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Chapter 1

Aspects of biochemistry

By the end of this chapter you should be able to:

a discuss how the structure and properties of water relate to the role that water plays as a medium of life;

b explain the relationship between the structure and function of glucose;

c explain the relationship between the structure and function of sucrose;

d discuss how the molecular structure of starch, glycogen and cellulose relate to their functions in living organisms;

e describe the generalised structure of an amino acid and the formation and breakage of a peptide bond;

f explain the meaning of the terms primary, secondary, tertiary and quaternary structure of proteins, and describe the types of bonding (hydrogen, ionic, disulphide) and hydrophobic interactions which hold the molecule in shape;

g outline the molecular structure of haemoglobin, as an example of a globular protein, and of collagen, as an example of a fibrous protein, ensuring that the relationships between their structures and functions are clearly established;

h know how to carry out tests for reducing and non-reducing sugars (including quantitative use of the Benedict's test), for starch and lipids and (the biuret test) for proteins;

i know how to investigate and compare quantitatively reducing sugars and starch;

j describe the molecular structure of a triglyceride and its role as a source of energy;

k describe the structure of phospholipids and their role in membrane structure and function.

The human body is made of many different types of molecule. Most of your body is water, which has small molecules made of two atoms of hydrogen combined with one atom of oxygen, formula H_2O. The other main types of molecule in organisms are proteins, carbohydrates, fats and nucleic acids. These molecules make up your structure, and they also undergo chemical reactions – known as **metabolic reactions** – that make things happen in and around your cells.

Up until the mid 1950s, we did not know very much about the structures of these molecules or how their structures might relate to the ways in which they behave. Since then, there has been an explosion of knowledge and understanding, and today a major industry has been built on the many applications to which we can put this knowledge. Biotechnology makes use of molecules and reactions in living organisms, and research continues to find new information about how molecules behave, and new uses for this technology in fields including medicine, agriculture, mining and food production.

In this chapter, we will look at the structures of the main types of molecule found in our bodies – and in those of every other living organism (Table 1.1). We will also see how these structures relate to the functions of the molecules.

Molecule	Percentage of total mass
water	60
protein	19
fat	15
carbohydrate	4
other	2

Table 1.1 Human body composition.

Water

Water is by far the most abundant molecule in our bodies. It is also one of the smallest and one of the simplest. Yet water is an amazing substance, with a collection of properties that is shared by no other. It is difficult to imagine how life of any kind could exist without water. The search for other life in the universe begins by searching for other planets that may have liquid water on them.

Water is a major component of all cells, often making up between 70% and 90% of the cell's mass. Your body is about 60% water. Water is also the environment of many living organisms, and life must have first evolved in water.

Water has very simple molecules, yet has some surprising properties. Other substances made of such small molecules tend to be gases at the temperatures found on most of the Earth, whereas water may be found as a solid, liquid or gas. The fact that water is often in liquid form allows it to act as the solvent in which metabolic reactions (the chemical reactions that take place in living organisms) can happen. Water provides a means of transporting molecules and ions from one place to another, because many of them can dissolve in it.

The structure of a water molecule

Figure 1.1a shows the structure of a water molecule. It is made up of two hydrogen atoms covalently bonded to one oxygen atom. The bonds are single covalent bonds, in which the single electron of each hydrogen atom is shared along with one of the six outer shell electrons of the oxygen, leaving four electrons which are organised into two non-bonding pairs. The bonds are very strong, and it is very difficult to split the hydrogen and oxygen atoms apart.

A covalent bond is an electron-sharing bond, and in this case the sharing is not equal. The oxygen atom gets slightly more than its fair share, and this gives it a very small negative charge. This is written δ− (delta minus). The hydrogen atoms have a very small positive charge, δ+ (delta plus). So, although a water molecule has a neutral electrical charge overall, different parts of it do have small positive and negative charges. This unequal distribution of charge in the molecule is called a **dipole**.

