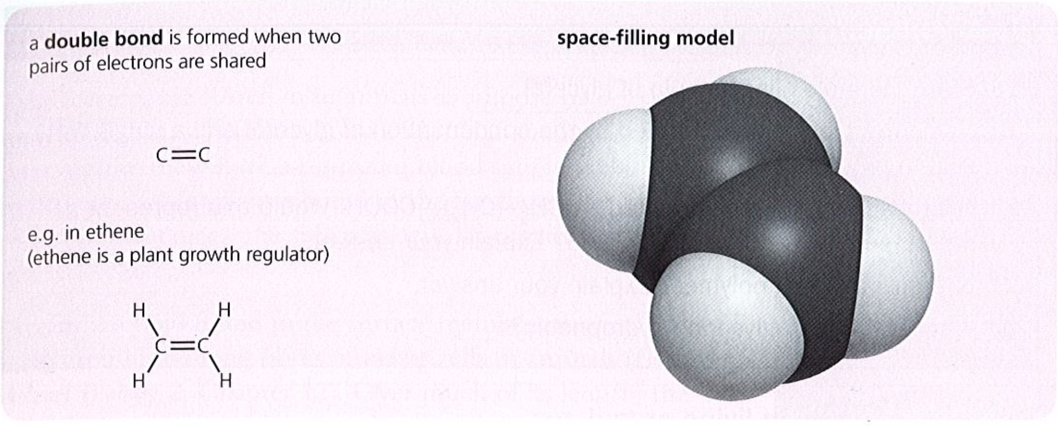


Figure 1.16 A carbon-carbon double covalent bond

A double covalent bond is formed when adjacent carbon atoms share *two pairs* of electrons, rather than the single electron pair shared in a single covalent bond. Carbon compounds that contain double carbon–carbon bonds are known to chemists as **unsaturated** compounds. On the other hand, when all the carbon atoms of the hydrocarbon tail of an organic molecule are combined together by single bonds, the compound is described as **saturated**. This difference is illustrated in Figure 1.17.

Key terms

Unsaturated fatty acid A fatty acid in which one or more pairs of adjacent carbon atoms in the hydrocarbon chain are linked by a double covalent bond (represented as C=C).

Saturated fatty acid One in which all the bonds between carbon atoms in the hydrocarbon chain are single covalent bonds (represented as C-C).