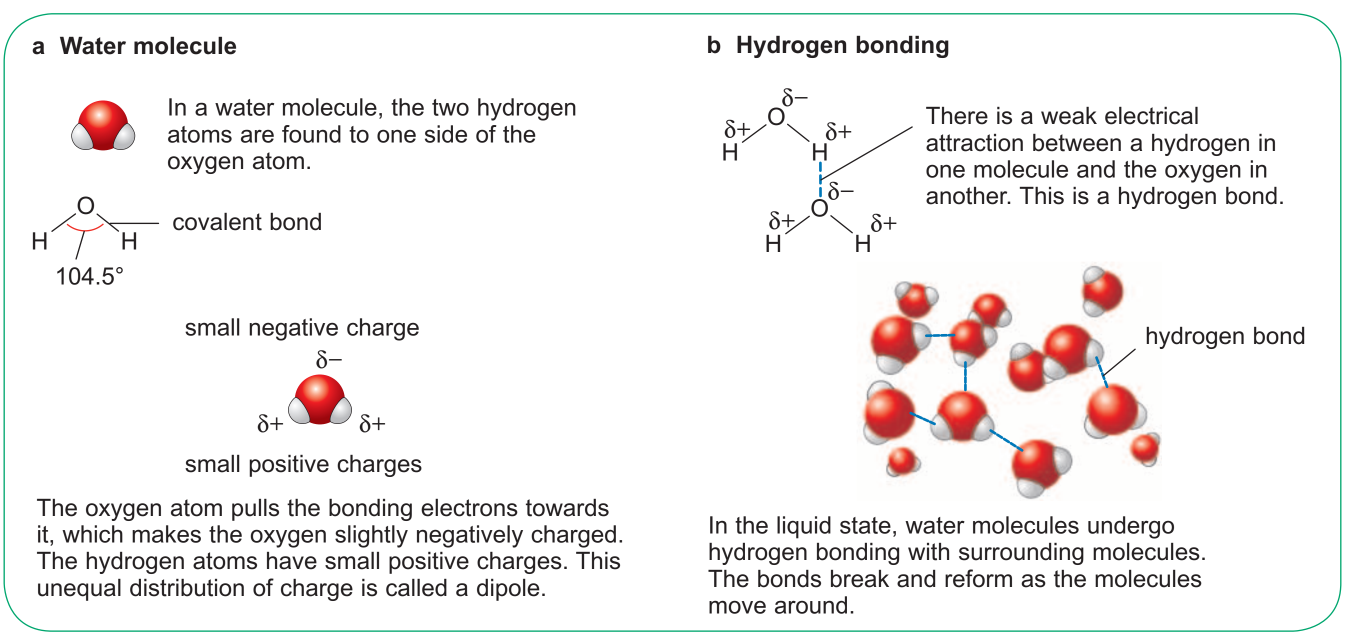

Figure 1.1 **a** The structure of a water molecule; **b** hydrogen bonding.

These tiny charges mean that water molecules are attracted to each other – the positively charged hydrogen atoms in one molecule are attracted to the negatively charged oxygen atoms in other molecules. The attraction is called a **hydrogen bond** (Figure 1.1b). Every water molecule is hydrogen bonded to its four nearest neighbours.

Hydrogen bonds are weak, long-distance bonds. As we will see later in this chapter, they are very common and very important in biological molecules.

In the next few pages, we will look in detail at some of the special properties of water, and how these make water so important to all living organisms.

Ice, liquid water and water vapour

In a solid substance, such as ice, the molecules have relatively little kinetic energy. They vibrate continuously, but remain in fixed positions. In liquid water, the molecules have more kinetic energy, moving around past each other, forming fleeting hydrogen bonds with each other. In water vapour, the molecules are far apart, scarcely interacting with each other at all.

In solid water – ice – the hydrogen bonds hold the water molecules in a rigid lattice formation. As in all solids, the molecules vibrate, but they do not move around. As the temperature of liquid water decreases, the water molecules have less and less kinetic energy and they slow down. This allows each molecule to form the maximum number of hydrogen bonds (four) with other water molecules. When this happens, the water molecules spread out to form these bonds. This produces a rigid lattice which holds the water molecules further apart than in liquid water (Figure 1.2). Ice is therefore less dense than liquid water, and so it floats. Hydrogen bonding is responsible for this unique property of water.

The fact that ice floats on liquid water is important for aquatic living organisms. As the temperature of the air above the water falls, the water at the surface also cools. The water freezes from the surface, forming a layer of ice with liquid water underneath. This happens because the maximum density of water occurs at 4 °C. As the surface water gets colder it gets denser and sinks to the bottom, displacing warmer water which rises to the surface and cools. However, when water gets colder than 4 °C, it becomes less dense than the warmer water below it and so it stays on the surface where it forms ice. The layer of ice insulates the water below it from further temperature changes. This water remains at 4 °C and stays liquid, providing an environment in which living organisms can continue to survive.

Changes in density of water as its temperature changes are the main cause of ocean currents and upwellings, which help to maintain the circulation of nutrients in seas and oceans.

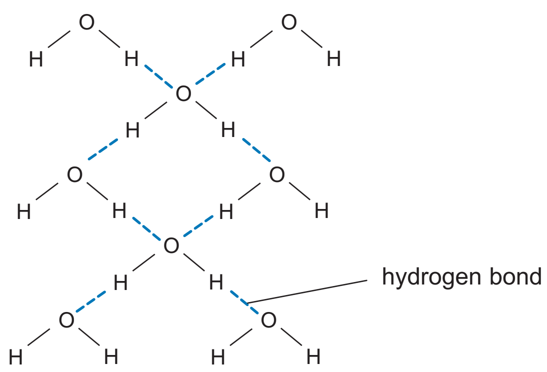

Figure 1.2 The structure of ice. Water molecules are held in a regular, fixed arrangement or lattice (shown in only two dimensions here).

Water, heat and temperature

Specific heat capacity

If you heat water, the temperature of the water rises. Temperature relates to the amount of kinetic energy that the water molecules have. As heat energy is added to the water, a lot of the energy is used to break the hydrogen bonds between the water molecules. Because so much heat energy is used for this, there is less heat energy available to raise the temperature. Water therefore requires a lot of heating in order to increase its temperature by very much. We say that it has a **high specific heat capacity**.

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The specific heat capacity of water is $4.2\,J\,g^{-1}\,°C^{-1}$. This means that it takes 4.2 joules of energy to heat 1 g of water by 1 °C.

You – like all living organisms – make good use of this property. Being largely water, your body does not change its temperature easily. Large changes in the temperature of your external environment have relatively small effects on the temperature of your body. This is true for all living organisms.

For organisms that live in water, it means that the temperature of their external environment is relatively stable. It takes a lot of heat energy in order to change the temperature in, say, a lake or the sea. Air changes its temperature much more easily, so terrestrial (land-living) organisms have to cope with far greater and faster temperature changes than aquatic organisms. Changes in temperature inside cells can result in disruption of metabolic reactions, most of which require enzymes to make them happen. As you will see in Chapter 4, enzymes require a stable temperature to function effectively.

Latent heat of vaporisation

The energy needed to break the hydrogen bonds between water molecules also affects water's boiling point. Other substances with molecules of a similar size and construction – such as hydrogen sulphide, H_2S – form gases at room temperature. There are no hydrogen bonds holding the hydrogen sulphide molecules together, so they are free to fly off into the air. However, because of the hydrogen bonds, water at room temperature is liquid. It has to be heated to 100 °C before all the molecules have enough energy to break apart from one another so that the water turns from a liquid to a gas.

In liquid water, even well below its boiling point, some of the individual molecules have greater kinetic energy than others. These may have enough energy to escape from the surface of the liquid and fly off into the air to form water vapour. This is called **evaporation**. Like boiling, it requires a lot of energy because it involves breaking hydrogen bonds. As these energetic molecules leave the liquid, they reduce its average temperature (because the molecules that are left behind are the less energetic ones). The energy involved is called the **latent heat of vaporisation**. Evaporation therefore has a cooling effect.

Once again, our bodies make good use of this property of water. When liquid sweat lies on the surface of the skin, the water in the sweat absorbs heat energy from the body as it evaporates (Figure 1.3). It is our major cooling mechanism. It also helps to cool plant leaves in hot climates, as water evaporates from the surfaces of the mesophyll cells inside them.

Latent heat of fusion

Water also requires a lot of energy to change state from a solid to a liquid, or from a liquid to a solid. To change ice to water, 300 J of energy are required for each gram of ice. To change water to ice, 300 J must be lost from each gram of water. This is called the **latent heat of fusion**. It means that it is quite difficult to freeze water, so it tends to stay a liquid. This is very important to living organisms because cytoplasm contains a lot of water. The high latent heat of fusion reduces the likelihood of ice crystals forming inside cells. Once frozen, most cells are permanently damaged, because ice

Figure 1.3 This scanning electron micrograph (SEM) (page 35) shows sweat droplets emerging from pores on human skin (×25).

crystals (which, you will remember, take up more space than liquid water) can pierce membranes.

Another factor that reduces the tendency of water to freeze is the presence of solutes. A salt solution has to be cooled well below 0 °C before it freezes. This is because the presence of the solute particles in between the water molecules disrupts the formation of hydrogen bonds between the water molecules, and therefore makes it more difficult for water molecules to assume the configuration they take up in ice (Figure 1.2).

Solvent properties of water

Water is an excellent **solvent**. The tiny charges on its molecules attract other molecules or ions that have charges on them (Figure 1.4 and Figure 1.5). The molecules and ions spread around in between the water molecules. This is called **dissolving**. A substance that dissolves in water is a **solute**, and the mixture of water and solute is called a **solution**.

Ionic compounds, such as sodium chloride, will generally dissolve in water. The ions have electrical charges on them, and these are attracted to the dipoles on the water molecules. The ions disperse among the water molecules.

Some covalent compounds can also dissolve in water. These tend to be ones that have small molecules and dipoles. Glucose and amino acids are examples of such compounds. (You can find out about the structures of glucose and amino acids on pages 8 and 14.) Even quite large covalent molecules can dissolve in water if they have plenty of small electrical charges on them. Many protein molecules come into this category, for example most enzymes and haemoglobin.

However, many other large covalent compounds are not soluble in water. These include starch, cellulose and other polysaccharides (pages 11 to 13) and many types of protein, especially fibrous proteins such as collagen (pages 20 to 21). Lipids are also insoluble in water (page 24).

The fact that water is such a good solvent is of huge importance to living organisms. When an ionic compound such as sodium chloride dissolves in water, the sodium ions and the chloride ions become separated from each other. This makes it easy for them to react with other ions or molecules. Many reactions, including most metabolic reactions, will only take place in solution, because this makes it possible for the ions or molecules to come into contact with each other. Cytoplasm contains many different substances dissolved in water, as do cell organelles such as mitochondria and chloroplasts (page 45).