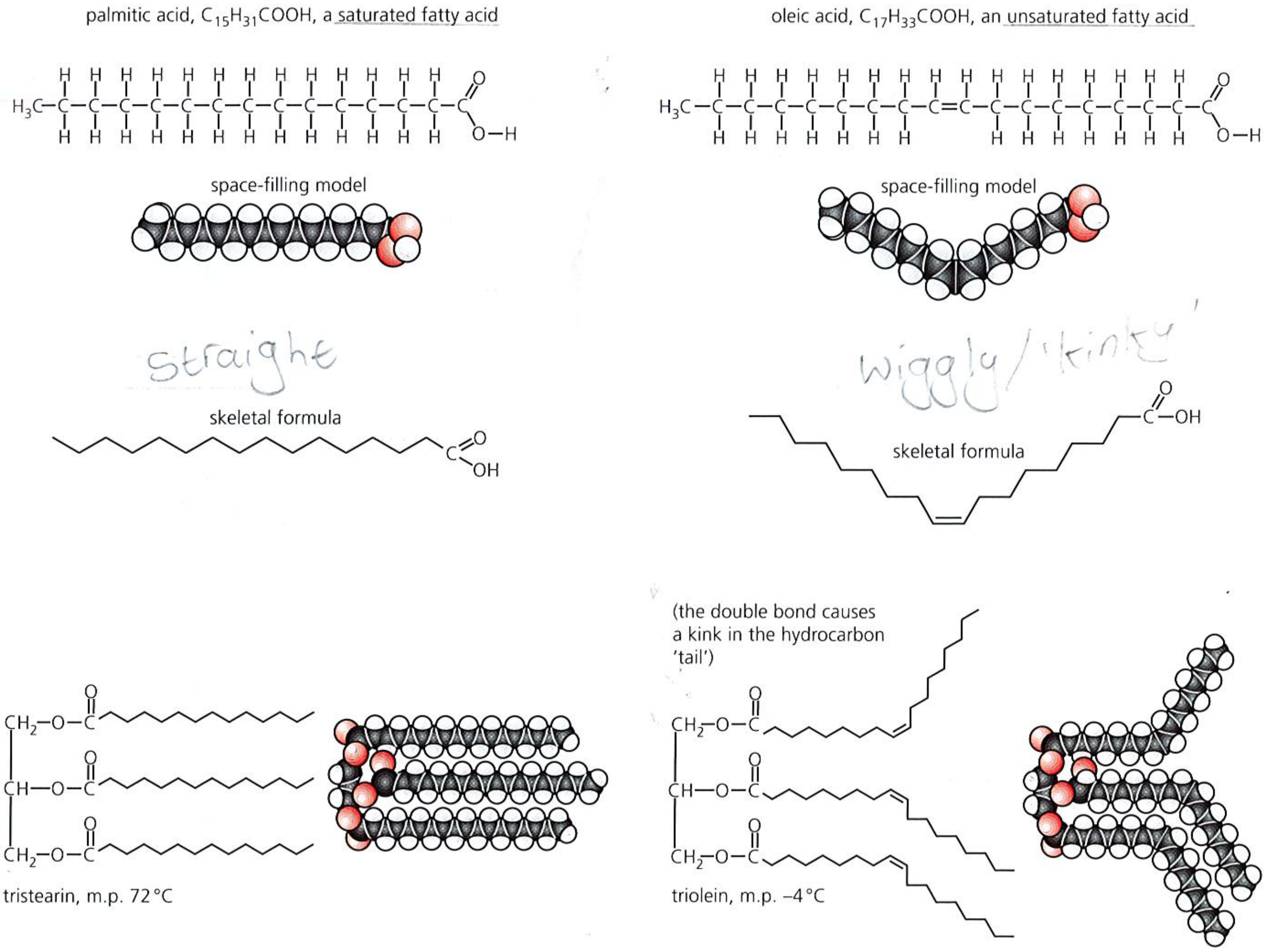


Figure 1.17 Saturated and unsaturated fatty acids and triglycerides formed from them

Test yourself

18 State the molecular formula of glycerol.

19 Name the type of bond formed by the condensation of glycerol and a single fatty acid to produce a monoglyceride.

20 A fatty acid can be represented as $CH_3–(CH_2)_n–COOH$. Would this represent a saturated or unsaturated fatty acid? Explain your answer.

21 Is a triglyceride a polymer? Explain your answer.

22 What makes a triglyceride hydrophobic?

The roles of lipids in living organisms

You need to be familiar with three ways in which the structure of lipids relates to their role in living organisms.

Energy storage

When triglycerides are oxidised during respiration, energy is released. Some is lost to the environment as heat but some is used to make ATP – the energy currency of cells, introduced in Chapter 9. Mass for mass, when fully respired, lipids release more than twice as much energy as do carbohydrates (Table 1.5). Lipids, therefore, form a more 'concentrated' energy store than do carbohydrates.

A fat store is especially typical of animals that endure long unfavourable seasons in which they survive on reserves of food stored in the body. Oils are often a major energy store in the seeds and fruits of plants, and it is common for fruits and seeds to be used commercially as a source of edible oils for humans, for example maize, olives and sunflower.

Table 1.5 Lipids and carbohydrates as energy stores – a comparison

Feature	Lipids	Carbohydrates
Energy released on complete breakdown / $kJ\,g^{-1}$	~37	~17
Ease of breakdown	Not easily hydrolysed – energy released slowly	More easily hydrolysed – energy released quickly
Solubility	Hydrophobic, so do not cause osmotic water uptake by cells	Sugars are highly soluble in water, so can cause osmotic water uptake by cells
Production of metabolic water	A great deal of metabolic water produced on oxidation	Less metabolic water produced on oxidation

Waterproofing

Since lipids are hydrophobic, they repel water.

Oily secretions from the sebaceous glands, found in the skin of mammals, act as a water repellent, preventing fur and hair from becoming waterlogged when wet. Birds have a preen gland that fulfils the same function for feathers. You might have seen birds preening – they use their beaks to spread lipids from this gland over their feathers.

Insulation

Lipids are poor conductors of both heat and hydrophilic ions.

Triglycerides are stored in mammals as adipose fat tissue, typically under the skin, where it is known as subcutaneous fat. Fat reserves like these have a restricted blood supply (Figure 1.18) so little body heat is distributed to the fat under the skin. In these circumstances, the subcutaneous fat functions as a heat insulation layer.

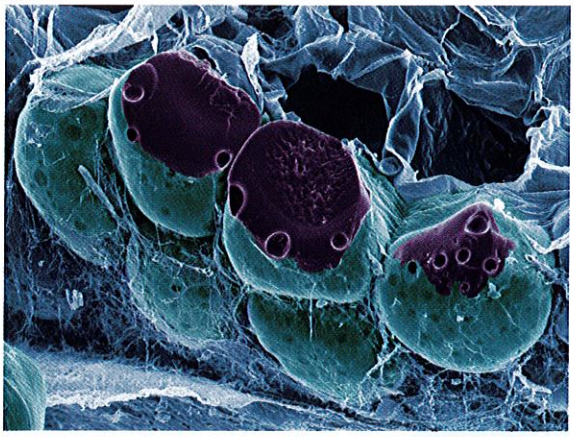


Figure 1.18 Adipose tissue

Myelin is a lipid found in the surface membranes of cells that wrap around the long fibres of nerve cells in animals (*Edexcel A level Biology 2*, Chapter 12). Over much of its length, the many layers of myelin insulate the fibre, preventing the passage of sodium and potassium ions that are essential for the conduction of the nerve impulse. As a result, nerve impulses travel along nerve fibres surrounded by myelin much faster than along those that are not surrounded by myelin.

Phospholipids

A phospholipid has a similar chemical structure to a triglyceride, except one of the fatty acid groups is replaced by a phosphate group.

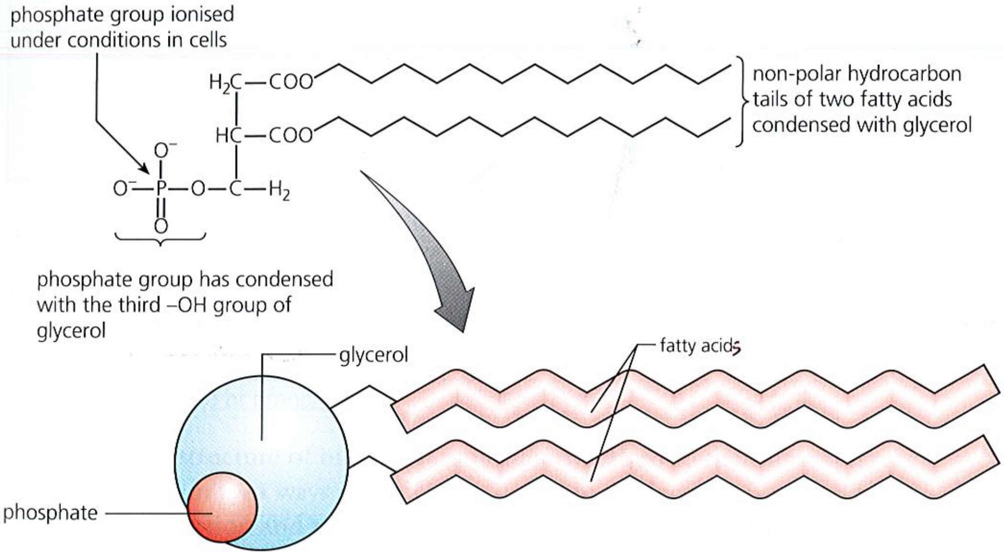
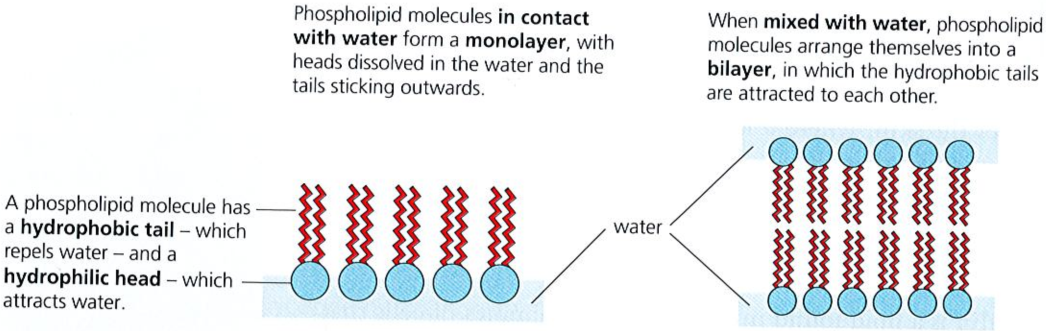


Figure 1.19 Phospholipid

You can see from Figure 1.19 that a phospholipid molecule has a 'head' composed of a glycerol to which is attached an ionised phosphate group. Since hydrogen bonds readily form between this phosphate group and water molecules, this part of the molecule has hydrophilic properties. The remainder of a phospholipid consists of two long, fatty acid residues, comprising hydrocarbon chains. As we have seen above, these 'tails' have hydrophobic properties.

So phospholipid molecules are unusual in being partly hydrophilic and partly hydrophobic. The effect of this is that a small quantity of phospholipid in contact with water will float, with the hydrocarbon tails exposed above the water. It forms a single layer (monolayer) of phospholipids (Figure 1.20).


Phospholipid molecules **in contact with water** form a **monolayer**, with heads dissolved in the water and the tails sticking outwards.

When **mixed with water**, phospholipid molecules arrange themselves into a **bilayer**, in which the hydrophobic tails are attracted to each other.

A phospholipid molecule has a **hydrophobic tail** – which repels water – and a **hydrophilic head** – which attracts water.

Figure 1.20 Phospholipid molecules and water

When slightly more phospholipid is added the molecules arrange themselves as a **bilayer**, with the hydrocarbon 'tails' facing together, away from the water, and the hydrophilic heads in the water (Figure 1.20). Their hydrophobic/hydrophilic nature and their ability to form a bilayer are two extremely important properties of phospholipids, as you will see when we consider cell surface membranes in Chapter 9.

Key term

Bilayer A single structure made of two layers of molecules, usually used to describe the arrangement of phospholipids in a cell membrane.

Test yourself

23 Some people believe that a camel stores water in its hump. In fact, the hump is a lipid store. Use information in Table 1.5 to suggest how this lipid store is an adaptation to living in desert conditions.

24 Explain how the structure of triglycerides results in their waterproofing properties.

25 How does a molecule of triglyceride differ from a molecule of phospholipid?

26 When mixed with water, phospholipids often form micelles – small droplets with the fatty acid 'tails' on the inside and the 'heads' on the outside. Suggest why.