Water can flow, and therefore it can carry dissolved substances from one place to another. This happens in our blood, and in the xylem

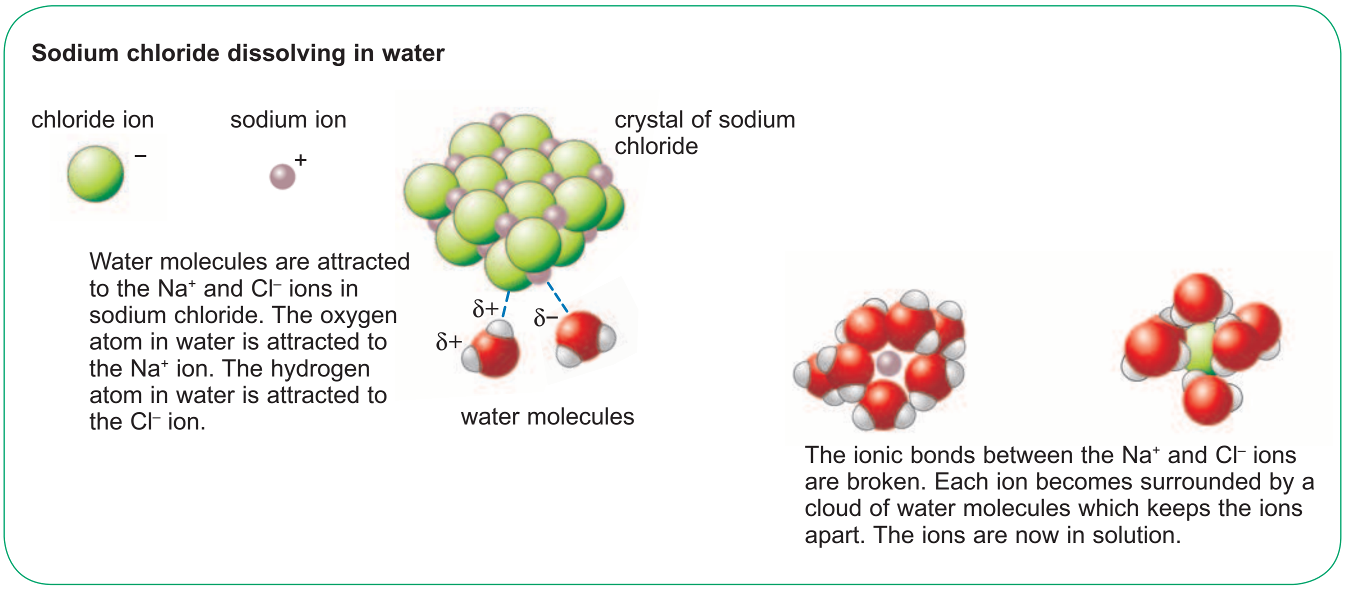

Figure 1.4 Water as a solvent. Sodium chloride readily dissolves in water.

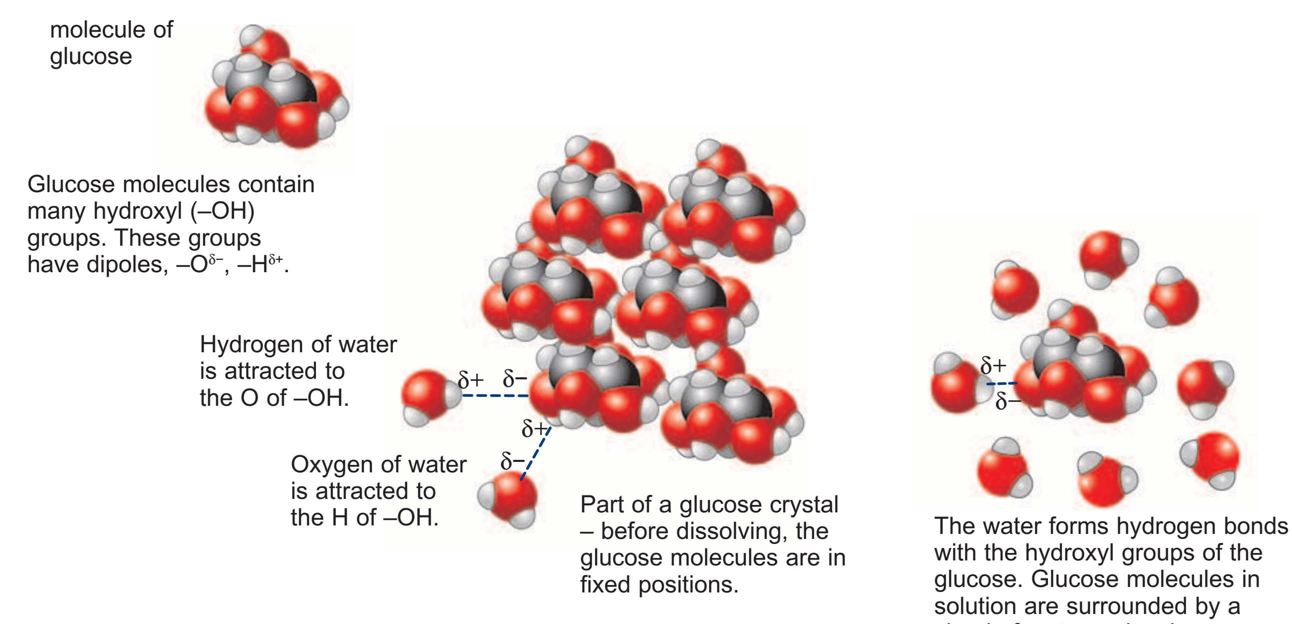

Figure 1.5 Water as a solvent. Glucose is a covalent molecule that dissolves in water.

vessels and phloem sieve tubes of a plant. Urea, the main nitrogenous excretory product of mammals, is removed from the body dissolved in water as urine.

Density and viscosity

Water molecules in liquid water are pulled closely together by the hydrogen bonds between them, and this makes water a relatively dense liquid. The density of pure water is 1.0 $g\,cm^{-3}$. Compare this, for example, with ethanol, which has a density of only 0.79 $g\,cm^{-3}$.

Most living organisms, containing a lot of water, have a density which is quite close to that of water. This makes it easy for them to swim. Aquatic organisms often have methods of slightly changing their average density – for example, by filling or emptying parts of their body with air – to help them to float or to sink.

It takes quite a lot of effort to swim through water. You have to push aside the molecules, which are attracted to one another and therefore reluctant to move apart. We say that water is a fairly **viscous** fluid. This is why aquatic organisms are often streamlined; their shape helps them to cut through water more easily.

Cohesion and surface tension

Water molecules tend to stick together, held by the hydrogen bonds that form between them. In liquid water, these bonds constantly form and break, each lasting for only a fraction of a second. The attractive force produced by these hydrogen bonds is called **cohesion**.

Cohesion makes it easy for water to move by **mass flow** – that is, a large body of water can flow in the same direction without breaking apart. This is important in the flow of blood in animals, and in the flow of water within xylem vessels in plants. It is also important in the formation of waves and other water movements that occur in lakes and oceans. These play a large part in the distribution of heat, dissolved gases and nutrients. They also determine the distribution of plankton (small organisms that drift in water).

We have seen that, within a body of water, each water molecule is attracted to others all around it. However, on the surface, the uppermost molecules have other molecules only below them, not above. So they are pulled downwards. These pulling forces draw the molecules closer together than in other parts of the water. This phenomenon is called **surface tension**. It forms a strong layer on the

Figure 1.6 The water strider hunts by running over the surface of the water.

surface of the water – so strong that small animals are able to walk on it without difficulty (Figure 1.6).

pH

pH is a measure of the concentration of hydrogen ions in a solution. The more hydrogen ions, the lower the pH. A solution with a pH of 7 is neutral. A pH below 7 is acidic; a pH above 7 is alkaline.

Water itself is partially dissociated into hydrogen and hydroxide ions:

$$H_2O \rightleftharpoons H^+ + OH^-$$

As there are equal amounts of hydrogen ions (protons) and hydroxide ions in pure water, it has a pH of 7.

Some substances that dissolve in water tend to produce either hydrogen ions or hydroxide ions. Some proteins are able to 'soak up' these hydrogen or hydroxide ions, preventing the pH of the solution from changing. They are called **buffers**, and they are very important in living organisms because they help to maintain an ideal pH for enzymes to work. Cytoplasm and tissue fluids in living organisms are usually well buffered, so their pH is generally somewhere between 7 and 8.

Transparency

Pure water is **transparent** to the visible wavelengths of light. This allows aquatic photosynthetic organisms, such as phytoplankton and algae, to obtain enough light for photosynthesis.

However, light only travels a certain depth through water, and so the depths of the oceans are totally dark. Blue light is able to pass through greater depths of water than red and green light.

Reactivity

Water takes part in many metabolic reactions. For example, when large polymer molecules (such as starch or proteins) are broken down into their simpler units, water is involved. These are **hydrolysis** reactions, and they occur throughout all living organisms. The hydrolysis of carbohydrates and proteins is described on pages 9 and 15.

Water is also used in **photosynthesis**, where it provides hydrogen ions that are combined with carbon dioxide to make sugars. The oxygen atoms from the water molecules are released as oxygen gas. This is the source of the oxygen that we breathe.

SAQ

1 Explain each of these statements.
  a Sweating can cool the body to below the temperature of the air surrounding it.
  b A long column of water moves up through xylem vessels without breaking.
  c Small covalent molecules such as glucose can dissolve in water.
  d Reactions can occur in solution that would not occur if the reactants were in a solid state.
  e Sea water will only freeze if the temperature drops well below the freezing point of fresh water, 0 °C.

Carbohydrates

Carbohydrates are substances whose molecules are made up of sugar units. The general formula for a sugar unit is $C_nH_{2n}O_n$. Carbohydrates include sugars, starches and cellulose. Sugars are always soluble in water and taste sweet. Starches and cellulose, which are both examples of polysaccharides, are insoluble in water and do not taste sweet (page 11).

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Monosaccharides

A carbohydrate molecule containing just one sugar unit is called a **monosaccharide**. Monosaccharides cannot be further hydrolysed. A monosaccharide is the simplest form of sugar.

Monosaccharides have the general formula $(CH_2O)_n$. They can be classified according to the number of carbon atoms in each molecule. Trioses have 3C, pentoses 5C and hexoses 6C (Table 1.2). Glyceraldehyde, ribose, glucose, fructose and galactose are examples of monosaccharides. **Glyceraldehyde** is a triose and is the first carbohydrate formed during photosynthesis. **Ribose** (a pentose) is a fundamental constituent of RNA, and a similar pentose, **deoxyribose**, is found in DNA. **Glucose** (a hexose) is the main respiratory substrate in many cells, providing energy when it is oxidised. All sugars taste sweet, and **fructose** is often found in fruits and in nectar – here, it attracts insects and other animals, which might then inadvertently disperse the plant's seeds, or transfer pollen from one flower to another.

In Figure 1.7, the sugars are all shown in their straight chain forms. However, pentoses and hexoses are usually also able to flip into a ring form, in which the chain links up with itself. Figure 1.8 shows the structure of two different ring forms of glucose. You can see that, in both of them, carbon atom 1 joins to the oxygen on carbon atom 5. The ring therefore contains oxygen, but carbon atom 6 is not part of the ring. In solution, glucose (and other monosaccharide) molecules continually flip between their ring and chain forms.

This ring can exist in two forms, known as **α-glucose** (alpha glucose) and **β-glucose** (beta glucose). Both of them have a six-membered ring, made up of five carbons and one oxygen. They differ only in the orientation of the −H and −OH groups on carbon 1. The alpha position is defined

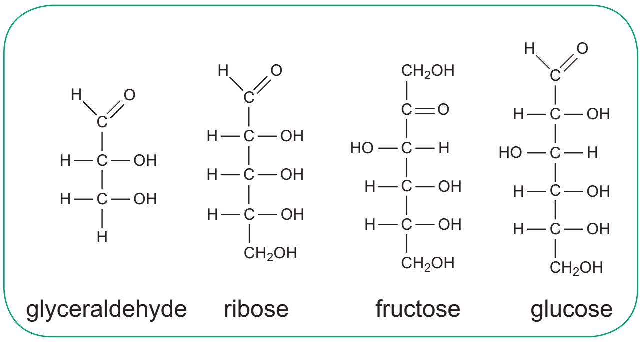

Figure 1.7 The straight chain structures of some common monosaccharides. Diagrams like this are called structural formulae.

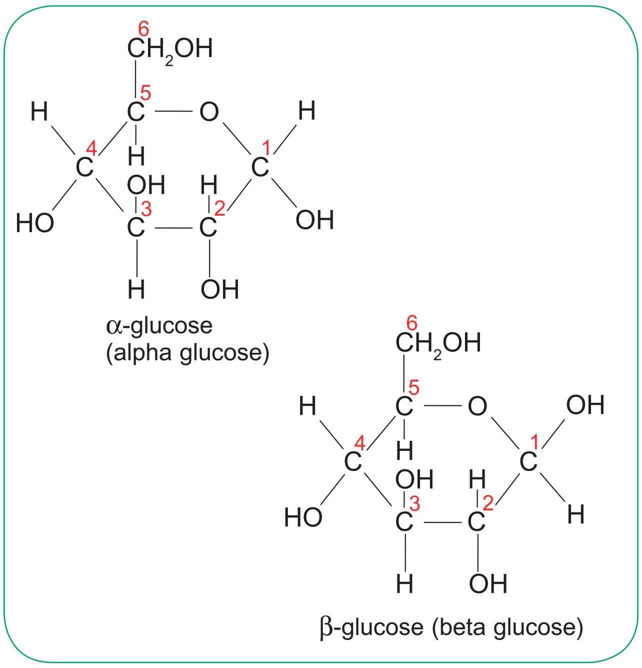

Figure 1.8 The ring forms of glucose molecules.

Type of sugar	Example	Functions
triose	glyceraldehyde	mainly as intermediates in metabolic pathways such as glycolysis (respiration) and in photosynthesis
pentose	ribose, deoxyribose	constituents of macromolecules (e.g. RNA, DNA, ATP)
hexose	glucose, fructose, galactose	soluble form of chemical energy that can be released by respiration; stored in some fruits to aid dispersal of seeds; found in nectar and honey (fructose and glucose)

Table 1.2 Some examples of monosaccharides.

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as the −OH being on the opposite side of the ring from carbon 6. The beta position is defined as the −OH being on the same side as the ring as carbon 6.

Figure 1.9 shows some different forms that can be taken up by a molecule of fructose. Unlike glucose, it forms a five-membered ring, containing four carbon atoms and one oxygen atom. The closure of the ring occurs between carbon 2 and carbon 5. As with glucose, alpha and beta forms exist.

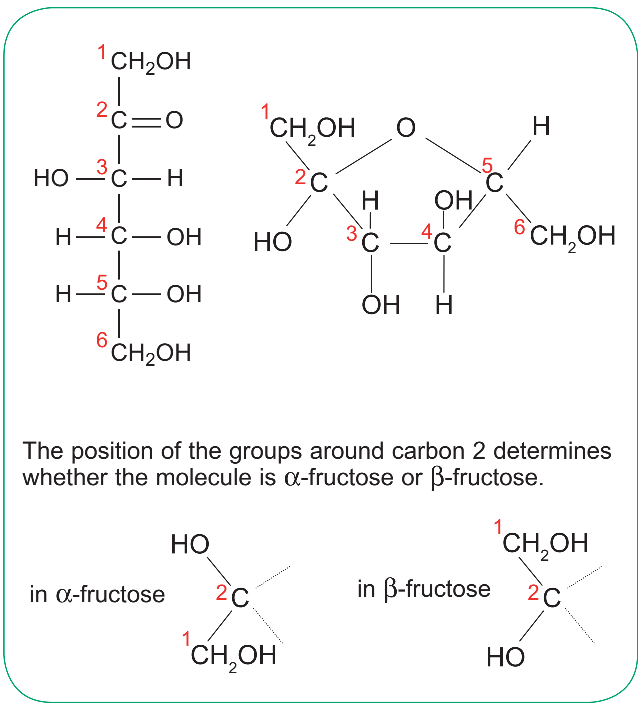

Figure 1.9 Structural formulae of straight chain and ring forms of fructose. In the diagram of the ring, fructose is shown in a non-standard orientation with the numbers running anticlockwise.

SAQ

2 The molecular formula for a hexose sugar is $C_6H_{12}O_6$. Write the molecular formulae for
- **a** a triose
- **b** a pentose.

Disaccharides

Two monosaccharide molecules can link together to form a sugar called a **disaccharide**. Like monosaccharides, disaccharides are soluble in water and taste sweet.

For example, two α-glucose molecules can react to form **maltose** (Figure 1.10). This is a condensation reaction, in which a water molecule is removed. The linkage formed between the two monosaccharides is called a **glycosidic bond**. It involves covalent bonds, and is very strong. In maltose, the glycosidic bond is formed between carbon atom 1 of one molecule and carbon atom 4 of the other. Both molecules are in the α form. We can describe this as an **α 1–4 glycosidic bond**.

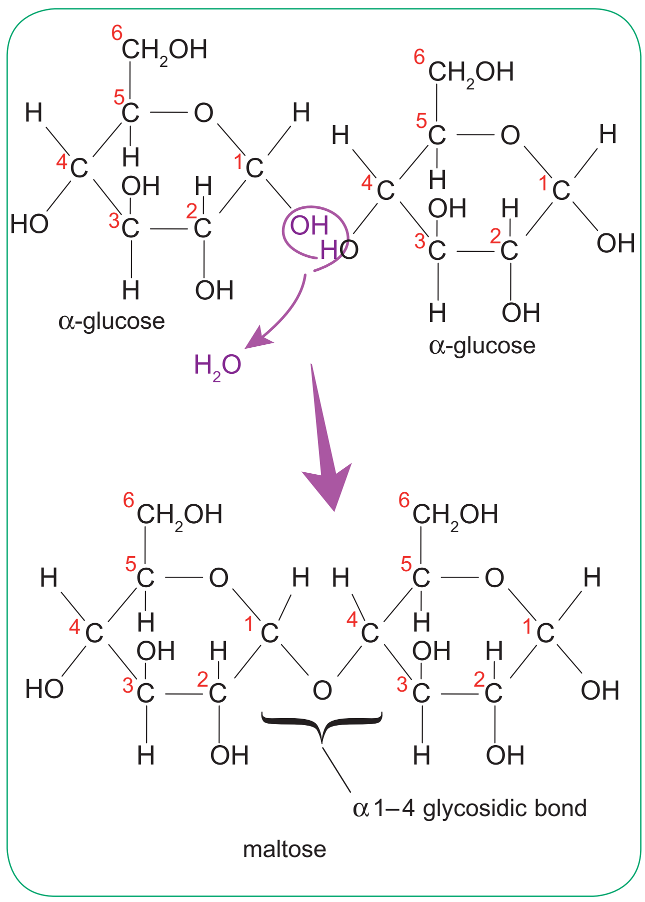

Figure 1.10 The formation of a glycosidic bond by a condensation reaction.

When carbohydrates are digested, glycosidic bonds are broken down by carbohydrase enzymes. The enzyme that breaks maltose apart is called maltase. This is a **hydrolysis reaction** (Figure 1.11).

Sucrose, ordinary table sugar, is a disaccharide that occurs naturally in the plant kingdom, especially in sugar cane, where it makes up 20% by weight, and in beets, where it makes up 15% by weight. As a result, sucrose is often known as cane sugar or beet sugar. Sucrose is the main form in which carbohydrates are transported in plants.

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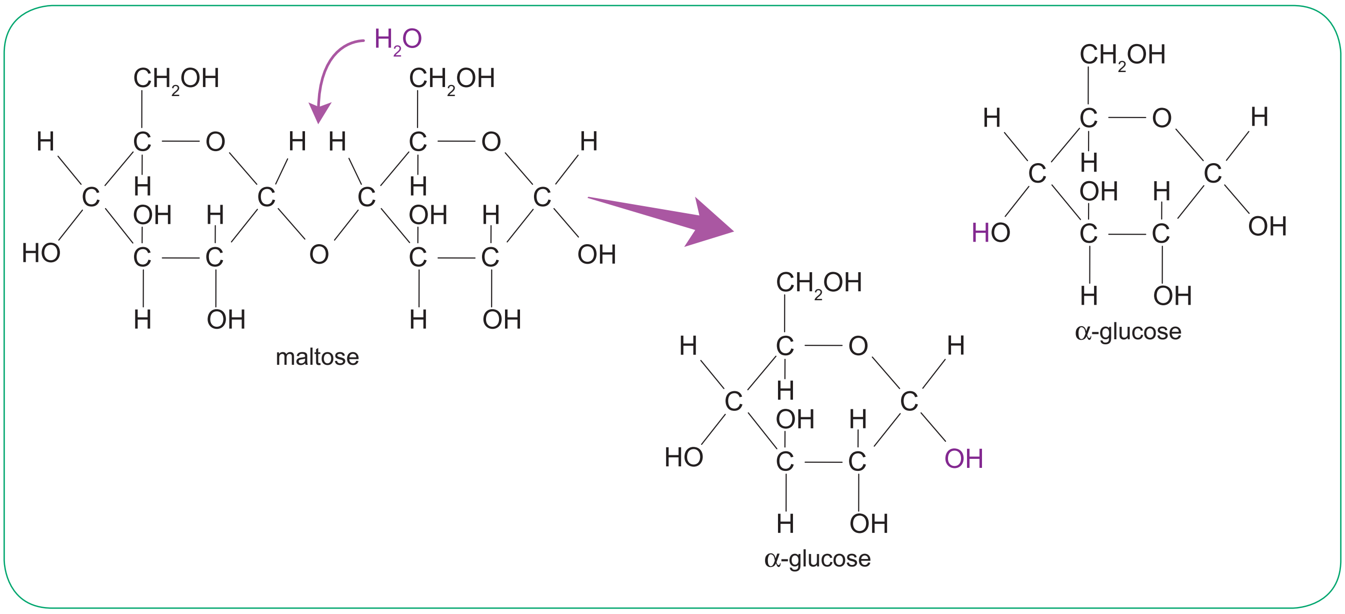

Figure 1.11 The breakage of a glycosidic bond by a hydrolysis reaction.

A sucrose molecule is made up of an α-glucose molecule linked to a β-fructose molecule by a 1–2 glycosidic bond (Figure 1.12). This is therefore an α 1–β 2 bond.

Sucrose can be an important source of energy for the human body. The enzyme sucrase hydrolyses sucrose to glucose and fructose. The fructose molecule is then rearranged (isomerised) to form glucose. Hence, every sucrose molecule produces two glucose molecules that can be used in respiration.

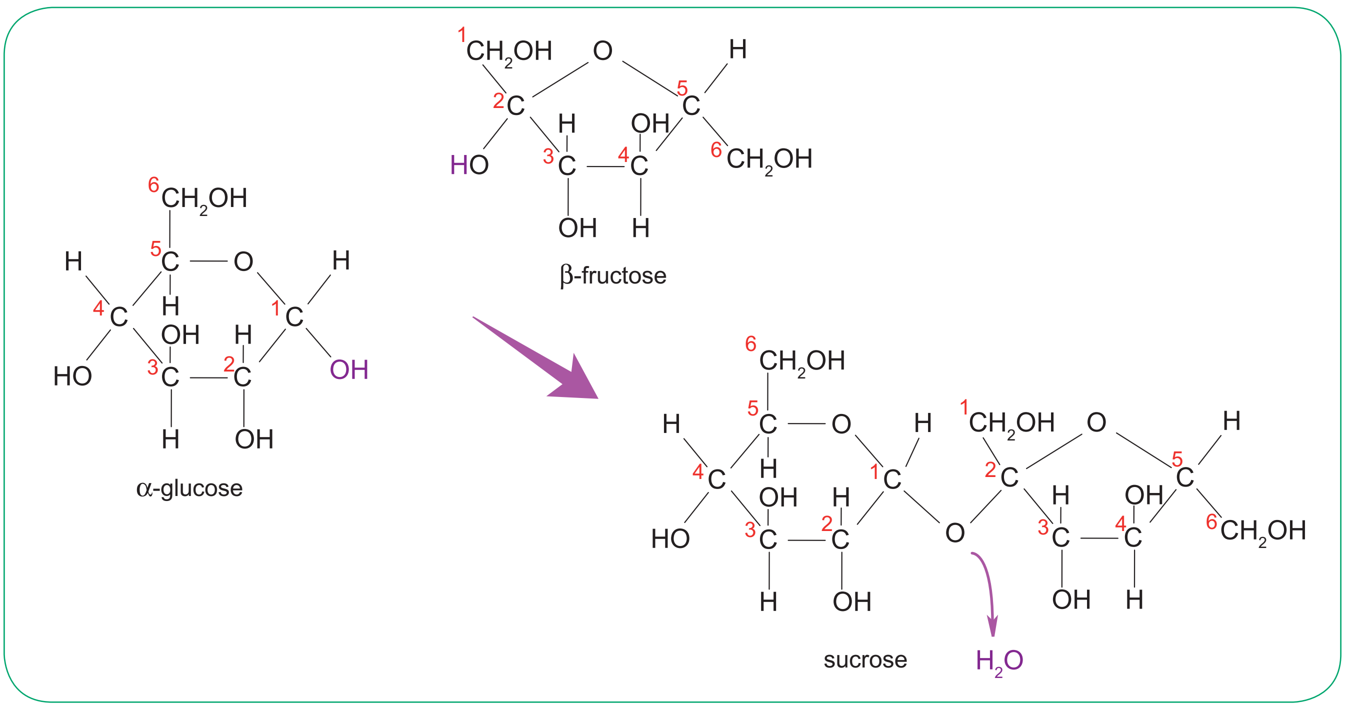

Figure 1.12 Formation of sucrose from glucose and fructose.